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Joint Winter Runway Friction Measurement Program (JWRFMP)

1997-98 Testing and Data Analysis

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by
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October 1999

Since the accepted measures in the industry are imperial, metric measures are not used in this report.

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16. Abstract

This study was part of a government/industry project called the Joint Winter Runway Friction Measurement Program (JWRFMP), led by Transport Canada and the National Aeronautics and Space Administration, with support from National Research Council Canada, the U.S. Federal Aviation Administration, the Norwegian Civil Aviation Authority, France's Direction générale de l'aviation civile, and organizations and equipment manufacturers from Austria, Canada, France, Germany, Norway, Scotland, Sweden, Switzerland, and the United States.

A statistical model and a physical model of the ground friction measurements devices are the two approaches currently being developed. The following equation represents a linear regression of the data for each device that participated in the JWRFMP to an International Runway Friction Index (IRFI) reference:

$$\mu_{IRFI} = a + b \times \textit{device friction measurement},$$

where a is the intercept and b is the gradient that were determined by the regression to the reference device. Unlike the statistical model, the physical method first develops a physical model relating the surface and tire characteristics. A regression is then applied and the properties with significant effects are retained in the model.

The statistical analysis was conducted to calculate the regression coefficients a and b. The average correlation (R^2) was 0.94. The average sensitivity was 0.018 and the average standard error of estimate was 0.04. Currently, the recommended procedure for harmonizing ground vehicle data is the Statistical IRFI.

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16. Résumé

Cette étude s'inscrivait dans le cadre d'un projet mené conjointement par le gouvernement et l'industrie, intitulé Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH). Transports Canada et la National Aeronautics and Space Administration (NASA) pilotent ce programme, appuyés par le Conseil national de recherches du Canada, la Federal Aviation Administration des États-Unis, l'Administration norvégienne de l'aviation civile, la Direction générale de l'aviation civile de France, ainsi que des organisations et des fabricants de matériel d'Autriche, du Canada, de France, d'Allemagne, de Norvège, d'Écosse, de Suède, de Suisse, du Royaume-Uni et des États-Unis.

Les travaux actuels se poursuivent dans deux grandes directions, soit l'élaboration d'un modèle statistique et d'un modèle physique des appareils de mesure du frottement. L'équation ci-après représente une régression linéaire des données recueillies par chaque appareil de mesure du coefficient de frottement utilisé dans le cadre du PCRGCAH sur les données recueillies par un appareil de référence IRFI :

$$\mu_{IRFI} = a + b \times \textit{coefficient de frottement enregistré par l'appareil,}$$

où *a* est l'ordonnée à l'origine et *b* le gradient, déterminés par la régression sur l'appareil de référence. Contrairement au modèle statistique, la méthode physique consiste d'abord à réaliser un modèle physique qui met en relation les caractéristiques de la surface et celles du pneu. Après analyse de régression, les variables associées à des effets significatifs sont intégrés au modèle.

L'analyse statistique avait pour objet d'établir les coefficients de régression *a* et *b*. La corrélation moyenne (R^2) s'est établie à 0,94, la sensibilité moyenne à 0,018 et l'écart type moyen à 0,04. Pour l'instant, la procédure recommandée pour harmoniser les données des véhicules au sol est l'IRFI statistique.

17. Mots clés
Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver, PCRGCAH, indice international de la glissance des pistes, IRFI, analyse statistique, modèle physique

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EXECUTIVE SUMMARY

Measuring the capability of a runway surface to provide aircraft tire braking action is fundamental to airport aviation safety, especially under winter conditions. The different seasons, mainly winter, result in the possibility of the runway having contaminants of varying natures and qualities that contribute to reduced braking friction capabilities. Because the operational window for aircraft movement can change quite rapidly and frequently in the winter, a service is warranted for the measurement of surface friction.

In the past, users of friction information have generally perceived the quality of the friction measurement service as poor. Often, these users have indicated that the reported friction values do not represent the actual braking friction that is experienced with aircraft tire braking.

International research of friction measurement confirmed that friction measurement devices measure and report different friction values for the same surface. Differences occurred among units of the same generic device as well as across different device types. The perception of non-uniformity was compounded by surfaces exhibiting large variances in reported values. These variances further augmented the differences among device types.

Measurements of friction were not calibrated to a common scale in the past. Also, being a non-dimensional ratio of forces, they were never associated with units of a scale, which could be another reason for the resulting differences. Ultimately, dynamic friction measurement results in the highest accuracy, but the procedure is limited to machine component calibrations. Research over the past four years has made significant advances toward solving these problems. Methods of measurement are being improved to increase measurement quality, remove uncertainties, and provide better correlation to aircraft tire braking. Prototype methods that incorporate ground friction measurement devices have shown very promising results.

This study was part of a government/industry project called the Joint Winter Runway Friction Measurement Program, led by the National Aeronautics and Space Administration and Transport Canada. Support is received from National Research Council Canada, the U.S. Federal Aviation Administration, the Norwegian Civil Aviation Authority, and France’s Direction générale de l’aviation civile. Organizations and equipment manufacturers from Austria, Canada, France, Germany, Norway, Scotland, Sweden, Switzerland, and the United States are also participating.

Objectives of the project include:

- Compiling a database containing all test data available from ground vehicles and aircraft that participated in the winter and summer runway friction programs.
- Using the data to determine a harmonized runway friction index: the International Runway Friction Index (IRFI).

IRFI Models

A statistical model and a physical model are the two approaches currently being developed. Both are valid for defined surface classification.

Statistical Model

Normally, regression techniques would be used to find relationships between the reported friction values of pairs of ground friction measurement devices. Such a technique assumes that one device's interaction with a surface is similar to another device's interaction with the same surface. The device, or an algebraic transformation of reported friction values, such as the average friction of two or more devices, would be selected as a reference. All devices would then be compared to the reference device to establish transformation constants. A simple linear regression, as shown in the equation below, is seen as a first step or an interim method, which can be applied by the aviation community in the near future. The following equation represents a linear regression of the data for each device to an IRFI reference:

$$\mu_{IRFI} = a + b \times \textit{device friction measurement}$$

where a is the intercept and b is the gradient that were determined by the regression to the reference device. Past attempts failed because the data were not acquired at the same time in the same wheel track. Also, the sample size was too small. Since 1998, the friction measurement and corresponding data collection have been carried out more systematically. Pairs of measurement devices run in a wave pattern so that they measure the same surface within 15 seconds of each other. However, even with this systematic approach there are considerable variations in the measured surface condition because of the lateral placement of the devices and the resulting effect of surface compaction. The database now includes more than 30,000 friction measurements.

Physical Model

Unlike the statistical model, this model first develops a physical relationship between the surface and the tire. A regression is then applied to the database to determine the constants that relate to the properties selected. Properties having little or no effect are disregarded and the properties with significant effects are retained in the model.

Bare ice and bare compacted snow were selected as generic surfaces for the investigation of the physical IRFI model. A bare condition means that there is no loose snow or fluid layer on the travelled surface. The proven exponential models, with speed and/or slip speed, have been successfully applied to pavement friction monitoring in the past and will facilitate a general unified technique across all surfaces.

The pavement friction models incorporate measurements of texture in their exponential constant term. More data, representing a greater speed and temperature range, are needed to fully develop the physical IRFI model. For details of the physical model, refer to *Friction Fundamentals, Concepts and Methodology.*[1]

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[1] A. Andresen and J.C. Wambold, *Friction Fundamentals, Concepts and Methodology,* Transportation Development Centre, Transport Canada, TP 13837E, October 1999.

(Virtual) IRFI Reference – 1998

Based on a review of virtual references in 1998, it was concluded that the best option was to use the average of the Transport Canada 1979 Surface Friction Tester (SFT79) and the Instrument de Mesure Automatique de Glissance (IMAG). There are several reasons for this choice:

- They were tested at both Gardermoen and North Bay.
- In the analysis they produced equivalent or better correlations, R^2 and CV.
- Their average was about the same as the average friction of the measurement devices.
- They can measure both force and torque, which is necessary for future work.
- They will likely be at the three sites in the coming years.

Statistical IRFI

All of the 1998 data were combined and the statistical analysis was run to calculate the regression coefficients. Table 1 is a summary of these values. The values *a* and *b* were applied to the device to calculate the IRFI and thus harmonize the friction measurement. The average correlation (R^2) was 0.94.

Table 1 Correlation Constants with all 1998 Data

Model IRFI = $a + b \times \mu_{device}$ Ref. = (SFT79 + IMAG)/2 1998 data				
Device	***a***	**St. Error *a***	***b***	**St. Error *b***
Airport Surface Friction Tester (ASFT)	0.0055	0.0147	0.6232	0.0574
Skiddometer (BV-11)	0.0395	0.0104	0.6424	0.0472
Electronic Recording Decelerometer (ERD)	0.0417	0.0269	0.8705	0.1211
GripTester with standard tire (GT-STD)	-0.0147	0.0066	0.9923	0.0442
GripTester with standard tire (GT-SC)	0.0285	0.0102	0.7523	0.0497
French IMAG	-0.0577	0.0105	1.291	0.0558
Norsemeter OSCAR	0.0146	0.0193	1.0205	0.1307
Norsemeter RUNAR	-0.1405	0.0338	1.348	0.1471

Sensitivity and the Standard Error of Estimate of the Statistical IRFI

Sensitivity is defined as the change in the predicted value, IRFI, for a given change in the measuring device, μ_{device}. Table 2 is for bare ice and compacted snow, and it gives the sensitivity to a 10 percent change in measurement and the standard error of estimate for each device. The average sensitivity is 0.018 and the average standard error of estimate is 0.02.

Table 2 Statistical IRFI Sensitivity

Device	Sensitivity	Standard Error of Estimate
ASFT	0.012028	0.0193
BV-11	0.013426	0.0209
ERD	0.039085	0.0449
ERD in a Nissan	0.018095	0.0184
GT-STD	0.005061	0.0051
GT-SC	0.007147	0.0095
IMAG	0.018074	0.014
OSCAR	0.026533	0.026
RUNAR	0.038688	0.0287
SFT79	0.006615	0.0084

Conclusions and Recommendations

Currently, the recommended procedure for harmonizing ground vehicle data is the Statistical IRFI, which includes the International Friction Index (IFI) for bare dry and bare wet surfaces. This works adequately for the equipment that was used in the Joint Winter Runway Friction Measurement Program for the past three years on ice, compacted snow, and compacted snow with a few millimetres of loose snow. It achieves the objective of providing a uniform number representing the friction sensed by the ground vehicles and has the advantage of only needing to classify whether the surface is bare and dry, bare and wet, or covered with ice and/or snow. In practice, the friction level should be able to separate these three surface types, especially when combined with tire and surface temperature measurements. The model gives good correlations with reasonable standard errors for bare ice and bare compacted snow surfaces. Its advantage is that the exact class of snow or ice does not have to be specified, only whether the surface is contaminated. The correlations from the NASA Wallops data will be applied to the bare and wet surfaces. For wet pavement, the IFI, as specified in ASTM Standard E1960, has been adopted; only the texture information, or the friction speed gradient, is needed in the correlation equation.

Additional data are required to validate the physical model for the IRFI. The physical IRFI model is felt to have a greater potential for relating ground vehicle data to aircraft braking performance. During the remaining test seasons, emphasis will be placed on obtaining data over a broader range of temperature and slip speeds, which should improve the significance of both models. In addition, the effect of contact pressure should be added to the physical model. Unlike the statistical method, this model requires that the snow or ice surface be identified to know which constants to use. However, the model should be able to correct for a wider set of conditions. The two models may be merged into a universal model in the future.

SOMMAIRE

Connaître l’adhérence des pneus d’un avion au freinage est essentiel à la sûreté des opérations aériennes aux aéroports. En hiver surtout, les pistes peuvent comporter des contaminants de natures diverses qui réduisent l’adhérence à divers degrés. De plus, en hiver, les conditions de décollage/atterrissage peuvent changer très rapidement et à une fréquence telle que la constitution d’un service aéroportuaire de mesurage de la glissance des chaussées est amplement justifiée.

Par le passé, les utilisateurs des données sur la glissance avaient une piètre opinion du service de mesure de la glissance des pistes. Ces utilisateurs se sont souvent plaints que les valeurs de glissance enregistrées n’avaient rien à voir avec le comportement des pneus au freinage.

Des travaux de recherche sur la glissance des pistes menés à l’échelle internationale ont confirmé que les appareils de mesure du coefficient de frottement captent et enregistrent différentes valeurs de glissance pour la même surface. Des écarts ont été observés non seulement entre les mesures prises par des appareils de différents types, mais aussi entre les mesures effectuées par un même appareil. Les valeurs enregistrées sur une même surface affichaient de larges écarts, ce qui ne faisait rien pour dissiper la perception de non-uniformité. Et ces fluctuations étaient d’autant plus grandes que différents types d’appareils étaient utilisés.

On ne prenait pas la peine alors de rapporter les mesures du frottement à une échelle commune. De plus, comme ces mesures représentaient un rapport non dimensionnel, elles n’ont jamais été associées aux unités d’une échelle, autre explication possible des écarts enregistrés. Finalement, la mesure du frottement dynamique donne la plus grande précision, mais cette procédure se heurte à une difficulté, soit le calage intégré des éléments de chaque appareil. La recherche menée ces quatre dernières années a grandement contribué à résoudre ces problèmes. Ainsi, grâce au perfectionnement des méthodes de mesure, les mesures sont de meilleure qualité et mieux corrélées avec la performance en freinage des pneus aéronautiques, et les incertitudes sont éliminées. Des méthodes novatrices utilisant des appareils de mesure du frottement au sol ont donné des résultats très encourageants.

Cette étude s’inscrivait dans le cadre d’un projet mené conjointement par le gouvernement et l’industrie, intitulé Programme conjoint de recherche sur la glissance des chaussées aéronautiques l’hiver (PCRGCAH). Transports Canada et la National Aeronautics and Space Administration (NASA) pilotent ce programme, appuyés par le Conseil national de recherches du Canada, la Federal Aviation Administration des États-Unis, l’Administration norvégienne de l’aviation civile et la Direction générale de l’aviation civile de France. Des organisations et des fabricants de matériel d’Autriche, du Canada, de France, d’Allemagne, de Norvège, d’Écosse, de Suède, de Suisse, du Royaume-Uni et des États-Unis participent également au programme.

Objectifs du projet :

- Constituer une base de données contenant toutes les données d'essai recueillies par les appareils de mesure au sol et les avions qui ont participé aux campagnes d'essais tenues aussi bien en hiver qu'en été.
- Utiliser les données pour établir un indice harmonisé de glissance des pistes, désigné indice international de glissance des pistes (IRFI, pour *international runway friction index*).

Modèles d'IRFI

Les travaux de recherche actuels se poursuivent dans deux grandes directions, soit l'élaboration d'un modèle statistique et d'un modèle physique des appareils de mesure du frottement au sol. Les deux modèles sont valides pour des types bien définis de surfaces.

Modèle statistique

Habituellement, on se sert de techniques de régression pour établir les relations entre les coefficients de frottement enregistrés par deux appareils différents. Pour utiliser cette technique, on doit supposer que l'interaction d'un appareil avec une surface s'apparente à l'interaction d'un autre appareil avec la même surface. L'appareil, ou une transformation algébrique des coefficients de frottement enregistrés, comme la moyenne des valeurs obtenues par deux ou plusieurs appareils, est choisi comme appareil de référence. Tous les appareils sont alors comparés à l'appareil de référence pour l'établissement des constantes de transformation. Une régression linéaire simple (voir l'équation ci-après) est considérée comme une première étape ou une méthode provisoire que pourraient appliquer les milieux aéronautiques dans un proche avenir. L'équation ci-dessous représente une régression linéaire des données de chaque appareil sur les données d'un appareil de référence IRFI :

$$\mu_{IRFI} = a + b \times \textit{coefficient de frottement enregistré par l'appareil}$$

où a est l'ordonnée à l'origine et b le gradient, déterminés par la régression sur l'appareil de référence. Les tentatives antérieures de développer un indice uniforme avaient échoué parce que les données étaient recueillies à des moments et à des endroits différents. De plus, les échantillons de données n'étaient pas assez grands. Mais depuis 1998, la mesure des coefficients de frottement et la collecte des données correspondantes sont davantage systématiques. Ainsi, deux appareils de mesure sont lancés l'un à la suite de l'autre, de sorte qu'ils mesurent la même surface à 15 secondes d'intervalle. Mais, malgré cette approche systématique, il subsiste des écarts considérables entre les valeurs obtenues, car le fait de décaler latéralement les appareils produit, au nombre des appareils mis en œuvre, un effet de tassement. La base de données comprend maintenant plus de 30 000 valeurs de mesure du frottement.

Modèle physique
Contrairement au modèle statistique, ce modèle consiste à établir d'abord une relation physique entre la surface et le pneu. Une régression est alors appliquée à la base de données pour déterminer les constantes reliées aux variables sélectionnées. Les variables qui produisent peu ou pas d'effet sont laissées de côté, tandis que celles qui produisent des effets significatifs sont intégrées au modèle.

Les surfaces dégagées de glace et de neige tassée ont été désignées surfaces génériques aux fins de l'étude du modèle physique d'IRFI. Par surface dégagée, on entend une surface exempte de neige poudreuse ou de couche de liquide. Les modèles exponentiels éprouvés, avec vitesse et/ou pourcentage de glissance, ont été appliqués avec succès, par le passé, à la surveillance de la glissance des chaussées et ils constituent une technique générale et unifiée pour l'étude de toutes les surfaces.

Dans les modèles exponentiels de glissance des chaussées, le terme exponentiel constant comporte des valeurs de texture. Des données supplémentaires touchant des plages de vitesses et de températures plus étendues demeurent à colliger, pour compléter l'élaboration du modèle physique d'IRFI. Pour plus de détails sur le modèle physique, se reporter à *Friction Fundamentals, Concepts and Methodology.*[2]

Appareil de référence (virtuel) IRFI – 1998

Après analyse, en 1998, des résultats enregistrés par les appareils de référence virutels, il a été conclu que la meilleure option était d'utiliser la moyenne des valeurs enregistrées par le glissancemètre de Transports Canada (SFT79) et l'Instrument de mesure automatique de glissance (IMAG). Ce choix s'appuie sur plusieurs raisons :

- Les deux appareils ont été utilisés aussi bien à Gardermoen qu'à North Bay.
- L'analyse des données a débouché sur des corrélations aussi bonnes sinon meilleures (R^2 et CV).
- Ils ont produit des moyennes qui se rapprochent des valeurs de frottement moyennes des appareils de mesure.
- Ils permettent tous les deux de mesurer à la fois la force et le couple, paramètres dont on aura besoin lors des travaux à venir.
- Il est probable que les trois sites d'essai disposeront des deux appareils dans les années à venir.

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[2] A. Andresen et J.C. Wambold, *Friction Fundamentals, Concepts and Methodology,* Centre de développement des transports, Transports Canada, TP 13837E, Octobre 1999.

IRFI statistique

Toutes les données de 1998 ont été réunies et soumises à une analyse qui visait à établir les coefficients de régression. Le tableau 1 récapitule ces valeurs. Les valeurs *a* et *b* ont été appliquées à l'appareil pour établir l'IRFI et ainsi harmoniser la mesure du frottement. La corrélation moyenne (R^2) était de 0,94.

Tableau 1 Constantes de corrélation entre toutes les données de 1998

Modèle IRFI = $a + b \times \mu_{appareil}$ Réf. = (SFT79 + IMAG)/2 – données de 1998				
Appareil	***a***	**Écart type *a***	***b***	**Écart type *b***
Glissancemètre aéroportuaire (ASFT)	0,0055	0,0147	0,6232	0,0574
Skiddomètre suédois (BV-11)	0,0395	0,0104	0,6424	0,0472
Décéléromètre électronique (ERD)	0,0417	0,0269	0,8705	0,1211
GripTester avec pneu ordinaire (GT-STD)	-0,0147	0,0066	0,9923	0,0442
GripTester avec pneu ordinaire (GT-SC)	0,0285	0,0102	0,7523	0,0497
IMAG français	-0,0577	0,0105	1,291	0,0558
Norsemeter OSCAR	0,0146	0,0193	1,0205	0,1307
Norsemeter RUNAR	-0,1405	0,0338	1,348	0,1471

Sensibilité et écart type de l'estimation du modèle statistique d'IRFI

La sensibilité est la modification de la valeur prédite, l'IRFI, en fonction d'une modification donnée de l'appareil de mesure, $\mu_{appareil}$. Le tableau 2 concerne des surfaces recouvertes de glace et de neige compactée. Il donne la sensibilité à une modification de 10 p. cent de la mesure et l'écart type de l'estimation donnée par chaque appareil. La sensibilité moyenne est de 0,018 et l'écart type moyen de l'estimation est de 0,02.

Tableau 2 Sensibilité de l'IRFI statistique

Appareil	Sensibilité	Écart type de l'estimation
ASFT	0,012028	0,0193
BV-11	0,013426	0,0209
ERD	0,039085	0,0449
ERD dans une Nissan	0,018095	0,0184
GT-STD	0,005061	0,0051
GT-SC	0,007147	0,0095
IMAG	0,018074	0,014
OSCAR	0,026533	0,026
RUNAR	0,038688	0,0287
SFT79	0,006615	0,0084

Conclusions et recommandations

Pour l’instant, la procédure recommandée pour l’harmonisation des données des différents appareils de mesure du coefficient de frottement est de se servir de l’IRFI statistique, qui comprend l’indice international de glissance (IFI) pour surfaces dégagées sèches et dégagées mouillées. Cette technique fonctionne bien avec les appareils utilisés au cours des trois dernières années du programme, dans des conditions de glace, de neige tassée et de neige tassée recouverte de quelques millimètres de neige poudreuse. Elle atteint l’objectif de disposer d’un indice uniforme, peu importe l’appareil utilisé, pour mesurer le coefficient de frottement, en exigeant peu de chose de l’utilisateur, soit qu’il définisse la surface comme dégagée sèche, dégagée mouillée ou couverte de glace et/ou de neige. Dans les faits, le degré de glissance devrait pouvoir être rattaché à ces trois types de surfaces, surtout lorsqu’il est combiné aux mesures de la température des pneus et de la piste. Le modèle affiche de bonnes corrélations et des écarts types raisonnables pour les pistes recouvertes de glace et de neige tassée. Son avantage est qu’il n’exige pas que l’on précise la catégorie exacte de neige ou de glace : il suffit d’indiquer que la surface est contaminée. Les corrélations avec les données des essais de la NASA aux îles Wallops seront appliquées aux surfaces dégagées et mouillées. Pour les chaussées mouillées, l’IFI a été adopté, selon les prescriptions de la norme ASTM E1960; seule l’information sur la texture, ou le gradient de vitesse dû au frottement, doit être précisée.

D’autres données doivent être recueillies pour permettre la validation du modèle physique de l’IRFI. Ce modèle physique semble présenter un lien plus direct entre les données des véhicules au sol et la performance en freinage des avions. Au cours des campagnes d’essai qu’il reste à effectuer, l’accent sera mis sur la collecte de données couvrant des plages plus étendues de températures et de pourcentages de glissance, ce qui devrait accroître la valeur des deux modèles. De plus, l’effet de la pression de contact avec le sol devrait être intégré au modèle. Contrairement à la méthode statistique, ce modèle exige que le type de contamination (neige ou glace) soit précisé, car le choix de la constante utilisée en dépend. Toutefois, il reste à rendre le modèle capable de compenser les variations d’un ensemble plus grand de conditions. Il est à espérer que les deux modèles pourront un jour être combinés dans un modèle universel.

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ACRONYMS AND DEFINITIONS

Acronyms

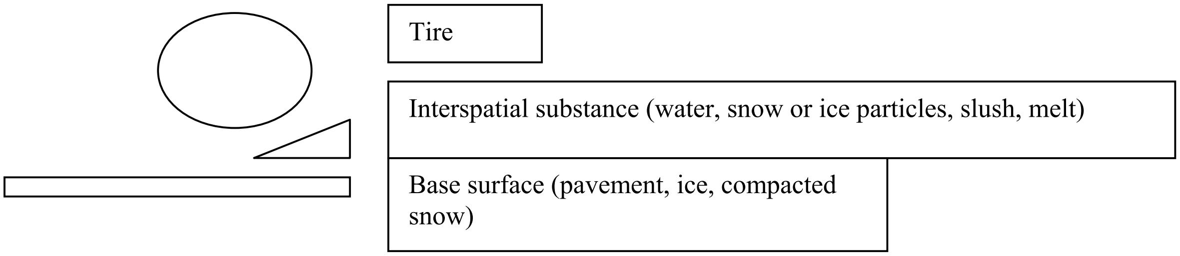
ASFT	Airport Surface Friction Tester, manufactured by Airport Surface Friction Tester AB, Ystad, Sweden
ASTM	American Society for Testing and Materials
BV-11	Skiddometer (Bromsvagn “Braking Vehicle”), manufactured by Airport Equipment Company (AEC), Stockholm, Sweden
CV	Coefficient of Variation
ERD	Electronic Recording Decelerometer
ERDNisson	ERD mounted in a Nisson SUV
FAA	Federal Aviation Administration, USA
GT-STD	GripTester with standard tire
GT-SC	GripTester with slushcutter tire
GTNDISC	GripTester with plastic disc tire
IB	Bare ice
IFI	International Friction Index
IMAG	Instrument de Mesure Automatique de Glissance, France
IRFI	International Runway Friction Index
ITTV	Integrated Tire Test Vehicle
JWRFMP	Joint Winter Runway Friction Measurement Program
NASA	National Aeronautics and Space Administration, USA
NB	North Bay
NRC	National Research Council Canada
OSCAR	Optimum Surface Characteristics Analyzer Recorder, manufactured by Norsemeter a.s., Rud, Norway
RUNAR	Runway Analyzer and Recorder, manufactured by Norsemeter a.s., Rud, Norway
SB	Bare compacted snow
SD	Compacted snow with a layer of loose snow
STBA	Service Technique des Bases Aériennes, Paris, France
SFT	Surface Friction Tester, manufactured by Saab AB, Stockholm, Sweden
TC-SFT79	1979 SFT owned by Transport Canada

Definitions

Interspatial substance - a transient layering of water or snow and/or ice particles mixed with variable amounts of free water and trapped de-icer, anti-icer or other chemicals, capable of detaching a moving vehicle tire from the frictional base surface and sometimes instantaneously forming a new frictional base surface through tire compacting forces.

Frictional base surface - a surface material that supports the bulk of braking slip friction in interaction with a braked tire.

Frictional interface - the contact area of a braked tire and a frictional base surface. The contact area between a braked tire and an interspatial substance does not provide adequate braking slip friction (i.e., aquaplaning and snow planning), although skin friction may occur.



1 INTRODUCTION

Measuring the capability of a runway surface to provide aircraft tire braking action is fundamental to airport aviation safety, especially under winter conditions. The different seasons, mainly winter, result in the possibility of the runway having contaminants of varying natures and qualities that contribute to reduced braking friction capabilities. In addition, because the operational window for aircraft movement can change quite rapidly and frequently in the winter, a service is warranted for the measurement of surface friction. The measured results of such services have had serious deficiencies, which have been acknowledged by experts worldwide.

The equipment used and procedures followed in measuring winter surfaces report noncalibrated values with respect to a common unit of measure of surface friction. A value from one type of device at one airport does not provide the same information as a value from another device operated at another airport, even if the two devices are of the same type. In general, a simple transformation of measured values from one device to another has not been possible in the past.

No satisfactory method or technique has been developed to predict the tire braking action of aircraft by using friction data collected by ground vehicles. Only limited, indirect correlations have been achieved between selected ground friction measurement devices and a few aircraft types. One technique that has been used is a grading scale of measured friction values collected by selected panels of pilots and based on past experience of braking action quality. A quantitative relationship between ground friction measurement devices and aircraft tire braking is needed.

Only Canada has a standard, the James Brake Index (JBI), which has been used to predict required runway length. In recent years this index has been revised and renamed the Canadian Runway Friction Index.

1.1 NASA/FAA/Transport Canada Joint Winter Runway Friction Measurement Program

The international government/industry initiative, called the Joint Winter Runway Friction Measurement Program (JWRFMP), is being led by the National Aeronautics and Space Administration (NASA) and Transport Canada, with support from the U.S. Federal Aviation Administration (FAA), the Norwegian Civil Aviation Authority, France’s Direction générale de l’aviation civile and National Research Council Canada (NRC). Also participating are organizations and equipment manufacturers from Canada, the United States, Austria, France, Germany, Norway, Scotland, Sweden, and Switzerland. The primary objective is to perform instrumented aircraft and ground vehicle tests aimed at improving the safety of aircraft ground operations. One of the program goals is flight crew recognition of less-than-acceptable reported runway friction conditions prior to the “go/no go” or the “land/go around” decision point. With this goal in mind, related studies are being conducted to look at contaminant drag, effects of runway treatments on friction, and, especially, the harmonization of ground vehicle friction measurement. Harmonization will enable friction data to be reported to a unified common index worldwide, which will then be used to predict aircraft braking performance. This report addresses the development of a common harmonized index, called the International Runway Friction Index (IRFI).

A few instrumented test aircraft and a variety of ground friction measurement vehicles were used at several different test sites in North Bay, Ontario, Canada, in 1996 and 1997. In 1998, testing at Jack Garland Airport, North Bay, Canada, and at Oslo Airport, Gardermoen, Norway, involved special tests and the verification of the IRFI on compacted snow and ice. Testing in 1999 involved the NRC Falcon 20 at North Bay and the NASA 757 at K.Y. Sawyer Airport in Michigan. Ground vehicle testing was conducted at both sites and again at the airport in Gardermoen, and included 11 different ground friction measurement devices (at times with several measurement devices of the same type but with different tires). To date, five aircraft have been used: Dash 8, Falcon 29, and Boeing 727, 737, and 757. Plans for future testing include wide-body aircraft and military cargo aircraft, along with new or improved ground testing equipment.

It is expected that dissemination, acceptance, and implementation of the test results throughout the aviation community will be facilitated by several organizations. These include the International Civil Aviation Organization, the American Society for Testing and Materials (ASTM), the Joint Aviation Authority, the International Federation of Air Line Pilots Association, the Air Line Pilots Association, the Air Transport Association, and Airports Council International.

The JWRFMP probably has the most extensive runway friction data ever collected at temperatures of 0^{o}C and below. The data are being added to NASA's tire friction database. Through ASTM Committee E17 on Vehicle-Pavement Systems, work is ongoing to develop a harmonized friction index, or IRFI, which is anticipated to become a standard used by airports to assess the condition of a runway under winter conditions.

The JWRFMP was established to resolve the major elements of the deficiencies stated in Section 1. After three years of testing, with the participation of experts from several countries, a systematic, standardized approach is being developed to achieve harmonized friction measurements. This will lead to a methodology for predicting how aircraft tire braking may behave in response to the most recent reported runway friction properties.

This approach, which is recognized by many as the most viable, was introduced by several speakers at the International Meeting on Aircraft Performance on Contaminated Runways, held in Montreal on October 20-22, 1996. The approach combines some elements of the International Friction Index (IFI), proposed by the World Road Association, with the use of inexpensive digital computing for handling the numerous and detailed pieces of information necessary to reach the objectives of harmonization and better aircraft tire braking predictions.

The results reported in this document provide comparisons of the different participating measurement devices, with different tires used to measure runway friction for both summer and winter conditions. This was a necessary step to achieve harmonization of different friction measurement devices. It was also necessary to compare the results to the aircraft tire friction. First, the results from the NASA Integrated Tire Test Vehicle (ITTV) with an aircraft tire were compared to the results of tires used on different ground friction measurement devices, and then comparisons were made with a virtual reference. The variables included surface temperature, tire contact pressure and load, slip speed, and vehicle speed. The project required use of the test data and results from the ongoing JWRFMP and information from the NASA annual friction workshops. The results of this study will be used to develop the IRFI and to harmonize the different friction measurement devices.

2 JWRFMP PROGRAM OBJECTIVE

In cooperation with other researchers from Transport Canada, NRC, NASA, and the FAA, the objective is to establish an International Runway Friction Index to harmonize all ground friction measurement so that the common values can be reported and used by airports around the world.

Program Sub-objectives

- Compile a database containing all test data available on winter and summer runway friction measurements from different devices and tires, including data on aircraft tire braking performance.
-
- Use the data to develop a harmonized runway friction index.
-

3 TRAVELLED SURFACE CLASSIFICATION

The travelled winter surfaces of roadways and airport runways consist mostly of solidified water in different crystalline forms. Compacted snow is white or grey in colour, mainly because of the high air content and the many crystal structures that characterize snow, and the specific gravity can be 25 to 75 percent of that of liquid water. When the air content is reduced, the snow becomes ice and the specific gravity then approaches that of liquid water.

The mechanical strength of compacted snow is less than that of paved surfaces. General experience suggests that, when working with a rigid surface such as pavement, the tire-surface frictional interaction will sacrifice the tire. However, in the case of snow and ice, the interaction will sacrifice the surface. Some researchers have used a tire friction measurement device to measure the mechanical strength of a travelled winter surface.

The temperature range for winter surfaces subjected to vehicle traffic is relatively narrow from a material science aspect and is close to the melting point of ice and snow. Normally, surface material becomes softer as it approaches the melting temperature. The material's temperature also has a significant influence on its mechanical properties: friction values between a tire and ice/snow increase with decreasing temperatures.

Even if the ice/snow surface is the affected part of the tire-surface interaction, the material may also exhibit textural effects in the friction process. While there is currently no way to measure the texture of winter surfaces, there are apparent differences in the texture of travelled snow and that of ice, because of the broken, foam-like crystalline structure of snow, compared to the denser ice.

4 IRFI MODELS

The two approaches currently being used, a statistical model and a physical model, are valid for defined surface classifications. In both approaches, runway measurement is divided into segments. The statistical method differentiates between segments that are winter-contaminated and those that are wet or dry, whereas the physical method separates segments that have the same surface classification, and harmonization is performed on a segment-by-segment basis, applying the appropriate harmonization constants for each surface class.

4.1 Statistical IRFI Model

Normally, regression techniques would be used to find relationships between the reported friction values for pairs of devices. One device, or an algebraic transformation of reported friction values, such as the average friction of two or more devices, would be selected as a reference. All devices would then be compared with the reference device to establish transformation constants. The model assumed that when the interaction of one measurement device with one surface changed, all other similar tire-surface interactions would change in a similar way under the same conditions.

The statistical model provides good correlations with reasonable standard errors for bare ice and bare compacted snow surfaces, with the advantage that it is not necessary to identify the exact class of snow or ice contaminating the surface. For bare dry pavement and bare wet pavement, another set of correlations must be used. In addition, texture information or speed gradient is needed in the correlation equation for bare dry and bare wet pavement. For bare wet pavement, the International Friction Index as specified in ASTM Standard E-1960 is recommended.

The field test data sampling for the model includes both ice and snow surfaces in order to create a data set of sufficient range to enable linear regressions.

4.2 Physical IRFI Model

Unlike the statistical model, the physical model first develops a physical model relating the surface and the particular device and tire characteristics. Regression analysis is applied to the database from the model device to determine the constants that relate to the properties selected. Properties having little or no effect are disregarded and the properties with significant effects are retained in the model.

The bare ice and bare compacted snow surfaces were selected as two generic surfaces for investigating the use of the physical IRFI model. A bare condition means that there is no loose snow, snow particles, or fluid layer on the travelled surface. The proven exponential models, with speed and/or slip speed so successfully applied to pavement friction monitoring, would facilitate a general unified technique across all surfaces, provided they also work for winter surfaces.

The pavement friction models incorporate measurements of texture in their exponential constant term ("speed constant"). By using an exponential model of tire-winter surface friction, an equivalent measurement of texture for snow and ice could be associated with the exponential constant for different winter surfaces. Measurements at several speeds would be required to determine an exponential constant since methods for separate texture measurements are not available for ice and snow, as they are for pavement without ice or snow.

The surface temperature of the material was chosen as an indicator of general mechanical strength (e.g., colder temperatures will raise the general friction force level). One could envisage that surface temperature would also influence the exponential "constant."

The physical model could include the effects of non-bare base surfaces, such as drag information for different layer thicknesses and densities of loose substances. This would enable selective treatments of different types of travelled winter surfaces, in combination with different types of braking vehicles. For example, harmonization on bare ice surfaces would yield different results than harmonization on compacted snow for the same device. A more in-depth analytical exploration of physical friction models can be found in Andresen et al. [1].

5 DEVELOPMENT OPTIONS CONSIDERED

A simple linear regression, called the statistical IRFI, is seen as a first step or an interim method that can be applied by the aviation community now. This model is a linear regression of the data for each device to a (virtual) IRFI reference:

IRFI = $a + b \times$ device friction measurement, where *a* is the intercept and *b* is the gradient, and where these constants were determined by regression with the reference device. Past attempts failed because the data used were not collected at the same time in the same wheel track. In 1998, the data were collected more systematically: pairs of measurement devices made each run consecutively, in a wave, so that they measured the same surface within about 15 seconds of each other. Previous data were not collected in this manner, and it was found that the surface characteristics could change so quickly that the different measurement devices had actually tested different surfaces and so the regression analysis was not valid.

6 ESSENTIAL ELEMENTS OF THE STATISTICAL IRFI MODEL

6.1 Supporting Test Data

An instrumented NASA Langley Boeing 737 Transport and an NRC Dassault Falcon-20 aircraft were used during January and March of 1996 at Jack Garland Airport in North Bay, Ontario, Canada. The Falcon-20 and seven ground friction measurement devices from six countries provided aircraft and/or ground friction measurements for over 30 winter runway conditions, including ice, loose snow, compacted snow, and ice and snow with sand and/or urea. During January, February, and March 1997, similar tests were performed with an FAA Boeing 727 transport, the NRC Falcon-20, and a DeHavilland Dash 8 aircraft, together with 13 ground friction measurement devices. Data obtained during these investigations quantified the severe reduction in runway friction, particularly in the 0^{o}C range.

The 1998 testing was conducted at North Bay and at the new Oslo Airport in Gardermoen, Norway. Special tests were done to verify the IRFI on compacted snow and ice. A total of 9,284 runs were made by ground vehicles through 1998 over a temperature range from -30^{o}C to $+8^{o}$C. A total of 257 sets of conditions were tested, sometimes with similar surface conditions, but most often with different air and surface temperatures. The surface conditions included bare dry, bare wet, smooth ice, rough ice, loose and packed snow of varying depths, slush, and various combinations of these conditions.

6.2 (Virtual) IRFI Reference Selection

A true value is needed to perform a linear regression; therefore, a virtual device called the reference was developed from combinations of devices. Based on a review of different measurement devices (see appendix A), it was concluded that the best option was to use the average of the TC-SFT79 and the Instrument de Mesure Automatique de Glissance (IMAG) for the reference. There were several reasons for this choice:

- They were tested at both Gardermoen and North Bay.
- In the analysis they produced equivalent or better correlations, R^2 and CV.

- Their average was about the same as the average friction of the ground measurement devices.

- They can measure both force and torque, which is necessary for future work.

- They will likely be at the three sites in the coming years.

6.3 IRFI Correlations

Using the reference described in subsection 6.2, a set of correlation constants was calculated. Table 1 gives the correlation constants for IRFI, based on the Gardermoen data only. The table also gives the standard error for each of the constants, and the average correlation R^2 was 0.94 (0.96 if the variable slip devices are removed). The complete documentation of the correlation analysis is given in Wambold et al. [2] and includes plotting (or graphic representations) of the correlation for each device.

Table 1 Correlation Constants

Model IRFI = $a + b \times \mu_{device}$ Ref.1=(SFT79 + IMAG)/2 Gardermoen data only				
Device	*a*	St. Error *a*	*b*	St. Error *b*
ASFT	0.0055	0.0147	0.6232	0.0574
BV-11	0.0358	0.0086	0.6106	0.0397
ERD	-0.0049	0.0148	0.9834	0.086
GT-STD	-0.0147	0.0066	0.9923	0.0442
GT-SC	0.0254	0.0063	0.733	0.0322
IMAG	-0.0575	0.014	1.3243	0.0843
OSCAR	0.0146	0.0193	1.0205	0.1307
RUNAR	-0.1008	0.0395	1.1188	0.1762
SFT-79	0.0387	0.0048	0.7772	0.0283

Inspection of the *b* multipliers for each device clearly reveals that different friction devices measure very different values of friction. The multipliers cover a range of 0.61 to 1.32. Thus, the harmonization constants themselves make the need for harmonization evident.

6.4 Validation Method for IRFI

The validation procedure used was a four-step process:

1. All new data were collected in pairs. All measurement devices were run in waves so that their runs were as close as possible, typically 10 seconds between a pair of

devices. For each 100 metres, each device measured and reported its speed, average friction, and surface temperature (if equipped to do so). All the data were then paired for all measurement devices for each 100 metres. This pairing of data was needed to take out the effects of the changes in the surfaces with time and distance along the site. With sun or wind, a surface can change within minutes. The 1998 Gardermoen tests also clearly showed that surface condition changes with distance along a site, even when the surface appears homogeneous. Generally, these differences would appear to be minor, but when doing regression, the pairs need to see the same surface to obtain accurate regression constants. Because surface temperature appears to play a major role in these differences, it is important that surface temperature be measured as a function of position to verify this correlation.

2. The IRFI constants from the previous year were applied to any equipment that was included the previous year in order to calculate the IRFI for each paired 100 metres. These IRFIs were then compared with the reference to determine each measurement device's standard deviation, coefficient of variation, and the root mean square error, in order to give a measure of how well the IRFI harmonized each device. An overall standard deviation, coefficient of variation, and root mean error, can also be calculated. Initially, these tests were compared only for surfaces tested in previous years, after which any new surfaces were included to verify their effect on the IRFI.

3. The data for the current year (1997-98) were then used to calculate the current IRFI constants for comparison to the previous IRFI constants. These comparisons were used to show the stability of the IRFI. In addition, any new type of surface was tested for use of the IRFI, and any new device was brought into harmonization.

4. The paired data for the current year were combined with all paired data from previous years, and the IRFI constants were again calculated for the whole database as the most accurate IRFI. Again, the changes from the previous set of constants can be compared to evaluate the significance of the change.

6.4.1 Validation of IRFI with 1998 North Bay Data

In the first effort to validate the harmonization of the statistical IRFI, the correlation constants listed in Table 1 (determined from 1998 Gardermoen data only) were applied to an independent data set: the 1998 North Bay data. Figure 1 shows the average of all measurements after they were adjusted by the harmonizing constants. For a first try, using the model based only on Gardermoen data, the different devices reported similar values. In a few cases, the values differed by 0.05; however, in most cases, the differences were less than 0.05. In subsection 6.4.2, the constants are recalculated using all of the 1998 data. These constants will then be applied to the devices in 1999 for further validation. As the database grows, the constants should improve and give better results. Certainly, a 0.05 range in reported friction values with this first set of data represents a significant improvement in harmonization compared with previous and current friction values reported by the different devices.

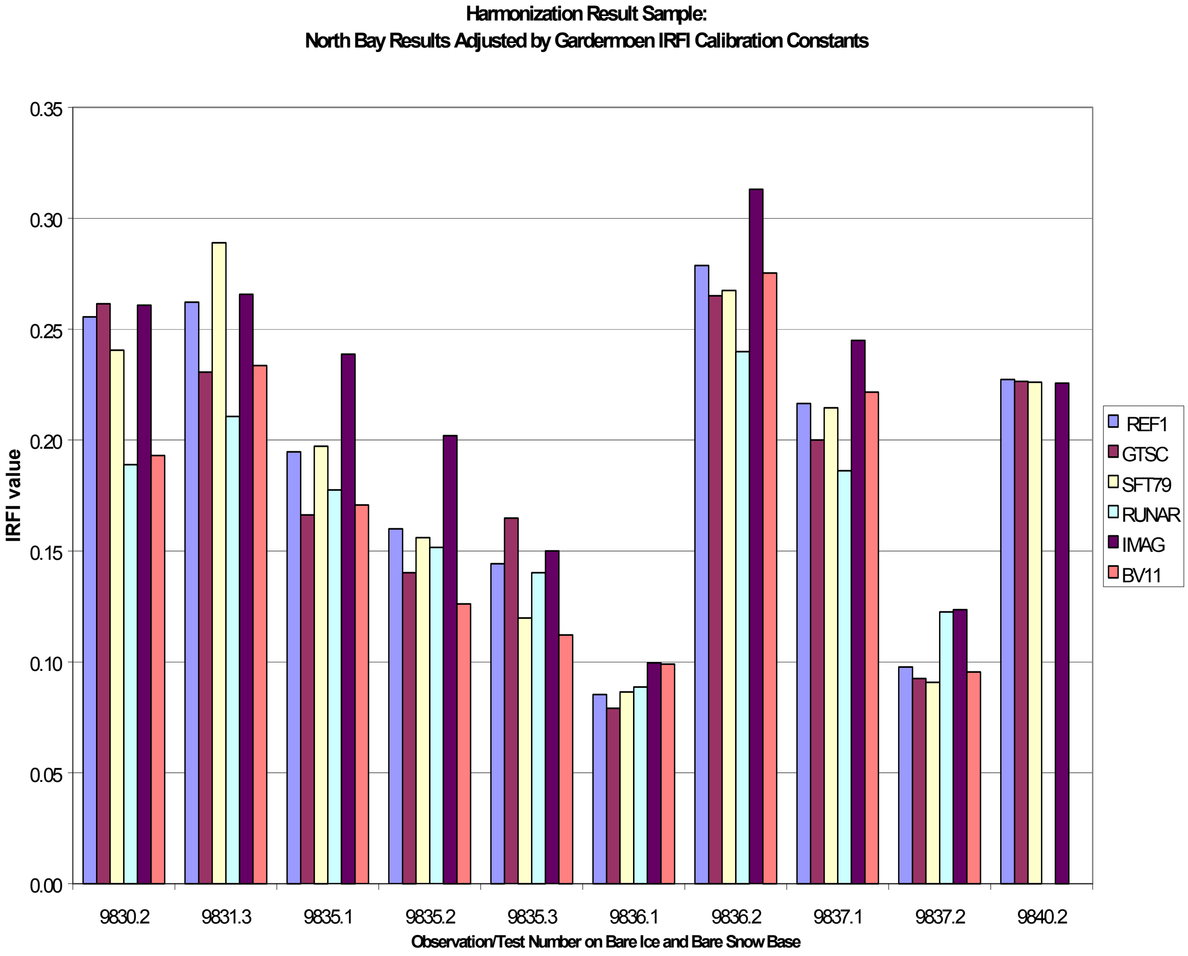


Figure 1 Average of All Measurements After Adjustment by the Harmonization Constants. (The bars are grouped by the tests conducted.)

6.4.2 Update of IRFI with All 1998 Data

All of the 1998 data from Gardermoen and North Bay were combined and the statistical analysis was conducted again to recalculate the regression coefficients. Table 2 is a summary of the new values to replace those given in Table 1. These new values will be applied to the 1999 data as tests are run, in order to evaluate their effect on harmonization. Table 3 gives the differences between the results using just the Gardermoen data and the results using North Bay data as well. Average R^2 values remained the same.

Table 2 Correlation Constants with All 1998 Data

Model
IRFI = $a + b \times \mu_{device}$
Ref. 1= (SFT79 + IMAG)/2 Gardermoen and NB

Device	*a*	St. Error *a*	*b*	St. Error *b*
ASFT[1]	0.0055	0.0147	0.6232	0.0574
BV-11	0.0395	0.0104	0.6424	0.0472
ERD[2]	0.0417	0.0269	0.8705	0.1211
GT-STD[1]	-0.0147	0.0066	0.9923	0.0442
GT-SC	0.0285	0.0102	0.7523	0.0497
IMAG	-0.0577	0.0105	1.291	0.0558
OSCAR[1]	0.0146	0.0193	1.0205	0.1307
RUNAR	-0.1405	0.0338	1.348	0.1471
SFT-79	0.0413	0.0039	0.7875	0.0203

Notes:
1. The device was used only in Gardermoen, thus NB adds no new data.
2. The data represent one vehicle in Gardermoen and a different one in NB.

Table 3 Difference of Correlation with All 1998 Data Compared to Gardermoen Only Correlations

Model IRFI = $a + b \times \mu_{device}$

Difference between correlation values using all the 1998 data minus the values from Gardermoen only data

Device	*a*	St. Error *a*	*b*	St. Error *b*	R^2
ASFT[1]	0	0	0	0	0
BV-11	0.0037	0.0018	0.0318	0.0075	-0.052
ERD[2]	0.0466	0.0121	-0.1129	0.0351	-0.359
GT-STD[1]	0	0	0	0	0
GT-SC	0.0031	0.0039	0.0193	0.0175	-0.0396
IMAG	-0.0002	-0.0035	-0.0333	-0.0285	-0.0008
OSCAR[1]	0	0	0	0	0
RUNAR	-0.0397	-0.0057	0.2292	-0.0291	-0.0027
SFT79	0.0026	-0.0009	0.0103	-0.008	-0.0013
Average	0.0018	0.0009	0.016	-0.0006	-0.0506

Notes:
1. The device was used only in Gardermoen, thus NB adds no new data.
2. The data represent one vehicle in Gardermoen and a different one in NB.

6.4.3 Standard Error of Estimate and Sensitivity of the Statistical IRFI

Table 4 gives the sensitivity for a 10 percent measurement difference and the standard error of estimate for each device as well as the averages for all devices.

Table 4 Statistical IRFI Sensitivity

Device	Sensitivity	Standard error of estimate
ASFT1	0.012028	0.0193
BV-11	0.013426	0.0209
ERD[2]	0.039085	0.0449
ERDNissan[1]	0.018095	0.0184
GT-STD[1]	0.005061	0.0051
GT-SC	0.007147	0.0095
IMAG	0.018074	0.014
OSCAR[1]	0.026533	0.026
RUNAR	0.038688	0.0287
SFT79	0.006615	0.0084
Average	0.018475	0.01952

Notes:
1. The device was used only in Gardermoen, thus NB adds no new data.
2. The data represents one vehicle in Gardermoen and a different one in NB.

The ERD device results, North Bay and Gardermoen combined, give much greater errors than the other devices; however, a different vehicle was used at each site, and the North Bay data were not paired well. This shows the importance of proper pairing of tests and the effect of different vehicle characteristics.

6.4.4 Load Effect on the Statistical IRFI Model

Figure 2 shows that the correlation constant *b* (gradient) is significantly dependent on the net tire contact pressure. This is to be expected since the shear strength of snow improves with increased compaction load.

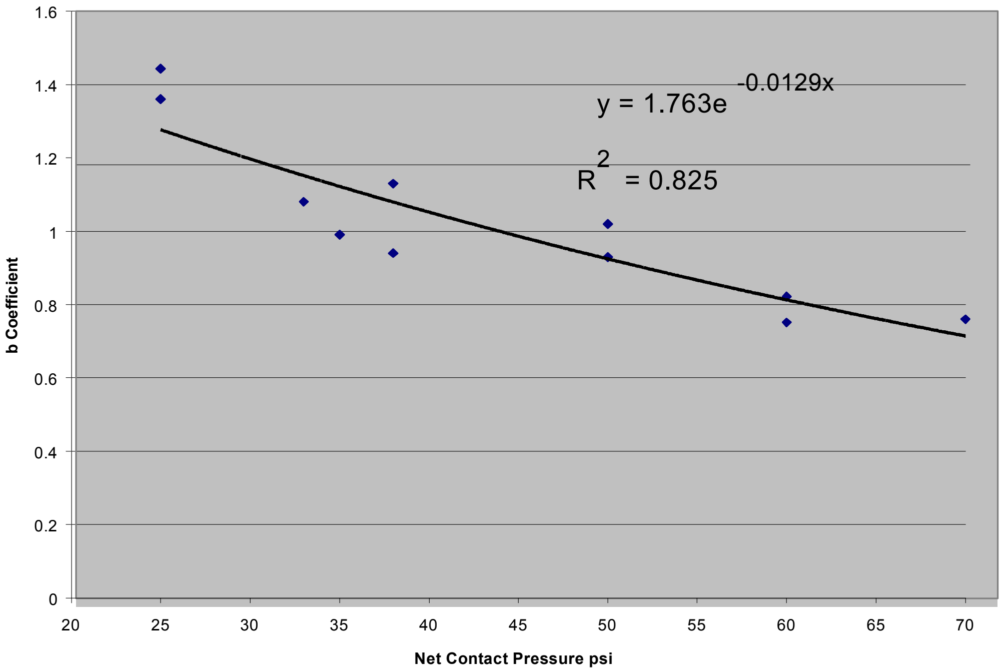


Figure 2 Coefficient *b* vs. Net Contact Pressure

6.5 Limitations of and How to Improve the Statistical IRFI

At this time the surfaces tested, which include ice, packed snow, and loose snow on packed snow, provide a limitation on the Statistical IRFI. As new measurement devices are developed, they will have to be run on a wide range of surfaces with a device that is already calibrated. Since the average of the IMAG and TC-SFT79 was used as a reference, it will be difficult to maintain this reference; therefore, a true reference device, such as the proposed Service Technique des Bases Aériennes or the ASTM ISR reference vehicle, is needed for future correlations. No correlations can be expected to remain stable with time: devices change, new tires are installed, and the equipment is subjected to wear. Thus there is a need to have periodic correlations to maintain accuracy.

A second limitation is that there is a different correlation for bare dry and bare wet pavement versus ice and snow surfaces, and thus a different set of constants needs to be developed if one chooses not to adopt the IFI.

The need for different transformation equations for different surface classes ties the statistical IRFI approach to the physical approach. The linear equations developed as a separate statistical model may well function as a default transformation when other, more refined transformations are not available in the physical approach.

The exercise performed with a chosen reference demonstrates that harmonization can be achieved with a statistical model. The issue of making available a permanent reference device for the airport industry is more an administrative issue than a technical one. A reference device is required for any of the approaches under consideration**.**

7 ESSENTIAL ELEMENTS OF THE PHYSICAL IRFI

The concept of a physical model came about as a result of acknowledging that each friction measurement device has a unique friction interaction with a given surface. This interaction has many variables and parameters, but only speed and surface temperature were chosen as major variables for the first cut, because of straightforward measurement techniques and common availability of data.

By studying each friction measurement device separately, it is possible to avoid the potential complexity of a large number of device-dependent variables and parametres. For this study, it was not necessary to investigate the details of the measuring device as long as it was treated as having a consistent and highly repetitive behaviour when interacting with the same surface condition. Every friction measurement device manufacturer claims that its product displays such consistency.

The physical model provides a simplified process transformation function for a friction measurement device with friction value, speed, and surface temperature as variables. For example, for a smooth, solid ice surface, the transformation function is thought to be valid for a range of test speeds and surface temperatures. After mapping the transformation function once for smooth ice over a range of surface temperatures and test speeds, the friction value at a given speed and temperature can be predicted. However, rough ice will introduce texture effects into the friction equation and yield a different transformation function.

A physical model is valid for a friction device-surface pair. Further investigation is needed to determine just how many surface classifications are required. A decisive factor in determining this need is the degree of precision and reproducibility required by the end user of the friction information. A minimum classification set of bare ice and bare compacted snow now constitute the two fundamental surface classes.

The physical model is given the mathematical form of a modified pavement friction model. Pavement friction models are generally of the following mathematical form:

Predicted Friction Value = $a \times \mathrm{EXP}(-b \times \text{Measuring Speed})$

The a and b parameters of the mathematical model differ from one device-surface pair to another. The physical model may be determined with regression techniques, imposing the modified friction model to fit the sampled data.

When surface temperature measurements are included to improve the physical model quality, the model equation becomes

Predicted Friction Value = (1 - c × Surface Temperature) × a × EXP(-b × Measuring Speed),

where a, b, and c are parameters determined by regression.

The use of travel speed is permissible since the measuring device operates at a fixed slip ratio. The fixed slip ratio multiplied by the travel speed constitutes the slip speed of the device. Harmonization calculations are typically done with slip speed as the speed parameter. The b parameter includes the slip ratio for the device and in this respect, it differs from the IFI.

The physical model equation is a prediction of the friction of the particular surface class for a device. With a, b and c having been experimentally determined, the friction value of the device can be computed for a surface temperature and measuring speed when operating on that surface class. The difference between a predicted value and an actual measurement can be used to moderate the predicted harmonized friction value to a better quality and/or assist in selecting a proper surface class. It also has the potential for self-monitoring of the performance of a device over time to see if it deviates from the calibration runs with an IRFI reference device. This use of the physical model equation is called a Friction Master Model for the device on a defined surface class.

7.1 Working with the Physical Model

First, the physical model must be determined for the device and surface class. The reported friction values could then be adjusted to a standard calibration temperature before a comparison of the devices is performed. Since some devices have a speed dependence for the reported friction, the friction values should be adjusted to a standard calibration speed before a comparison of the devices is made.

Rather than transforming the reported friction values twice to the standard calibration coordinates of speed and temperature, one could use the predicted friction values at the calibration temperature and a range of speed to determine the calibration constants.

The suggested and tested procedure uses the predicted friction values at a chosen calibration temperature of -6^{o}C, corresponding to 267 K or 21^{o}F. At this temperature, a range of friction values is predicted for a range of measuring speeds. The comparison between the reference device and the uncalibrated device is then performed by nonlinear regression to determine the calibration constants.

A solution to avoid nonlinear regression is to exploit a special case of regression mathematics. When a fit is made between data generated from two exponential equations, choosing the power equation as the relationship between the two sets of data, no further error is introduced by using the model-predicted values to harmonize devices.

The simple calibration equation then becomes

IRFI = A × Reported Friction Value (FR) Adjusted to Calibration Temperature^B,

which is the reported friction value adjusted to a standard calibration temperature, raised to the power of B, and then multiplied by A. The speed dependence does not appear in the calibration equation, but was included when fitting the physical model.

The disadvantage of using an exponential friction model at the harmonizing level is that the reported friction values must be forced to fit an exponential. For the physical model, three parameters were determined: a, b, and c. In the harmonization step, A and B are determined, yielding five constants for each device-surface pair, with both speed and temperature as independent variables.

To use the physical model in operational runway measurements, the surface class must be determined (from a multiple-choice menu) to pick the appropriate A and B harmonization constants of the device. The harmonized friction value is then computed by raising the average measured friction value to the power of B and multiplying it by A.

7.2 Physical Models Derived from Tests in 1998

Modified pavement friction models were fitted to the devices that participated in the JWRFMP in 1998. The surface classes available were bare ice (IB), bare compacted snow (SB), and compacted snow with a small layer (3 to 6 mm) of loose or drifting snow on top (SD).

The mathematical friction equation fitted was of the following form:

$$f_{\mathrm{device}}(v,t) = (1 - (c/100 \times (t - 273.16))) \times a \times \mathrm{EXP}\,(-b/100 \times v),$$

where the two independent variables are t, the surface temperature in Kelvin, and v, the measuring speed in km/h. Parameters a, b, and c have dimension and are unique for the device-surface pair. The factors of 100 are included for technical reasons in operating the statistics software in order to get a sufficient number of significant digits as output from the model fitting. A few device-surface pairs were poorly modelled as evaluated by usual statistical criteria, but most were good and some were excellent.

The model parameters are presented in Table 5. Shown is a column of standard error of estimates for each model fit, a measure of the actual variability about the regression plane (fitted equation) of the underlying population of sampled data. The devices are named with their database codes or so-called tire configuration identifications.

The *a* values, which are indicators of the general friction level, span a range of 0.02 to 0.16 for bare ice and 0.10 to 0.22 for bare compacted snow, which suggests that the multipliers are generally higher for snow than for ice.

It is noteworthy that all devices except IMAG have a negative *c* parameter on surface class IB, which means that friction increases with rising temperature on dry, smooth ice. This finding should be verified in future tests. The relationship to ambient air temperature should also be investigated since the *c* parameter here is worked out on the basis of all test runs. It has been noted that a difference occurs in the temperature gradient being negative or positive if the ambient temperature is either higher or lower than the surface temperature.

The error of the model fit is generally comparable to the standard error that the device exhibits during test runs.

Table 5 Physical Model Parameters

Device	**Bare Ice (IB)**				**Bare Compacted Snow (SB)**				**Compacted Snow w/ Layer (SD)**			
	a	b	c	Std. Error	a	b	c	Std. Error	a	b	c	Std. Error
ASFTAERO	0.1611	0.2871	-3.0002	0.041	0.1703	0.2581	9.7025	0.032	0.1694	0.1367	11.557	0.030
BV11STD	0.0294	2.2622	-0.0681	0.039	0.2182	0.0314	5.7266	0.066	0.1784	0.3050	13.102	0.043
ERDNISSAN & ERDSTD	0.0889	0.0383	-0.7626	0.027	0.1014	0.0000	18.541	0.058	0.1517	0.0000	4.5283	0.030
GTNDISC	0.0642	0.8252	-3.2053	0.033	0.2204	0.1752	3.6122	0.057	0.1308	0.0653	13.264	0.027
GT_STD	0.1179	0.0372	-4.7514	0.021	0.1747	0.0208	2.4076	0.027	0.2194	0.1028	0.3346	0.027
IMAGSTD	0.0775	0.7340	0.1163	0.016	0.2077	0.0628	0.4609	0.042	0.1795	0.0887	1.9274	0.025
OSCAR524F	0.0619	0.5392	-5.2312	0.029	0.1695	0.1137	2.4288	0.019	0.2380	0.2333	-0.6489	0.022
ITTV26					0.1332	0.0000	-1.301	0.038				
RUNARV	0.0605	2.5729	-2.6459	0.033	0.1351	0.9873	0.7561	0.041	0.1147	1.0887	2.0315	0.032
SFT791551100	0.0660	0.1698	0.7442	0.026	0.1840	0.0154	4.1758	0.048	0.1260	0.1540	14.947	0.027

7.3 Master Model Speed and Temperature Curves

The work with physical modelling suggests that the mechanical properties of travelled winter base surfaces are strongly influencing the friction measurements. Snow and ice were noted to be the affected part of the tire-surface interaction. This supports the concept of Friction Master Models closely related to the ice and snow surface materials. The material is basically the same, solidified water, but appears in different mixtures with air and in different crystalline forms under different environmental conditions. One would expect that a given device would repeatedly yield the same measure of friction when interacting with a surface material of solidified water with the same air content and crystalline form, and under the same environmental conditions.

To study a three-variable model in two dimensions, one of the variables must be kept constant. In the development of the master curves, the surface temperature was kept constant when measuring the influence of test speed, and the speed was kept constant when measuring the influence of temperature. The illustrations given in the NASA report [2] include plots for each device to highlight differences among devices.

Interpretations of the master curves must be done with care. The data samples have uncertain surface temperatures associated with them because readings were taken by different instruments using different methods. The reported measured speeds are also of variable quality, with some digitally recorded and others read from strip charts. Further testing should be properly instrumented to remove these uncertainties.

One way of interpreting large differences is to suggest that the data belong to another surface class. If the master models can be proven reliable, then the differences may be used in a computerized system together with other data to identify the surface class measured or to sort the data into surface class bins.

Figure 3 gives the standard deviations of the differences between predicted and measured friction values.

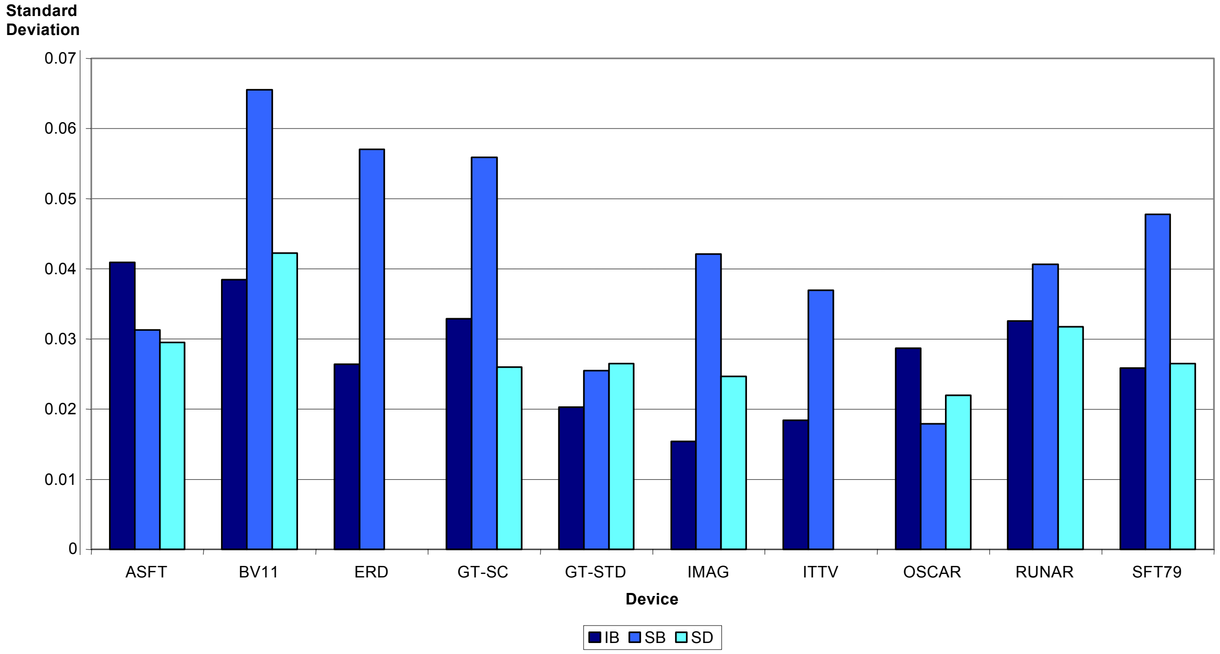


Figure 3 Standard Deviations of Differences Between Predicted and Measured Friction Values

The standard deviations appear to be less on a surface with some loose snow (SD) compared to bare snow (SB) because the loose material will fill and neutralize any surface texture that otherwise would have contacted the tire and caused more impact forces from the asperities. One might also explain the lower standard deviation by the presence of partial snow planing.

7.4 Other Considerations for the Physical IRFI

Other physical parameters that need further investigation are:

- surface and temperature variations of the field tests;
- displacement drag, fluid planning, and compacting effects from snow;
- surface temperature measurement to determine friction level;
- tire load/contact pressure.

These parameters are discussed in detail in Appendix B.

7.5 Lack of Evaluation Criteria for the Physical IRFI

A useful evaluation of friction-device performance and of harmonization methods requires clear performance objectives and evaluation criteria from the potential users of reported friction values. There are three principal user groups: airport operators, aircraft operators, and aviation regulators. Each user group has different reasons and contexts for applying the output from friction measurements.

An airport has a specific use for friction measurements: to assess the runway surface condition for which the airport is responsible. The airport is also obliged to communicate the friction measurement results to the aircraft operators. For airport surface maintenance quality evaluations, harmonization of friction testing values is warranted. The maintenance staff can rely on the relative values of friction, measured by their local device under different conditions, when deciding on maintenance actions. For example, the friction measurement device could be used to identify ice surface areas on the runway that may not be easily detected by visual inspections. It is the responsibility of operations management to monitor the friction values for operational safety and for compliance with threshold values for safe operations as regulated by aviation authorities. A harmonized value will also allow for systematic, standardized treatment across all airports.

For airport regulating authorities, it is desirable to have a common scale of friction measurement in order to have conformity of the quality standards that are applied through regulations for airport operations. A critical item in their set of objectives for friction testing of airport runway surfaces is the defined minimum value of friction below which the runway must be closed to traffic. The bias and precision of the measurement of this minimum friction value is often undefined, or related to the demonstrated performance of certain friction devices. It should be an objective of the JWRFMP to establish the bias and precision for this threshold value. Rather than discussing how the harmonization results of the JWRFMP meet established quality criteria for this purpose, the possibilities of setting new systematic and standardized criteria are addressed here briefly.

Criteria for bias and precision of friction measurements by aircraft operators do not exist in quantitative terms, although some operators use nominal friction values in connection with flight manual or company operational procedures. There is a need for aircraft operators to have quality criteria of friction measurements established for their use. In turn, these criteria would help set the standards for the friction measurement devices and IRFI.

A statistical quality criterion applicable to measurements by a single device may encompass a minimum sample size for a defined surface length, a maximum standard deviation or coefficient of variation, and a confidence interval. Findings in the JWRFMP suggest that this criterion would be different for different surface classes. Additionally, a maximum permissible bias needs to be defined, relative to the reference for the common scale of friction, as determined in group harmonization trials.

Table 6 gives a summary of friction testing statistics based on samples of uncalibrated friction values of test runs across a surface. The statistics are an expression of variance of the surface and device combined. The number of samples in a test run varied from 3 to 30, and the table values are the average statistics for all friction devices. It can be said to represent the non-harmonized practice of friction measurement of today with a mix of common device types.

Table 6 Summary of Average Measured Statistics

Average Statistics for Non-harmonized Friction Coefficient	Bare Ice	Bare Compacted Snow	Compacted Snow with Loose Snow (3-6 mm)
Standard Deviation	0.018	0.022	0.020
Coefficient of Variation	20.3%	9.96%	8.8%

Statistics based on harmonized friction values are expected to be better and will be evaluated with the data population collected in 1999.

A performance requirement of standard deviation that would accept most of the devices most of the time must be set higher than the averages given in Table 6. A case of doubling the average is shown in the Table 7.

This poses a problem to some of the existing practice of classifying surface friction in qualitative terms, such as “good”, “medium”, “medium-to-poor”, etc. The friction value range between the classes “medium-to-poor” and “poor” is, for instance, 0.05. With a standard deviation of 0.04, it is difficult to classify with certainty the surface as belonging to either of the neighbouring classes. This illustrates the need for better precision, which is an expected result of harmonization.

Table 7 Summary of Measurement Statistics with Doubled Averages

Required Statistics for Non-Harmonized Friction Coefficient	Bare Ice	Bare Compacted Snow	Compacted Snow with Loose Snow (3-6 mm)
Standard Deviation	0.035	0.040	0.040
Coefficient of Variation	40%	20%	18%

7.6 Limited Slip Speed Range of Database

Most friction measurement devices operate at low slip speeds, and the range of slip speeds that can be covered in field tests is narrow compared to the range covered by aircraft during maximum braking applications. The potential to derive correct friction models from the field tests is therefore limited, as is illustrated by Figure 4. The error of observations in the examined slip speed range may lead to false models outside the examined range.

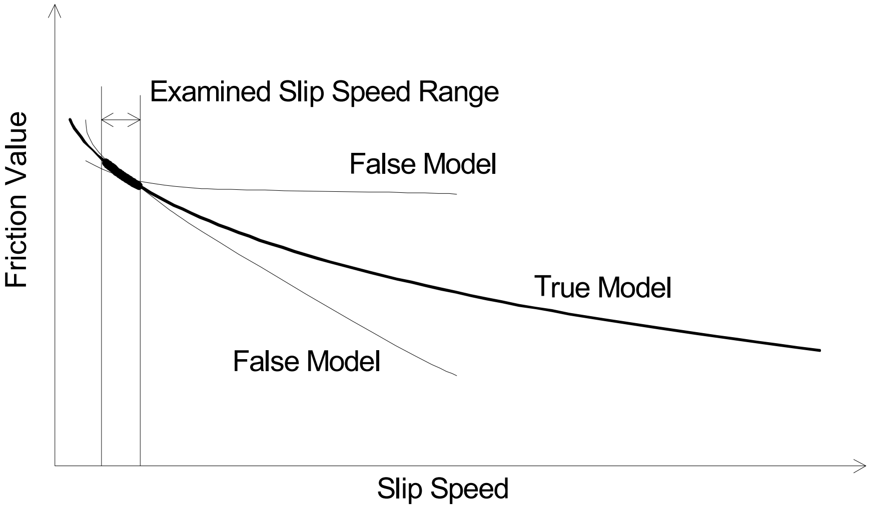


Figure 4 Error from Examined Slip Speed Range

It is advisable to extend the slip speed range in the current database with other devices that can be set at higher slip ratios.

8 CONCLUSIONS AND RECOMMENDATIONS

Currently, the statistical IRFI (along with the IFI) is the recommended interim procedure for harmonizing ground vehicle data for bare dry and bare wet surfaces. This works satisfactorily for the equipment that was used in the Joint Winter Runway Friction Measurement Program during the past three years on the following surfaces: ice, compacted snow, and compacted snow with up to a few millimetres of loose snow. It achieves the objective of providing a uniform number representing the friction sensed by the ground vehicles and has the advantage of only needing to classify whether the surface is bare and dry, bare and wet, or covered with ice and/or snow. In practice, the friction level should be able to identify these three surface types.

Additional data will be required to validate the models for the IRFI, with the physical IRFI having a greater potential for relating ground vehicle data to aircraft braking performance. The effects of contact pressure will also be added to the model. Unlike the statistical method, the physical model requires that more surface classes be identified in order to determine which constants to use; however, the physical model should be able to correct for a much wider set of conditions.

A reference device, which is required for calibration, must be a dedicated device for this purpose only, and the aviation community must agree on its provision, ownership, and services. The devices chosen for the exercises to demonstrate that IRFI is possible were only those that participated in the JWRFMP, and none of these was designated as a final IRFI reference device. All harmonization constants must be reworked once a permanent IRFI reference is available.

There is no proof that the participating devices in the JWRFMP are representative of other devices of the same generic type that are operated at airports worldwide. On the contrary, when more than one unit of the same type participated in the same runs in field testing, the reported differences among them were often of the same order of magnitude as between different types. This suggests that harmonization constants must be determined and applied to individual devices, rather than to generic groups of devices, as was done in the past. This means that a master device can be calibrated, based on the single reference device, to serve as a secondary standard, and the manufacturer or owner of this secondary standard can then calibrate other devices to this master.

For any common scale of friction measurement to work satisfactorily for the industry, annual harmonization meetings of devices must be arranged to determine the current harmonization constants, which will be valid only for a limited time (i.e., as long as the maintenance quality and product repeatability and durability will allow).

The work in the JWRFMP so far has confirmed that friction devices do not report the same values for the same surface and conditions unless they are harmonized on a regular basis.

REFERENCES

1. Andresen, A., et al., “Friction Fundamentals, Concepts, and Methodology”, Transportation Development Centre, Transport Canada, TP 13837E, October 1999.

2. Wambold, J.C., et al., “Third Year-Joint Runway Friction Measurement Program”, NASA, FAA and Transport Canada, January 1999.

APPENDIX A

(Virtual) IRFI REFERENCE SELECTION

To perform a linear regression, a true value is needed, thus a virtual device, called the reference and made up of combinations of devices, was constructed. All feasible combinations of devices were investigated and it was decided that the best option was to use the average of two devices. A single device would be adequate; however, if that device gave an erroneous reading, everything would be harmonized incorrectly and the error would not be detected. If two devices showed a disagreement, then the erroneous reading would be detected.

Figure A1 shows the effect on the gradient, *b*, with reference choices. Except for increasing or decreasing the gradient *b*, all the references that were analyzed provide similar results for one device relative to another. However, only references 1 and 4 have a mean value of *b* that is close to one (see NASA report[3] for a list of the pairs of devices that made up the various references). Figure A2 shows the coefficient of correlation for each device and each of the references. Again, all references provide similar results, with references 2, 3, and 5 being the worst. Figure A3 is a plot of the coefficient of variation (CV) by device for each reference and shows that references 2, 3, and 5 produce somewhat higher CVs.

Based on the review of different devices as reference, it was concluded that the best option was to use reference 1, the average of the TC-SFT79 and the IMAG. There were several reasons for this choice:

- They were tested at both Gardermoen and North Bay.
- In the analysis they produced equivalent or better correlations, R^2 and CV.
- Their average was about the same as the average friction of the ground measurement devices.
- They can measure both force and torque, which is necessary for future work.
- They will likely be at the three sites in the coming years.

The ITTV was considered as well, but the variation of the data was too great to be used as the reference at this time; in addition, it was not part of the 1998 Gardermoen study, where a lot of calibration data were collected. It will be considered carefully in 1999, since it is felt that the use of a measurement device with an aircraft tire should provide a better reference for aircraft predictions.

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[3] Wambold, J.C., et al., “Third Year-Joint Runway Friction Measurement Program”, NASA, FAA and Transport Canada, January 1999.

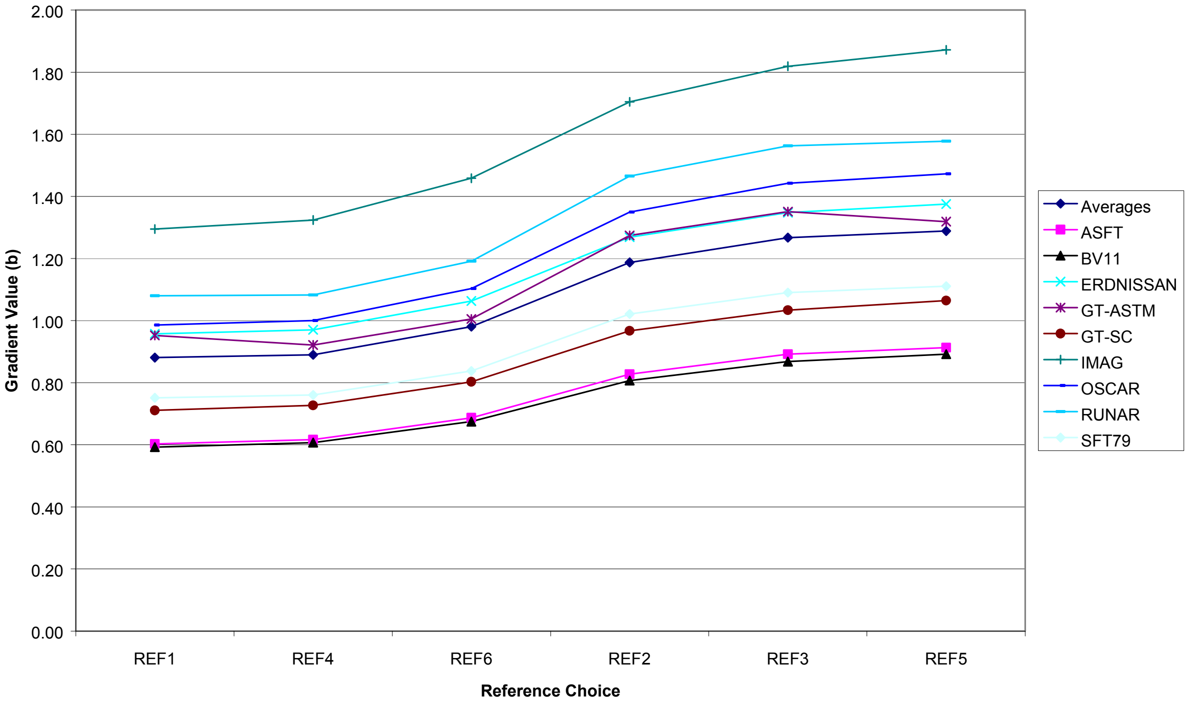

Figure A1 Effect of Gradient by Reference Choice

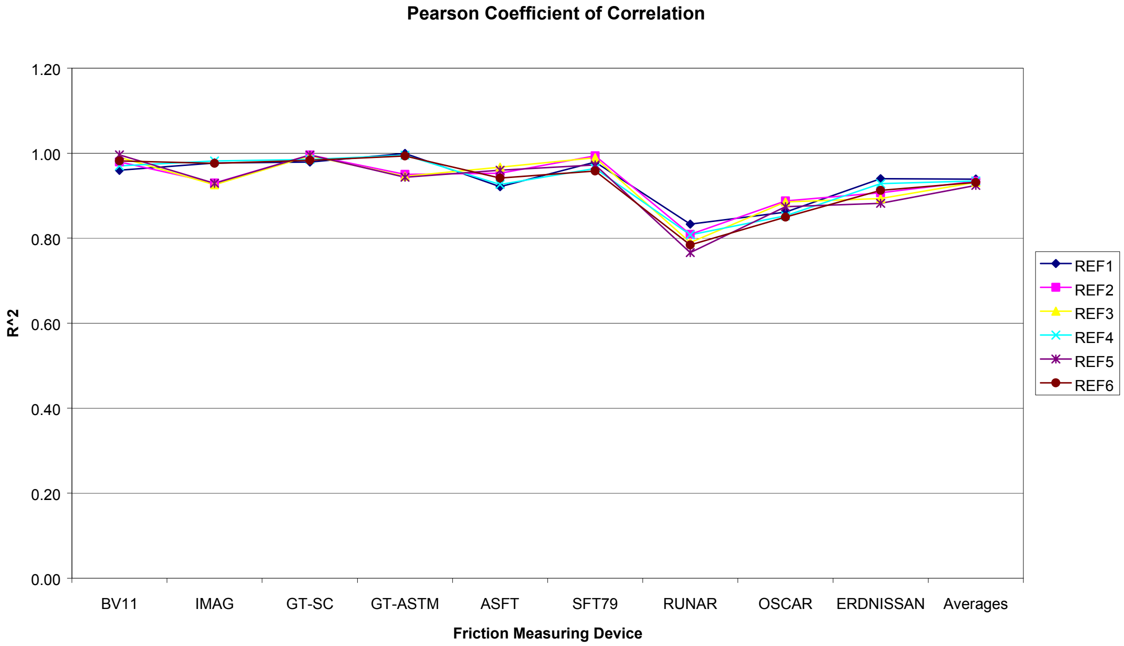

Figure A2 Coefficient of Correlation by Device for Different Harmonization References

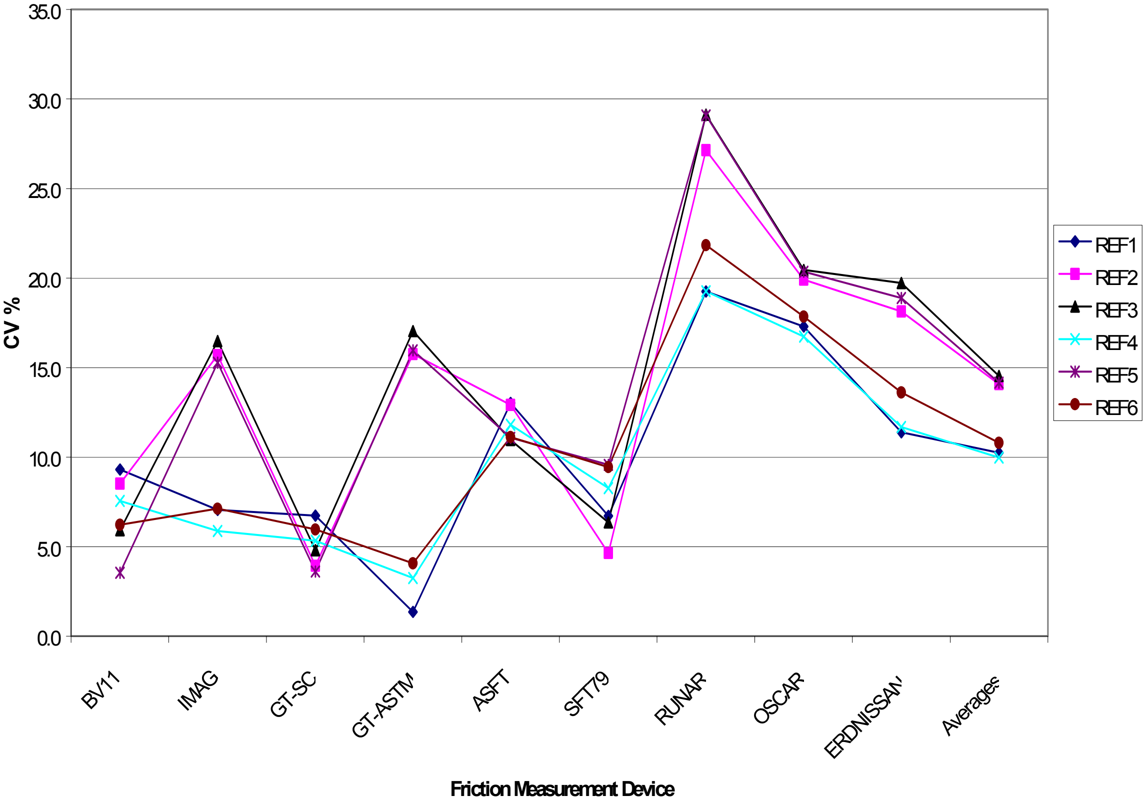

Figure A3 Coefficient of Variation of Friction Values by Device for Different Harmonization References

APPENDIX B

OTHER CONSIDERATIONS FOR THE PHYSICAL IRFI

Surface and Temperature Variations of the Field Tests

Each test conducted in 1998 was illustrated to show the variations in friction with each run in the test and with ambient and surface temperatures; this information can be found in the appendices of the NASA report.[4] An inspection of the illustrations for ice reveals that the surface temperature gradient, as well as the nominal surface temperature, seem to have an influence on the measured friction values, but the temperature data are too scarce and uncertain for a numerical analysis of this relationship.

In some cases where the test surface was segmented, it can be seen that some segments exhibit a markedly different friction level, suggesting that another surface class is present rather than the one coded for the segment. These results indicate a need to reduce the segment lengths in future tests, so that variations in a test surface are visible and available for corrections and so that large surface variances may be reduced when needed.

Displacement Drag, Fluid Planing, and Compacting Effects from Loose Snow

It is a well-known fact that loose snow layers adversely affect the friction values reported from friction measurement devices. Displacement drag and compacting forces are sensed together with the true braking slip friction forces; they are not separated. The real area of contact between the tire and the base surface is reduced by the interspersed loose snow, which again reduces the braking slip force. There is a need to evaluate the error in the reported friction values resulting from drag, planing, and compacting forces; there is also a demand by aircraft operators for drag information regarding contaminated runways, for take-off estimations.

A method for determining the fluid dynamic effects using master friction models has been developed and tested with the available data in the 1998 database for surface classes SB and SD. The method essentially subtracts the SB friction values from the SD friction values to determine the difference. Since SB surfaces do not have a fluid cover, the difference is attributed to the fluid dynamic effects. The data included in the method were taken from test surfaces where the first segments of compacted snow were bare and the remaining segments had a fluid cover of loose snow 3 to 12 mm thick. This method is believed to have practical merit in those cases where a bare compacted snow surface is found on a runway that also has sections of loose snow cover.

This method looks promising and should be investigated further with a larger database of pairs of bare compacted snow and loose snow-covered surfaces. Friction measurement devices that measure both force and torque should be among the devices used in future studies for verification of this method.

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[4] Wambold, J.C., et al., "Third Year-Joint Runway Friction Measurement Program", NASA, FAA and Transport Canada, January 1999.

Surface Temperature Measurement to Determine Friction Level

Another spinoff from speed and surface-temperature-dependent master friction models is the capability to predict the friction when measuring surface temperature at a known speed for a known surface class. The current database does not have sufficient surface temperature data to evaluate this capability. The effectiveness and quality of this feature should be further investigated either as a solitary method or in conjunction with other low-cost devices to improve prediction quality. Friction measurement devices equipped with rapid-response surface temperature measurement systems should be used to collect more data to further study this feature.

Tire Load Contact Pressure

In the 1998 tests, the ITTV conducted a series of tests on a 22 x 6 aircraft tire (the same as the nose wheel tire on the Falcon 20). The series consisted of running variable loads of 455 kg to 2,270 kg (1,000 to 5,000 lb.) on an ice surface and on a packed snow surface. Figure B1 shows a clear drop in friction as the load is increased on both surfaces. Figure B2 shows the same data, where friction force rather than friction is plotted against load (friction force divided by load). Here, the force increases with load and reaches a constant level at higher loads. It appears that at about 1,818 kg (4,000 lb.), the shear strength of the snow is reached, and there is no further increase in friction force. Since friction is friction force divided by load, the friction (mu) will decrease linearly from that load onward with higher loads.

These tests show the importance of load (contact pressure) on this tire, and thus the need to have similar characteristics for all of the tires being used, if one is to model one tire and test with another. In the case of the smaller, lighter-loaded ground friction tires, it has been shown that increased contact pressure has increased the friction, while for the larger, much higher-loaded aircraft tire, the opposite is true. This finding was expected since the aspect ratio of the aircraft tires is nearly constant with load, while the ground test tires have a constant width with a change in length and thus a changing aspect ratio with load.

The contact pressure studies of most of the ground friction equipment has been done,[5] and it is expected that the NASA ITTV will be able to run varying loads on the ground friction equipment tires in 2000. In addition, the contact areas are measured for each aircraft tire tested in the program. It is recommended that data on other aircraft tires be obtained along with the effect of load on those tires.

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[5] See body of report.

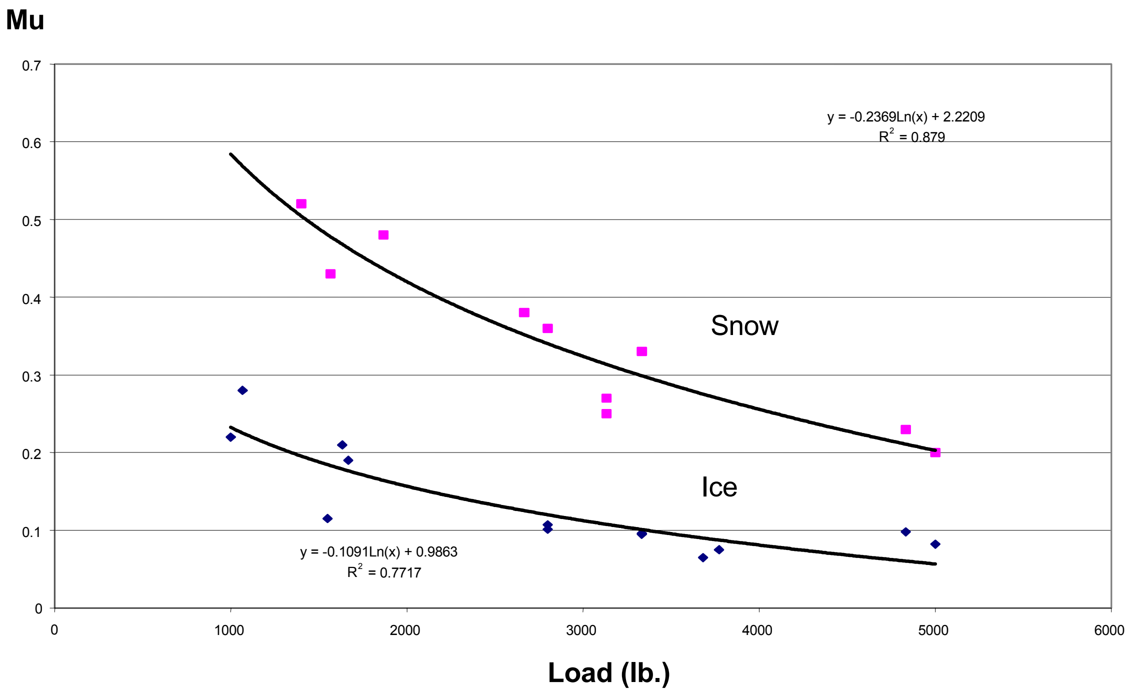

Figure B1 Mu vs. Load for the ITTV

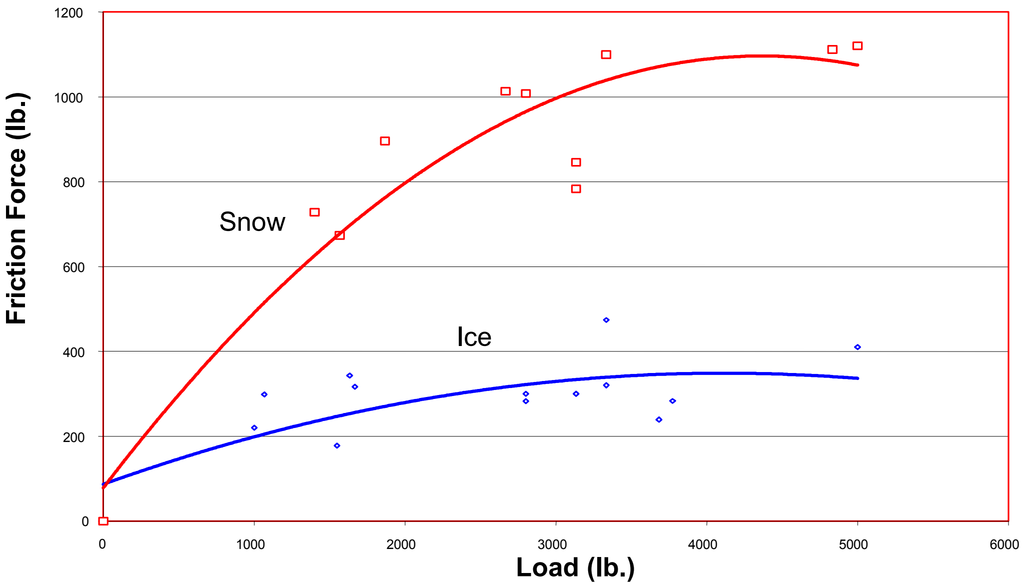

Figure B2 Friction Force (Shear) vs. Load for the ITTV