Cold Regions Science and Technology 117 (2015) 43–51

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A decision support model to assess the braking performance on snow and ice contaminated runways

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ARTICLE INFO

Article history:
Received 13 March 2015
Received in revised form 8 May 2015
Accepted 5 June 2015
Available online 10 June 2015

Keywords:
Winter contaminated runways
Friction measurements
Braking action
Braking performance

ABSTRACT

Pilots need accurate predictions on the quality of runway surface conditions when operating on snow/ice contaminated runways. These predictions are typically made by friction measurements, or by expert judgments of runway inspectors. This study presents a decision support model (the IRIS runway model) for runway inspectors that interprets descriptive data from SNOWTAM reports and predicts the braking action on the common scale from 1 to 5, ranging from "poor" to "good". The model is tested on two airports in Norway during the winter seasons 2008/2009 to 2010/2011. Two other predictors of the braking action (assessments by runway inspectors and friction measurements) were also included. Analyses of 1261 friction-limited landings of commercial airplanes were used to compare predicted and measured braking actions.

The IRIS runway model was found to be more conservative than the assessments of Norwegian runway inspectors, and even more conservative than friction measurements. In 86% of the landings, the IRIS runway model predicted the conditions within ±1 category of what the airplanes experienced, compared to 77% achieved by the runway inspectors. The predictions by the friction measurement devices were the least conservative and predicted the conditions within ±1 category in 61% of the landings. The model is now implemented in 15 airports in Norway.

1. Introduction

Before pilots can land on snow/ice contaminated runways, they need accurate information on the prevailing surface conditions. Hence, reporting the surface conditions is an important task for winter maintenance personnel at airports. During winter operation, a ground vehicle regularly drives over the runway and the runway inspector collects visual information like the type and depth of the snow/ice contamination, percentage of coverage of the contaminant and the presence of sand and chemicals. In addition it is common to perform friction measurements during these inspections, using a ground friction measurement device (GFMD). All this information is transmitted to the pilots in a so-called SNOWTAM report (ICAO, 2013).

Pilots refer to slipperiness of the runway as the braking action, or braking performance. They typically use a scale of five categories ranging from "poor" to "good". Sometimes a sixth category "NIL" is used, meaning it is very slippery and is considered unsafe to land. GFMDs have been used since the 1950s to predict the braking action (Norheim, 2004). Throughout the world, many different models and makes are operative at airports and their readings are often directly reported to the pilots. Unfortunately, different GFMDs do not always give consistent readings on the same surface (Sinha, 2004) and large efforts have been devoted to correlate devices with each other and to airplane braking performance (Andrássy, 1999; Boccanfuso, 2004; Croll, 2004). Despite these efforts, there still seems to be no consensus on how to interpret these readings and the quality of their predictions.

The use of friction measurement devices has been debated (Norheim, 2004; Norheim et al., 2001) and several aircraft accidents have occurred where the conditions were significantly worse than measured by the GFMDs (AIBN, 2011). One of the reasons why it is so difficult to get a valid prediction with GFMDs is that the test tires form scaled tribosystems, compared to the aircraft tire. Parameters like the travel speed, tire characteristics, normal load, braking mode and contact time differ significantly between the GFMDs and the aircraft tires. During braking the rotational speed of the tire is less, compared to a free-rolling tire, inducing slip. As the tire rolls and slides friction is created by hysteresis within the rubber (Bowden and Tabor, 1954; Moore, 1975), by deformations within the snow/ice (Klein-Paste and Sinha, 2010b; Tusima, 1977) and by the creation and destruction of interfaces at the contact points (Makkonen, 2012). The high sliding speeds can induce frictional melting

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http://dx.doi.org/10.1016/j.coldregions.2015.06.002

(Higgins et al., 2008) and loose material (water, slush, wet or dry snow) has to be squeezed out of the contact area before friction can be obtained. The interactions of these multiple friction and lubrication mechanisms act simultaneously on different length scales. This makes it extremely difficult, if not practically impossible, to realistically recreate all these processes during a measurement with a scaled test tire, compared to the aircraft tire. Recent modeling efforts on tire–pavement interactions (Gerthoffert et al., 2015; Makkonen and Tikanmäki, 2014; Michael et al., 2015) help to further understand how different tribosystems behave on a given contaminated surface. But to the best of the authors' knowledge, these models have not yet reached a stage where they have been successfully applied to correct predictions of GFMDs for aircraft braking performance in operational winter conditions.

In 2009, the Norwegian Civil Aviation Authority changed the legislation and prohibited that readings from GFMDs are directly reported to pilots (CAA-Norway, 2009). Instead, trained and authorized runway inspectors (typically the team leaders of the winter maintenance staff) have to estimate the braking action on the scale from 1 to 5 ("poor" to "good"). They are still allowed to use a GFMD, but only as a decision support tool to come to his/her estimate. This change in legislation placed more value on the expert judgment of runway inspectors and less focus on friction measurements. This focus shift is also reflected in the latest SNOWTAM format (ICAO, 2013) which no longer facilitates for reporting measured friction values.

But it also created a need for additional decision support systems. The Norwegian airport operator Avinor had started a large R&D project to develop an Integrated Runway Information System (IRIS). All relevant weather and runway data was collected, together with landing data from two commercial airliners. An airplane braking model was utilized to calculate the aircraft braking coefficient (Klein-Paste et al., 2012). The goal was to develop a decision support system that provided winter maintenance personnel all relevant weather information (to help them making the right winter maintenance decisions) and help runway inspectors to asses the runway condition (the braking action).

In this paper we present the IRIS runway model, which is the decision support tool to assess runway conditions. For this model we used the approach to directly relate the characterization of the contaminants to airplane braking performance (Norheim et al., 2001), without using GFMD readings. In essence it is an expert model that judges the visual information collected during an inspection to predict the braking action. A similar approach was explored by Federal Aviation Administration (FAA) through its Take-off and Landing Performance Assessment — Aviation Rulemaking Committee TALPA-ARC (Subbotin and Gardner, 2013).

In this study we compare three different predictors (IRIS model, runway inspector assessments and friction measurements) with the measured airplane braking coefficient of landings on winter contaminated runways. Therefore, Table 1 introduces a common scale, which relates the different predictors to each other.

2. Description of the model

The IRIS model evaluates a set of information given in the SNOWTAM report and prevailing weather data and returns the prediction P on a scale from 1 to 5, according to Table 1. The model does not predict 0, because SNOWTAM reports are only issued in Norway when the runway is open for air traffic. Hence during very poor conditions the runway is closed and there is no input data available for the model. An overview of the model's input and output is given in Fig. 1.

The model evaluates seven different factors that influence the quality of surface conditions. The mathematical structure of the model is given in Eq. (1).

$$P = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 \quad (1)$$

where x_1 to x_7 represent the factors described in Table 2. Variable x_1 can be considered as the base prediction and its value ranges between 1 and 5 and is based on the observed type of contamination that is present on the runway. Variables x_2 to x_7 are the additional factors that either downgrade or upgrade the base prediction. Their values range from -2 to $+2$ and it reflects the number of categories that are either downgraded ($-$) or upgraded ($+$). When P exceeds 5 it is set to 5 and when it becomes lower than 1 it is set to 1. This is done to ensure that P stays within the range from "poor" to "good". Note that there are no weighing coefficients used in Eq. (1) to adjust the relative sensitivity of the different factors. This "weighing" is performed within the factor by adjusting how quickly the factor upgrades, or downgrades the prediction P.

2.1. Type of contamination, x_1

The SNOWTAM format (ICAO, 2003) defines nine different contamination codes K, given in Table 3. Reporting multiple layers is allowed, for example 47, meaning dry snow on ice. The multiple layers consist of maximum one "loose layer" like rime, dry snow, slush, or water, and maximum two "solid layers" like ice, compact snow, or frozen ruts. To reduce the number of possible combinations, the multiple layers involving ruts are grouped together with the multilayers involving compact snow. When the contamination consists of both ice and compact snow, it is considered as ice.

A look-up table was created that classifies the different types of contamination and assigns a value of x_1 to them (see Table 4). The choice of classification is based on experience from winter maintenance personnel, earlier published classifications (Subbotin and Gardner, 2013) and evaluations of braking performance during operational conditions (Klein-Paste et al., 2012). Note that wet snow is judged more slippery than slush in Table 4, which is in accordance with measurements on Norwegian runways (Klein-Paste et al., 2012). This aspect can be physically explained because slush is easier being squeezed out to the contact area, compared to wet snow which is still a compressible material (Colbeck et al., 1978) but it can also be caused by the fact that slush is reported in 3 mm intervals whereas wet snow is reported in 6 mm intervals.

Groups of contamination codes have been defined to assist selection of conditions in the later parts of the model. The following groups have been defined:

notContaminated = [0 1 2]
dryContaminated = [3 4 7 8 9 37 38 47 48 78 87]
wetContaminated = [5 6 27 28 57 58 67 68]

Table 1
Scales to express the tire–pavement friction of runway surfaces.

Braking action	Descriptive braking action	Airplane braking coefficient (Klein-Paste et al, 2012)	Estimated friction (ICAO, 2013)	IRIS model P	Measured Friction coefficient (ICAO, 2003)
5	Good	$\mu_B > 0.2$	5	5	≥0.4
4	Medium-good	$0.2 \geq \mu_B > 0.15$	4	4	0.36 to 0.39
3	Medium	$0.15 \geq \mu_B > 0.10$	3	3	0.30 to 0.35
2	Poor-medium	$0.10 \geq \mu_B > 0.075$	2	2	0.26 to 0.29
1	Poor	$0.075 \geq \mu_B > 0.05$	1	1	≤0.25
0	NIL	$0.05 \geq \mu_B$			

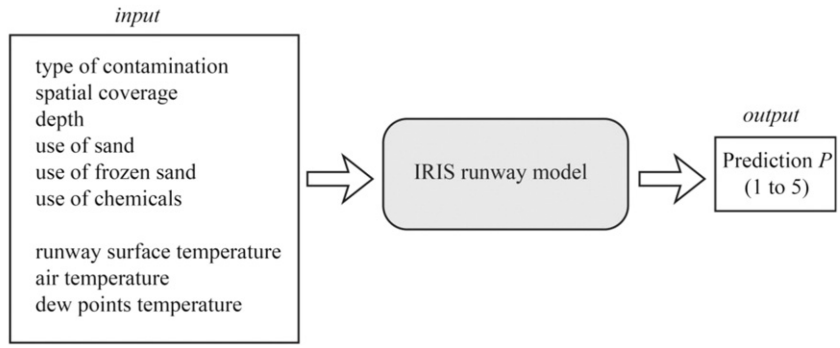

Fig. 1. Overview of the model.

solidContaminated = [7 8 87]
looseAndDryContaminated = [3 37 38 378 4 47 48]
solidBaseLayer = [7 8 87 27 28 37 38 47 48 57 58 67 68]

2.2. Spatial coverage, x_2

When a runway section is only partly covered, the available friction tends to be higher (Klein-Paste et al., 2012). Therefore, P is upgraded when the spatial coverage S is 50% or less. When S is 10% or less, the runway section is considered to be insignificantly contaminated. In this case, P is set to 5 (good) and the model ignores the other evaluations made in x_3 to x_7. The algorithm to calculate x_2 is given in Eq. (2).

$$\begin{array}{ll} x_2 = 0 & | \quad S > 50 \\ x_2 = +1 & | \quad 10 < S \le 50 \\ P = 5 & | \quad S \le 10 \end{array} \tag{2}$$

2.3. Depth of loose snow/slush, x_3

The mean depth of dry snow, wet snow, or slush is reported in millimeters. The SNOWTAM format specifies an accuracy of 20 mm for dry snow, 10 mm for wet snow, and 3 mm for slush. However, the Norwegian legislation deviates from the SNOWTAM standard by reporting depths in intervals of 8 mm, 6 mm, and 3 mm respectively. The actual depths are always rounded upwards to the nearest reported interval (2 mm slush is reported as 3 mm slush). The effect of contamination depth on friction is not obvious. Loose snow (dry or wet) that enters the contact area gets compacted and friction is predominantly created at the snow–rubber interface, leaving a clear track of snow behind (Klein-Paste and Sinha, 2006). This suggests that once the tire has lost contact with the pavement the friction does not significantly decrease further with increasing snow depth. On slush however, friction is created between the rubber and the pavement texture after the slush has been squeezed out of the contact area. Here it is expected that an increased slush thickness decreases the friction. A conservative approach was chosen for the model by downgrading all types of loose snow with increasing depth. The model counts the number of intervals n_i that was reported. For example 12 mm wet snow means $n_i = 2$, while 12 mm slush would be $n_i = 4$. P is downgraded when the n_i exceeds 1, as given in Eq. (3).

$$\begin{array}{ll} x_3 = 0 & | \quad n_i = 1 \\ x_3 = -1 & | \quad n_i = 2 \\ x_3 = -2 & | \quad n_i \ge 3 \end{array} \tag{3}$$

2.4. Runway temperature, x_4

The effect of runway temperature on the surface conditions depends on the type of contamination. When a runway is bare and dry, there will be little difference in available tire–pavement friction if the temperature is around 0 °C or say, −10 °C. But when the runway is covered with ice, there is clearly a higher chance to get slippery conditions around 0 °C, compared to −10 °C. Hence, different profiles for downgrading or upgrading the conditions are needed. Three different profiles have been defined:

Profile 1: No temperature effect
In this profile, the base prediction is neither upgraded nor downgraded for the prevailing runway temperature. This profile is used when the runway surface is dry, damp, wet, or if the contamination contains wet snow, slush, wet ice, or wet compact snow:

$$K \in [notContaminated, wetContaminated] \tag{4}$$

Profile 2: "ice/compact snow"
This profile is used when the runway is contaminated with solid contaminations: ice, compact snow, and frozen ruts, while there is no loose snow present:

$$K \in [solidContaminated] \tag{5}$$

In these instances, P is downgraded when the temperature is at or above −2 °C, while it is upgraded when the temperature is below −8 °C. An additional downgrading will take place when the temperature is above −0.5 °C. When the runway

Table 2
Description of the factors.

Variable	Description
x_1	Type of contamination
x_2	Spatial coverage
x_3	Depth of loose snow/slush
x_4	Runway temperature
x_5	Humidity
x_6	Presence of anti-/de-icing chemicals
x_7	Presence of sand

Table 3
Contamination codes for describing the contamination type.

K	Description
NIL	Bare and dry
1	Damp
2	Wet
3	Rime
4	Dry snow
5	Wet snow
6	Slush
7	Ice
8	Compacted or rolled snow
9	Frozen ruts or ridges

Table 4
The values for x_1 for the different types of contamination. The contamination codes are given in parentheses.

$x_1 = 1$	$x_1 = 2$	$x_1 = 3$
Wet ice (27)	Wet snow (5)	Slush (6)
Wet compact snow (28)	Wet snow on ice (57)	Ice (7)
	Wet snow on compact snow (58)	Compact snow (8)
	Slush on ice (67)	Rime on ice (37)
	Slush on compact snow (68)	Rime on compact snow (38)
		Dry snow on ice (47)
		Dry snow on compact snow (48)
$x_1 = 4$		**$x_1 = 5$**
Rime (3)		Dry (NIL)
Dry snow (4)		Damp (1)
Frozen ruts (9)		Wet (2)

temperature is that close to the melting point, it is likely that melting has started or is about to occur.

Profile 3: "loose snow"

Although compact snow and ice can give relatively high friction at temperature well below 0 °C, it can become more slippery when loose snow crystals are present (Gnörich and Grosch, 1974; Klein-Paste and Sinha, 2010a). Therefore, profile 3 is similar to profile 2, except that it does not upgrade the prediction at lower temperatures. This profile is used when loose snow (dry snow or rime) is reported.

$$K \in [looseAndDryContaminated] \tag{6}$$

The values for x_4 for the different temperature profiles are summarized in Table 5.

2.5. Humidity, x_5

At temperatures well below 0 °C, runways covered with ice or compact snow tend to be more slippery when the humidity of the air above the runway is high (AIBN, 2011). The reason might be that rime crystals deposit on the ice and thereby create loose particles or that the surface topography of the ice changes (also known as "self-polishing"). A measure for high humidity is the difference between the air temperature T_{air} and dew point temperature T_{dew}. The difference, ΔT, is given by:

$$\Delta T = T_{air} - T_{dew}. \tag{7}$$

The IRIS model takes this effect into account by downgrading the prediction when the following criteria are valid:

$$\begin{array}{ll} x_5 = -1 & | \quad K \in solidContaminated \text{ and } T_{air} < -3 \ ^\circ\text{C and } \Delta T \leq 3 \ ^\circ\text{C} \\ x_5 = 0 & | \quad \text{otherwise.} \end{array} \tag{8}$$

Table 5
The temperature profiles for x_4.

RWY temp			Profile 1	Profile 2	Profile 3
	$T_{RWY} >$	-0.5	0	-2	-2
-0.5	$\geq T_{RWY} >$	-2	0	-1	-1
-2	$\geq T_{RWY} >$	-8	0	0	0
-8	$\geq T_{RWY}$		0	1	0

2.6. Chemicals, x_6

Anti- or deicing chemicals are often used to ensure that a wet runway does not freeze, to prevent bonding of snow/ice to the pavement, or to remove thin ice layers. Generally, when chemicals are applied on a wet surface, the frictional conditions are not improved, but it prevents deterioration of the conditions. Hence it does not justify an upgrade of the prediction. When chemicals are applied on initially dry (compact) snow or ice, a melting process starts. In these cases the frictional conditions often gets worse, before they get better as the snow/ice has been melted or removed.

The IRIS model therefore downgrades the prediction when chemicals are applied on dry snow, rime, compact snow, or ice. Downgrading is only performed when the spatial coverage is larger than 50%. The SNOWTAM format does not contain standardized codes for chemicals, but allows reporting in plain text. A Boolean *Chem* was defined to indicate if the use of chemicals had been described in the text field of the SNOWTAM report.

$$\begin{array}{ll} x_6 = -1 & | \quad K \in dryContaminated \text{ and } Chem = true \text{ and } S > 50\% \\ x_6 = 0 & | \quad \text{otherwise} \end{array} \tag{9}$$

2.7. Sanding, x_7

Many airports use sand to improve the tire–pavement friction. In Norway, sand is applied either dry or pre-wetted with hot water. The warm pre-wetted sand freezes to the runway, creating a sandpaper-like finish. This type of sand is called frozen sand. Sanding can increase tire–pavement friction (Comfort and Gong, 1999; Comfort et al., 1998), but it is difficult to get high level of tire–pavement friction when sand is used, particularly with loose sand. Therefore, the IRIS model upgrades P when sand is used, but sets a maximum limit for P ($P = 3$ for loose sand and $P = 4$ for frozen sand).

Frozen sand is most effective when it is spread on a solid contamination layer. This ensures a strong bond between the sand and the ice. In all other cases the model considers frozen sand as loose sand. Frozen sand may also loosen when the temperatures are too high. Since runway temperature sensors can be buried under a layer of compacted snow/ice, the air temperature is used to decide if the temperatures are two high. A Boolean *Sand* was defined to indicate if the text field of the SNOWTAM contains information that sand was present. A second Boolean *FrozSand* was defined to indicate if the sand was frozen to the runway. The model consists of three different routines (*noSand*, *looseSand* and *frozenSand*, respectively) and the appropriate routine is selected by:

$$\begin{array}{ll} Routine = noSand, \quad x_7 = 0 & | \quad sand = false \\ Routine = looseSand & | \quad sand = true \text{ and } frozSand = false \\ Routine = looseSand & | \quad sand = true \text{ and } frozSand = true \text{ and } T_{air} < -2 \\ Routine = looseSand & | \quad sand = true \text{ and } frozSand = true \text{ and } T_{air} \geq -2 \text{ and } K \notin solidContamination \\ Routine = frozenSand & | \quad sand = true \text{ and } frozSand = true \text{ and } T_{air} \geq -2 \text{ and } K \in solidContamination. \end{array} \tag{10}$$

2.7.1. Loose sand routine

When loose sand is used, friction is created by ploughing through an ice or compacted snow layer. The particles scratch the surface and create deformation in the ice/snow (Klein-Paste and Sinha, 2010b). This may explain "common experience" among runway maintenance personnel that "the sand needs something to bite in". They experience that sanding on a bare or wet runway actually reduces the friction. This might be counterintuitive, but can be rationalized because presence of sand particles will reduce the ability of the rubber to drape around the asperities of the pavement. Also sanding in loose snow (wet or dry snow) without a solid base layer is experienced as having little effect. The model will therefore upgrade the prediction only when loose sand is used on a base layer that includes compacted snow or ice.

$$\begin{array}{lll} x_7 = 0 & | \ Routine = looseSand & \text{and} \quad K \notin solidBaseLayer \\ x_7 = +1 & | \ Routine = looseSand & \text{and} \quad K \in solidBaseLayer \end{array} \tag{11}$$

After calculating x_7, the model ensures that the prediction does not exceed its defined maximum level for loose sand:

$$P = 3 \quad | \quad Routine = looseSand \quad \text{and} \quad \sum_{i=1}^{7} x_i > 3. \tag{12}$$

2.7.2. Frozen sand routine

When frozen sand is used and the conditions are favorable for its usage the model upgrades the prediction by 2 categories.

$$x_7 = +2 \quad | \quad Routine = frozenSand \tag{13}$$

After calculating x_7, the model ensures that the prediction does not exceed its defined maximum level for either frozen sand:

$$P = 4 \quad | \quad Routine = frozenSand \quad \text{and} \quad \sum_{i=1}^{7} x_i > 4. \tag{14}$$

2.8. Example

The following example describes a runway section that is covered with ice, 100% coverage, no depth of loose contamination (only ice), sanded with loose sand, no chemicals are used, air temperature = −2 °C, RWY temperature = −2 °C, Dewpoint = −4 °C.

The base judgment for ice (7) makes $x_1 = 3$.
The 100% coverage makes $x_2 = 0$.
No depth of loose contamination makes $x_3 = 0$.
Temperature profile 2 is selected (because ice is reported) and with RWY = −2 °C results in $x_4 = -1$.
The air temperature is above −3 °C, hence $x_5 = 0$.
No chemicals are applied, hence $x_6 = 0$.
Loose sand is being used on a solid base layer, hence $x_5 = +1$.

This lead to a final judgment of: $3 + 0 + 0 + -1 + 0 + 0 + 1 = 3$ (medium).

3. Results

3.1. Model performance during three winter seasons

The IRIS runway model was used to predict the conditions described in 9073 SNOWTAM reports, issued at Tromsø Airport (ENTC) and Oslo Airport (ENGM) during the winter seasons 2008/2009, 2009/2010, and 2010/2011. Each SNOWTAM describes the conditions on the three runway sections A, B, and C, resulting in a total of 27,219 section reports. The prediction frequency of each category (poor to good) of the IRIS model is presented in Fig. 2a. For comparison, the prediction frequency of the runway inspectors is shown in Fig. 2b. The prediction frequency of friction measurement devices could not be determined in a comparable manner because friction measurements were not always preformed while issuing a SNOWTAM.

Fig. 2a shows that the IRIS model uses all five categories. “Poor” is predicted in 2%, while “good” is predicted in 30% of all section reports. Most frequently the IRIS model predicted “medium” (47%). In comparison with the assessments of the runway inspectors (Fig. 2b) the IRIS model predicts the conditions “poor” and “poor to medium” not significantly more often than the runway inspectors. However, it tends to be more conservative when predicting on the right-hand side of the distribution (“medium-good” and “good”). The runway inspectors assessed the conditions as “Good” in 50% of all section reports, compared to the 30% of the IRIS model.

3.2. Comparison with measured airplane braking performance

A total of 46,153 landings of Boeing 737-600,-700, and -800 airplanes were registered during the winter seasons 2008/2009 to 2010/2011. In 1261 landings (2.7%), the airplane braked sufficiently to reach the maximum attainable tire–pavement friction (so called friction limited landings). From these landings, the airplane braking coefficient μ_B could be determined, using the methodology described earlier (Klein-Paste et al., 2012).

For each friction limited landing, the corresponding SNOWTAM and weather data was used to calculate the prediction of the IRIS model. This data was complemented with the prediction from the runway inspectors and the readings from the GFMDs. Both airports use continues fixed-slip friction measurement devices. All the results were converted to the common scale presented in Table 1. This provides a set of four predictions for the 1261 landings. In Fig. 3, the predictions of the IRIS model, runway inspectors and friction measurements are compared to the airplane braking performance. The difference (airplane − prediction) shows the number of categories the prediction deviated from the conditions experienced during landing. A difference of 0 means a correct prediction. A negative difference means that the airplane experienced the conditions worse than predicted. The percentage of predictions within ±1 category to the measured airplane braking action are indicated with a red dashed envelope.

Fig. 3 shows that the IRIS model performed better than the other predictors. The IRIS model predicted in 86% of the landings the runway conditions within ±1 category of what the airplane experienced. In contrast, the runway inspectors predicted the conditions in 77% of the landings within ±1 category. The GFMDs performed less with 61% of the predictions within ±1 category difference. Interestingly, the distribution of the friction measurements is more shifted towards the negative differences. This means that friction measurements more often predicted a too high friction category.

4. Discussion

For the three winter seasons at the two airports in Norway, the IRIS model was able to predict the conditions more accurate (closer to what the airplanes experienced), compared to the other predictors. This means that by using the IRIS model, the Norwegian runway inspectors can obtain a useful decision support while assessing the braking action. It also proves that the approach of directly interpreting the information in the SNOWTAM is useful and can improve the reporting accuracy.

The IRIS model provided the most conservative estimates of the three investigated predictors. It was particularly more conservative than the friction measurements. Meanwhile, the IRIS model appears not to be over-conservative. It reported “poor” braking action only in 2% of all SNOWTAM reports. Being conservative is of course very good when it comes to important safety issues like landings on contaminated runways. But for airports that are frequently operating under winter conditions, an over-conservative decision support model will not be experienced as a support anymore. It can be compared to an alarm that goes off too often. It loses its credibility by its users and will ultimately fail its main purpose, which is to improve safety. For airports that face winter conditions rather seldom, the IRIS model may however not be conservative enough. It should be kept that winter operations are considered as “normal daily life” at Norwegian airports. Their winter season stretches approximately from November to April. On average, the middle portions of the Tromsø and Oslo runways (B sections) were contaminated 30% of the winter seasons. The airports are well-equipped, the

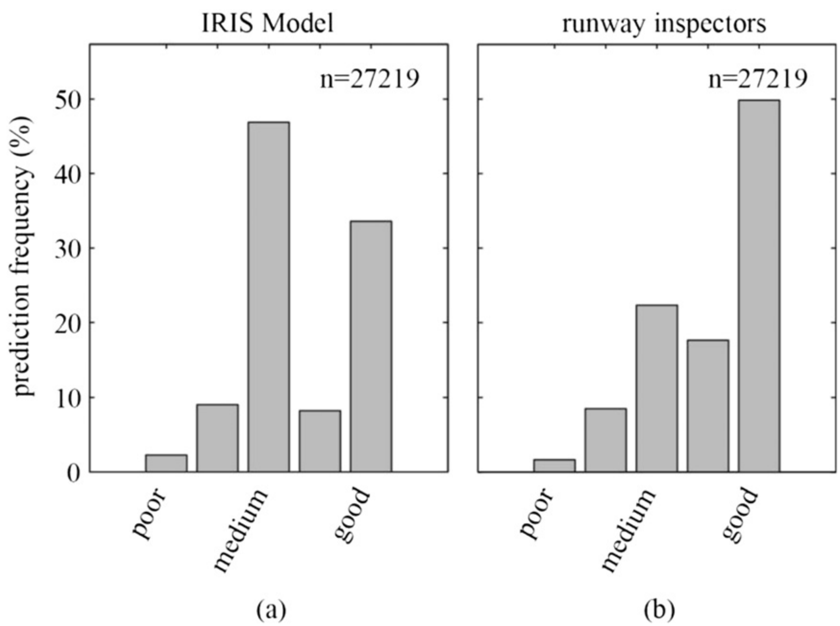

Fig. 2. (a) The prediction frequency of the IRIS model and (b) the assessments of runway inspectors for all SNOWTAM reports during three winter seasons.

maintenance staff is trained and most runway inspectors have more than 10 year experience. But Norwegian Airports are not unique in the world. There are many airports in the colder regions of the world where winter conditions are a part of their daily life.

The IRIS model should however not be seen as "the solution" to the problem of predicting surface conditions. This problem has been an issue since the 1950s (Norheim, 2004) and will probably be debated in the future as well. Also the IRIS model fails in some cases to give the correct prediction of what the airplane actually experienced. There may be several reasons for this "failure", such as the quality of the input data, spatial variation in the contamination, uncertainties in measuring the actual experienced braking action, and variations of the conditions in time. It is of course possible to obtain an improvement when more data is available, our understanding of how the different factors influence the braking action increases and our analytical techniques to determine actual experienced braking action improves. But replacing the assessment of runway inspectors with the IRIS model (in other words using the model to make the decision, rather than being a decision support tool) is dangerous because it totally dependent on the data that is subjectively collected and it lacks the capability to detect extreme situations, such as rain fall on a contaminated runway after a SNOWTAM has been issued.

A question that often came up during this project was "why not using the landing data directly and send the measured airplane braking coefficient to the next incoming airplane?" Although it is technically possible there are some important limitations with this approach: (1) pilots seldom use the wheel brakes sufficient to get an accurate measurement of the conditions. When pilots only brake gently (and get most retardation from revers engine thrust and aerodynamic drag) it is not possible to get an accurate measurement with today's commercial airplanes. In this study, sufficient wheel braking was only used during 2.7% of the landings. The majority of the landings could therefore not be used to determine how much friction was available. (2) An airplane seldom travels over the whole runway length while braking. More typical, the wheel braking is performed in the last stage of the landing. This means that not all runway sections get a measurement. (3) A single landing contains a large amount of variability, particularly on partly contaminated runways. A direct use is prone to drawing conclusions

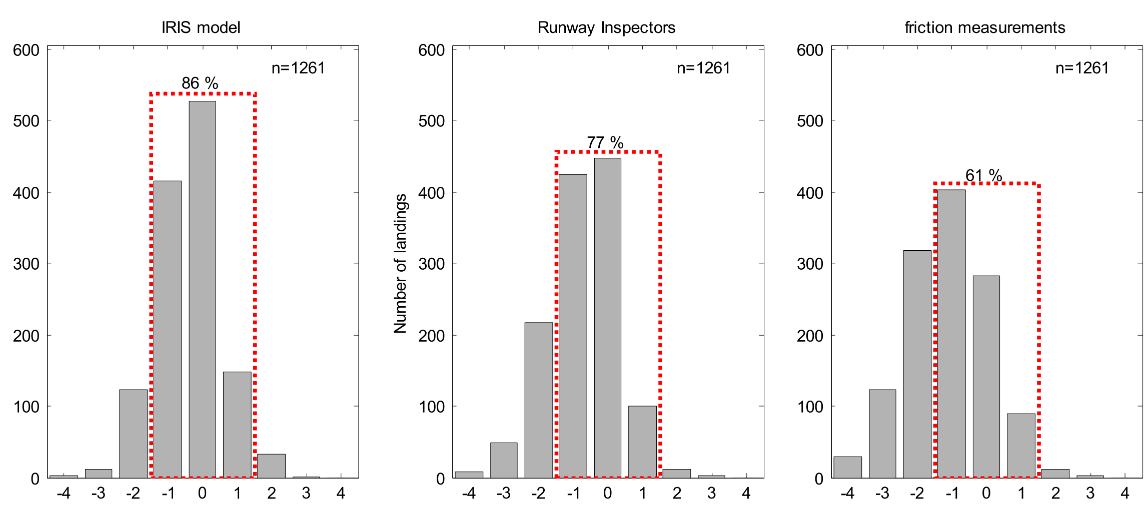

Fig. 3. The comparison of the four different friction predictors with airplane braking performance. A negative difference means the airplane experienced the conditions worse than predicted.

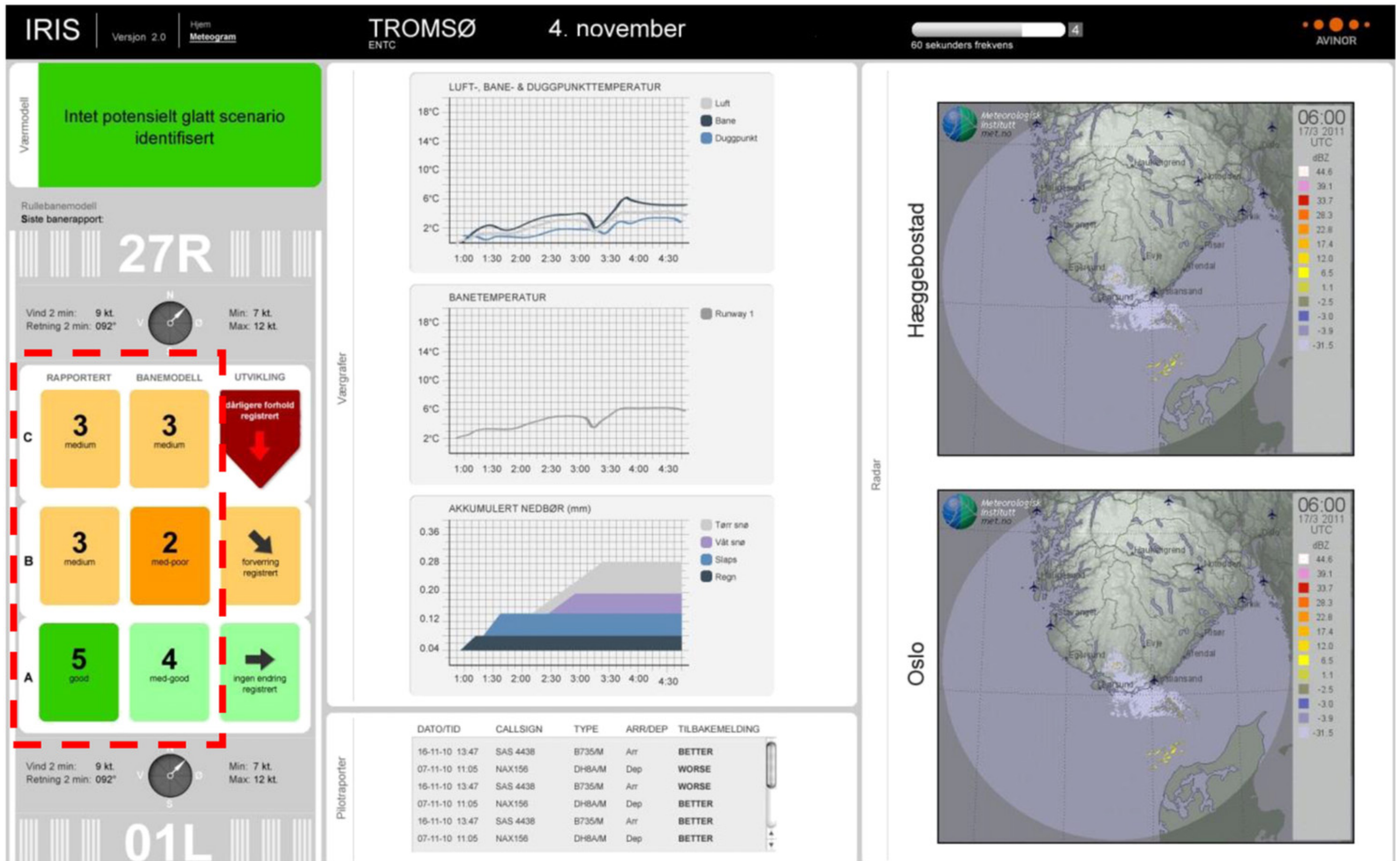

Fig. 4. Screenshot of the IRIS user interface. The left column shows the weather and runway model, the middle column presents temperature and accumulated precipitation graphs and pilot reports, and the right column shows the weather radar images. The IRIS runway model (marked by the red dashed rectangle) is presented for each runway section beside the actually reported conditions.

based on scatter in the data, rather than real existing trends. For these reasons we believe that it is better to use landing data as a reference for the development of predictive models, rather than making it the predictor itself.

5. Implementation

The IRIS runway model has been implemented in the IRIS system, which is at the time of writing installed at 15 airports in Norway. A screen shot of the information screen is shown in Fig. 4. Runway inspectors can evaluate their assessment of the conditions with the outcome of the runway model *after* they issued the SNOWTAM. The outcome of the IRIS runway model is presented together with their assessment for the three runway sections. Initially this presentation was chosen because it was uncertain how well the model would perform, and to avoid artificially good correlation between the model and the assessment of the runway inspectors. If the inspectors wanted to follow the outcome of the runway model they had to issue a new SNOWTAM, and this could be detected in the data afterwards. But during the implementation process, this way of presenting the IRIS model had an interesting unintended effect: Rather than blindly accepting the outcome of the IRIS model while making their assessments, runway inspectors evaluated their assessment performance each time they looked at the screen. The side-by-side presentation of their assessment and the outcome of the IRIS model led to numerous discussions between ground staff on how to judge runway surface conditions and to why the runway model predicted differently. It was found that these discussions were very valuable in enhancing the expertise and training of the runway inspectors.

Using the IRIS runway model puts higher demands on the accuracy of the descriptive data in the SNOWTAM report. For many airports, a SNOWTAM is only used by pilots as a planning tool before take-off, to see the conditions the destination airport. Hence although runway inspections are made, they are not always converted into a SNOWTAM. Often runway inspections are directly communicated to Air Traffic Control by radio. Using the IRIS runway model requires a systematic method to collect all the input parameters shown in Fig. 1. The IRIS model is therefore intended for airports that frequently operate under winter conditions and where the maintenance staff is trained and experienced in assessing runway conditions.

6. Conclusions

A decision support model (the IRIS runway model) has been developed that predicts the braking action on winter contaminated runways by systematically evaluating available information from the SNOWTAM report and meteorological measurements. The model is intended as a support tool for airports that are used to operate under winter conditions.

The IRIS runway model was used to interpret 9073 SNOWTAM reports, covering three full winter seasons. It was found to be more conservative than the assessments by Norwegian runway inspectors. Despite this increased conservatism, the number of cases that the model predicts "poor" conditions is still low (about 2%), reserving this designation for only a limited number of situations.

The predictions of the IRIS model, runway inspector assessments, and friction measurements were compared with the attained braking action of 1261 commercial airplane landings on winter contaminated runways that were fully braking (called a friction limited landing). For these landings, The IRIS model was found to perform better than the assessment by runway inspectors. In 86% of the landings, the IRIS runway model predicted the conditions within ± 1 category of what the airplane experienced compared to 77% achieved by the runway inspectors. The predictions by the friction measurement devices were the least conservative and predicted the conditions within ± 1 category in 61% of the landings. It shows that it can be a real decision support tool that contributes to more accurate reporting of runway surface conditions.

The IRIS model has been implemented at 15 airports in Norway that frequently operate under winter conditions (up to 100 days per year). The model is intended for such airports and will require a systematic collection of SNOWTAM information. Airports that are facing much more seldom under winter conditions probably need more conservative estimates than given by the IRIS model.

Acknowledgments

This research was funded by the Norwegian Aerodrome Operator Avinor. The authors thank Tor-Børre Langedahl, Avinor AS, for the financial and moral support during this project.

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