BY RICK DARBY

Slippery When Wet

Grooved runways help, but a variety of other safety measures also could reduce wet-runway overruns.

Worldwide, the likelihood of a jet or large turboprop overrunning the runway on landing was about seven times greater when the runway was wet rather than dry, based on accidents during the period 1990–2007. The risk of an overrun accident when landing on a grooved wet runway was significantly lower than that.

Those are among the findings of a study performed by a consulting firm for Transport Canada.[1] The study, designed to assess the costs and benefits of regulatory options to change procedures for landing on wet runways, resulted in a report that considered the problem of these landings from many aspects.[2]

"Degraded aircraft performance on wet runways has accounted for the majority of aircraft accident overruns on landing," the report says. "Recent catastrophic accidents in São Paulo, Brazil, and Toronto, Ontario, have highlighted the concerns of landing on wet runways."[3]

Based on a detailed examination of wet runway landing overrun occurrence reports and studies, aircraft test data and analysis of landing performance on wet runways, a computer model was created for estimating the distribution of required landing distances under specific conditions. "This model was used to estimate the risks and benefit-costs for a range of aircraft under various conditions to provide an understanding of the risks and the likely overall benefit-costs of the alternate regulatory options considered," the report says.

The accident and incident analysis and computer model showed that "the risks of overrun accidents are much lower in countries or regions where runways are grooved." Those with grooved runways at major airports include Australia, much of Europe, Hong Kong, Japan, Malaysia, the United Kingdom, the United States and other countries. Canada is an exception; almost none of its runways are grooved, the report says.

"The ratio of the risk of an overrun accident on a wet runway compared to the risks on a dry runway was estimated to be approximately 10 on un-grooved/non-PFC (porous friction course) runways and 2.5 on grooved/PFC runways," the report says. "Grooved or PFC runway reduced the risks of an accident on a wet runway by approximately 75 percent."

A review of landing overruns in Canada from 1989 through March 2007 identified 27 involving jets and 11 involving turboprops. Of the 27 jet overruns, the runway was wet for 10, or 37 percent, and contaminated for 14, or 52 percent.[4] Almost half of the jet overruns involved large passenger-carrying aircraft in scheduled or major charter carrier service. The remaining approximately 50 percent of overruns were disproportionately high for the operators' level of exposure. "Since approximately 90 percent of jet aircraft movements are conducted by large passenger aircraft, the risk of aircraft overruns is far greater for cargo and corporate jet aircraft," the report says.

Four of the 27 jet overruns resulted in serious injuries or substantial aircraft damage, and there were no fatalities. The 2005 Toronto overrun produced 12 serious injuries and destroyed the A340 (*ASW*, 2/08, p. 40). "Considering both the jet and turboprop overruns, in most cases where the aircraft was damaged or destroyed, the aircraft struck an object or went down a slope or ravine," the report says. "In only a few cases was the aircraft damaged where the overrun area was flat and free of objects, usually the nose wheel breaking off."

Overrun distances — the distance traveled past the end of the runway — varied from 10 to 1,500 ft (three to 457 m; Figure 1). "Surprisingly, overrun distances tended to be greater for occurrences on wet runways than on contaminated runways," the report says.

In the United States, between 1990 and 2006, 27 landing overruns involving large turboprops and jets were identified. Although runway conditions were not always specified in the occurrence reports, the runway was classified as wet for 10, or 37 percent, of the occurrences and contaminated for three occurrences, or 11 percent. The risk ratio of landing overruns for wet versus dry runways was in the range of 4 to 6, the report says, and considering accidents only, the risk ratio was between 3 and 5.

"Aircraft without reverse thrust or disking [flat pitch] capability are also over-represented in overrun occurrences for wet runways," the report says. It cites downhill runway grade as a factor in 40 percent of wet runway overruns, compared with 26 percent of all overruns. Tail wind was a factor in 30 percent of wet runway overruns, compared with 26 percent of all overruns. Other factors, such as excessive speed, landing long, improper braking and equipment failure or malfunction, were not correlated with wet runways.

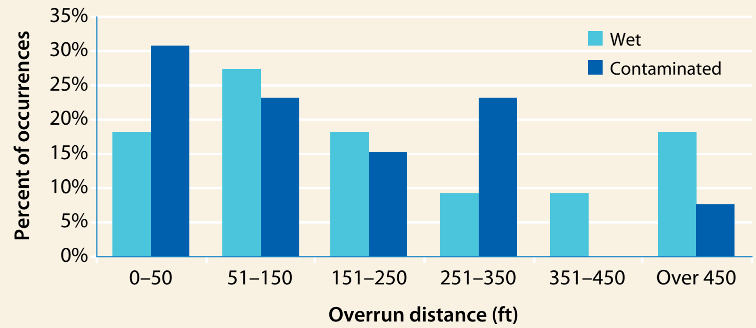
Of the five wet runway accidents examined, two were on un-grooved runways, and in one of those, hydroplaning occurred. Three were on grooved runways, and two of the three occurred during heavy rain.

In countries other than Canada and the United States, 40 landing overrun accidents were identified between 1990 and 2007 (Table 1). Fifty-five percent were on wet runways, and 5 percent on runways contaminated by ice and/or snow. More than half were fatal.

"Of the 40 accidents, in only three cases was the runway known to be grooved, and for all three, the runway was dry at the time of the accident," the report says. "None of the 22 wet runway accidents were on runways known to be grooved at the time of the accident."

Approximate landing overrun accident rates were calculated for the period 1990–2006 for Canada, the United States and the rest of the world (Table 2). "The rate for wet runway conditions increases by a factor of

Landing Overrun Distances, Canadian Jets, 1989–March 2007



Source: Jacobs Consultancy Canada

Figure 1

Landing Overrun Accidents, Large Jets and Turboprops, Excluding United States and Canada, 1990–2007

		All Accidents		Wet Runway Accidents	
Consequences	Accidents	40	100%	22	100%
	Number of fatal accidents	19	48%	13	59%
Runway condition	Dry	4	10%	0	0%
	Unknown	12	30%	0	0%
	Wet	22	55%	22	100%
	Snow/ice	2	5%	0	0%
Operator/ service	Passenger jet	25	63%	17	77%
	Passenger turboprop	8	22%	2	10%
	Cargo	7	19%	3	15%
Aircraft type	Jet	32	80%	20	91%
	Turboprop	8	20%	2	9%

Source: Jacobs Consultancy Canada

Table 1

Approximate Landing Overrun Accident Rates, 1990–2006

		All Runway Conditions		Wet Runway Conditions	
Countries	Annual Landings	Number of Accidents	Rate/Million Landings	Number of Accidents	Rate/Million Landings
U.S.	11,332,000	18	0.09	5	0.2
Canada	929,000	4	0.25	3	1.7
Rest of the world	13,683,000	37	0.16	20	0.6
Total	**25,944,000**	**59**	**0.13**	**28**	**0.4**

Note: Runways were assumed to be wet 11 percent of the time in Canada, 12 percent in the United States and 15 percent for the rest of the world.

Source: Jacobs Consultancy Canada

Table 2

Frequency of Runway Conditions at European Airports

Country	Aircraft Landings	Wet/ Contaminated	Estimated Contaminated	Estimated Wet	Dry
Austria	123,772	24.0%	4.0%	20.0%	76.0%
Belgium	143,351	22.0%	2.0%	20.0%	78.0%
Denmark	160,431	19.0%	3.0%	16.0%	81.0%
Finland	123,614	21.0%	5.0%	16.0%	79.0%
France	780,890	14.0%	2.0%	12.0%	86.0%
Germany	849,203	23.0%	5.0%	18.0%	77.0%
Greece	145,026	5.0%	0.0%	5.0%	95.0%
Ireland	94,143	29.0%	0.0%	29.0%	71.0%
Italy	562,159	11.0%	1.0%	10.0%	89.0%
Luxembourg	22,599	20.0%	4.0%	16.0%	80.0%
Netherlands	217,137	20.0%	3.0%	17.0%	80.0%
Norway	315,806	26.0%	5.0%	21.0%	74.0%
Poland	56,392	19.0%	5.0%	14.0%	81.0%
Portugal	100,052	9.0%	0.0%	9.0%	91.0%
Spain	571,605	6.0%	0.0%	6.0%	94.0%
Sweden	275,322	19.0%	5.0%	14.0%	81.0%
Switzerland	254,665	20.0%	5.0%	15.0%	80.0%
Turkey	250,000	12.0%	0.0%	12.0%	88.0%
United Kingdom	886,949	20.0%	1.0%	19.0%	80.0%
Overall	**5,933,116**	**17.1%**	**2.4%**	**14.7%**	**82.9%**

Note: Aircraft include commercial jets and large turboprops. "Contaminated" includes snow, ice and slush.

Source: Jacobs Consultancy Canada:

Table 3

three overall, but the variation between countries is more pronounced," the report says. "The rate for Canada increases six-fold, for the rest of the world it increases four-fold, while the U.S. rate only doubles. The Canadian rate is eight times the U.S. rate, and the rate for the rest of the world is three times that of the U.S. … The Canadian rate is based on a very small number of accidents, three, but is statistically significantly higher than the U.S. rate at the 0.01 significance level [a probability of one in 100 that the result is due to chance] and the high rate is consistent with the increased risks associated with un-grooved runways. The rate for the rest of the world is based on many more accidents and the high rate is also consistent with a significant proportion of the landings being on un-grooved runways."

An analysis of runway conditions at five major Canadian airports during November through March determined that the runways were wet 12.1 percent of the time. Another analysis found that the percentage of movements on wet runways in Europe varied from 5 percent in Greece to 29 percent in Ireland (Table 3). For the 19 countries, taking into account the numbers of landings in each country, it was estimated that typically 15 percent of landings are conducted on wet runways.

Aviation regulations in Canada, the United States and Europe require that the runway conditions at the destination airport be taken into account before an airplane is dispatched. The landing weight of the airplane must allow a full-stop landing within 60 percent of the landing distance available for jets and 70 percent for turboprops.[5]

The report says that while Canadian, U.S. and European civil aviation authorities require the airplane flight manual (AFM) to include information about an adjustment factor for landing on *contaminated* runways, "there is no such requirement for landing performance on a wet runway. The only specific operational requirement for landing when the runway is wet is that an additional factor of 15 percent be applied to the landing field length required."

The extra 15 percent, or more, may compensate for poor braking. The report says, "The effectiveness of braking on a wet runway is reduced due to hydroplaning; i.e., when the rolling or sliding tire is lifted away from the pavement surface as a result of water pressures built up under the tire. Braking efficiency on a wet runway depends on the surface texture of the runway and whether the runway is grooved; the tread depth and type of the tire; tire pressure; rubber contamination on the runway; and the depth of water.

"Braking friction is far more dependent on these factors on a wet runway than a dry runway. Also, braking friction on a dry runway is fairly constant with aircraft speed, but on wet runways the friction is much less at high speeds, especially on smooth runways and/or with low tread-depth tires. Thus, situations where the aircraft has higher landing ground speeds such as tail winds and/or high loads result in a greater loss of friction and longer stopping distances."

Airplane operating manuals (AOMs) of five Canadian carriers and AFMs of two manufacturers showed wet/dry landing distance ratios for eight aircraft types, all based on using reverse thrust or an equivalent (Figure 2).[6] Six of the aircraft types have a wet/dry ratio of 1.15 to 1.22. Two have a higher ratio of 1.36 and 1.38, respectively.

The wet/dry landing distance ratios were reviewed for six of the aircraft types when the runway is covered with 6 mm (0.24 in) of water. They range from 1.35 to 1.55.

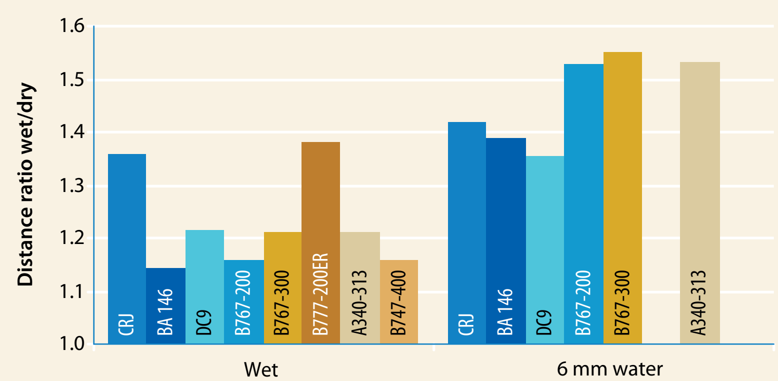
The wet/dry landing distance ratio also varies with the weight (Figure 3). For the McDonnell Douglas DC-9, British Aerospace (now BAE Systems) 146 and Canadair Regional Jet (CRJ), the wet/dry ratios are 2 to 5 percent higher for high weight compared with low weight.

Reverse thrust significantly affects the landing distance calculation for wet runways. The wet/dry landing distance ratios obtained from its AOM for a Boeing 747-400 for no, partial and full use of reverse thrust when landing on a wet runway are 1.16, 1.26 and 1.41 respectively. The report says, "With full reverse [thrust], the landing distance ratio is close to the 15 percent wet runway dispatch adjustment factor, but the landing distance increases by 21.6 percent … when reverse thrust is not used."

A Transport Canada landing performance study modeled the effect of reverse thrust for several aircraft and runway types. The average effect of not using reverse thrust on wet runway landing distance was as follows:

- Category B/C (un-grooved) runway, 10.5 percent increase;
- Category D/E (grooved) runway, 80 percent anti-skid efficiency, 6.6 percent increase; and,
- Category D/E, 90 percent anti-skid efficiency, 4.9 percent increase.

Wet vs. Dry Landing Distance
With Reverse Thrust for Selected Aircraft Types

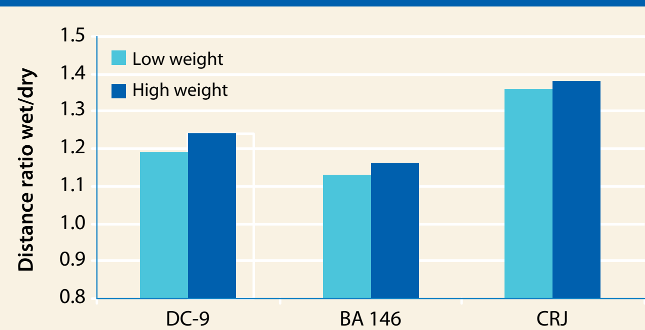


Note: Data were obtained from aircraft operations manuals and aircraft flight manuals.

Source: Jacobs Consultancy Canada

Figure 2

Effect of Aircraft Weight on
Wet/Dry Landing Distance for Selected Aircraft Types



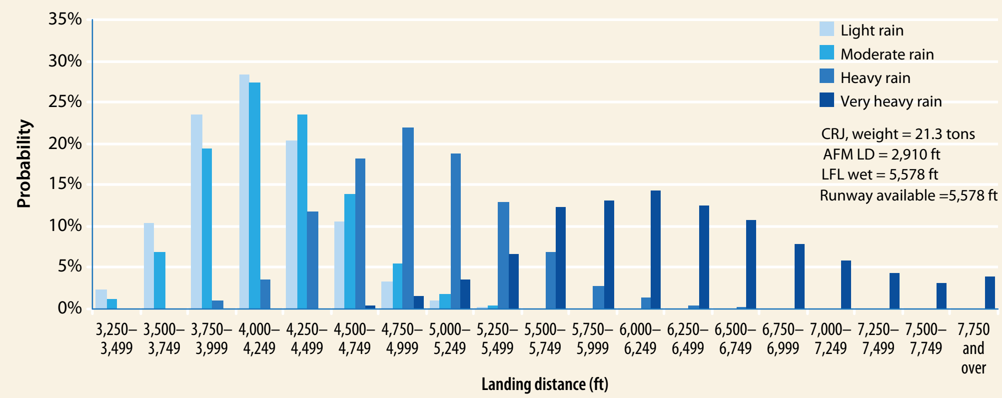
Source: Jacobs Consultancy Canada

Figure 3

The current adjustment factor for wet runways does not take into account whether jets have reverse thrust capability or turboprops have disking capability, the report says.

The consultants conducted a risk analysis for common aircraft types landing on wet runways under various conditions of runway lengths available, grades and altitudes, as well as factors such as wind speeds and aircraft weights. One example was a probability distribution of landing distances for a CRJ at maximum landing weight on a 5,578 ft (1,700 m) wet, un-grooved runway (Figure 4). With no or light rainfall, the chance of an overrun was found to be "very low." In moderate rainfall, the landing distance increased, but the odds of an overrun were still "low."

Probable Landing Distances for a CRJ on a Wet 5,578 ft Runway



CRJ = Canadair Regional Jet; AFM LD = aircraft flight manual landing distance; LFL = landing field length.

Note: Aircraft is a Canadair Regional Jet, weight restricted.

Source: Jacobs Consultancy Canada

Figure 4

Using the risk model, the report considers three proposed regulatory alternatives for an increased dispatch factor for landing on wet runways. "Currently, the only additional requirement related to landing on wet runways is that at the time of dispatch, the landing field length required must be increased by 15 percent," the report says. "This results in a factor which must be applied to the AFM landing distance of 1.92 for turbojet aircraft and 1.64 for turboprop aircraft."

The proposed alternatives are:

Option 1. Increased Dispatch Factors and No En Route Requirement

The wet runway landing dispatch factor would be set as follows:

- Jet without reverse thrust: 2.00 (grooved or PFC runways), otherwise 2.45.
- Jet with reverse thrust: 1.92 (grooved or PFC runways), otherwise 2.10.
- Turboprop: 1.64 (grooved or PFC runways), otherwise 1.90.

Option 2. Increased Dispatch Factors Plus En Route Requirement

In addition to the dispatch factors in Option 1, there would be a requirement that at the beginning of the final approach:

- If the runway is un-grooved and the depth of water on the runway is greater than 3 mm (0.12 in) or if rainfall at the airport is reported as "heavy," the required landing distance must be recalculated assuming the runway is flooded (i.e., water depth greater than 3 mm) and the braking action is "poor" using manufacturer's guidance material; or
- If the runway is grooved or PFC and the depth of water on the runway is greater than 3 mm or if rainfall at the airport is reported as "very heavy," the required landing distance must be recalculated assuming the runway is flooded, using manufacturer's guidance material.

If the calculated distance is less than the runway length available, the pilot must not attempt to land, except in an emergency.

Option 3. Current Dispatch Factors With En Route Requirement

Wet runway dispatch factors the same as under current regulations (1.92 for jets and 1.64 for turboprops) and the en route requirement at the beginning of final approach the same as under Option 2.

Based on the risk model, the report says:

- "Increasing the wet runway dispatch factors as under Option 1 reduces the risks of landing on wet un-grooved runways to a little above those for landing on dry runways, and slightly less than those for landing on wet grooved runways, for aircraft with reverse thrust;

- "The dispatch factor of 2.45 under Option 1 for aircraft without reverse thrust reduces the risks to below those for a dry runway. A factor of 2.25 gives risks comparable with those on a dry runway;
- "The en route landing distance calculation as described under Option 2 greatly reduces the risks when landing on an un-grooved runway under heavy rainfall conditions and, overall, results in a significant reduction in the risks;
- "Use of the current dispatch factors and the en route requirement, Option 3, reduces the risk from the current regulations significantly, but risks are still much greater than for a dry runway and greater than for Options 1 and 2; [and,]
- "The en route calculation as described under Option 2 for landing on a grooved runway typically has no effect on the risks for many aircraft, as the adjustment factor based on manufacturer's material for landing on runways with 3 to 6 mm (0.23 in) of water is usually below the current wet runway adjustment factor."

In terms of the benefit-cost ratios of the options, the report concludes:

- "Increasing the dispatch factor on un-grooved runways and for aircraft without reverse thrust when the arrival runway is expected to be wet as outlined in Option 1 incurs a relatively small penalty on many flights, and does not target the flights most at risk;
- "Requiring pilots to recalculate the landing distance just prior to landing assuming braking will be 'poor' when rainfall is heavy and the runway is un-grooved targets landings at greatest risk. Benefit-cost ratios are close to, or greater than, 1.0 when the en route check requirement is made with the current dispatch factor requirements. This approach is cost-beneficial, but the requirement does not reduce the risk for landings in less wet conditions, and the overrun rate is still much higher than on dry or grooved runways;
- "When the en route check requirement is applied with the increased dispatch factors, Option 2, for all wet runway landings, costs far exceed the benefits for most aircraft; [and,]
- "The requirement to increase dispatch factors only when the weather forecast is for moderate to heavy rainfall at the time of arrival at the destination improves the benefit-cost ratio by a factor of eight, provided the forecasts are accurate. Benefit-cost ratios would be greater than one for the majority of aircraft landings. The requirement to make an en route landing distance calculation assuming braking is 'poor' if rainfall is heavy would reduce the risks in situations where the forecasts were inaccurate and rainfall is heavier than expected."

The report concludes that "few flights would be affected by the increased dispatch factor or en route landing distance calculation requirements considered. The costs of grooving would be much greater than savings to airlines and will vary depending on the runway length and surface type, types and weights of aircraft and the runway safety areas at the airport. The benefits may exceed the costs of runway grooving at some airports, particularly where the grooving has a long lifespan, the runway safety area is small and/or a high proportion of aircraft landings are at, or close to, being weight restricted."

Notes

1. Biggs, David C.; Hamilton, Gordon B.; Jacobs Consultancy Canada. *Risk and Benefit-Cost Analyses of Procedures for Accounting for Wet Runway on Landing.* July 2008. Available via the Internet at <www.tc.gc.ca/tdc/menu.htm>.
2. The study was limited to operations of jet and turboprop aircraft with a maximum takeoff weight greater than 5,670 kg (12,500 lb).
3. On July 17, 2007, an Airbus A320 landing in heavy rainfall at Congonhas Airport, São Paulo, Brazil, overran the runway and crashed into a building. All 189 passengers and crew were killed. An Air France A340 overran the runway at Toronto Pearson Airport on Aug. 2, 2005, and came to rest in a ravine. All occupants evacuated safely; the aircraft was destroyed by a post-crash fire.
4. Transport Canada defines a wet runway as a surface condition where there is a thin layer of water and the layer of water is 3 mm (0.11 in) or less in depth. A contaminated runway means a runway that has any portion of its surface covered by a contaminant, including standing water, slush, snow, compacted snow, ice or frost, or sand and ice control chemicals.
5. The formula for calculating the additional landing distance is 1/60 percent = 1.67 (1 + 0.67) or 1/70 percent = 1.43 (1 + 0.43).
6. The wet/dry *landing* distance ratio is much closer to 1 than the wet/dry *stopping* distance, because the former includes the period from when the airplane is 50 ft above the runway until touchdown, during which the runway condition has no effect on braking.