TP 14192E

Joint Winter Runway Friction Measurement Program (JWRFMP)

2001 Testing and Data Analysis

Prepared for
Transportation Development Centre
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16. Abstract

This report is a Joint Winter Runway Friction Measurement Project (JWRFMP) report updating the research and data collection up through the year 2001 (the sixth year of the project) as related to the capability of a runway surface to provide tire braking action during winter operations. The project was 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 Air Traffic and Airport Management, 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.

The data was used to develop the International Runway Friction Index (IRFI) and the correlation constants were calculated for devices tested in the 1997-1998 test season (TP 13836E). The constants were calculated by combining the two years of data. However, in 2000, it was established that not only does a calibration not apply across similar types of devices, it changes from year to year for a particular device. Thus, the correlation constants are given on a year-by-year basis up to and including 2001.

During the year 2000, the ASTM E 2100 standard "The International Runway Friction Index", IRFI, was issued. The use of the IRFI reduced the standard error from as high as 0.2 (without IRFI), down to an average under 0.05.

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16. Résumé

Le présent rapport fait le point sur le Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH). Il rend compte des études réalisées et des données colligées jusqu'en 2001 (la sixième année du projet) sur les caractéristiques des chaussées aéronautiques propres à accentuer la performance en freinage des avions lors d'opérations hivernales. Le programme était dirigé par Transports Canada et la National Aeronautics and Space Administration, appuyés par le Conseil national de recherches du Canada, la U.S. Federal Aviation Administration, l'Air Traffic and Airport Management de Norvège et la Direction générale de l'aviation civile de France, ainsi que par des organisations et des fabricants de matériel d'Autriche, du Canada, de France, d'Allemagne, de Norvège, d'Écosse, de Suède, de Suisse et des États-Unis.

Les données ont servi à élaborer l'indice IRFI (*International Runway Friction Index*). De plus, des constantes de corrélation ont été calculées pour les appareils utilisés au cours des saisons d'essais 1997 et 1998 (les données des deux années ont été combinées) et les résultats ont été présentés dans le rapport TP 13836E. Toutefois, en 2000, il a été établi que non seulement une valeur obtenue avec un appareil ne peut s'appliquer à d'autres appareils semblables, mais qu'elle varie d'une année à l'autre pour un même appareil. C'est pourquoi les constantes de corrélation sont données pour chaque année, et ce jusqu'en 2001.

En 2000, la norme ASTM E 2100, *The International Runway Friction Index*, IRFI, a été publiée. Cette méthode a permis de réduire l'écart type, le faisant passer d'un sommet de 0,2 (sans IRFI) à une valeur moyenne inférieure à 0,05.

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EXECUTIVE SUMMARY

Measuring the capability of a runway surface to provide aircraft wheel-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. A service is warranted for the measurement of winter surface friction, because the operational window for aircraft movement can change quite rapidly and frequently in the winter.

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 six 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 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 Air Traffic and Airport Management (NATAM), 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).
- Relating aircraft stopping performance to ground vehicle IRFI.

The objective of this report is to update the 2000 JWRFMP report (TP 14062E) with the data collected, analysis and findings through the year 2001.

Statistical IRFI 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, which can be applied by the aviation community. 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 32,627 friction measurements.

Stability of the Harmonization Method

The correlation constants were calculated for devices that participated in the 1998-1999 test seasons and were reported in the 1997-98 JWRFMP report (TP 13836E) and the Fourth Year JWRFMP report. The constants were calculated by combining the two years of data. However, in 2000, it was established that not only does a calibration not apply across similar types of devices, it changes from year to year for a particular device. Figure 1 shows the variations of the IRFI multiplier *b* for the past four years (1998 to 2001). IMAG (IRV) is not shown since it is the reference and thus is always *b* = 1.0.

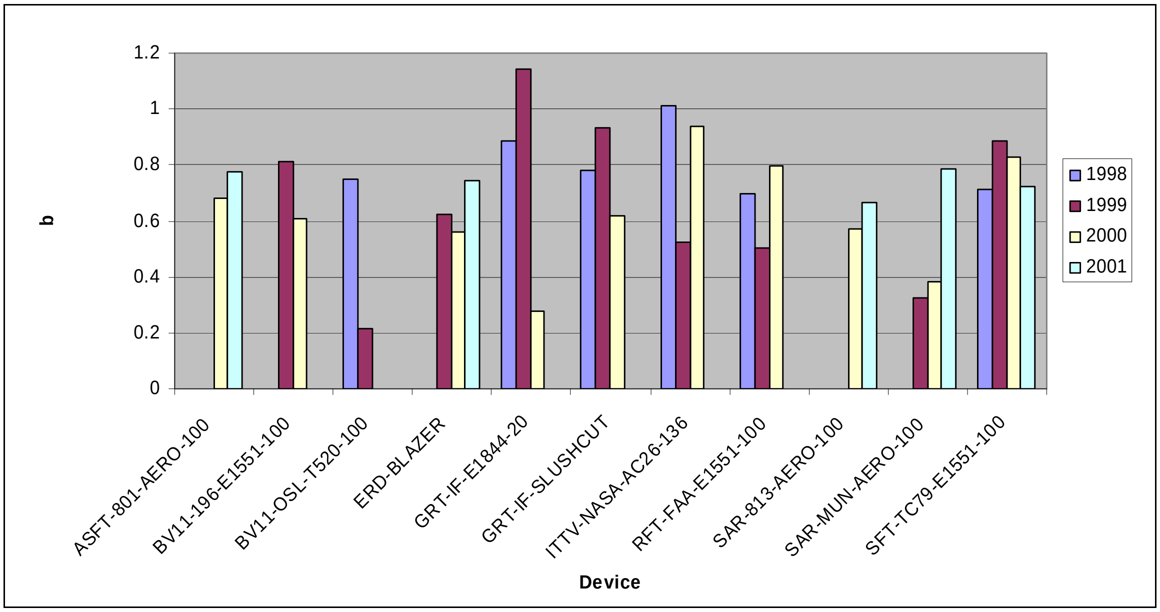

Figure 1 – Mutipier *b* vs. years (1998-2001) by device

Reproducibility of SARSYS Devices

At the Erding test site four devices of the same brand and type were tested. This enabled a limited study of reproducibility, i.e. how different each device of the same type measured the same surface segments. This was the first opportunity for a reproducibility study in the JWRFMP.

With the surfaces available for testing at the Erding site, the SARSYS devices exhibited reproducibility as expressed in standard deviation in the order of 0.08 friction units for ribbed tires and 0.05 for blank tires. The reproducibility varied with changes in friction level for both ribbed and blank tires.

Conclusions and Recommendations

The ASTM standard E 2100 defines and prescribes how to calculate IRFI for winter surfaces. IRFI is a harmonized reporting index to provide information to aircraft operators on the tire-surface friction characteristics in the aircraft movement area.

In addition to reporting surface conditions to aircraft, IRFI can be used by airport maintenance staff to monitor the winter frictional characteristics for surface maintenance actions.

The method evaluates each 100 m (300 ft.) and averages them for each third of the runway. The IRFI method reduces the present variations of the 100 m surface lengths from as much as 0.2 down to typically 0.04. The sampling scheme of a full runway length (spot or continuous measurements) may yield additional variation.

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 device chosen for the exercises of the JWRFMP, to demonstrate that IRFI is possible, was an IMAG and called the International Reference Vehicle (IRV). The IRV must be evaluated at some point for stability. If it is not stable with time, other references will need to be investigated. All harmonization constants would have to be reworked when a permanent IRFI reference has been designated. In the meantime at least harmonization was demonstrated to work and was accomplished with the devices participating in the JWRFMP.

There is proof that the participating devices in the JWRFMP are not representative of the other devices even when they are of the same generic type. 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. To accomplish this, a master device can be calibrated to the IRFI reference device in order to serve as a secondary reference and the manufacturer or owner of this secondary reference can then calibrate other devices to this master.

Ongoing work has shown that the IRFI can be used to predict aircraft braking performance. This will be discussed in a separate report.

SOMMAIRE

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

Par le passé, les utilisateurs de 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 en freinage.

Des travaux de recherche sur la glissance des pistes menés à l'échelle internationale ont confirmé que pour une même surface, les appareils de mesure du coefficient de frottement captent et enregistrent des valeurs différentes. 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 contribuait aucunement à 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'étaient jamais 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 six dernières années a grandement contribué à résoudre ces problèmes. Ainsi, grâce au perfectionnement des méthodes de mesure, les résultats sont de meilleure qualité et mieux corrélés 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.

La présente 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), piloté par la National Aeronautics and Space Administration et Transports Canada, appuyés par le Conseil national de recherches du Canada, la U.S. Federal Aviation Administration, la Norwegian Air Traffic and Airport Management (NATAM) et la Direction générale de l'aviation civile de France. Des organismes et des fabricants de matériel d'Autriche, du Canada, de France, d'Allemagne, de Norvège, d'Écosse, de Suède, de Suisse et des États-Unis ont également participé 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*).
- Établir une relation entre la distance d'arrêt des aéronefs et l'IRFI obtenu à l'aide d'un véhicule de mesure au sol.

Ce rapport vise à mettre à jour le rapport de 2000 du PCRGCAH (TP 14062E) à l'aide des données recueillies en 2001, des analyses faites sur celles-ci et des conclusions qui en ont été tirées.

Modèle statistique de l'IRFI

Habituellement, on se sert de techniques de régression pour établir les relations entre les coefficients de frottement enregistrés par deux appareils différents. Ces techniques supposent que l'interaction d'un appareil donné 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 ou valeur 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 n'étaient pas recueillies en même temps ni dans les mêmes trajectoires de roues. 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 de la surface.
La base de données comprend maintenant 32 627 valeurs de mesure du frottement.

Stabilité de la méthode d'harmonisation

Des constantes de corrélation ont été calculées pour les appareils qui ont servi aux essais de 1998 et de 1999 (les données des deux années ont été combinées) et les résultats ont été présentés dans le rapport 1997-1998 (TP 13836E) et celui de la Quatrième année du PCRGCAH. Cependant, en 2000, il a été établi que non seulement une valeur obtenue avec un appareil ne peut s'appliquer à d'autres appareils semblables, mais qu'elle varie d'une année à l'autre pour un même appareil. La figure 1 illustre les fluctuations du multiplicateur *b* au cours des quatre dernières années, soit de 1998 à 2001. L'IMAG (IRV) n'est pas compris dans la figure car, comme il s'agit de l'appareil de référence, on a toujours *b* = 1,0.

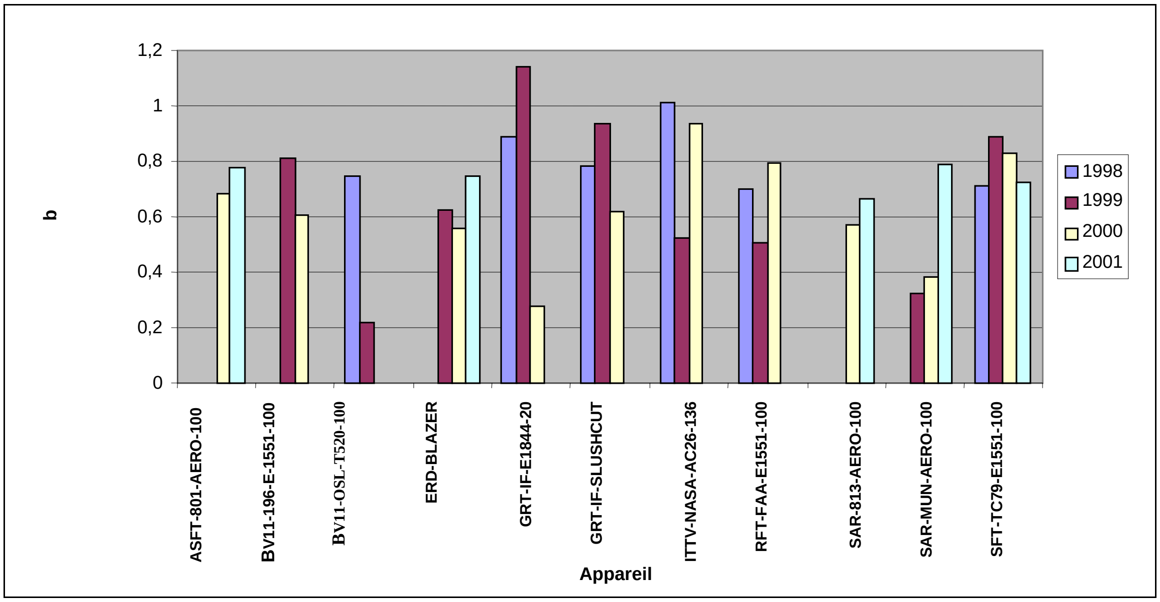

Figure 1 – Mutiplicateur *b* en fonction de l'année (1998-2001) par appareil

Appareils SARSYS et reproductibilité

Quatre appareils de même type et de même marque ont été utilisés pour des essais au site Erding, à la fin de 2001. Ces essais devaient permettre d'étudier la reproductibilité, c'est-à-dire dans quelle mesure quatre appareils de même type obtiennent des résultats identiques (ou différents) lorsqu'ils analysent des tronçons d'une même surface. C'était la première fois que la question de la reproductibilité était étudiée dans le cadre du PCRGCAH.

Les résultats obtenus à l'aide des appareils SARSYS lancés sur les surfaces du site Erding à la disposition des chercheurs ont débouché sur un écart type de reproductibilité de l'ordre de 0,08, en unité de frottement, dans le cas des pneus nervurés, et de 0,05, dans le cas des pneus unis. La reproductibilité variait avec la fluctuation du degré de frottement, que les pneus soient nervurés ou unis.

Conclusions et recommandations

La norme E 2100 de l’ASTM prescrit la méthode de calcul de l’Indice international de glissance des pistes (IRFI) en conditions hivernales. L’IRFI est un indice harmonisé destiné à renseigner les exploitants d’aéronefs sur les caractéristiques d’adhérence pneu-surface dans les aires de mouvement pour aéronefs.

Cet indice peut également servir accessoirement au personnel d’entretien des chaussées aéronautiques dans le cadre de la surveillance de l’adhérence des pistes en hiver et des activités d’entretien des pistes.

La méthode prescrite par l’ASTM consiste à évaluer la glissance pour chaque longueur de 100 m (300 pi) de piste, puis à calculer la moyenne pour chaque tiers de la piste. Cette méthode permet de réduire l’écart obtenu, pour des longueurs de 100 m, d’une valeur qui atteint parfois 0,2 à une valeur se situant généralement aux alentours de 0,04. Le mode d’évaluation de la glissance sur la pleine longueur de la piste (mesures ponctuelles ou continues) peut être une source de variation additionnelle.

Il importe de disposer d’un appareil de référence affecté spécifiquement à l’étalonnage des appareils individuels de mesure. La communauté aéronautique doit déterminer qui en sera le propriétaire, à quels moments s’en servir et quels services il permettra d’offrir. Le PCRGCAH a choisi l’IMAG pour démontrer la validité opérationnelle d’un indice IRFI. L’IMAG est le véhicule de référence actuellement utilisé par le PCRGCAH. Ce véhicule doit d’ailleurs être soumis à une évaluation de sa constance. Si cet appareil n’est pas constant dans le temps, il faudra étudier la possibilité d’utiliser d’autres instruments de référence. Toutes les constantes d’harmonisation devront être recalculées lorsqu’un indice de référence IRFI sera établi. Entre-temps, on a démontré qu’il était possible d’harmoniser les appareils utilisés par le PCRGCAH.

Les essais du PCRGCAH ont montré que les résultats obtenus ne sont pas les mêmes avec tous les appareils de mesure, même s’ils sont du même type. Il y a donc lieu de définir des constantes d’harmonisation et de les appliquer aux appareils individuels, et non au type auquel ils appartiennent, comme cela se faisait dans le passé. Une des solutions possibles serait de caler un appareil (dit «maître») sur l’appareil de référence IRFI (étalon primaire) et d’utiliser ensuite cet appareil comme étalon secondaire pour caler des appareils individuels.

Les travaux en cours ont établi que l’indice IRFI pouvait être utilisé pour prédire la performance en freinage des aéronefs. Les résultats de ces travaux seront présentés dans un rapport distinct.

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DEFINITIONS AND NOMENCLATURE

Acronyms

ASFT	Airport Surface Friction Tester - Ystad, Sweden
ASTM	ASTM International
BV-11	Skiddometer (Bromsvagn “Braking Vehicle”), manufactured by Airport Equipment Company (AEC), Stockholm, Sweden
CRFI	Canadian Runway Friction Index
DGAC	Direction Genérale De L’Aviation Civile Français
E-274	E-274 Locked Wheel – Dynatest and ICC, USA
ERD	Electronic Recording Decelerometer
ERDNissan	ERD mounted in a Nissan SUV
FAA	Federal Aviation Administration, USA
GT	GripTester, manufactured by Findlay Irvine, Scotland
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
IRV	International Reference Vehicle
ITTV	Instrumented Tire Test Vehicle – NASA, USA
JWRFMP	Joint Winter Runway Friction Measurement Program
NASA	National Aeronautics and Space Administration, USA
NATAM	Norwegian Air Traffic and Airport Management
NRC	National Research Council, Canada
PTI	Pennsylvania Transportation Institute, USA
RFT	Runway Friction Tester manufactured by Dynatest, Michigan, USA
ROAR	Road Analyzer and 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
SFT-TC79	1979 SFT owned by Transport Canada

Definitions:

device configuration, **n.** - a term used to designate the entire test system as used for any friction measurement; it includes, but is not limited to, type of device (force or torque measurements), tire type, size and inflation pressure, slip ratio, normal load and braking system control mode.

base surface, **n.** - the type of surface evaluated. There are four classes;
(1) bare pavement dry, (2) bare pavement wet, (3) bare compacted snow, and (4) bare ice.

surface, **n.** - a generic term used in the act of reporting frictional characteristics; it includes the base surface class and the base surface condition.

compacted snow, **n.** - a compressed solid mass of snow that is sufficiently strong to prevent a normally loaded tire operating in a rolling mode from penetrating to the pavement or breaking up the surface.

ice, **n.** - water with or without contaminants frozen into a continuous solid body with or without cracks.

local friction device, **n.** - a particular friction testing device used at a given location to measure friction; the friction values evaluated with this device may be calibrated to IRFI values to provide harmonization.

master friction device, **n.** - a particular friction testing device used at a given location to calibrate local friction devices; the friction values of this device must be calibrated to IRFI values.

movement area, **n.** - that part of the airport (aerodrome) used for take-off, landing and taxiing of aircraft, consisting of the manoeuvreing area and the apron(s).

IRFI reference device, **n.** - a particular friction measuring device selected as a benchmark or reference; it is used to calibrate any local or master friction device to permit local friction device values to be converted to IRFI values for selected base surfaces.

harmonization, **n. -** the transformation of the outputs of different devices used for measurement of a specific phenomenon so that all devices report similar values.

1.0 INTRODUCTION

Measuring the capability of a runway surface to provide aircraft wheel-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 [1-4]. In addition, because the operational window for aircraft movement can change 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.

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.

Canada and the U.S. Air Force used a standard measurement method, the James Brake Index (JBI), to predict required runway length. In recent years this index has been revised and renamed the Canadian Runway Friction Index in Canada. The U.S. Air Force has started using a Mu-Meter and now a GripTester.

1.1 NASA/FAA/TC Joint Winter Runway Friction Measurement Program

The international government/industry initiative, called the Joint Winter Runway Friction Measurement Program (JWRFMP), is being led by Transport Canada (TC) and the National Aeronautics and Space Administration (NASA), with support from the U.S. Federal Aviation Administration (FAA), the Norwegian Air Traffic and Airport Management (NATAM), France's Direction générale de l'aviation civile (DGAC) and the National Research Council Canada (NRC). Also participating are organizations and equipment manufacturers from Canada, the U. S., 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) and its verification through 2001.

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.I. 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).

In 2000, tests were again conducted at North Bay with the Falcon 20; in addition, tests were conducted at Munich Airport, Germany with a variety of aircraft, including a DU328 and an A320 Airbus. In 2001, two test sessions were conducted at North Bay. In the second session a NAVCAN Dash 8 was involved. Between the two sessions, tests were conducted at Erding Air Force Base outside of Munich and a Fairchild/Dornier DU328 aircraft was tested. To date, data from the following seven aircraft have been obtained: two Dash 8s, DU328, Falcon 20, 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 AASTM International, 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, the ASTM E 2100 standard for IRFI was developed, and 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 six years of testing, with the participation of experts from several countries, a systematic, standardized approach has been developed to achieve harmonized friction measurements. This should lead to a methodology for predicting how aircraft tire braking compares 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 [5]. 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 will provide comparisons of the different participating testers, with different tires used to measure runway friction for both summer and winter conditions. This is a necessary step to achieve harmonization of different friction measurement devices. In the further development of the IRFI, the International Reference Vehicle (IRV) was introduced in 2000 and is used as the reference to calibrate other testers. The IRV is a special version of the IMAG donated by STBA for that purpose.

Also, it will be necessary to compare the results of IRFI to the aircraft tire friction data obtained from the aircraft testing.

2.0 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.

The objective of this report is to update the 1999-2000 JWRFMP reports [2, 3, and 4] and present the data, analysis and finding through the 2001 test year.

3.0 EQUIPMENT TESTED

A variety of instrumented test aircraft and ground friction measuring vehicles have been used at different test sites in the U.S., Canada, Norway and Germany. The NASA B-737 and an NRC Dassault Falcon-20 aircraft were used during January and March 1996 at the Jack Garland Airport in North Bay, Ontario. Seven ground friction measuring devices from six different countries collected comparable friction data for several winter runway conditions including dry, wet, solid ice, dry loose snow and compacted snow.

In the January-March 1997 winter season, similar tests were performed at North Bay with an FAA B-727, the NRC Falcon-20 and a De Havilland Dash-8 aircraft, together with 13 ground friction measuring devices. Data obtained during these investigations helped define the methodology for an IRFI to harmonize the friction measurements obtained with the different ground test vehicles.

In the January-February 1998 winter season, additional data was collected at North Bay, Ontario, with the Falcon-20 and Dash-8 aircraft, together with 11 different ground test vehicles, to further refine the IRFI methodology. Based on the Electronic Recording Decelerometer (ERD), a Canadian Runway Friction Index (CRFI) was established for use by pilots to determine their aircraft stopping distance under compacted snow and ice conditions. In March 1998 several different ground friction measuring devices took part in conducting nearly 800 test runs under compacted snow- and ice-covered surface conditions at a new test track facility located at Gardermoen Airport near Oslo, Norway.

During the January-March 1999 winter season, Falcon-20 aircraft and ground vehicle data was collected at North Bay. Also, in 1999 a NASA B-757 aircraft and ground vehicle data was collected at a new test site, Sawyer Airbase in Gwinn, Michigan. These tests were followed with additional ground vehicles (nine different devices) that obtained friction data at the Ottar K. Kollerud test track at Gardermoen Airport, in Norway. Data from these tests was used to further refine and improve the IRFI methodology and define the present correlation constants in the IRFI standard. It is interesting to note that under similar runway conditions at these three different test sites, friction data from the same ground vehicles tested at all three sites were in close agreement and the IRFI methodology was further substantiated.

During the January - March 2000 winter season, one week of testing at North Bay, Ontario, involved the Falcon-20 aircraft and ten ground friction measuring vehicles. Tests with an Aero Lloyd A320, a Sabena Airlines A320, a Deutsche British Airways B-737-300 and a Fairchild/Dornier 328 aircraft were conducted at Munich Airport, Germany, February 21-25, 2000. Thirteen ground test vehicles took part in the Munich testing. In 2000, 60 test runs were conducted with five aircraft and over 1000 runs were completed with the ground vehicles.

In 2001 two sessions were conducted at North Bay (January 27 to February 2, and March 20-22) and a third test session at Erding Air Force Base in Germany (February 26-March 2). At the first session at North Bay, ERD comparisons were made as well as tests between ERD and IRV, and IRFI validation runs. At the second session, a NAV Canada Dash 8 was tested. At the Erding tests, A Fairchild/Donier DU328 was tested along with 10 ground friction devices, including four SARSYS devices, from Düsseldorf airport, Frankfort airport, Munich airport, and Strate WHD Technik; two BV-11s from Vienna airport and Zurich airport; other devices were an ASFT, TC SFT79, and an IMAG.

Four years of NASA Aircraft Tire/Runway Friction Workshop data (1998-2001) have been combined with data from seventeen weeks of winter testing at North Bay, Ontario (1996-2001), one week at Sawyer Airbase, Gwinn, Michigan (1999), two weeks at Gardermoen, Norway (1998-99), and one week at Munich, Germany (2000) and one week at Erding Air Force Base, Germany.

In summary, the number of runs and segments runs made year by year, since 1998, are given in Figure 1 as a bar chart. Segments are typically 100 m sections and in most cases there were three segments in a run. Figure 2 gives the number of runs and segment runs made by site.

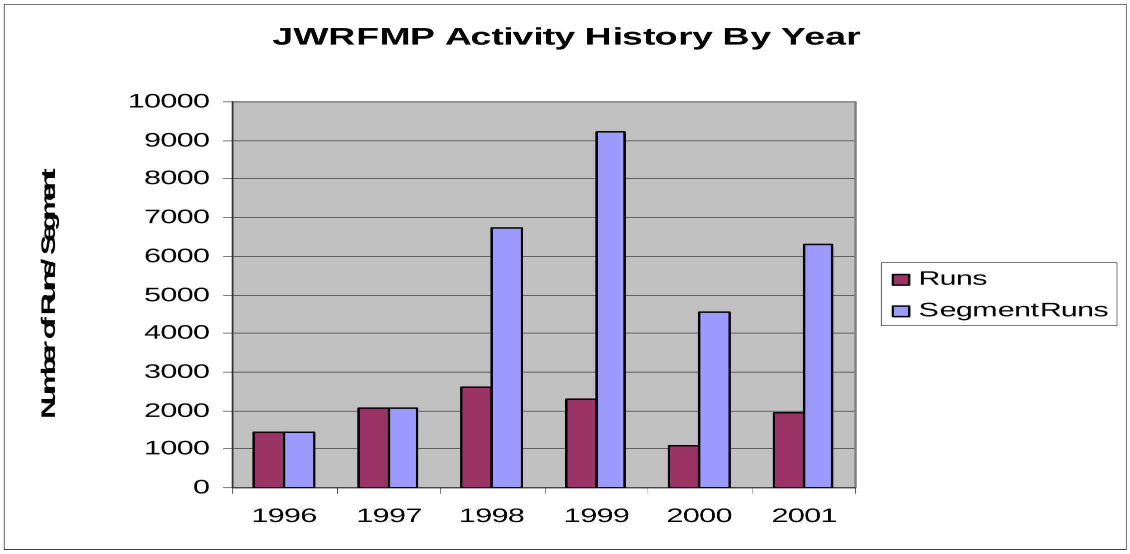

Figure 1. Number of runs and segment runs made by year

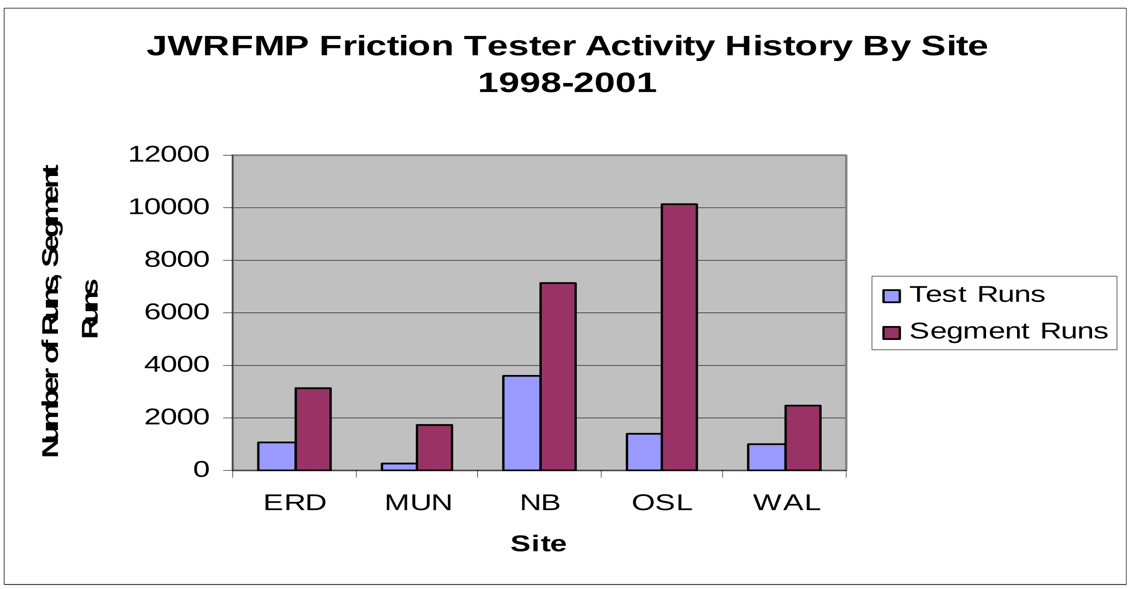

Figure 2. Number of runs and segment runs made by site

Since the beginning of the JWRFMP in January 1996, 10 aircraft and 40 different ground devices have collected friction data at North Bay; Ontario, Sawyer Airbase; Gwinn, Michigan; NASA Wallops Flight Facility, Virginia; Oslo, Norway; Munich, Germany; and Erding Air Force Base, Germany. A total of over 450 aircraft runs and over 11,000 ground vehicle runs (over 30,000 data point) were conducted on nearly 40 different runway conditions. More than 300 individuals from nearly 50 organizations in 12 countries have participated with personnel, equipment, facilities and data reduction/analysis techniques. The CRFI and the IRFI are two major outcomes from these efforts to harmonize ground vehicle friction measurements and to identify the relationship to aircraft stopping performance. Two international aviation conferences have been held in Montreal (Oct. 1996 and Nov. 1999) [5,6] to disseminate the test results and obtain recommendations for future testing. Data from the seven annual NASA Tire/Runway Friction Workshops have been successfully completed to add dry and wet surface ground vehicle friction data to the database. Efforts were initiated in 2000 not only to get funding support from the European Union, but also to get expanded support from the aircraft manufacturers and the airlines. Dialogue to obtain assistance from the International Civil Aviation Organization, Air Line Pilots Association and the Airports Council International will continue.

A substantial friction database has been established, with both ground vehicle and aircraft winter friction measurements. For each friction value, the database provides the name/type of device, test location, speed, tire specifications, surface conditions and ambient weather conditions. Table 1 is a list of all of the aircraft that have run tests in the JWRFMP and Table 2 is a list of all of the ground friction devices that have taken part in the JWRFMP.

Table 1. List of test aircraft that took part in the JWRFMP, 1996 to 2001

AIRCRAFT TYPE	OWNER/OPERATOR	MANUFACTURER
Falcon-20	National Research Council Canada	Dassault Aircraft Company
B-737-100	NASA Langley Research Center	Boeing Commercial Airplane Group
B-727-100	FAA Technical Center	Boeing Commercial Airplane Group
Dash-8	DeHavilland Aircraft Company	DeHavilland Aircraft Company
Dash-8	NAV CANADA	DeHavilland Aircraft Company
B757-200	NASA Langley Research Center	Boeing Commercial Airplane Group
A320	Aero Lloyd	Airbus Industrie
A320	Sabena Airline	Airbus Industrie
B-737-300	Deutsche British Airways	Boeing Commercial Airplane Group
DU 325	Dornier	Fairchild/Dornier

At all test sites, NRC provided an ice and snow specialist who classified the winter contaminant. Typically he measured the water content, density, air and surface temperature, and depth of the contaminant. He also provided observations on the tire tracks produced by the test aircraft and ground vehicles. This data along with the hourly flight weather has also been included in the database.

Table 2. Ground friction devices that took part in the JWRFMP, 1996 to 2001

Owner	Device Name	Notes	Manufacturer
Airport Surface Friction Tester AB, Sweden	Airport Surface Friction Tester Ford Taurus		Airport Surface Friction Tester AB, Sweden
Airport Surface Friction Tester AB, Sweden	Airport Surface Friction Tester Generic		Airport Surface Friction Tester AB, Sweden
Oslo Airport, Norway	Airport Surface Friction Tester SAAB 9-5		Airport Surface Friction Tester AB, Sweden
Airport Surface Friction Tester AB, Sweden	Airport Surface Friction Tester SAAB 9-5C		Airport Surface Friction Tester AB, Sweden
NASA Langley Research Center	BOWMONK mounted in Blazer		Bowmonk, United Kingdom
FAA Technical Center	BV-11 Trailer		Airport Equipment Company, Sweden
Oslo Airport, Norway	BV-11 Trailer		Airport Equipment Company, Sweden
Vienna Airport, Austria	BV-11 Trailer Vienna Airport		Airport Equipment Company, Sweden
Zürich Airport, Switzerland	BV-11 Trailer Zurich Airport		Airport Equipment Company, Sweden
NASA Langley Research Center	Diagonal Braking Vehicle		NASA Langley Research Center, USA
Transport Canada	ERD mounted in Chevrolet Blazer		Transport Canada, Canada
Transport Canada	ERD mounted in NISSAN Van		Transport Canada, Canada
Transport Canada	ERD mounted in truck Staff23 North Bay		Transport Canada, Canada
Transport Canada	ERD-179 mounted in Chevrolet Blazer		Transport Canada, Canada
Transport Canada	ERD-234 mounted in Chevrolet Blazer		Transport Canada, Canada
Irvine Findlay Inc., Scotland	Griptester Trailer		Irvine Findlay Inc., Scotland
Department of National Defense, Canada	Griptester Trailer		Irvine Findlay Inc., Scotland
Norwegian Air Traffic and Airport Management	Griptester Trailer		Irvine Findlay Inc., Scotland
French Civil Aviation Administration	IMAG Trailer		S.T.B.A Airports, France
NASA Langley Research Center	Instrumented Tire Test Vehicle (ITTV)		NASA Langley Research Center, USA
French Civil Aviation Administration	IRFI Reference Vehicle Trailer (IRV)		S.T.B.A Airports, France
Ministry of Transportation, Ontario	Norsemeter ROAR Trailer		Norsemeter AS, Norway
Department of Transportation, Iowa	Norsemeter SALTAR		Norsemeter AS, Norway
Norwegian Road Research Laboratory, Oslo	Optimum Surface Characteristics Analyzer Recorder (OSCAR)		Norsemeter AS, Norway
Norwegian Air Traffic and Airport Management	RUNAR Prototype Trailer		Norsemeter AS, Norway
FAA Technical Center	Runway Friction Tester (RFT)		K.J.Law Engineers, Inc., USA
Munich Airport, Germany	SARSYS SAAB 9000 Mrk V3		SARSYS, Sweden
Dusseldorf Airport, Germany	SARSYS SAAB 9-5C, Ser # 813		SARSYS, Sweden
Frankfort Airport, Germany	SARSYS		SARSYS, Sweden
Strate WHD Technik	SARSYS		SARSYS, Germany
FAA Technical Center	Surface Friction Tester (SFT)		SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1979		SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1985		SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1985 Turbo		SAAB GM, Sweden
Hannover Airport, Germany	Surface Friction Tester		SARSYS, Sweden
NASA Langley Research Center	Tapley meter mounted in Blazer		Tapley, Canada
Pennsylvania State University, PTI	ASTM E 274 2 wheel Trailer	Wallops Only	Pennsylvania State University, USA

Table 2. (Cont.) Ground friction devices that took part in the JWRFMP, 1996 to 2001

Owner	Device Name	Notes	Manufacturer
Pennsylvania State University, PTI	ASTM E 274 Trailer Mk III	Wallops Only	Pennsylvania State University, USA
Department of Transportation, Virginia	ASTM E 274 Trailer	Wallops Only	International Cybernetics, USA
Department of Transportation, Virginia	British Pendulum Tester	Wallops Only	W.F. Stanley, United Kingdom
Federal Highway Administration	British Pendulum Tester	Wallops Only	W.F. Stanley, United Kingdom
Pennsylvania State University, PTI	British Pendulum Tester	Wallops Only	W.F. Stanley, United Kingdom
Nippo Sangyo Co.,Ltd	Dynamic Friction Tester	Wallops Only	Nippo Sangyo Co., Ltd., Japan
Generic device	Mu-Meter Trailer	Wallops Only	Douglas Equipment Company, United Kingdom

4.0 DEVELOPMENT OPTIONS CONSIDERED

Two approaches were considered as models, a statistical model and a physical model valid for defined surface classifications. In both approaches, runway measurements are associated with surface segments of the runway. The statistical method differentiates between segments that are winter-contaminated versus 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 the surface class. Because further development of the physical model would require texture data and analysis from full length, operational runways and since the statistical model was working satisfactorily, further work on the physical model was suspended in 2000. It would be a worthwhile effort in the future to continue studying the data collected to establish the physical parameters so that reported friction values can be normalized before applying the statistical harmonization method. This should lead to the reduction of errors.

The correlation constants for the statistical model were calculated for devices that took part in the 1998-1999 test seasons, and these constants were reported in the 1997-98 JWRFMP report and the Fourth Year-Joint Runway Friction Measurement Program reports [2, 3]. The constants were calculated by combining the two years of data. However; since 2000 it was established that not only does a calibration not apply across similar types of devices, but it also changes from year to year for a particular device. Thus, correlation constants are now calculated on a yearly basis. Section 6 provides a more detailed discussion on device stability and reproducibility.

5.0 ESSENTIAL ELEMENTS OF THE STATISTICAL HARMONIZATION METHOD FOR IRFI

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 IFI 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.

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) an IRFI reference:

$$\text{IRFI} = a + b \times \text{device friction measurement} \quad (1)$$

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. This change in time is critical when regressions are being made, but not as critical for operating conditions.

5.1 IRFI Reference Selection

A true value is needed in order to perform a linear regression; therefore, a virtual device, called the reference, was developed from combinations of devices for the 1998-1999 years. Based on the review [2, 3] it was concluded that the best option for the reference was to use the average of the SFT-TC79 and the IMAG. However the SFT-TC79's instrumentation was updated in 1999, making it appear as another device, and the virtual device reference was dropped. In late 1999, STBA offered a second and dedicated IMAG to the JWRFMP and it was accepted and designated as the International Reference Vehicle (IRV) for the JWRFMP. The IRV is now dedicated to the project and not used for any other purpose. A separate study was performed to relate the IMAG used in 1998, 1999 and 2000 to the IRV [4]. This study concludes that the IRV = 0.95 * IMAG. Thus the reference now used for calibration is IRV or 0.95*IMAG, if IRV data is not available.

5.2 IRFI Correlations

The four tables in appendix A give the IRFI correlation constants *a* and *b* for each of the years 1998 to 2001. In 1998 the *a* values ranged from -0.05 to 0.08 with an average of 0.03. In 1999 the *a* values ranged from 0.00 to 0.17 with an average of 0.09, in 2000 from 0.04 to 0.25 with an average of 0.15, and in 2001 from 0.02 to 0.21 with an average of 0.09. Similarly the *b* value varied from 0.70 to 1.01 in 1998 with an average of 0.82, 0.21 to 1.14 in 1999 with an average of 0.67, 0.28 to .99 in 2000 with an average of 0.62, and from 0.61 to 0.93 in 2001 with an average of 0.74.

5.3 Errors of Fitted IRFI Values

Also given in the four tables in Appendix A are the correlation R^2 and the standard error of estimate for each of the years 1998, 1999, 2000 and 2001. In 1998 the R^2 ranged from 0.45 to 0.99 with an average of 0.86, in 1999 the R^2 ranged from 0.05 to 0.74 with an average of 0.46, in 2000 the R^2 ranged from 0.10 to 0.99 with an average of 0.62, and in 2001, the R^2 ranged from 0.41 to 0.98 with an average of 0.83. Similarly, the standard error of estimate varied from 0.023 to 0.076 in 1998 with an average of 0.047, 0.031 to 0.062 in 1999 with an average of 0.045, from 0.023 to 0.096 in 2000 with an average of 0.059, and from 0.04 to 0.1 in 2001 with an average of 0.07.

In looking at these values, it appears the correlations were not as good in 1999 and 2000 as in 1998. On the average this is true due to several reasons. In 1998 extra care was exercised in a number of the field tests to ensure no loose snow was present on the bare compacted snow and bare ice surfaces. In 1999, the test program included tests in deep snow and more tests were conducted with loose snow on ice and packed snow, making the sites more variable. In 2000, tests in Germany were conducted when the conditions were very poor due to lack of snow and the test beds were very variable. This shows the need for good test conditions to maintain the best accuracy.

It should also be noted that devices tested at all sites generally had better R^2 and standard error of estimate than those just tested in Europe. Even so, the average standard error of estimate was less than 0.05 and more than half of the devices were lower. This is in comparison to as much as 0.2 without the IRFI. harmonization applied.

5.4 Errors of Predicting IRFI Values

Due to the natural scatter in friction values typically obtained on a runway surface, the predicted IRFI value will show a similar scatter when harmonization is applied to individual reported friction values by a local airport device. The harmonization method is not designed to moderate any surface variability or take into account local runway variability.

The pairs of data samples collected to determine a harmonization equation has variability about the fitted equation line, often expressed in standard deviation. The prediction interval for a given confidence level is proportional to this standard deviation. In other words, the range in error when calculating IRFI values for a harmonized device is a characteristic of the original paired data collection for the determination of the harmonization equation.

It is therefore not possible to calculate what errors the IRFI values would have at a local airport runway that was not part of the original paired data collection.

One may, however, venture to state that provided that the harmonization paired data collection has a sufficient range in friction levels and surface textures and includes representative operational runway characteristics, the error would be within the bounds of the harmonization data set variability. This variability is largely surface variability. Such bounds have been found typically in JWRFMP data sets to be in the order of +/- 0.10 friction units for a 95% confidence level, i.e. 19 of 20 calculations will be within an error of 0.10 friction value. Most of this error is due to surface variability. One may therefore argue that these bounds are not relevant for the friction values of harmonization transforms, since they largely stem from surface variability. The fitted harmonization transform is a product of averaging out much of the surface variability to find the quantitative relationship between two devices.

5.5 Limitations of the Statistical IRFI

No correlations can be expected to remain stable with time since, for example, the 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.

The IRFI has initially been studied as a common unit of friction measure. When bringing the IRFI transforms into practical use at airports that have different sampling techniques of their runways, it must be expected that the practical implementations will diverge in reported IRFI values. Notably, continuous friction measuring devices sample contaminated and non-contaminated sections of a runway and include these sections in the harmonization. A spot measuring device may collect only selected contaminated sections of the runway. The IRFI was not designed to overcome differences in sampling techniques.

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 was solved with the donation of the IRV by STBA. However, there is still a need to evaluate the reference device to aircraft. Based on this evaluation, there may still be a need to design and build a special reference device. With this in mind, ASTM Committee E17 has formed a working group to address this possibility.

6.0 STABILITY OF THE HARMONIZATION METHOD

6.1 Reproducibility Concerns

When several friction measuring devices of the same standard type are brought together to measure the same surface object, the degree with which they report the same value of friction is called reproducibility. Any differences in reported friction values across the devices can be expressed in terms of standard deviation or standard error relative to the arithmetic means of all the measures from all devices studied.

Recent and unique studies performed by the Norwegian Air Traffic and Airport Management as described in [5 to 8] have demonstrated that reproducibility of two different kinds of continuous friction measuring devices was 0.05 friction units for both kinds operated at 65 km/h. This was achieved when the devices were in a technical state as normally used at Norwegian airports. Every effort was made to operate the devices under equal conditions during the field testing. The studies included 25 and 15 units, respectively, of standard GripTesters and non-standard BV11s configured with ASTM smooth measuring tires. The measurements were made under self-wet conditions on a total of 32 surface segments of 100 m each, made of 8 different asphalt mixtures. The macrotexture of these recipes ranged from 24 km/h to more than 260 km/h in IFI speed numbers, corresponding to 0.3 to 2.5 mm mean texture depth as measured by the sand patch method according to ASTM E 965. The friction values were averages of three runs across each segment by each device.

After thorough machine part inspections, replacements of out-of-tolerance worn parts, instrumentation calibration by the manufacturer, and fitting of new measuring tires, the reproducibility of the GripTesters was improved from 0.05 to 0.03 friction units in terms of standard deviation as shown in Figure 3. A similar exercise was not performed for the BV11s; Figure 4 shows the results from the BV11s.

It is believed that a significant part of the 0.03 value of reproducibility stems from surface and field test variability. The devices were not measuring exactly the same tracks and had different host vehicles and drivers. The self-wet systems had no feedback control of the water flow. However, the figure should be taken as an indication of what the reproducibility in terms of standard deviation can be at its best for a cross section of asphalt surfaces. It may be more prudent in many evaluations to use the 0.05 figure, as first presented above, as representative of operational equipment states, when equipment is partly worn and fitted with partly worn measuring tires.

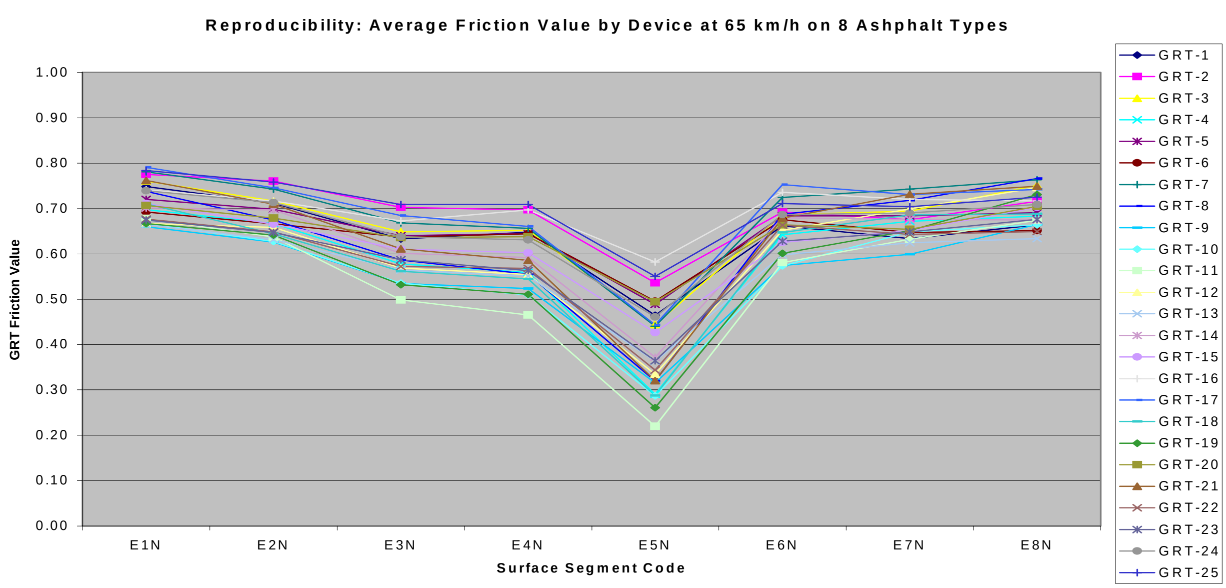

Figure 3. A sample extract of the NATAM database [7, 8, and 9] for GripTester devices. Each friction value shown by marker is the average of three runs.

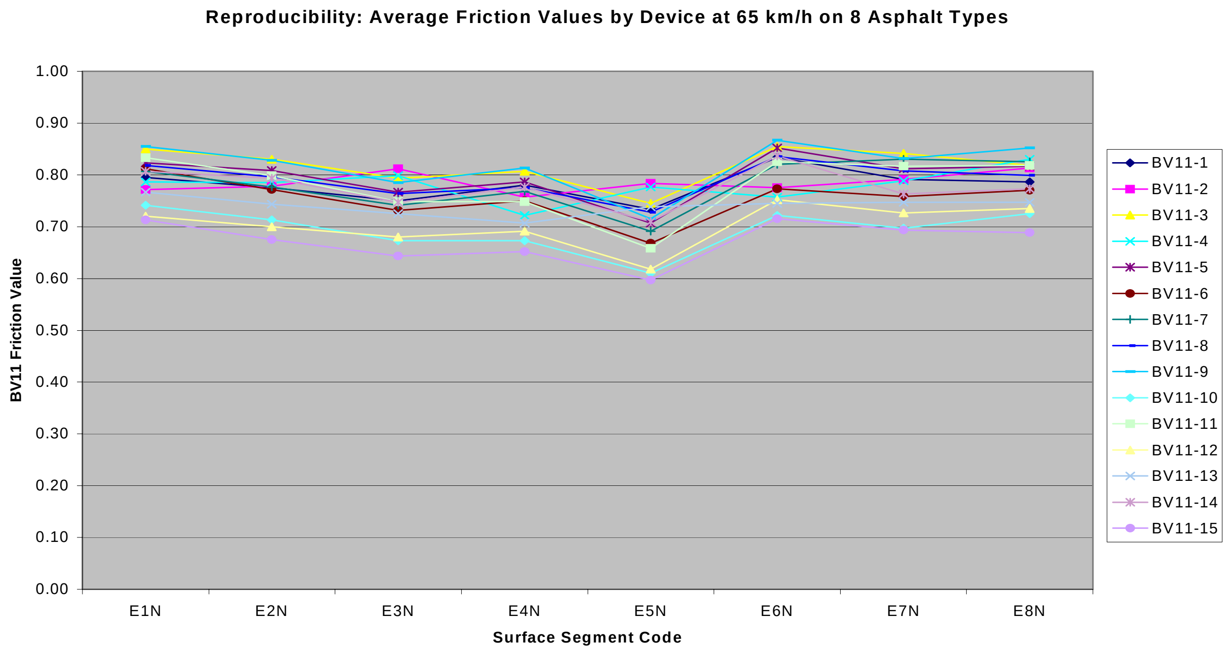

Figure 4. A sample extract of the NATAM database [8, 9, and 10] for BV-11 devices. Each friction value shown by marker is the average of three runs.

6.2 Reproducibility of SARSYS Devices

At the Erding test site, four devices of the same brand and type took part. Their participation enabled a limited study of reproducibility, i.e. how different each device of the same type measured the same surface segments. This was the first opportunity for a reproducibility study in the JWRFMP.

A common way to evaluate the reproducibility is to regard the reported friction values from each device as reported from a device and calculate the standard deviation of the individual reported friction values for each object measured.

The winter contaminated surface can change friction characteristics rapidly and the devices therefore run closely, one after the other, in groups across the same surface segments within two minutes of elapsed time per group run. The reported friction values for each segment in each group run constitute a reproduction set of data. The SARSYS devices will be analyzed in the following two configurations. The first configuration of devices includes a fitted high pressure ribbed tire at 100 psi. The second configuration includes a fitted low pressure blank tire at 30 psi. Note that not all devices ran in every group run.

6.2.1 High Pressure Ribbed Tires

Figure 5 shows all group runs by run sequence; more precisely, Figure 5 shows each reproduction set of data per segment for each run within a test number for the SARSYS devices when running at 65 km/h fitted with ribbed tires inflated at 100 psi.

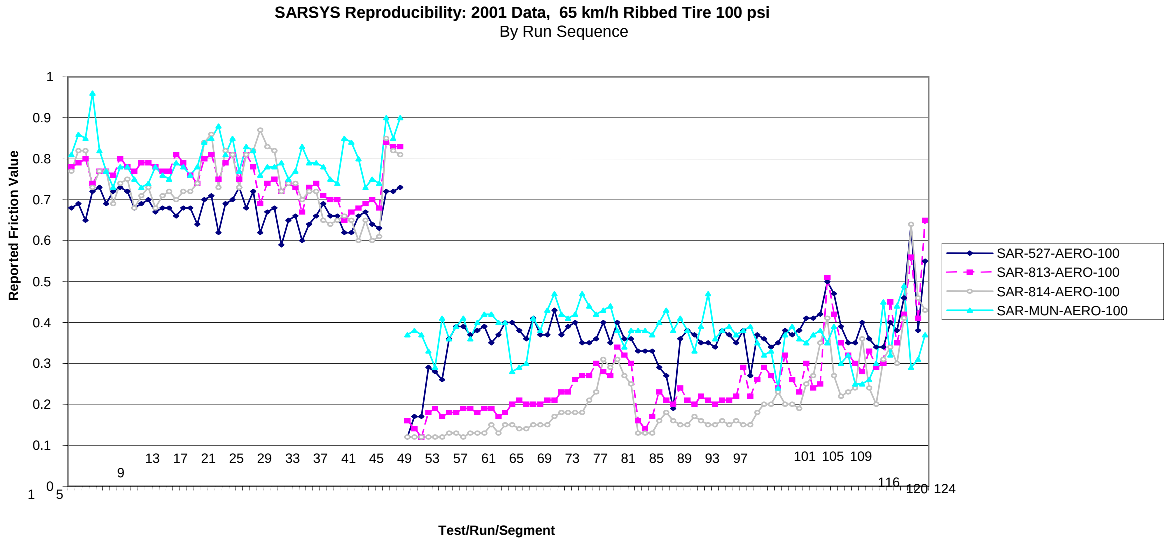

Figure 5. All reproduction data sets by run sequence at 65 km/h with ribbed tires inflated at 100 psi

It is evident that each device takes a position relative to the other that has a consistent trend when looking at the high friction section on right and on the low friction on the left. Since the reported friction values do not overlap in each region, the trends may principally be attributed to the performance of the device and not to surface variability. The data is therefore suitable for reproducibility studies.

It may be more enlightening to view the data of Figure 5 in an order of ascending friction level. With the friction values of device SAR-813-AERO-100 data sorted in ascending order the data groups appear as shown in Figure 6.

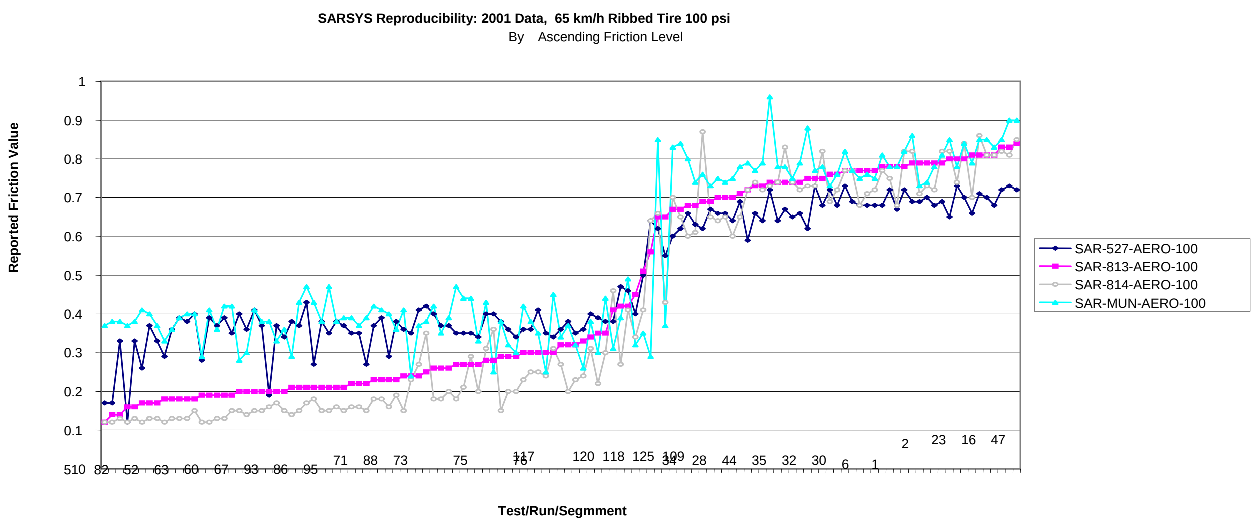

Figure 6. The reproduction data sets sorted in ascending order of device

From Figure 6 it is apparent that each device exhibit trends of performance that vary with the friction level. Relative to the others, the SAR-527-AERO-100 device measures high in the low friction region and low in the high friction region. SAR-MUN-AERO-100 is consistently high in both regions. SAR-813-AERO-100 and SAR-814-AERO-100 follow each other.

The average friction value across the total set of reproduction data sets is shown in the bar chart of Figure 7. The grand average of all is 0.47 SARSYS friction units. The lowest average is 0.41 and the highest is 0.54, a span of 0.13 SARSYS friction units. A reason why the SAR-527-AERO-100 is close to the grand average is the shifting trend as seen in Figure 6. The example serves to show that caution should be exercised in interpreting the performance of a device by only studying averages as in Figure 7.
The standard deviation has been calculated within each reproduction group of data. The results are displayed as a line chart in Figure 7. The average standard deviation was found to be 0.084 SARSYS friction units. However, looking at Figure 8 it is noticeable how the standard deviation decreases with increasing friction level. The data groups are presented in the same order as in Figure 6 left to right.

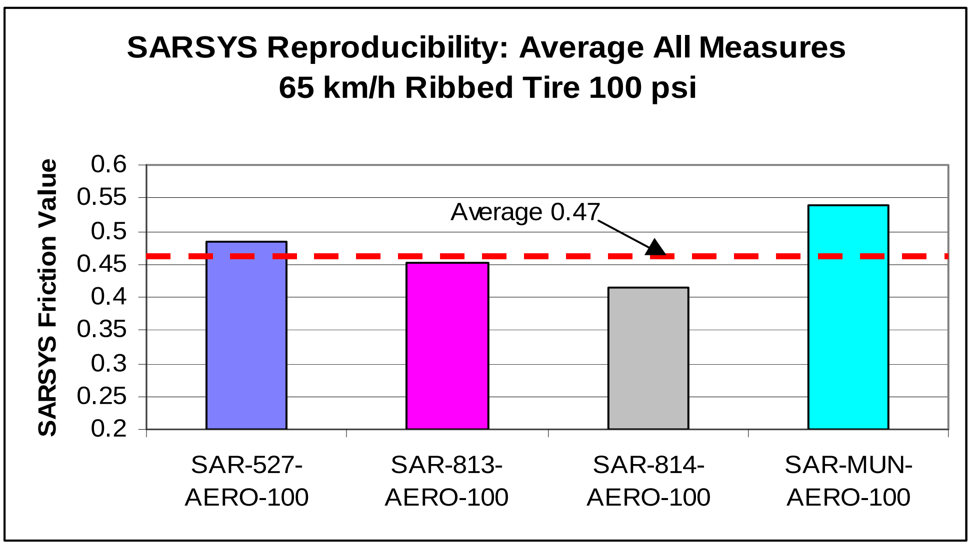

Figure 7. Average friction value of each device fitted with ribbed tires

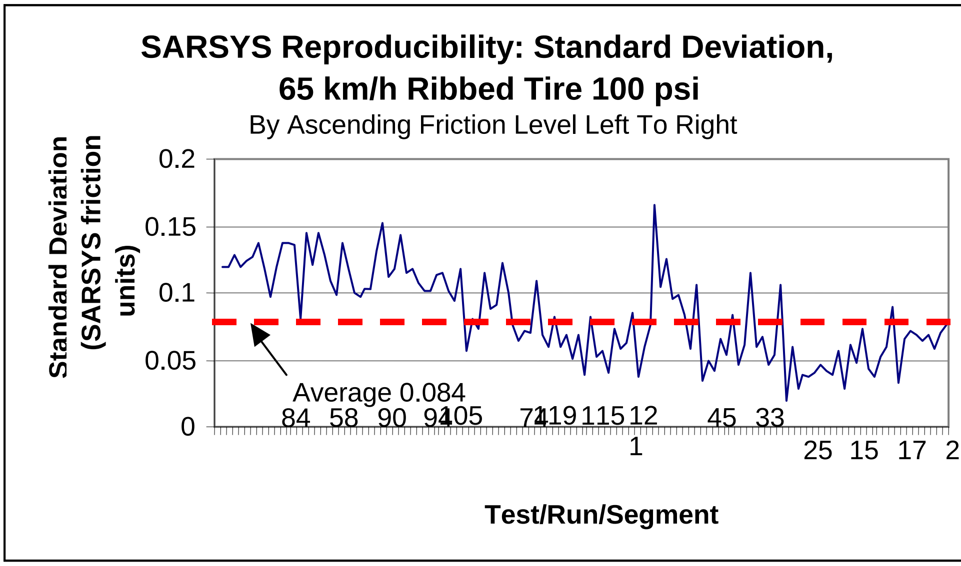

Figure 8. Standard deviation of the SARSYS devices at 65 km/h with ribbed tires 100 psi

6.2.2 Low Pressure Blank Tires

The reproduction data groups obtained with blank tires are displayed in Figure by run sequence. Again one observes consistent trends supporting a finding that each device has a different performance characteristic. But opposite to the finding for the ribbed tires case, the blank tires do not show any flip-flop of characteristics with change of friction level.

This becomes visually clearer in Figure 10 where the data is sorted in ascending friction level using device SAR-813-AERO-100.

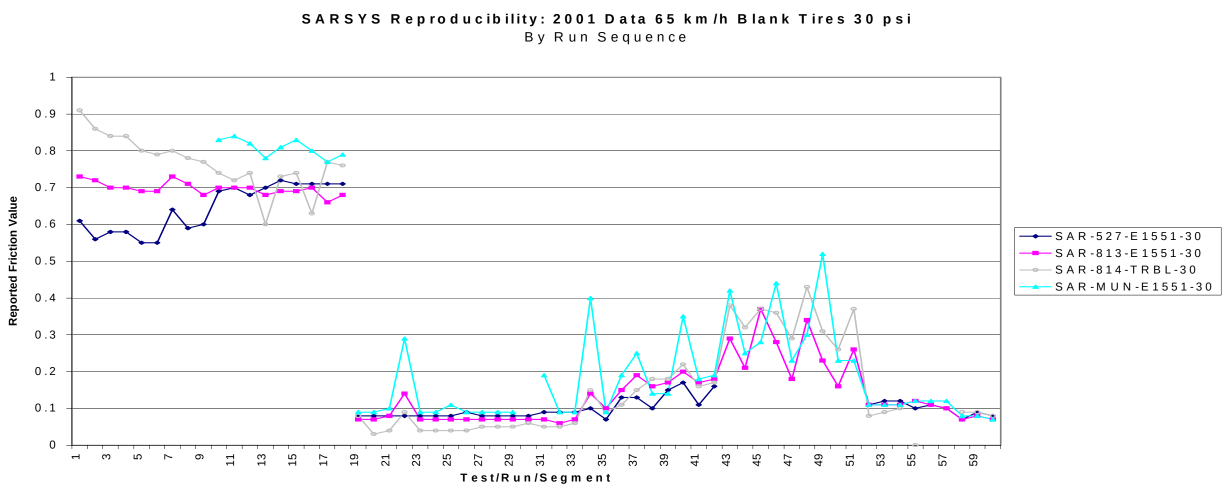

Figure 9. All reproduction data sets by run sequence at 65 km/h with blank tires inflated at 30 psi

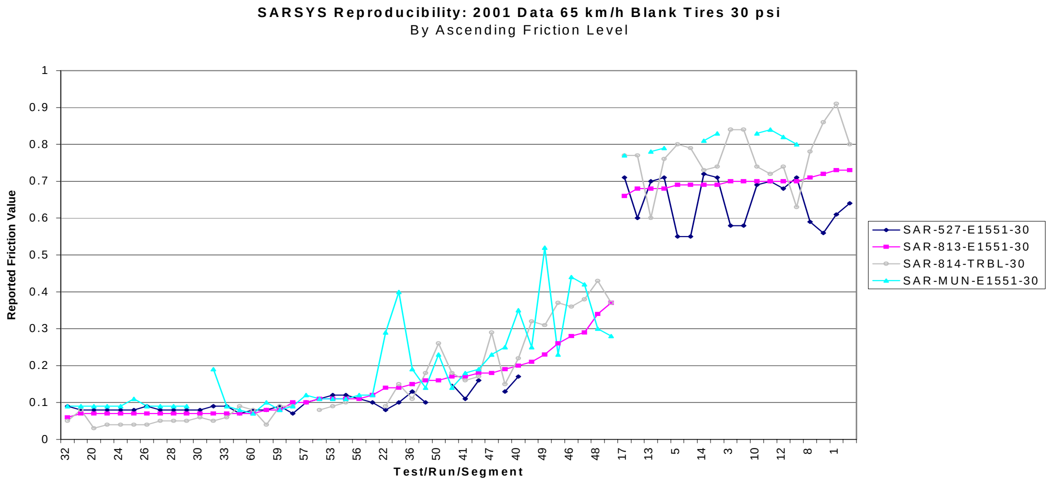

Figure 10. The reproduction data sets for blank tires sorted in ascending order of device SAR-813-AERO-100

The average friction value across the total set of reproduction data sets is shown in the bar chart of Figure 11. The grand average of all is 0.31 SARSYS friction units. The lowest average is 0.29 and the highest is 0.34, a span of 0.05 SARSYS friction units.

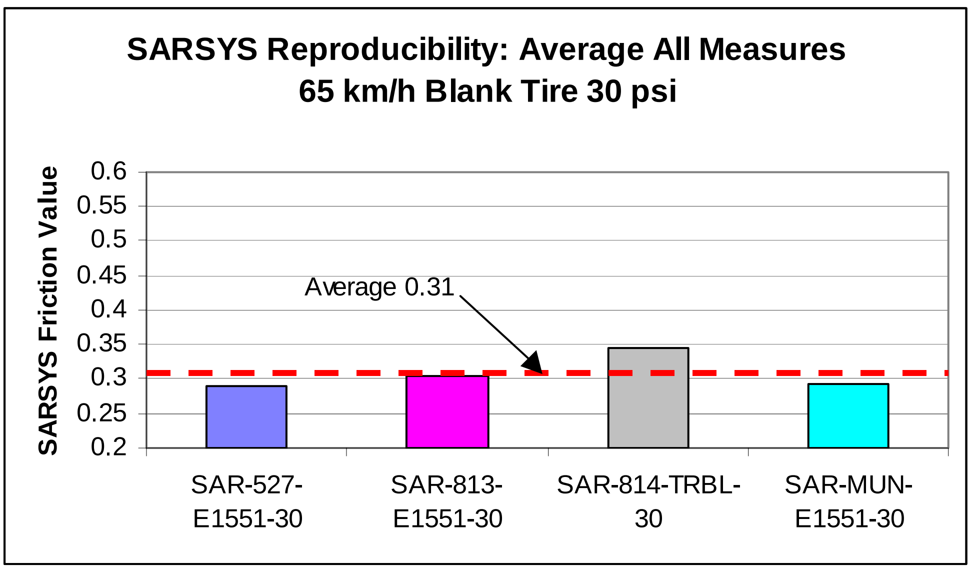

Figure 11. Average friction value of each device fitted with blank tires

The standard deviation has been calculated within each reproduction group of data. The results are displayed as a line chart in Figure 12. The average standard deviation was found to be 0.053 SARSYS friction units. The standard deviation increases with increasing friction level, opposite to what one observed in the case of ribbed tires.

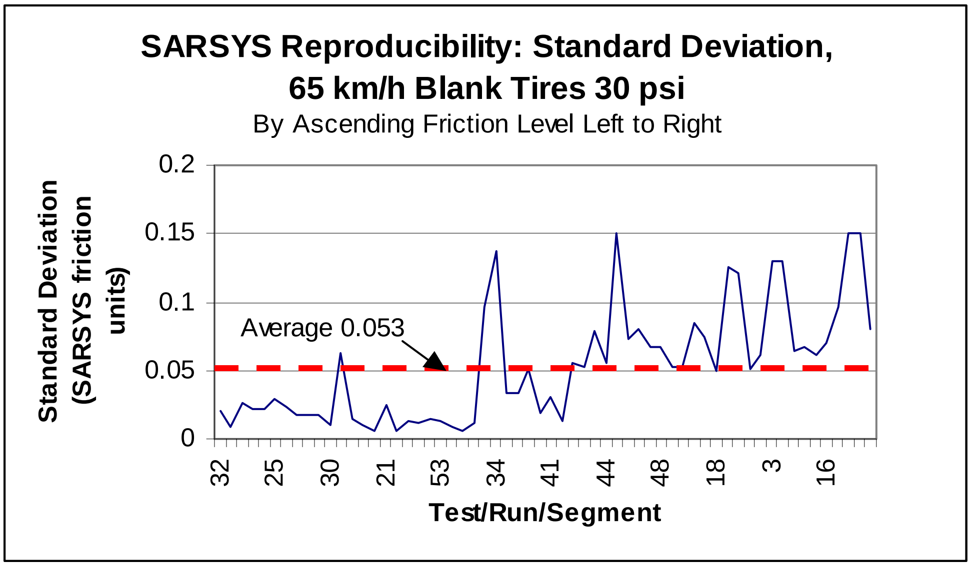

Figure 12. Standard deviation of the SARSYS devices at 65 km/h with blank tires 30 psi

6.2.3 Reproducibility Summary

With the surfaces available for testing at the Erding site, the SARSYS devices exhibited reproducibility as expressed in standard deviation in the order of 0.08 friction units for ribbed tires and 0.05 for blank tires. The reproducibility varies with changes in friction level for both ribbed and blank tires.

6.3 Time Stability of Individual Devices

In order to evaluate the time stability of the individual devices, a year-by-year comparison of the IRFI constants in JWRFMP was made. Appendix A gives the values of the IRFI constants *a* and *b* for each of the years 1998, 1999, 2000, and 2001. In addition the regression R^2, standard error, number of data points and some comments are given for each device. The year-by-year regressions also show that the same types of devices can produce very different results that require different IRFI regression constants. The tables clearly show that not only are there differences within a class of devices, but that an individual device changes from year to year. To show this, a bar chart of how the multiplying constant *b* varies is given in Figure 13 below. Only devices that were calibrated for two or more years in a row are included.

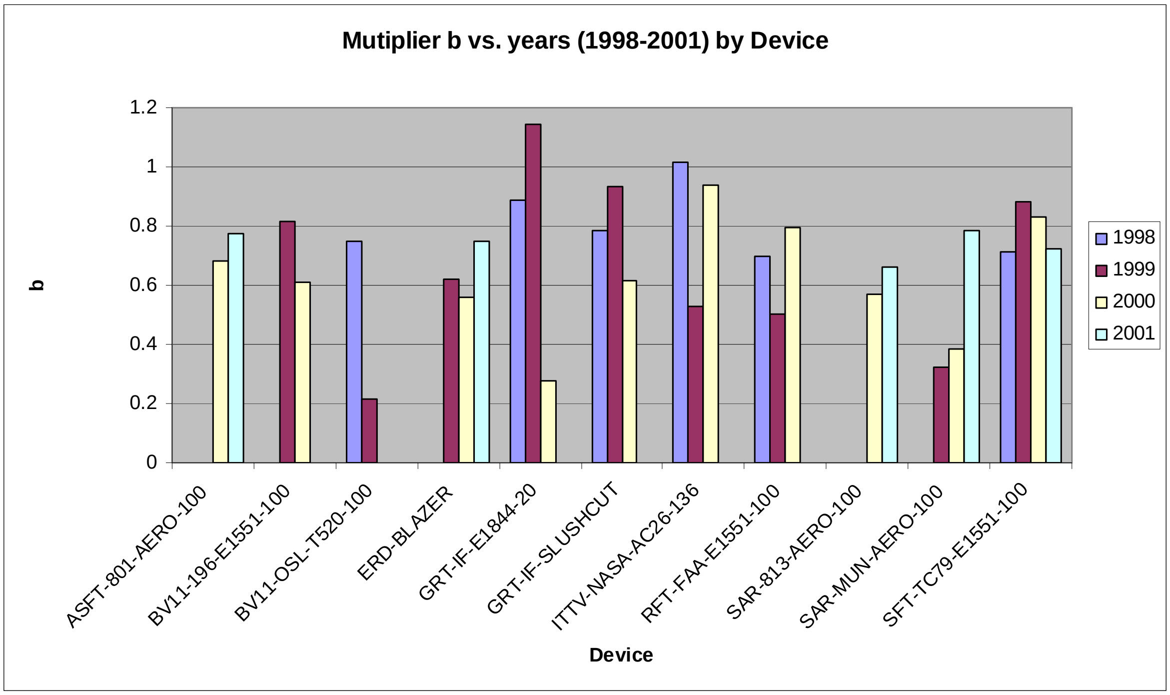

Figure 13. IRFI multiplier constant *b* vs. years 1998 to 2001

Based on the findings from the research of 2000, the ASTM standard was modified to require annual determination of the IRFI harmonization coefficients.

7.0 THE ASTM E 2100 STANDARD

This section describes the method developed and standardized by ASTM in the year 2000. The standard's number and title are: ASTM E 2100-00, Standard Practice for Calculating the International Runway Friction Index. A separate Transport Canada report [9] provides more detail, a summary of which is given here.

The local friction device can be harmonized in one of two ways: by conducting field testing with the IRFI reference device or with a secondary harmonized device called a master device. The method of using a secondary harmonized device was introduced by the standards committee because of practical reasons such as a limited availability of the IRV to all regions of the world and the costs of bringing local devices to field test sites with the only IRV. A method of secondary harmonized references had not been researched by the JWRFMP prior to this.

The field test collects friction data for each surface class for which the local device can be used. When a local friction device has different selectable modes of operation (for example, fixed or variable slip measurement), each mode of operation is treated separately. The local friction device is operated according to the manufacturer's instructions for the device and run within the range of speeds for which it is to be harmonized. If there is a standard test method for the device, it should also be followed.

7.1 Method 1: Harmonization with the IRFI Reference Vehicle

The local device is harmonized to report an IRFI by measuring friction on surfaces with the IRFI Reference Vehicle. A minimum of 8 surfaces covering a range of friction values from 0.1 to 0.7 as measured by the IRFI Reference Vehicle shall be included. Harmonization constants *a* and *b* are determined for the speed at which the local device normally operates. Test speeds shall be maintained within ±3 km/h (1.6 knots, 2 mph). The measurements with the local friction device and the IRFI reference device shall be taken on a segment within 2 minutes of each other.

Linear regressions are as follows:

$$FR_{ref} = a + b \bullet FR_{local}, \tag{2}$$

where FR_{ref} is the friction value reported by the reference device and FR_{local} is the local device measured value. The harmonization constants for the device are *a* and *b*. The correlation coefficient of the regression and the standard error of estimate shall be reported. Typical values for devices that have been harmonized are given in the tables of Appendix A. These results were for specific local devices that were harmonized in the JWRFMP. They are not applicable to other local friction devices or to other test speeds, which must be calibrated with the device configuration for that device.

Subsequent measurements made by the local friction device can be harmonized using the regression constants of the device:

$$IRFI = a + b \bullet FR_{local}, \tag{3}$$

Whenever the local friction device is modified, repaired or recalibrated, new harmonization constants shall be determined. Note: Many operator handbooks use the term calibration for set-up, including adjustments to dynamometers or weight scales of the machine prior to measurements. In this report recalibration is associated with the replacement of sensors (strain gauges) or other mechanical-electronic parts of the instrumentation that have a multi-year service life.

7.2 Method 2: Harmonization with a Master Device

The local device is harmonized to report an IRFI by measuring friction on surfaces with a master device that has been calibrated to the IRFI reference device. A minimum of

8 surfaces covering a range of friction values from 0.1 to 0.7 as measured by the master device shall be included. Harmonization constants (a'', b'') shall be determined for the speed at which the device normally operates.

The master device is harmonized by measuring friction on several base surfaces with the IRFI reference device. All surfaces shall be included. A minimum of 5 repeated runs on 8 surfaces covering a friction range from 0.1 to 0.7 as measured by the IRFI reference device are to be included. The harmonization constants (a', b') are determined at speeds at which the device normally operates. Test speeds shall be maintained within ±3 km/h (1.6 knots, 2 mph).

The measurements with the local friction device and the master device and for the master device with the IRFI reference device shall be taken on a segment within 2 minutes of each other.

A linear regression is of the form:

$$FR_{ref} = a' + b' \bullet FR_{master}, \quad (4)$$

$$FR_{master} = a'' + b'' \bullet FR_{local}, \quad (5)$$

Substituting equation 5 into equation 4 gives:

$$FR_{ref} = a' + b' \bullet (a'' + b'' \bullet FR_{local}), \quad (6)$$

Then: $a = a' + b' \bullet a''$ and $b = b' \bullet b''$, (7, 8)

Where FR_{ref} is the friction value reported by the reference device for each 100 m segment, FR_{master} is the master device measured value for each 100 m segment and FR_{local} is the local device measured value for each 100 m segment. The harmonization constants for the device are then a and b. The correlation coefficient of the regression and the standard error of estimate shall be reported.

Subsequent measurements made by the local friction device can be harmonized using the regression constants of the device:

$$IRFI = a + b\, FR_{local}, \quad (9)$$

Whenever the local friction device is modified, repaired or changes its calibration, new harmonization constants shall be determined.

It is foreseen that the propagated error for a two-stage harmonization, such as the standard error of estimates, will be up to twice the value of a one-stage harmonization.

As discussed in section 5.5, the prediction intervals are largely due to surface variability. Using a one-stage or two-stage transform may therefore not influence the error in calculated harmonized values heavily.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The ASTM Standard E 2100-00 defines and prescribes how to calculate IRFI for winter surfaces. The IRFI is a standard reporting index to provide information on friction characteristics of the movement area to aircraft operators.

The IRFI can be used by airport maintenance staff to monitor the winter frictional characteristics in support of surface maintenance actions.

The IRFI method typically reduces the present variations among different devices from 0.2 down to 0.05 friction units.

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 device chosen for the exercises to demonstrate that IRFI is possible was an IMAG device called IRV. The IRV must be evaluated at some point for stability. If it is not stable with time, other references would need to be investigated. All harmonization constants will have to be reworked when a permanent IRFI reference has been designated.

There is proof that the participating devices in the JWRFMP are not representative of the other devices even when they are of the same generic type. 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 and is the current paradigm in the aviation industry. To accomplish this, a master device must be calibrated to the IRFI reference device in order to serve as a secondary reference and the manufacturer or owner of this secondary reference can then calibrate other devices to this master.

For any common scale of friction measure 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 similar values for the same surface and conditions unless they are harmonized on a regular basis, at least annually.

Further testing with a two-stage harmonization procedure is recommended to establish what differences in IRFI values a Master Reference harmonization method exhibits relative to harmonization with the IRFI Reference Vehicle.

Standardization of runway friction sampling techniques must be considered to avoid divergence in reported IRFI values due to differences in sampling techniques. There is a danger that two different IRFI regimes may evolve, one for continuous friction measuring equipment and one for spot measuring equipment. The goal of one common friction index worldwide would then not be fulfilled.

Preliminary work has shown that the IRFI can be correlated to various aircraft braking; this work needs to be completed.

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APPENDIX A Yearly IRFI Constants

Table A.1 IRFI Constants for 1998

Device tire configuration	a	b	R^2	StdError of Estimate	No of data points	Comment
ERD-NISSAN	0.03	0.90	0.45	0.076	176	Good plot,
ERD-23	0.08	0.83	0.72	0.042	83	
ASFT-ASFT-AERO-100	-0.05	0.91	0.78	0.072	536	
BV11-OSL-T520-100	0.03	0.75	0.85	0.061	528	
GRT-NCAA-SLUSHCUT	0.03	0.78	0.88	0.044	635	Good plot
GRT-NCAA-E1844-20	0.01	0.89	0.91	0.035	360	Good plot
SFT-TC79-E1551-100	0.05	0.71	0.95	0.034	683	Very good plot
BV11-196-T520-100	0.01	0.82	0.96	0.036	154	Two data clusters.
ITTV-NASA-AC26-136	0.08	1.01	0.96	0.037	141	
RFT-FAA-E1551-100	0.02	0.70	0.98	0.032	42	Two data clusters
SFT-212-E1551-100	0.02	0.74	0.99	0.023	42	Two data clusters
minimum	-0.05	0.70	0.45	0.02	42.00	
average	0.03	0.82	0.86	0.04	307.27	
maximum	0.08	1.01	0.99	0.08	683.00	

Table A.2 IRFI Constants for 1999

Device tire configuration	a	b	R^2	StdError of Estimate	No of data points	Comment
BV11-OSL-T520-100	0.17	0.21	0.05	0.059	798	
SAR-MUN-AERO-100	0.14	0.32	0.11	0.062	678	
RFT-FAA-E1551-100	0.10	0.50	0.26	0.032	87	
ASFT-ASFT-AERO-100	0.10	0.49	0.37	0.052	607	
ERD-BLAZER	0.12	0.62	0.43	0.049	756	
ITTV-NASA-AC26-136	0.13	0.53	0.46	0.042	277	
ASFT-OSL-AERO-100	0.13	0.70	0.47	0.044	286	
SFT-TC79-E1551-100	0.09	0.88	0.63	0.040	1181	Even plot
GRT-NCAA-SLUSHCUT	0.02	0.93	0.65	0.031	432	
GRT-DND-E1844-20	0.02	0.94	0.67	0.036	490	Good, even plot
BV11-196-E1551-100	0.07	0.81	0.68	0.033	223	
GRT-NCAA-E1844-20	0.00	1.14	0.74	0.031	748	Good, even plot
minimum	0.00	0.21	0.05	0.03	87.00	
average	0.09	0.67	0.46	0.04	546.92	
maximum	0.17	1.14	0.74	0.06	1181.00	

Table A.3 IRFI Constants for 2000

Device tire configuration	*a*	*b*	R^2	StdError of Estimate	No of data points
GRT-IF-E1844-20	0.23	0.28	0.10	0.052	24
ERD-BLAZER	0.16	0.56	0.43	0.096	286
GRT-IF-SLUSHCUT	0.12	0.62	0.64	0.057	60
SAR-MUN-AERO-100	0.19	0.38	0.65	0.058	55
BV11-ZUR-T49-20	0.25	0.31	0.66	0.060	24
SFT-TC85-E1551-100	0.17	0.59	0.68	0.121	49
RFT-FAA-E1551-100	0.11	0.80	0.71	0.068	104
ITTV-NASA-AC26-136	0.15	0.94	0.75	0.064	112
ASFT-801-AERO-100	0.14	0.68	0.76	0.061	120
BV11-196-E1551-100	0.14	0.61	0.78	0.090	91
SFT-HAN-AERO-100	0.17	0.56	0.78	0.059	114
SAR-813-AERO-100	0.15	0.57	0.79	0.061	102
ASFT-USFT-AERO-100	0.04	0.99	0.79	0.084	97
BV11-VIE-T520-100	0.16	0.56	0.81	0.056	108
SFT-TC79-E1551-100	0.13	0.83	0.88	0.023	66
minimum	0.04	0.28	0.10	0.02	24.00
average	0.15	0.62	0.68	0.07	94.13
maximum	0.25	0.99	0.88	0.12	286.00

less poor R^2

Device tire configuration	*a*	*b*	R^2	StdError of Estimate	No of data points
RFT-FAA-E1551-100	0.11	0.80	0.71	0.068	104
ITTV-NASA-AC26-136	0.15	0.94	0.75	0.064	112
ASFT-801-AERO-100	0.14	0.68	0.76	0.061	120
BV11-196-E1551-100	0.14	0.61	0.78	0.090	91
SFT-HAN-AERO-100	0.17	0.56	0.78	0.059	114
SAR-813-AERO-100	0.15	0.57	0.79	0.061	102
ASFT-USFT-AERO-100	0.04	0.99	0.79	0.084	97
BV11-VIE-T520-100	0.16	0.56	0.81	0.056	108
SFT-TC79-E1551-100	0.13	0.83	0.88	0.023	66
minimum	0.04	0.56	0.71	0.02	66.00
average	0.13	0.73	0.78	0.06	101.56
maximum	0.17	0.99	0.88	0.09	120.00

Table A.4 IRFI Constants for 2001

Device tire configuration	*a*	*b*	R^2	StdError of Estimate	No of data points	Comment
ASFT-801-AERO-100	0.11	0.78	0.41	0.043	54	
ASFT-801-UNIT-100	0.09	0.64	0.56	0.072	136	
SAR-527-AERO-100	0.02	0.93	0.77	0.093	171	
ERD-BLAZER	0.10	0.75	0.77	0.097	215	
SAR-814-AERO-100	0.21	0.61	0.78	0.089	156	
SAR-813-AERO-100	0.16	0.66	0.82	0.080	159	
ASFT-801-E1551-30	0.07	0.84	0.85	0.095	125	
SAR-MUN-AERO-100	0.03	0.79	0.88	0.070	180	
BV11-VIE-T520-100	0.08	0.77	0.89	0.073	306	
SAR-MUN-E1551-30	0.08	0.65	0.92	0.074	126	
BV11-ZUR-T49-20	0.07	0.69	0.93	0.060	267	
SFT-TC79-E1551-100	0.09	0.72	0.93	0.056	240	
SAR-527-E1551-30	0.09	0.79	0.94	0.066	120	
SAR-814-TRBL-30	0.10	0.69	0.94	0.061	150	
SAR-813-E1551-30	0.08	0.79	0.94	0.061	156	
SFT-TC79-AERO-100	0.07	0.72	0.98	0.039	78	Two data clusters
minimum	0.02	0.61	0.41	0.04	54.00	
average	0.09	0.74	0.83	0.07	164.94	
maximum	0.21	0.93	0.98	0.10	306.00	

less poor R^2

Device tire configuration	*a*	*b*	R^2	StdError of Estimate	No of data points	Comment
SAR-527-AERO-100	0.02	0.93	0.77	0.093	171	
ERD-BLAZER	0.10	0.75	0.77	0.097	215	
SAR-814-AERO-100	0.21	0.61	0.78	0.089	156	
SAR-813-AERO-100	0.16	0.66	0.82	0.080	159	
ASFT-801-E1551-30	0.07	0.84	0.85	0.095	125	
SAR-MUN-AERO-100	0.03	0.79	0.88	0.070	180	
BV11-VIE-T520-100	0.08	0.77	0.89	0.073	306	
SAR-MUN-E1551-30	0.08	0.65	0.92	0.074	126	
BV11-ZUR-T49-20	0.07	0.69	0.93	0.060	267	
SFT-TC79-E1551-100	0.09	0.72	0.93	0.056	240	
SAR-527-E1551-30	0.09	0.79	0.94	0.066	120	
SAR-814-TRBL-30	0.10	0.69	0.94	0.061	150	
SAR-813-E1551-30	0.08	0.79	0.94	0.061	156	
SFT-TC79-AERO-100	0.07	0.72	0.98	0.039	78	
minimum	0.02	0.61	0.77	0.04	78.00	Two data clusters
average	0.09	0.74	0.88	0.07	174.93	
maximum	0.21	0.93	0.98	0.10	306.00	