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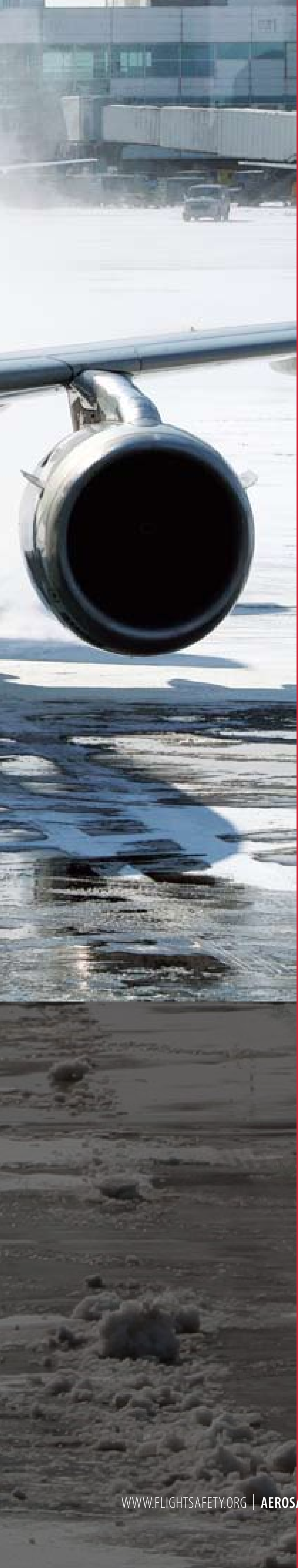
Treacherous THAWING

BY REINHARD MOOK

Slush may induce poor/nil aircraft braking action, contrary to runway friction readings.

One of the most slippery runway conditions possible may occur if aircraft tires fail to penetrate a layer of slush to contact the paved surface. This risk is not news, but global warming may result in more frequent encounters with slush even in the coldest regions. Four winters of research on the deceleration of commercial transport airplanes landing at one airport in Norway found that temporary loss of directional control could occur when the slush was 3 mm (0.12 in) deep.

Mechanical consistency is the physical property of slush most relevant to braking, yet sand applied to slush by airport operators barely improved airplane braking. The research airport's Skiddometer, a continuous friction measurement system, in frozen-contaminated wet



conditions typically indicated significantly better aircraft braking action than could be achieved.[1]

It turns out that a *derived airplane braking coefficient* no better than 0.04 to 0.06 — corresponding to "poor/nil" braking action reports — might be expected while skidding/hydroplaning on any combination of liquid water and ice fragments, and in the case of tires lifted off the paved surface by an air-ice mixture, this coefficient can drop even below 0.04 (Table 1, p. 16).

Landings by Boeing 737-400s, 737-500s, 737-700s and 737-800s were observed and analyzed during the winters of 2004–2005 through 2007–2008 at Svalbard Airport Longyear. With few exceptions, flights were canceled or diverted when the Skiddometer friction coefficients were in the lower end of the 0.30s. When no aircraft arrived, no airplane braking coefficients could be derived for the data set.[2]

Not considered during the Svalbard research were the autobrake setting, the manual braking technique or the landing weight. The vector component of wind along the runway also was not taken into account in calculating the time needed for braking to a stop on slush. As a consequence, the derived airplane braking coefficients in the table are only estimates.

At the microscopic level, slush is flexible tiny fragments of ice lubricated by liquid water, with the fragments usually rounded by melting. The most important effect of slush on deceleration is the reduced shear forces between the tires and the runway pavement during braking. Thus, as a rule, deceleration on slush is influenced significantly by sliding or skidding. A recent report by the Accident Investigation Board Norway (AIBN) found that, due to the predominance of gliding friction when operating on slush, the airplane braking coefficient does not depend on aircraft velocity.[3]

Shear forces decrease, for example, when the slush layer rests on an icy base with melting at the common boundary. Another type of boundary layer — liquid water below a slush base — may result from gravity or from compaction by the tire footprint squeezing the slush.

Another factor is *flood resistance* — resistance to a rolling wheel by a plowing process, such as the displacement of slush — and the impingement of slush, including spray, against the aircraft — both contributing substantially to aerodynamic drag forces.

How Slush Forms

Slush may accumulate directly by precipitation, depending on generating processes in the cloud region, and the air temperature and water vapor in the lower troposphere. Slush also may form indirectly from sleet or snow followed by rainfall, or snow and rain falling intermittently. Snow precipitated into a film or a shallow layer of standing water also can change to slush by capillary force and water adsorption.

In other cases, starting with a snow layer, a heat input can induce melting and transform the snow to slush. This heat can be stored in and released from the asphalt or concrete runway. Snow also can be heated when solar radiation penetrates a snow layer or ice layer and is absorbed partly in this layer and partly in the pavement surface. Mechanically weak ice crystal aggregates easily can be broken up by the loads applied by aircraft and vehicles.

When chemicals are spread over a dry runway to melt snow as it falls, if the snowfall exceeds the melting rate and water drains, snow will accumulate. If snow falls on a film of melting snow, the result is white snow seen from the air that covers and hides the likely presence of slush. This article assumes water freezing at 0 degrees C (32 degrees F). In the case of chemical treatment, slush may be present even at air temperatures considerably below freezing. Separation of the frozen aggregates, chemical salts and liquid water in this scenario results in the aircraft wheel's load acting on a spongy, slimy form of slush.

A molecular film of slush may even be generated for an extremely brief time when the surface is heated to melting temperature at the contact areas between a tire heated by friction as it moves and the ice or compacted snow on a runway. Similarly, hoar frost and loose snow crystal fragments left on a runway after snow-removal operations on a microscopic scale may change to slush for an extremely brief time.

Predicted and Measured Deceleration on Contaminated Runway

Runway Condition	Landings Measured	Runway Environment Temperatures: Air °C/°F	Dew Point °C/°F	Frost Point °C/F	DP Spread °C/°F	FP Spread °C/°F	Surface Contamination °C/°F	Runway Braking Coefficients: Derived Airplane Braking Coefficient Min	Mean	Max	Skiddometer Friction Coefficient Min	Mean	Max
A. Slush on asphalt	5	2.9/37.2	1.9/35.4	—	1.0/1.8	—	0/32	0.05	0.06	0.07	0. 29	0.34	0.38
The slush depth was 1 mm (0.04 in) without sanding for four landings and 3 mm (0.12 in) with sanding for one landing. A head wind of 13 kt was measured. Weather included low clouds with a rain-snow mix (sleet) during four landings and rain during one landing.													
B. Slush on ice or compacted snow	9	2.1/36.8	0.4/32.7	—	1.7/4.1	—	0/32	0.04	0.05	0.07	0.30	0.36	0.41
The slush depth was 1 mm with sanding for seven landings and 3 mm with sanding for two landings. A head wind of 11 kt was measured. Weather included broken low and middle-high clouds with rain during four landings, sleet during three landings and wet-runway conditions after precipitation during two landings.													
Exception	1	6.2/43.2	—	−1.2/29.8	—	7.4/13.4	0/32	—	0.08	—	—	0.32	—
Compacted snow transformed to slush to a maximum depth of 2–3 mm with sanding. A head wind of 5 kt was measured. Weather included a few middle-high clouds and sunshine.													
C. Water on ice or compacted snow	2	2.8/37.0	1.3/34.3	—	1.5/2.7	—	0.2/32.4	0.04	0.05	0.06	0.27	0.30	0.35
The runway cover was 1 mm water with sanding for both landings. A head wind of 15 kt was measured. Weather included an overcast of low clouds, rain and/or wet-runway conditions after rain.													
Exception	1	2.5/36.5	—	−3.3/26.1	—	5.8/10.4	0.3/32.5	—	0.06	—	—	0.34	—
The runway cover was 1 mm water on soggy ice. A head wind of 9 kt was measured. Weather included broken middle-high clouds and high clouds and wet-runway conditions after rain.													
D. Ice or compacted snow with "dry" surface	13	−4.1/24.6	—	−7.5/18.5	—	3.4/6.1	−6.8	0.08	0.11	0.13	0.32	0.38	0.47
The runway cover was loose or hard-frozen snow with sanding for all landings. A head wind of 7 kt was measured. Weather included scattered middle and/or high clouds with no precipitation.													
Exception	3	−3.5/25.7	—	−5.8/21.6	—	2.3/4.1	−7.0/19.4	0.06	0.07	0.08	0.34	0.37	0.41
The runway cover was the same as for the 13 landings above. A head wind of 6 kt was measured. Weather included broken middle-high clouds with no precipitation.													
E. Extremely cold ice or compacted snow with "dry" surface	9	−14.2/6.4	—	−18.8/−1.8	—	4.6/8.2	−17.4/0.7	0.12	0.14	0.18	0.38	0.45	0.51
The runway cover was frozen hard and sanded for all landings. A head wind of 10 kt was measured. Weather included clear sky or few high or middle-high clouds with no precipitation.													
F. Drifting snow on stationary compacted snow	5	−8.9/16.0	—	−13.0/8.6	—	4.1/7.4	−11.8/10.8	0.05	0.07	0.09	0.34	0.36	0.40
The runway cover was frozen hard with partial sanding for all landings. A head wind of 21 kt was measured. Weather included middle-high clouds and high clouds, with drifting snow and no precipitation.													
G. Blowing snow on stationary compacted snow	3	−15.1/4.8	—	−17.0/1.4	—	1.9/3.4	−16.0/3.2	0.03	0.03	0.04	0.32	0.38	0.48
The runway was covered by drifting snow and partially sanded for all landings. A two-minute head wind of 28 kt was measured. Weather included scattered middle-high clouds with no precipitation.													
H. Recent snow on ice or compacted snow	4	−2.3/27.9	—	−3.4/25.9	—	1.1/2.0	−3.8/25.2	0.04	0.06	0.07	0.29	0.32	0.36
The runway cover was less than 10 mm (0.4 in) snow with sanding for all landings. A head wind of 10 kt was measured. Weather included scattered low clouds and middle-high clouds, with snow falling or snowy conditions after snowfall.													
I. "Black" asphalt with dry surface	8	−4.4/24.1	—	−9.5/14.9	—	5.1/9.2	1.2/34.2	0.18	0.21	0.23	—	—	—
The runway was free of contaminants and sand for all landings. A head wind of 4 kt was measured. Weather included clear sky or scattered high clouds with temporary direct solar radiation.													

Min = minimum value; Max = maximum value; DP = dew point; FP = frost point; — = not relevant

Notes: *Spreads* are the difference between air temperature and dew point temperature or between air temperature and frost point temperature. Air temperature, dew point temperature and frost point temperature were measured 2.0 m (6.7 ft) above ground level. *Surface contamination* means the surface temperature of the contamination — 0 degrees C/32 degrees F for slush, ice or compacted snow bordering slush or water. Standing water may have a higher temperature. The *derived airplane braking coefficient* was calculated from measurements of actual deceleration during landings of Boeing 737-400s, 737-500s, 737-700s and 737-800s. The *Skiddometer friction coefficient* readings were taken from section B of Runway 10/28 at Svalbard Airport, Longyear, Norway, using a Skiddometer BV11, a continuous friction measurement system towed behind an airport vehicle. All numbers are arithmetic means except where noted. Data were collected during winters 2004–2005 through 2007–2008.

Source: Reinhard Mook

Table 1

In the case of hardened ice or snow, however, a liquid water film may be produced only at the microscopic surface elevations of ice crystals.

Nature of Slush

In nature, a transition occurs from so-called dry snow, which always contains supercooled liquid water, to wet snow. The familiar ability to form a snow ball, due to the adhesive property of liquid water present, is considered a practical distinguishing mark for wet versus dry when describing snow, but the transition is not instant or unequivocal. Increasing the proportion of liquid water at the freezing-point temperature gradually produces slush.

When liquid water exceeds two-thirds of the runway cover by weight, the viscous properties quickly approach those of water. In a mixture containing less than 25 percent ice particles in water, the cover cannot be reported as slush any more.

In daylight and from the air, snow cover on a runway looks white. To be more exact, however, there are gray tones because reflected light is scattered back to the observer from the ice particles within the snow layer and from the air between the particles. When the pores and cavities in the snow are occupied by liquid, light reaches and is absorbed by the relatively dark pavement, making the layer of slush appear darker than snow when viewed from above. When more than about one-third of the snow by weight consists of liquid water, the relative whiteness of snow changes to a dark gray mass. From the air under poor light or visibility conditions, a slush cover on a runway may be difficult to detect. If the ambient light and visibility are suitable, a transition toward darker gray may indicate a change in the runway cover from snow to slush.

Rolling Resistance

The resistance met by a rolling wheel on an aircraft landing gear has several components relevant to a slush-contaminated runway:

- Some rolling resistance is due to, and increases with, dampening of vibrations by the tire material and the tire's deformation, and with speed due to the formation of waves on the tire's circumference. When the rolling resistance increases sufficiently, sliding and eventually skidding inevitably occur, and the temperature of the tire increases;[4]
- Some rolling resistance is flood resistance, dependent on the contaminant volume displaced over time. Viscosity, the proportion of liquid water in slush and the geometry of the ice particles become essential variables that affect skidding/aquaplaning if the tires do not penetrate to the paved surface;
- When the aircraft is turning, some rolling resistance is generated by friction, which increases as acceleration and speed increase;
- Some rolling resistance is generated by the roughness of the contaminated runway, which induces greater vibration in tires than a contaminant-free runway and raises the tire temperature; and,
- Some rolling resistance arises from the friction in wheel bearings, misalignment of wheels and aerodynamic drag.

Slush Distribution Pattern

Visualizing a tire that does not contact the pavement helps explain the problem pilots may face. A tire moving on the runway toward an observer would show the slush, including sand grains, being pushed aside. Very few sand grains get deposited at the bottom of the slush layer, due mainly to resistance from surrounding ice particles that prevent sinking and partly to the buoyancy of the sand grains. However, sand grains heated by absorbed radiation may cause melting that causes them to sink into the slush layer, just as can occur when they are on top of an ice layer.

Sand grains caught in slush under a tire become enclosed in the compacted solid part of the slush. Water is squeezed out and forms boundary layers both on the side of the tire and on the pavement. These layers effectively prevent adequate braking shear forces between the tire and pavement. Sand grains embedded in a mass of loose wet ice particles are ineffective in increasing friction, except when they create microscopic "bridges" between the tire and the stationary base.

A side view of the same tire would show large quantities of slush accumulating and being pushed like a wedge ahead of the wheel, and the tire sinking into a layer of the compressed or laterally displaced slush. Layers of squeezed liquid water appear in the tire footprint. Due to adhesion, water and some slush stick to parts of the rolling tire as they repeatedly contact the runway and then the air.

Braking conditions improve greatly when the slush is sufficiently pushed away from the tire's footprint for tire-pavement contact, but experience and research show that this may not occur. Moreover, measurements of the depth of slush by airport personnel may be inexact or taken at a site that does not represent the entire runway.

Airplane Braking Coefficients

The theoretical maximum friction coefficient for a tire in motion — that is, deceleration with the minimum amount of slip — rarely is achieved in practice. However, autobrake computations and techniques of manual braking approximate generating the maximum shear forces possible between the tire and pavement. The mean derived airplane braking coefficient on slush is best determined after deceleration to a speed range in which the aircraft can be analyzed like any rolling braked vehicle. For the 737 series, this means after slowing to about 55 kt. During this stage of the landing roll, the thrust reverser is assumed to be in the stowed position, and the tires are assumed to have attained maximum temperature.[5]

Flight data recorded from aircraft sensors, which could have aided observation of the deceleration process on slush, were not available for the Svalbard research. Ideally, the angular velocity of wheels as a function of time would be known. Therefore, as an approximation, the mean deceleration was calculated from the interval of time needed to reduce a given speed by a given amount. To compensate for the inability to directly monitor speed, the following basic assumption was used for every flight: The speed would be about 55 kt 12 seconds after the nosewheel touched down on the runway.

The flight crews probably attempted near-maximum braking for the whole deceleration period, including at speeds greater than 55 kt. Even if the deceleration temporarily achieved were greater than the mean value calculated, however, the derived airplane braking coefficients on slush still would be extremely small.

Data Interpretation

While the Skiddometer friction coefficients represent friction conditions between the measuring wheel and the pavement, based only on one measuring device, derived airplane braking coefficients describe the airplane's total braking including the influences of tires, braking system with antiskid and other factors. The Svalbard research showed that the derived airplane braking coefficients in wet conditions could be only 20 to 30 percent of the Skiddometer friction coefficients.

This research found that Skiddometer friction coefficients overestimated the braking action when slush was the predominant form of water-ice contamination. Therefore, it is likely that landings have been performed when the runway conditions should have been reported to the flight crews as "poor" braking action.

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From the table, this discrepancy is striking for so-called "thawing conditions" — runway-contamination conditions A, B and C on the table, in which slush or liquid water covered sanded ice or compacted snow, and the derived airplane braking coefficients were extremely small. These conditions, along with the condition D exception and conditions G and H, confirm the AIBN's determination that in wet conditions, a spread less than or equal to 3 degrees C correlates with poor braking action.[6]

The exceptions in Table 1, excluding the exception to condition D, show a spread exceeding 3 degrees C while runway conditions A and C, excluding the exception to condition C, show dew point temperatures warmer than the corresponding contaminant temperature. This indicates heat released by the formation of dew, so increased melting should be expected.

Conditions D and E in the table reflect the well-known phenomenon of friction increasing on ice as temperature decreases below the freezing point. Surface temperatures, governed by a net outward radiation of heat, were lower/colder than the adjacent air; the difference was 3.2 degrees C in condition E, for example. At lower temperatures, the structure of the ice aggregates — except for existing liquid water, if any, and any more water generated by melting during contact with a heated tire — explain this phenomenon. The exception to condition D shows that very slippery conditions occurred, most likely due to ice deposits from water vapor. Condition F shows that a runway covered by ice or compacted snow — despite a rather low prevailing temperature — may be slippery because of the polishing effect of wind-blown ice fragments.

When the mean wind velocity exceeds 25 kt — as in condition G — or when wind gusts exceed 35 kt, the density of ice crystal fragments suspended in cold air just above the stationary surface may lift the aircraft wheels. This unusual effect, for which aquaplaning is the best analogy, might be called "nival planing." Condition G notably has the smallest derived airplane braking coefficient — 0.03. The rather small air temperature–frost point spread might be explained by the ice fragments suspended in the air, as well as the low temperatures.

Condition H reflects cases of recent snow on the runway at a rather high temperature when the ice aggregates still contained liquid water. This may contribute to slippery conditions when a lubricating layer becomes established under the pressure and heating of a tire. In condition I — a nominally black dry runway heated by solar radiation — derived airplane braking coefficients were on the order of 0.2, obviously too low as note 2 below explains.

Lessons for Operators

In winter 2007-2008, the Civil Aviation Authority–Norway (CAA–N) advised air traffic controllers to only report current braking conditions to pilots as "good," "medium" or "poor" in the cases of slush, wet ice or wet snow on the runway. The category "medium" covered friction coefficients from 0.3 to 0.4 derived from measured friction levels, however, which spanned conditions considered unacceptable for landing to conditions considered acceptable for landing.[7] Updated guidance was published in mid-2008.[8]

It should become possible soon for flight crews to consider information about contaminant status such as stratification and composition; decisive parameters such as surface temperature and flow of energy, that is, heating and cooling; and significant processes such as condensation, thawing and precipitation (*ASW,* 10/07, p. 24). Meanwhile, frozen-contaminated wet conditions with a spread less than or equal to 3 degrees C always should be considered as poor.

Standardized observations could be based on derived airplane braking coefficients — empirically determined — taking into account factors missing from this research, such as autobrake setting, wind and landing weight. As scientific understanding of takeoff and landing on slush evolves, such types of supplementary information for flight crews one day might be considered essential.

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Knut Lande of AIBN provided comments on the draft article.

Notes

1. The Skiddometer BV11, a continuous friction measurement system designed to be towed behind an airport vehicle, was used in this research; it is manufactured by Patria Vammas of Vammala, Finland.
2. Underestimation resulted from this study's assumptions about flight crew use of *friction-limiting braking* — that either the AUTOBRAKE 3 setting, deceleration at 7.2 ft (2.2 m) per second squared, or the AUTOBRAKE MAX setting, deceleration at 14 ft (4.3 m) per second squared, were selected and that antiskid worked to produce the maximum shear forces possible between tire and pavement. In condition I in Table 1, however, far less braking actually was applied.
3. Lande, K. "Winter Operations and Friction Measurements." In *International Cooperation: From Investigation Site to ICAO, Proceedings of the 38th Annual International Seminar* (Volume 11), International Society of Air Safety Investigators, Aug. 27–30, 2007, Singapore.
4. Hegmon, R.R.; Henry, J.J. "Thermal Analysis of a Skidding Tire." *Wear* (Volume 24) 361–380, 1973.
5. European Aviation Safety Agency (EASA). Notice of Proposed Amendment no. 14/2004, *Draft Decision of the Executive Director of the Agency on Certification Specifications for Large Aeroplanes (CS-25), Operation on Contaminated Runways,* Section 7.3.1 "Default Values." EASA has adopted correlations between measured friction coefficients and derived *default friction values,* which represent the effective braking coefficient of an antiskid-controlled braked wheel/tire. The Svalbard research and AIBN research, however, have not confirmed the EASA values except 0.20 for compacted snow and 0.05 for ice. Wet snow and dry snow have been assigned the same value — 0.17 — by EASA; similarly, standing water and slush have the same value expressed as one equation.
6. Lande.
7. CAA-N. "Friction on Contaminated Runways." Aeronautical Information Circular (AIC– I) 07/06, Nov. 20, 2007.
8. CAA-N. "Friction on Contaminated Runways." AIC-I 03/08, July 3, 2008. Considering operator feedback from winter 2007–2008, the CAA-N has introduced a five-level runway-friction scale correlated with Skiddometer friction coefficients. The CAA-N says that only these levels, not coefficients, will be reported to pilots for determining airplane braking coefficient. The estimated levels reported are *good* for friction coefficients greater than or equal to 0.40; *medium/good* for 0.36–0.39; *medium* for 0.30–0.35; *medium/poor* for 0.26–0.29; and *poor* for less than or equal to 0.25. Extra vigilance is warranted for wet ice, wet snow and slush, however, because the CAA-N does not distinguish between wet and dry conditions on contaminated runways; the reported level — given the Skiddometer's accuracy of plus/minus 0.025 — may cause pilots to overestimate the precision of any airplane braking coefficient; and the relevant International Civil Aviation Organization standard for wet conditions allows the accuracy of runway friction measurements to deviate on the order of plus/minus 0.2.