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Evaluation of IRFI Calibration Procedures for New and Existing Devices

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Evaluation of IRFI Calibration Procedures for New and Existing Devices

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September 2001

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16. Abstract

A test series to verify the ASTM E 2100 method of the International Runway Friction Index (IRFI) to calibrate the International Reference Vehicle (IRV) to a master device and then to use the master device to calibrate local devices was conducted at the 2001 NASA Wallops Runway Friction Workshop.

The analysis clearly shows that when the IRFI harmonization constants are applied to the data, all devices produce similar friction values.

The results of this study show that master devices can be calibrated with the IRFI reference device and then used to calibrate other devices. However, there are several precautions that are needed:

1. At least six (eight recommended) surfaces with friction ranging from 0.1 to 0.7 are recommended for the calibrations;
2. Only devices that calibrate with a 0.05 or less average mean error should be used as a master device;
3. Calibrations using devices in self-wetting mode need to be verified for winter use;
4. On surfaces where devices in self-wetting mode are used, only devices with similar slip ratios can be calibrated against each other.

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16. Résumé

Une série de tests ont été effectués à l'atelier sur le frottement des pistes de 2001, de la NASA, à Wallops, au moyen des appareils et des pneus indiqués au tableau 1. Il s'agissait de vérifier la méthode ASTM E 2100 d'élaboration de l'Indice international de la glissance des pistes (IRFI) dans le but d'étalonner le Véhicule de référence international (IRV) sur un étalon primaire et de se servir ensuite de l'étalon primaire pour l'étalonnage des appareils locaux.

L'analyse montre clairement que lorsque les constantes d'harmonisation avec l'IRFI sont appliquées aux données, les valeurs de frottement sont similaires pour tous les appareils.

Pour l'étalonnage annuel, les étalons primaires peuvent être comparés au véhicule de référence de l'IRFI, puis utilisés eux-mêmes comme étalons secondaires pour les autres appareils. Or, la procédure doit observer plusieurs conditions :

1. Il faut disposer d'au moins six (huit sont recommandées) surfaces avec coefficient de frottement de 0,1 à 0,7 pour faire les étalonnages.
2. Seuls les appareils dont l'erreur moyenne est de 0,05 ou moins devraient être utilisés comme étalons primaires.
3. L'étalonnage se faisant à l'aide d'appareils avec arrosage automatique doit être vérifié avant d'être utilisé en hiver.
4. Dans le cas des surfaces avec film d'eau appliqué en arrosage automatique, seuls les appareils ayant des taux de glissement similaires peuvent être étalonnés entre eux.

17. Mots clés
Indice international de la glissance des pistes, IRFI, Véhicule de référence international, IRV, étalon primaire, ASTM E 2100-00

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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 during winter conditions. The different seasons, mainly winter, result in the possibility of the runway having contaminants of varying nature and qualities that contribute to reduced wheel braking friction capabilities. A service is warranted for runway condition reporting because the operational window for aircraft movement can change quite rapidly and frequently in the wintertime. Such a service includes measurement of tire-surface friction.

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 best accuracy, but the procedure has been limited to machine component calibrations. Research over the past four years has confirmed that different friction measuring devices report considerably different values, and this research has made significant advances to solve these problems. Methods of measurement are being improved to increase measurement quality, remove the uncertainties and provide better correlation to aircraft wheel braking.

This study was part of a government/industry project called the Joint Winter Runway Friction Measurement Program (JWRFMP), which is led by Transport Canada (TC) and the National Aeronautics and Space Administration (NASA). Support was received from National Research Council Canada, the U.S. Federal Aviation Administration (FAA), 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 also participated.

THE IRFI METHOD

This report describes the correlation method developed and standardized by ASTM E 2100-00 *Standard Practice for Calculating the International Runway Friction Index.* The linear regression technique is 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. All devices are then 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.

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

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. The friction measurement and corresponding data collection must be carried out more systematically.

A test series to verify the E 2100 method of the International Runway Friction Index (IRFI) to calibrate the International Reference Vehicle (IRV) to a master device and then to use the master device to calibrate local devices was conducted at the 2001 NASA Wallops Runway Friction Workshop using the devices and tires listed in Table 1.

Table 1. Devices and tires tested at 2001 NASA Wallops Runway Friction Workshop

Device Description	Tire Type
IRFI-Int'l Reference Vehicle (IRV)	PIARC Smooth Treaded Tire
NASA GripTester	ASTM E-1844
TC Surface Friction Tester (SFT)-Turbo	ASTM E-1551
USAF GripTester	ASTM E-1844
FAA Runway Friction Tester (RFT)	ASTM E-1551
FAA Trailer BV-11	ASTM E-1551
FAA Surface Friction Tester (SFT)	ASTM E-1551
VA DOT E275 trailer	ASTM E-524
PA DOT E275 trailer	ASTM E-524

Two sets of surfaces were utilized to perform these tests. Set 1 was used to calibrate the IRV with a master device and Set 2 was used to correlate the master device to the local devices. Five runs were made at 65 km/h (40 mph) on each set of surfaces.

DATA AND ANALYSIS

Data Set 1 was used to pair each device with the IRV and determine the correlation constants a and b as well as R^2. The analysis clearly shows that when the IRFI harmonization constants are applied to the data, all devices produce similar friction values. The exception was the USAF GripTester, which measured three of the four surfaces to be nearly the same. It is obvious that the data was incorrectly read or the device was faulty.

The harmonizing constants were determined for each device when harmonized to the IRV (from data Set 1) and then these constants were used on each device to make it the reference (called a master device in ASTM E 2100) to harmonize the rest of the devices with data Set 2.

The data show that four surfaces for calibration of a master device with the IRV and then four surfaces for calibration of other devices with the master is not sufficient. Also, the data show that harmonization of 100% slip with fixed slip does not work on wet pavements because of the different slip speeds. This is to be expected since the slip speed of the fixed slip devices is on the order of 10 km/h, whereas the 100% slip devices have a slip speed of 65 km/h. At these slip speeds the fixed slip devices are near the peak with little influence of macrotexture, whereas the locked wheel devices are greatly affected by the macrotexture.

Figures 1 and 2 confirm that four surfaces are not enough. In Figure 1 the harmonization constants from data Set 1 are applied to data Set 2.

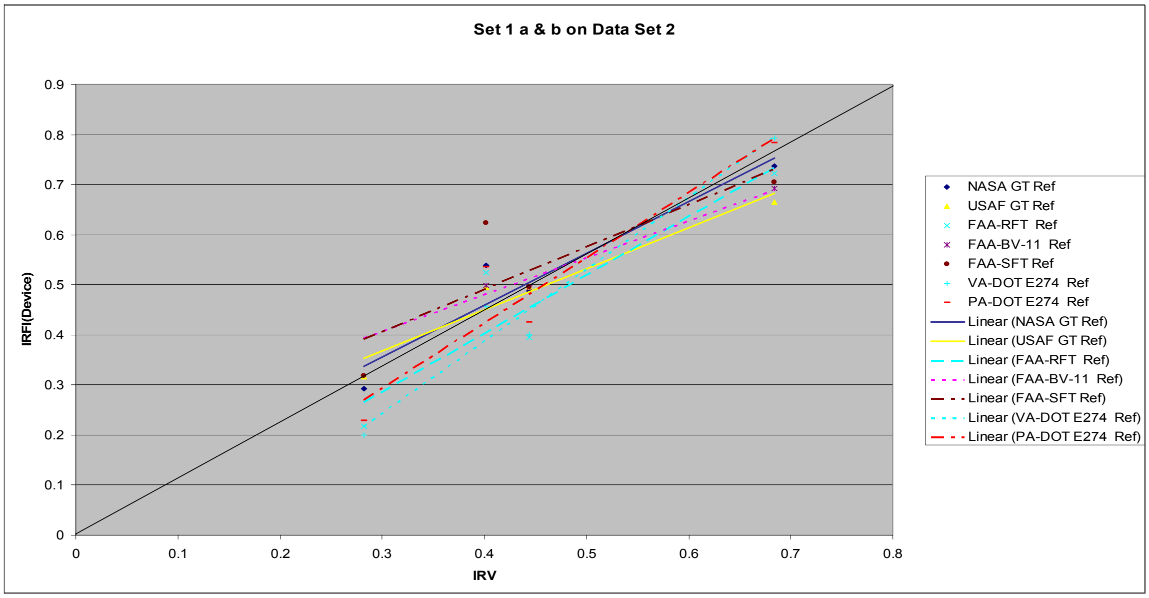

Figure 1. Correlation constants with IRV from data Set 1 applied to each device in data Set 2

Then, the harmonization constants for all eight surfaces were determined. Figure 2 shows the data with the correlation constants from all data applied to data Set 2 and shows much better harmonization than Figure 1.

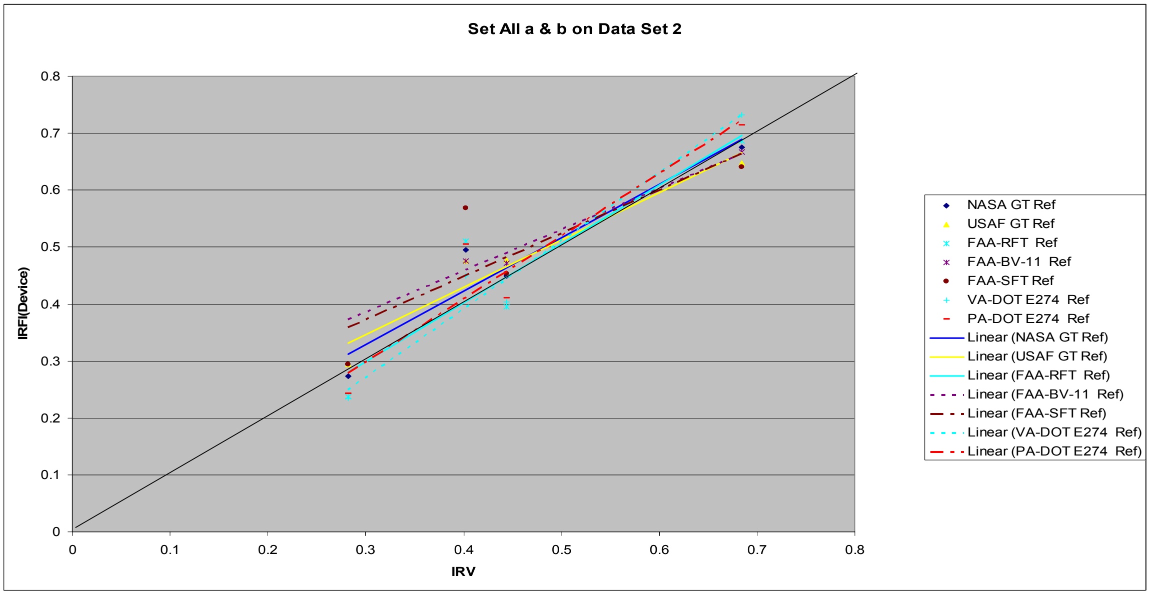

Figure 2. Correlation constants with IRV from all data applied to each device in data Set 2

MEAN ERRORS

The average absolute error of the devices without harmonization was 0.165 for the two sets combined. When the correlation constants were applied (predicted IRFI values) the average absolute error was reduced to 0.051 for data Set 1, to 0.081 with the correlation constants found from Set 1 applied to Set 2, and to 0.053 with the correlation constants from all the data applied to the data set. The average absolute error between each device and the IRV in data Set 2 was 0.132. Thus, the harmonization closed the range of reported friction values by device versus harmonized friction values 0.081 units or an average of 40 percent. When the complete data set was used, the average absolute error was reduced to 0.053 units or an average of 60 percent. When the NASA GripTester or the FAA Runway Friction Tester were used as master devices, the average absolute errors were 0.072 and 0.075.

CONCLUSIONS AND RECOMMENDATIONS

ASTM Standard E 2100-00 defines and prescribes how to correlate IRFI devices for winter surfaces. The IRFI is calibrated directly or indirectly to the IRFI reference device, thereby achieving harmonization of local friction devices to a common unit of measure regardless of the local friction device used.

There is proof that the devices that have participated so far in the JWRFMP are not representative of the other devices of the same generic type that are operated at airports worldwide. 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.

For any common scale of friction measure to work satisfactorily for the industry, annual harmonization meetings must be arranged to determine the current harmonization constants.

To accomplish annual calibration, master devices can be calibrated to the IRFI reference vehicle and then used as secondary references to calibrate other devices. The results of this study show that master devices can be calibrated with the IRFI reference device and then used to calibrate other devices. However, there are several precautions that are needed:

1. At least six (eight recommended) surfaces with friction ranging from 0.1 to 0.7 are needed for the calibrations.
2. Only devices that calibrate with a 0.05 or less average mean error should be used as a master device.
3. Surfaces where device self-wetting was used did work, but the correlations made in this report must be checked with ones made in winter conditions.
4. On surfaces where device self-wetting is applied, only devices with similar slip ratios can be calibrated against each other.

If item 3 can be verified, then surfaces where self-wetting devices are used could be used for calibration surfaces and the calibration constants could be used under winter conditions.

SOMMAIRE

Connaître l'adhérence des pneus d'un avion au freinage est essentiel à la sécurité 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.

Jusqu'à maintenant, la mesure du frottement n'était pas effectuée de manière uniforme. De plus, les valeurs de frottement n'étant pas exprimées par un ratio dimensionnel de forces, elles n'ont jamais été associées à des unités figurant sur une échelle, ce qui peut aussi expliquer les différences. À terme, la mesure du frottement dynamique donne une bonne précision, mais la procédure a été limitée à l'étalonnage des composants de la machine. Les recherches effectuées au cours des quatre dernières années ont confirmé que des appareils de mesure différents produisaient des valeurs très différentes. La présente recherche a cependant accompli des progrès significatifs pour régler ces problèmes. Les méthodes de mesure sont perfectionnées dans le but d'améliorer la qualité des résultats, d'éliminer les incertitudes et d'établir un meilleur rapport avec le freinage des aéronefs.

L'étude faisait partie de l'initiative conjointe gouvernement-industrie appelée Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH), sous la conduite de Transports Canada (TC) et de la National Aeronautics and Space Administration (NASA) des États-Unis. Le projet a reçu l'appui du Conseil national de recherches du Canada, de l'U.S. Federal Aviation Administration (FAA), de la Norwegian Civil Aviation Authority et de la Direction générale de l'aviation civile, en France. Ont également participé des organisations et des fabricants de matériel de plusieurs pays : Autriche, Canada, France, Allemagne, Norvège, Écosse, Suède, Suisse, États-Unis.

MÉTHODE D'ÉLABORATION DE L'INDICE INTERNATIONAL DE LA GLISSANCE DES PISTES (IRFI)

Le présent rapport décrit la méthode de corrélation faisant l'objet de la norme ASTM E 2100-00, *Standard Practice for Calculating the International Runway Friction Index*, et conçue pour élaborer l'Indice international de la glissance des pistes (IRFI). La technique de régression linéaire est utilisée pour calculer les rapports entre les valeurs de frottement mesurées par deux appareils. Cette technique repose sur l'hypothèse selon laquelle pour une surface donnée, l'interaction des deux appareils avec la surface est la même. Tous les appareils sont ensuite comparés à un appareil de référence de façon à établir des constantes de transformation. Bientôt, la communauté aéronautique pourra, comme première étape ou provisoirement, appliquer la régression linéaire simple illustrée par l'équation suivante.

$$\mu_{IRFI} = a + b \bullet \textit{appareil de mesure du frottement}$$

où *a* est l'ordonnée et *b* le gradient, valeurs déterminées par la régression sur l'appareil de référence. Les tentatives antérieures se sont révélées infructueuses parce que les données n'étaient acquises ni au même moment ni dans la même trace de roue. De plus, la taille de l'échantillon était trop petite. La mesure du frottement et la collecte des données correspondantes doivent être effectuées de manière plus systématique.

Une série de tests ont été effectués à l'atelier sur le frottement des pistes de 2001, de la NASA, à Wallops, au moyen des appareils et des pneus indiqués au tableau 1. Il s'agissait de vérifier la méthode ASTM E 2100 d'élaboration de l'Indice international de la glissance des pistes (IRFI) dans le but d'étalonner le Véhicule de référence international (IRV) sur un étalon primaire et de se servir ensuite de l'étalon primaire pour l'étalonnage des appareils locaux.

Tableau 1 Appareils et pneus testés – Atelier de la NASA sur le frottement des pistes, 2001, Wallops

Appareil	**Type de pneu**
Véh. de référence internat. (IRV), IRFI	Pneu lisse PIARC
GripTester (GT), NASA	ASTM E-1844
Glissancemètre (SFT)-Turbo, TC	ASTM E-1551
GripTester (GT), USAF	ASTM E-1844
Gissancemètre (RFT), FAA	ASTM E-1551
Remorque BV-11, FAA	ASTM E-1551
Glissancemètre (SFT), FAA	ASTM E-1551
Remorque E275, VA DOT	ASTM E-524
Remorque E275, PA DOT	ASTM E-524

Les essais ont porté sur deux ensembles de surfaces. Les surfaces 1 ont servi pour l'étalonnage du Véhicule de référence international (IRV) sur un étalon primaire, et les surfaces 2 pour mettre l'étalon primaire en corrélation avec les appareils locaux. Cinq passages ont été effectués à 65 km/h (40 mi/h) sur chaque type de surface.

DONNÉES ET ANALYSES

On a utilisé l'ensemble de données des surfaces 1 pour mettre chaque appareil en relation avec l'IRV et pour déterminer les constantes de corrélation *a* et *b*, de même que R^2. L'analyse montre clairement que lorsque les constantes d'harmonisation avec l'IRFI sont appliquées aux données, les valeurs de frottement sont similaires pour tous les appareils, sauf le GripTester (GT) de l'USAF, qui a donné des résultats pratiquement identiques pour trois des quatre surfaces. Cette anomalie est évidemment le résultat d'une lecture incorrecte des données ou d'une défectuosité de l'appareil.

Les constantes d'harmonisation ont été déterminées pour chaque appareil au moment de l'harmonisation avec l'IRV (à partir des constantes de l'ensemble de données 1). Les constantes ont ensuite été appliquées à chaque appareil, ce qui faisait de l'IRV l'appareil de référence (désigné étalon primaire {«master device»} dans la norme ASTM E 2100), afin d'harmoniser les autres appareils avec les données de l'ensemble 2.

Les données indiquent que quatre surfaces ne suffisent pas pour étalonner un appareil de référence avec l’IRV, pas plus que quatre surfaces pour comparer les autres appareils avec l’appareil de référence. Les données montrent également qu’il est impossible d’harmoniser un appareil à taux de glissement de 100 p. cent avec un appareil à glissement constant sur les chaussées mouillées en raison des diverses vitesses de glissement. On pouvait s’y attendre étant donné que la vitesse de glissement de l’appareil à taux glissement fixe est de l’ordre de 10 km/h, alors que les appareils à taux de glissement de 100 p. cent ont une vitesse de glissement de 65 km/h. À ces vitesses de glissement, les appareils à taux de glissement constant sont près de la valeur de pointe, la macrotexture de la surface ayant peu d’influence alors que les appareils qui freinent la roue de mesure sont très sensibles à la macrotexture.

Les figures 1 et 2 confirment que quatre surfaces ne suffisent pas. Dans la figure 1, les constantes d’harmonisation de l’ensemble de données 1 sont appliquées à l’ensemble de données 2.

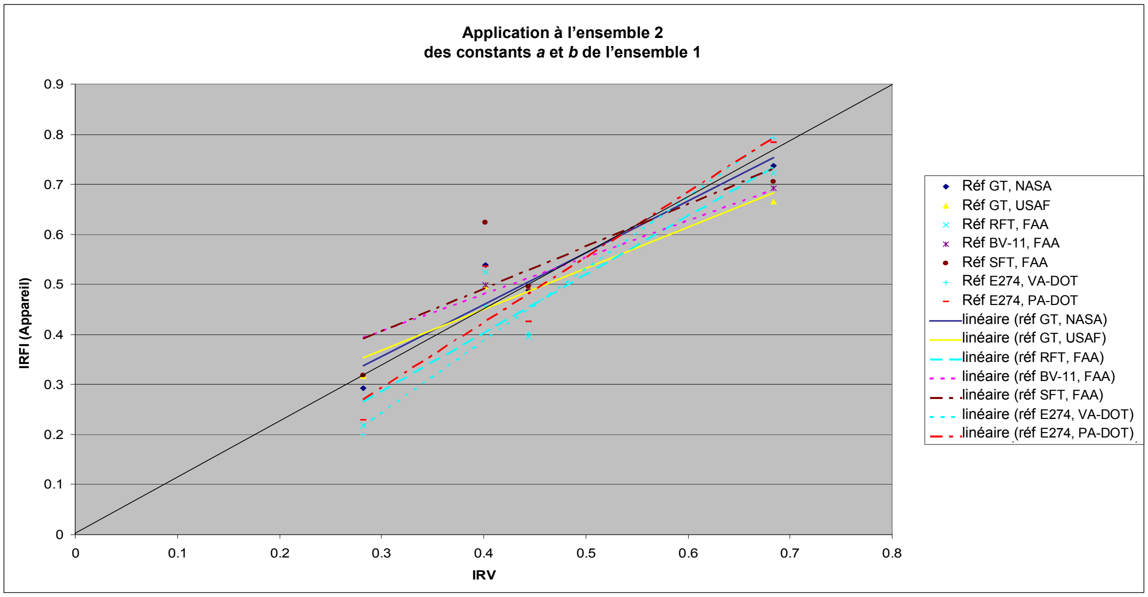

Figure 1 Application à l’ensemble de données 2 des constantes de corrélation (IRV) de l’ensemble de données 1

On a ensuite déterminé les constantes d’harmonisation. La figure 2 illustre les données ainsi que les constantes de corrélation de toutes les données, appliquées à l’ensemble de données 2 : l’harmonisation est meilleure que dans le cas de la figure 1.

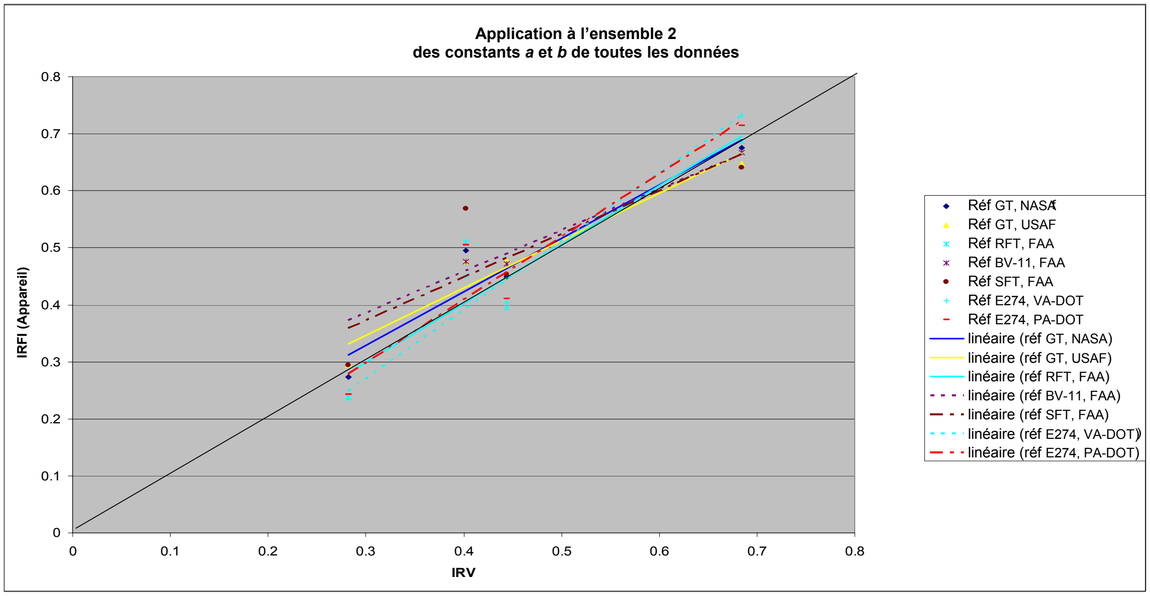

Figure 2 **Application à l'ensemble de données 2 des constantes de corrélation (IRV) de toutes les données**

ERREURS MOYENNES

Sans harmonisation, l'ensemble des appareils avaient une erreur moyenne absolue de 0,165 pour les deux ensembles de données combinés. Lorsqu'on a appliqué les constantes de corrélation (valeurs prévues de l'IRFI), l'erreur moyenne absolue est descendue à 0,051 pour l'ensemble de données 1, à 0,081 en appliquant à l'ensemble 2 les constantes de corrélation de l'ensemble 1, et à 0,053 en appliquant à l'ensemble des données les constantes de corrélation établies pour toutes les données. Pour l'ensemble de données 2, l'erreur moyenne absolue entre chaque appareil et l'IRV était de 0,132. Ainsi, l'harmonisation a permis de rétrécir de 0,081 unité, soit une moyenne de 40 p. cent, la plage des valeurs de frottement mesurées par appareil par rapport aux valeurs de frottement harmonisées. Pour l'ensemble complet de données, l'erreur moyenne absolue a été réduite de 0,053 unité, soit de 60 p. cent en moyenne. Avec le Grip Tester de la NASA ou le glissancemètre de la FAA, les erreurs moyennes absolues étaient respectivement de 0,072 et de 0,075.

CONCLUSIONS ET RECOMMANDATIONS

La norme ASTM E 100-00 définit les exigences relatives à la corrélation des mesures pour établir l'Indice international de la glissance des pistes (IRFI) l'hiver. L'IRFI est étalonné directement ou indirectement sur son appareil de référence, pour harmoniser les appareils de mesure locaux (sans égard au type) avec une unité commune ou de référence.

Les appareils utilisés jusqu'à maintenant dans le Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver ne sont pas représentatifs des appareils génériques utilisés dans le monde. Il conviendrait donc de calculer des constantes d’harmonisation et de les appliquer à chaque appareil en particulier plutôt qu’à un groupe générique, comme ce fut le cas dans le passé.

Pour établir une échelle commune de mesure du frottement qui satisfasse aux besoins de l’aéronautique, il convient de réunir les principaux intéressés une fois par année pour actualiser les constantes d’harmonisation.

Pour l’étalonnage annuel, les étalons primaires peuvent être comparés au véhicule de référence de l’IRFI, puis utilisés eux-mêmes comme étalons secondaires pour les autres appareils. Or, la procédure doit observer plusieurs conditions :

1. Il faut disposer d’au moins six (huit sont recommandées) surfaces avec coefficient de frottement de 0,1 à 0,7 pour les étalonnages.
2. Seuls les appareils dont l’erreur moyenne est de 0,05 ou moins devraient être utilisés comme étalons primaires.
3. Les surfaces de contrôle mesurées à l’aide d’un appareil avec arrosage automatique ont effectivement donné des résultats valables, mais les corrélations mentionnées dans le présent rapport doivent être comparées à des corrélations applicables à des conditions hivernales.
4. Dans le cas des surfaces avec film d’eau appliqué en arrosage automatique, seuls les appareils ayant des taux de glissement similaires peuvent être étalonnés entre eux.

Si l’élément 3 peut être vérifié, les surfaces mouillées par arrosage automatique pourront servir de références et les constantes d’étalonnage pourront être appliquées aux mesures en conditions hivernales.

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DEFINITIONS AND NOMENCLATURE

Acronyms

ASTM	ASTM International
DGAC	Direction générale de l'aviation civile, France
FAA	Federal Aviation Administration, USA
GT	GripTester - manufactured by Findlay Irvine, Scotland
JWRFMP	Joint Winter Runway Friction Measurement Program
IRFI	International Runway Friction Index
IRV	International Reference Vehicle, manufactured by STBA, Paris, France
NASA	National Aeronautics and Space Administration, USA
NRC	National Research Council Canada
PIARC	World Road Association (formerly Permanent International Association of Road Congresses)
RFT	Runway Friction Tester, manufactured by K.J. Law Engineers, Inc., Michigan, USA
SFT	Surface Friction Tester, manufactured by Saab, Sweden
TC	Transport Canada
PA-E274	ASTM E-274 Locked Wheel Tester, owned and operated by Pennsylvania Department of Transportation
VA-E274	ASTM E-274 Locked Wheel Tester, owned and operated by Virginia Department of Transportation

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 harmonized to IRFI values.

movement area, **n.** - that part of the airport (aerodrome) used for take-off, landing and taxiing of aircraft, consisting of the manouvring 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. Pavement surface friction characteristics are important and are required at all times, especially during winter conditions. Different seasons, especially winter, result in the possibility of the runway having contaminants of varying nature 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 wintertime, a service is warranted for measurement of tire-surface friction. The measured results of such services in the winter have had serious deficiencies, which have been acknowledged by experts worldwide.

The equipment used and procedures followed in measuring winter contaminated surfaces, do not report to a common unit of measure of surface friction. A value from one type of device at an airport does not necessarily 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.

In 1996, a multi-year government/industry study, called the Joint Winter Runway Friction Measurement Program (JWRFMP), was initiated by Transport Canada (TC) and the National Aeronautics and Space Administration (NASA), with support from National Research Council Canada (NRC), the U.S. Federal Aviation Administration (FAA), the Norwegian Civil Aviation Authority, and France’s Direction générale de l’aviation civile (DGAC). Also participating are organizations and equipment manufacturers from Austria, Canada, France, Germany, Norway, Scotland, Sweden, Switzerland, and the United States. The primary objective is to perform aircraft and ground vehicle tests aimed at improving the safety of aircraft ground operations by finding the relation between ground friction measurement and aircraft braking. 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 were 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: the International Runway Friction Index (IRFI) and the evaluation of the IRFI procedures for new and existing devices.

It is expected that dissemination, acceptance, and recommendation for implementation of the IRFI test method throughout the aviation community will be facilitated by several organizations. These include the International Civil Aviation Organization, ASTM International (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.

2.0 PROGRAM OBJECTIVE AND STUDY OBJECTIVE

In cooperation with other researchers from Transport Canada, NRC, NASA, DGAC and the FAA, the objective is to establish a method to provide airports, countries, regions and manufacturers with a way to correlate their equipment and thus harmonize all ground friction measurements so that the common values can be reported and used by airports around the world.

The study objective is to verify the ASTM E 2100 method of IRFI to harmonize the International Reference Vehicle (IRV) to a master device and then to use the master device to harmonize local devices.

3.0 THE IRFI METHOD OF ASTM E 2100-00

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 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 standard test method of the device and the manufacturer's instructions for the device, and run within the range of speeds for which it is to be harmonized.

The minimum length of the surface segment to be used for producing a friction value is 100 m and the maximum length is one third of a runway length. The friction values are reported digitally (with separate data series for each segment) in one file for the runway. The file has records ordered by segments.

3.1 ASTM E 2100-00 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 eight surfaces covering a range of 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. The measurements with the local friction device and the IRFI reference device shall be taken on a segment within two minutes of each other.

Linear regressions are as follows:

$$FR_{ref} = a + b \cdot FR_{local}, \qquad (1)$$

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 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:

$$\mathrm{IRFI} = a + b \bullet \mathrm{FR}_{\mathrm{local}} \tag{2}$$

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

3.2 ASTM E 2100-00 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 eight surfaces covering a range of 0.1 to 0.7 as measured by the master device shall be included. Harmonization constants 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 five repeated runs on seven segments covering a friction range of 0.1 to 0.7 as measured by the IRFI reference device shall be included. The harmonization constants 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 two minutes of each other.

A linear regression is of the form:

$$\mathrm{FR}_{\mathrm{ref}} = a' + b' \bullet \mathrm{FR}_{\mathrm{master}} \tag{3}$$

$$\mathrm{FR}_{\mathrm{master}} = a'' + b'' \bullet \mathrm{FR}_{\mathrm{local}} \tag{4}$$

Substituting equation 4 into equation 3 gives:

$$\mathrm{FR}_{\mathrm{ref}} = a' + b' \bullet (a'' + b'' \bullet \mathrm{FR}_{\mathrm{local}}) \tag{5}$$

Then: $a = a' + b' \bullet a''$ and $b = b' \bullet b''$, (6,7) where FR_{ref} is the friction value reported by the reference device, FR_{master} is the master device measured value 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.

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

$$IRFI = a + b\ FR_{local} \tag{8}$$

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

This report is a study of the second method, limited to summer surfaces, using self-wetting. Data was collected at the 2001 NASA Wallops Runway Friction Workshop.

4.0 TEST SERIES TO VERIFY THE E 2100 METHOD OF IRFI TO CALIBRATE IRV TO A MASTER DEVICE AND THEN TO USE THE MASTER DEVICE TO CALIBRATE LOCAL DEVICES

This test was conducted at the 2001 NASA Wallops Runway Friction Workshop using the devices and tires listed in Table 1.

Table 1. Test Devices Series 1

Device Description	**Tire Type**
IRFI-Int'l Reference Vehicle (IRV) at 65 km/h (15% slip)	PIARC Smooth Treaded Tire 150 kPa (22 psi)
NASA GripTester (GT) at 65 km/h (12% slip)	ASTM E-1844 138 kPa (20 psi)
TC Surface Friction Tester (SFT)-Turbo at 65 km/h (15% slip)	ASTM E-1551 690 kPa (100 psi)
USAF GripTester (GT) at 65 km/h (12% slip)	ASTM E-1844 138 kPa (20 psi)
FAA Runway Friction Tester (RFT) at 65 km/h (15% slip)	ASTM E-1551 690 kPa (100 psi)
FAA Trailer BV-11 at 65 km/h (15% slip)	ASTM E-1551 690 kPa (100 psi)
FAA Surface Friction Tester (SFT) at 65 km/h (15% slip)	ASTM E-1551 690 kPa (100 psi)
VA DOT E275 trailer at 65 km/h (100% slip)	ASTM E-524 165 kPa (24 psi)
PA DOT E275 trailer at 65 km/h (100% slip)	ASTM E-524 165 kPa (24 psi)

Two sets of surfaces at NASA's Wallops Flight Facility were utilized to perform these tests. Surfaces P, A, E and S6 made up Set 1 and surfaces K, D, MS3 and L make up Set

2(see Figure 1). Set 1 was used to calibrate the IRV with a master device. Set 2 was used to correlate the master device to the local device.

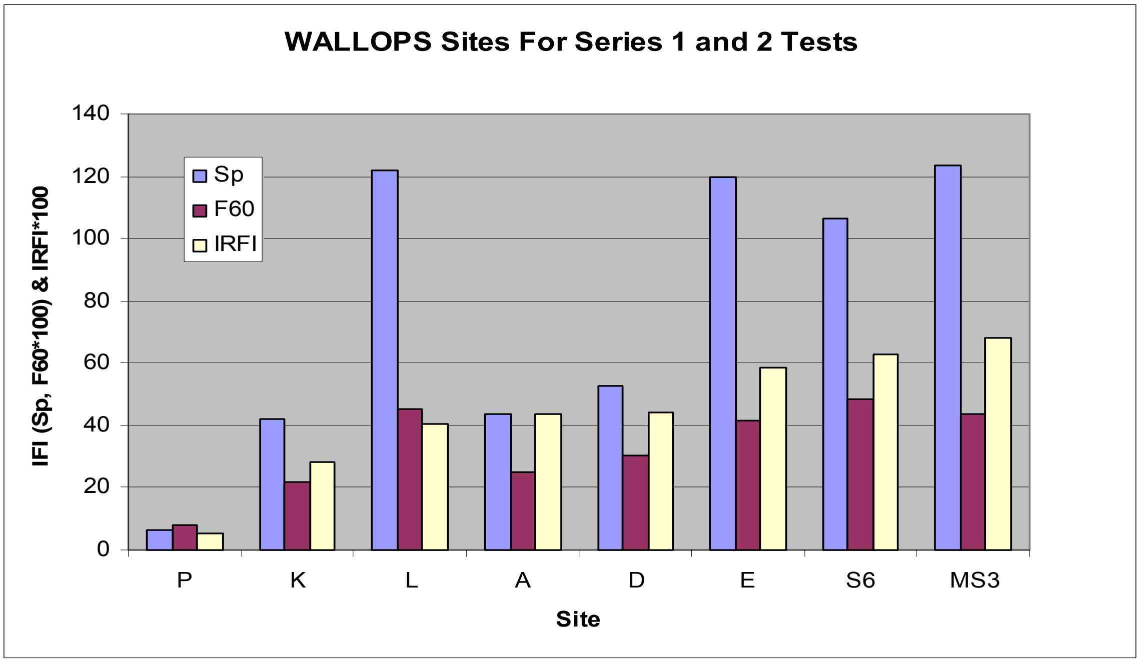

Figure 1. Surfaces Selected for Sets 1 and 2 Tests (see reference 2 about IRI (Sp,F60), where Sp is the speed gradient and F60 is the harmonized friction at 60 km/h)

These tests were run as follows:

- Morning tests: five runs made in waves (to meet ASTM paired requirements) at 65 km/h (40 mph) on surfaces A, D, E in one direction 22 and S6 coming back in direction 4.

- Afternoon tests: five runs made in waves (to meet ASTM paired requirements) at 65 km/h (40 mph) on surfaces K and L in one direction 28.

- Second morning tests: five runs made in waves (to meet ASTM paired requirements) at 65 km/h (40 mph) on surfaces P and MS3 in one direction 22.

Summary of Test Series

Speed	SURFACES							
Km/h	P	A	E	S6	K	D	MS3	L
65	5 runs	5 runs	5 runs	5 runs	5 runs	5 runs	5 runs	5 runs

All devices used self-watering and each ran a separate track, rather then all running the same track. This was done to avoid water buildup. All devices made each run in a group, following each other with one minute between devices. All runs were made in one direction only and then the entire group returned to start another run. This was done to avoid the affect of texture on direction and to allow time between runs to prevent water buildup. In addition the surfaces were washed with a water truck before runs were started to minimize the effect any change of starting from a dry pavement and the effect of washing with each run. Texture measurements were made by several devices before the surfaces were wetted; they reported mean texture depth, mean profile depth and outflow time. Values are reported in the NASA database and in the NASA Wallops Workshop reports.

5.0 DATA AND ANALYSIS

The original data for each of the five runs is available from NASA or from the JWRFMP database. Appendix A is a summary of the average of each of the five runs for all measurements made, Set 1, Set 2, and a set with all the data from Sets 1 and 2. The regression plots of each device to IRFI (IRV) are also given in Appendix A. The data and plots show that since the TC-SFT Turbo only made three sets of measurements on Set 1 and only two on Set 2, it was removed from the database and was not used in the analysis.

5.1 Analysis

First Data Set 1 was used to pair each device with the IRV and determine the correlation constants *a′* and *b′* as well as R^2 . Table 2 gives the results and Appendix A shows the trend line of the correlations. Note that on all figures showing correlations a black 45° line is given for reference. Figure 2 is a plot where the correlation constants are applied to each device's data and then plotted versus the IRV with the trend lines.

Table 2. Correlation Results from Data Set 1 (b′ x + a′)

SET 1

IRV @ 65 km/h (15%)	IRV=	
NASA GT-C @ 65 km/h (12%)	0.8438x + 0.0119	$R^2 = 0.9963$
TC-SFT Turbo @ 65 km/h (15%)	4.1776x - 2.5059	$R^2 = 0.6843$
USAF GT @ 65 km/h (12%)	0.9641x - 0.0029	$R^2 = 0.9816$
FAA-RFT @ 65 km/h (15%)	0.9771x - 0.0636	$R^2 = 0.9963$
FAA-BV-11 @ 65 km/h (15%)	0.8279x + 0.0099	$R^2 = 0.9444$
FAA-SFT @ 65 km/h (15%)	0.8086x + 0.0095	$R^2 = 0.9846$
VA-DOT E274 @ 65 km/h (100%)	1.2864x + 0.0051	$R^2 = 0.9298$
PA-DOT E274 @ 65 km/h (100%)	1.282x + 0.0228	$R^2 = 0.9668$

A word of caution: these values and others calculated in this report are valid only for the device as tested and are not valid for other devices of the same class.

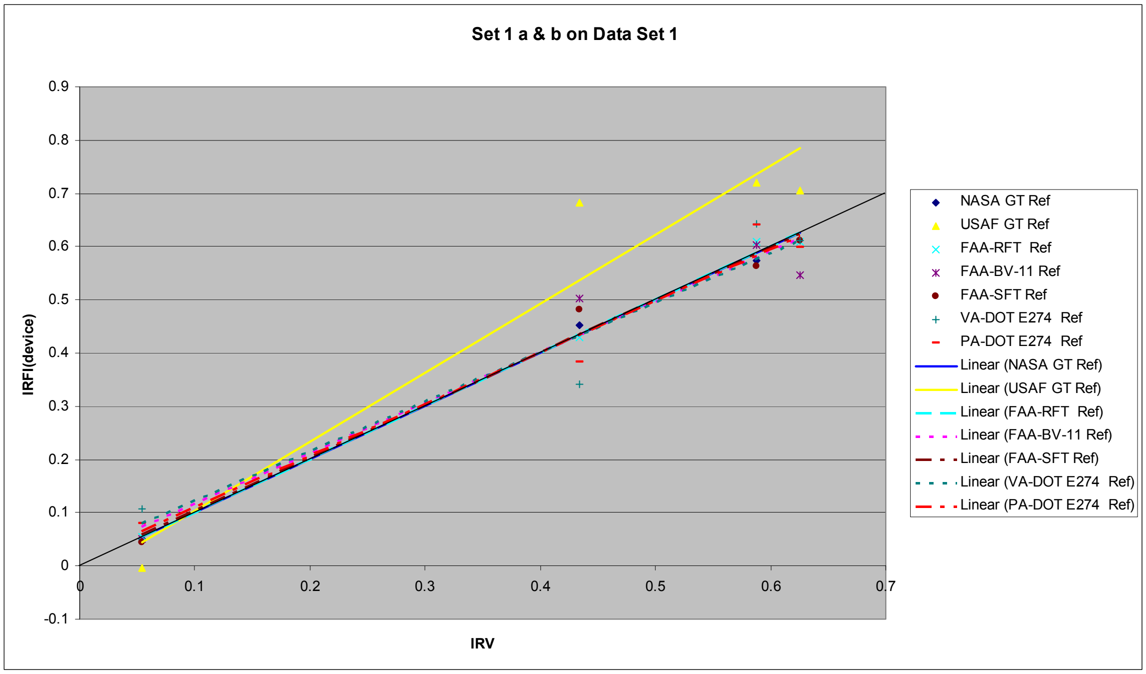

Figure 2. Showing the Harmonization of Data Set 1 from which the IRFI *a* and *b* Are Derived

Figure 2 (when compared to the plot in Appendix A of the original data of Set 1) shows how the IRFI harmonization constants derived from the data produce similar friction values for all devices when used to predict the IRFI (IRV) with the same data. The exception was the USAF GT, which measured three of the four surfaces to be nearly the same. It is obvious that the data was incorrectly read or the device was faulty.

Table 3 shows the harmonizing constants for each case where a device was harmonized to the IRV (from Data Set 1) and then used as the reference (called a master device in ASTM E 2100) to harmonize the rest of the devices.

Table 3. Correlation Constants Using Each Device as a Master Device (b'' x + a'')

a & b vs. Secondary Device	IRV	NASA GT Master	USAF GT Master	FAA-RFT Master
NASA GT @ 65 km/h (12%)	0.7457x + 0.0095	NASA GT	0.6549x + 0.1034	0.9728x - 0.1135
USAF GT @ 65 km/h (12%)	1.1045x - 0.115	1.2251x - 0.1164	USAF GT Ref	1.3891x - 0.2494
FAA-RFT @ 65 km/h (15%)	0.7154x + 0.066	0.8311x + 0.0641	0.6344x + 0.1497	FAA-RFT Ref
FAA-BV-11 @ 65 km/h (15%)		0.9481x - 0.0439	0.7165x + 0.0748	1.1147x - 0.195
FAA-SFT @ 65 km/h (15%)	0.6841x + 0.0076	0.8445x - 0.0361	0.6426x + 0.0746	0.9983x - 0.1849
VA-DOT E274 @ 65 km/h (100%)	0.8617x + 0.1463	0.9406x + 0.179	0.729x + 0.2335	1.0849x + 0.0789
PA-DOT E274 @ 65 km/h (100%)	0.8818x + 0.1295	1.0042x + 0.1453	0.7706x + 0.2102	1.1729x + 0.0347

a & b vs. Secondary Device	IRV	FAA-SFT Master	VA-E274 Master	PA- E274 Master
NASA GT @ 65 km/h (12%)	0.7457x + 0.0095	0.7511x + 0.0892	1.1269x - 0.2073	1.0657x - 0.1407
USAF GT @ 65 km/h (12%)	1.1045x - 0.115	1.069x - 0.0139	1.6338x - 0.3773	1.5298x - 0.2937
FAA-RFT @ 65 km/h (15%)	0.7154x + 0.066	0.7585x + 0.1255	1.1106x - 0.1379	1.0635x - 0.0822
FAA-BV-11 @ 65 km/h (15%)	*	0.6207x + 0.195	1.5408x - 0.4754	1.2892x - 0.2772
FAA-SFT @ 65 km/h (15%)	0.6841x + 0.0076	FAA-SFT Ref	1.0924x - 0.2482	1.0745x - 0.2064
VA-DOT E274 @ 65 km/h (100%)	0.8617x + 0.1463	0.8108x + 0.2473	VA-DOT E274 Ref	1.1967x + 0.0672
PA-DOT E274 @ 65 km/h (100%)	0.8818x + 0.1295	0.9005x + 0.2056	1.3511x - 0.0327	PA-DOT E274 Ref

The results show that four surfaces for calibration of a master device with the IRV and then four surfaces for calibration of other devices with the master are not sufficient. Also, the table shows that harmonization of 100% slip with fixed slip does not work on wetted pavements. This is to be expected since the slip speed of the fixed slip devices is near 10 km/h and the 100% slip is at 65 km/h. At these slip speeds the fixed slip devices are near the peak with little influence of macrotexture, whereas the locked wheel devices are greatly affected by the texture.

In Figure 3 the harmonization constants from Data Set 1 are applied to Data Set 2. Error in the prediction of IRFI (IRV) by each device can be read as the vertical distance between a 45^{o} line and the individual IRFI prediction lines by each device.

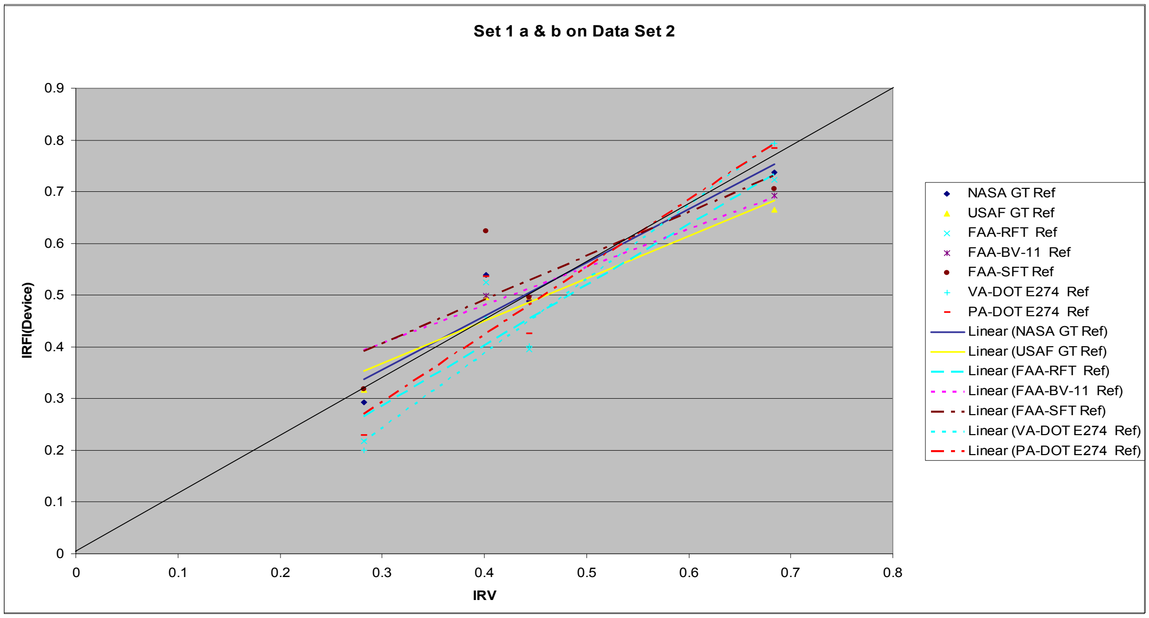

Figure 3. Correlation Constants with IRV from Data Set 1 Applied to Each Device in Data Set 2

The harmonization constants for all eight surfaces were then determined. Table 4 shows the comparison of the correlations for all data, Set 1 only and Set 2 only. Figure 4 shows the data with the correlation constants from all data applied to Data Set 2 and shows much better harmonization than Figure 3.

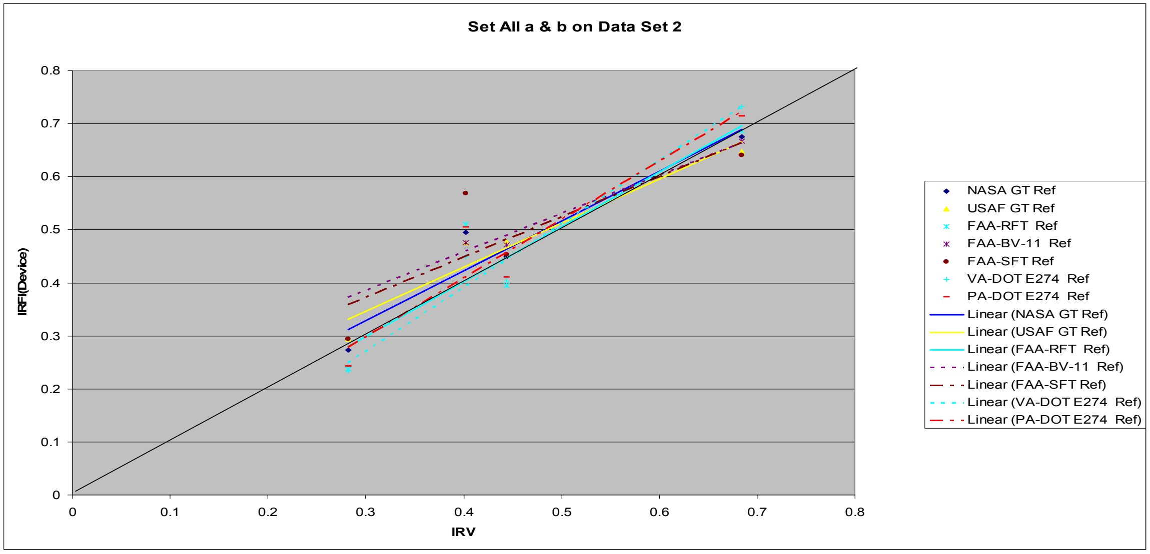

Figure 4. Correlation Constants with IRV from All Data Applied to Each Device in Data Set 2

5.2 Secondary Harmonization Results

The calibration results were then used with the NASA GT as the master and the other devices were calibrated as local devices. Figure 5 shows these calibrations as compared to the actual measurements made by the IRV.

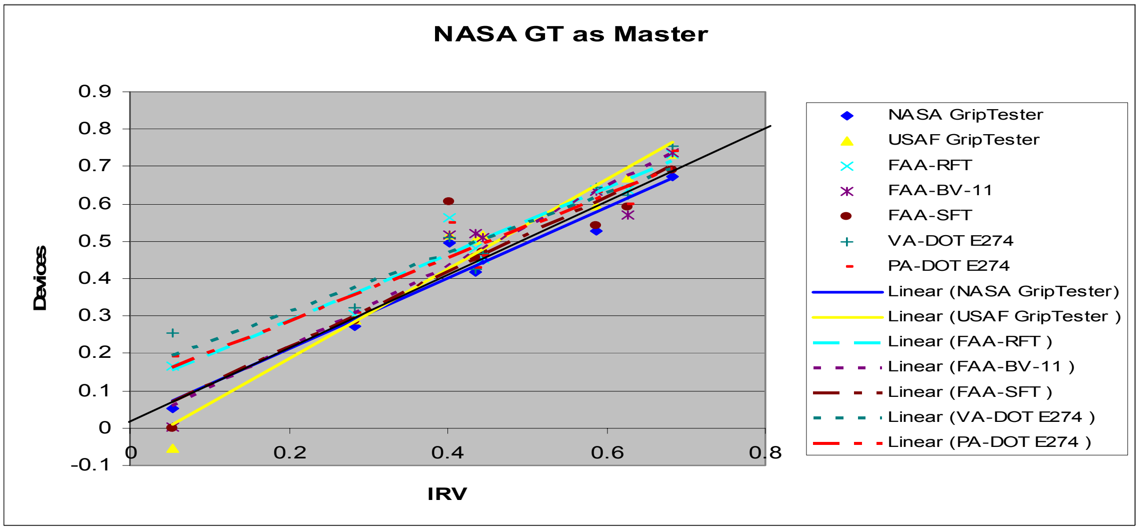

Figure 5. Master Calibrations of Devices Using NASA GT as Master

The procedure was then repeated using the FAA RFT as a master device to calibrate the other devices. Figure 6 shows these calibrations as compared to the actual measurements made by the IRV.

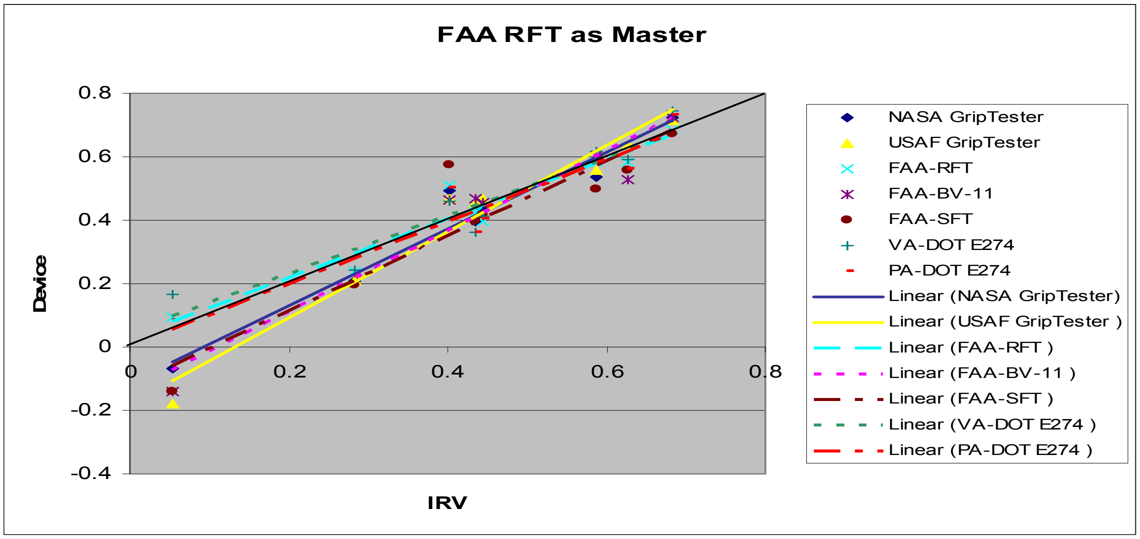

Figure 6. Master Calibrations of Devices Using FAA RFT as Master

6.0 AVERAGE ABSOLUTE ERROR

Table 4 gives the average absolute error for the three cases. First the standard error is given for the original device data for Set 1 and then for the same set of data with the calibration constants applied. Similarly, the average absolute error is then given for Data Set 2 and then all the data (Sets 1 and 2 combined).

Table 4. Average Absolute Error

<table>
<tr><th colspan="9">Set 1 Data</th></tr>
<tr><th></th><th>NASA GT</th><th>USAF GT</th><th>FAA-RFT</th><th>FAA-BV-11</th><th>FAA-SFT</th><th>VA-DOT E274</th><th>PA-DOT E274</th><th>AVG</th></tr>
<tr><td>STD Error</td><td>0.068</td><td>0.037</td><td>0.076</td><td>0.104</td><td>0.107</td><td>0.125</td><td>0.128</td><td>0.092</td></tr>
<tr><th colspan="9">Set 1 only with <i>a</i> & <i>b</i></th></tr>
<tr><td>STD Error</td><td>0.014</td><td>0.0149</td><td>0.014</td><td>0.053</td><td>0.028</td><td>0.060</td><td>0.041</td><td>0.051</td></tr>
</table>

<table>
<tr><th colspan="9">Set 2 Data</th></tr>
<tr><th></th><th>NASA GT</th><th>USAF GT</th><th>FAA-RFT</th><th>FAA-BV-11</th><th>FAA-SFT</th><th>VA-DOT E274</th><th>PA-DOT E274</th><th>AVG</th></tr>
<tr><td>STD Error</td><td>0.155</td><td>0.072</td><td>0.117</td><td>0.158</td><td>0.220</td><td>0.104</td><td>0.100</td><td>0.132</td></tr>
<tr><th colspan="9">Set 2 using <i>a</i> & <i>b</i> from Set 1</th></tr>
<tr><td>STD Error</td><td>0.088</td><td>0.057</td><td>0.076</td><td>0.063</td><td>0.116</td><td>0.077</td><td>0.088</td><td>0.081</td></tr>
</table>

<table>
<tr><th colspan="9">All Data Original</th></tr>
<tr><th></th><th>NASA GT</th><th>USAF GT</th><th>FAA-RFT</th><th>FAA-BV-11</th><th>FAA-SFT</th><th>VA-DOT E274</th><th>PA-DOT E274</th><th>AVG</th></tr>
<tr><td>STD Error</td><td>0.187</td><td>0.127</td><td>0.155</td><td>0.177</td><td>0.205</td><td>0.150</td><td>0.153</td><td>0.165</td></tr>
<tr><th colspan="9">Set 2 using <i>a</i> & <i>b</i> from All Data</th></tr>
<tr><td>STD Error</td><td>0.043</td><td>0.041</td><td>0.049</td><td>0.053</td><td>0.071</td><td>0.057</td><td>0.057</td><td>0.053</td></tr>
</table>

The average absolute error of the devices without harmonization was 0.092 for Set 1, 0.132 for Set 2 and 0.165 for the two sets combined. When the correlation constants are applied (predicted IRFI values) the average absolute error is reduced to 0.051 for Data Set 1, to 0.081 with the correlation constants found from Set 1 applied to Set 2, and to 0.053 with the correlation constants from all the data applied to the data set. The average absolute error between each device and the IRV in Data Set 2 was 0.132. Thus, the harmonization has closed the range of reported friction values by device versus harmonized friction values 0.081 units or an average of 40 percent. When the complete data set is used, the average absolute error is reduced to 0.053 units or an average of 60 percent.

It is believed that extending the number of surfaces in Data Set 1, particularly winter surfaces, would yield harmonization constants that would further reduce the average absolute errors in predicting IRFI from Data Set 2. It is unknown what the cost-benefit relationship is to enlarge the Data Set 1. The average absolute error in predicted IRFI values found in this investigation may be taken as a typical practically achievable value.

Table 5 gives the average absolute error when the NASA GT and then the FAA RFT are used as a master device to calibrate the other devices. The original average absolute error for the data set is repeated to allow comparison.

Table 5. Average Absolute Error with NASA GT and FAA RFT as Master Devices

<table>
<tr><th colspan="9">All Data Original</th></tr>
<tr><td></td><td>NASA GT</td><td>USAF GT</td><td>FAA-RFT</td><td>FAA-BV-11</td><td>FAA-SFT</td><td>VA-DOT E274</td><td>PA-DOT E274</td><td>AVG</td></tr>
<tr><td>STD Error</td><td>0.181</td><td>0.145</td><td>0.160</td><td>0.181</td><td>0.186</td><td>0.161</td><td>0.162</td><td>0.168</td></tr>
<tr><th colspan="9">All Data with <i>a</i> & <i>b</i> Applied Using NASA GT as the Master Device</th></tr>
<tr><td>STD Error</td><td>0.043</td><td>0.070</td><td>0.076</td><td>0.071</td><td>0.078</td><td>0.088</td><td>0.076</td><td>0.072</td></tr>
<tr><th colspan="9">All Data with <i>a</i> & <i>b</i> Applied Using FAA RFT as the Master Device</th></tr>
<tr><td>STD Error</td><td>0.071</td><td>0.092</td><td>0.049</td><td>0.088</td><td>0.106</td><td>0.060</td><td>0.059</td><td>0.075</td></tr>
</table>

The effect of secondary calibration with master devices is that the average absolute error increases about 0.02 or 35 percent. However, there is still a good improvement over the original device's measurements without calibration. The average absolute error is reduced from 0.168 to 0.072 and 0.075, or about 56 percent.

7.0 CONCLUSIONS AND RECOMMENDATIONS

ASTM Standard E 2100-00 defines and prescribes how to correlate IRFI devices for winter surfaces. The IRFI is calibrated directly or indirectly to the IRFI reference device, thereby achieving harmonization of local friction devices to a common unit of measure regardless of the local friction device used.

The harmonization of master devices in this study yielded an average absolute error of 0.053 IRFI values.

When applying a master device to further harmonize a local airport device, the cited error will be carried forward from the primary to the secondary harmonization. It is therefore recommendable to have a sufficiently large and representative data set of real operational conditions to minimize this error.

The harmonization using a master device yielded an average absolute error of 0.073.

There are indications that the participating devices so far in the JWRFMP are not representative of the other devices of the same generic type that are operated at airports worldwide. 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.

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.

To accomplish annual calibration, master devices can be calibrated to the IRFI reference vehicle and then used as secondary references to calibrate other devices. The results of this study show that master devices can be calibrated with the IRFI reference device with an average error of 0.053 and then used to calibrate other devices. However, there are several precautions that are needed:

1. At least six (eight recommended) surfaces with friction ranging from 0.1 to 0.7 are needed for the calibrations.
2. Only devices that calibrate with a 0.05 or less average mean error should be used as a master device.
3. Surfaces where device self-wetting was used did work, but the correlations made in this report must be checked with ones made in winter conditions.
4. On surfaces where device self-wetting is applied, only devices with similar slip ratios could be calibrated against each other.

If item 3 can be verified, then surfaces where device self-wetting is applied could be used for calibration surfaces and the calibration values can be used under winter conditions.

It is therefore recommended that:

1. The ASTM E 2100 Standard be amended to specify six to eight surfaces to be used for calibration.
2. Master devices achieve an average mean error of 0.05 or less in order to be considered a master device and that this requirement is added to the standard.
3. All or as many devices as tested at Wallops be taken to North Bay in 2002 and that the test procedure used at Wallops in 2001 be repeated to verify that the correlations on winter surfaces are the same as on surfaces at Wallops where device self-wetted was used.
4. Testing be conducted at Wallops to see whether running high slip devices at lower speeds (to give the same slip speed) would allow one to calibrate other devices with near the same slip ratio.

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REFERENCES

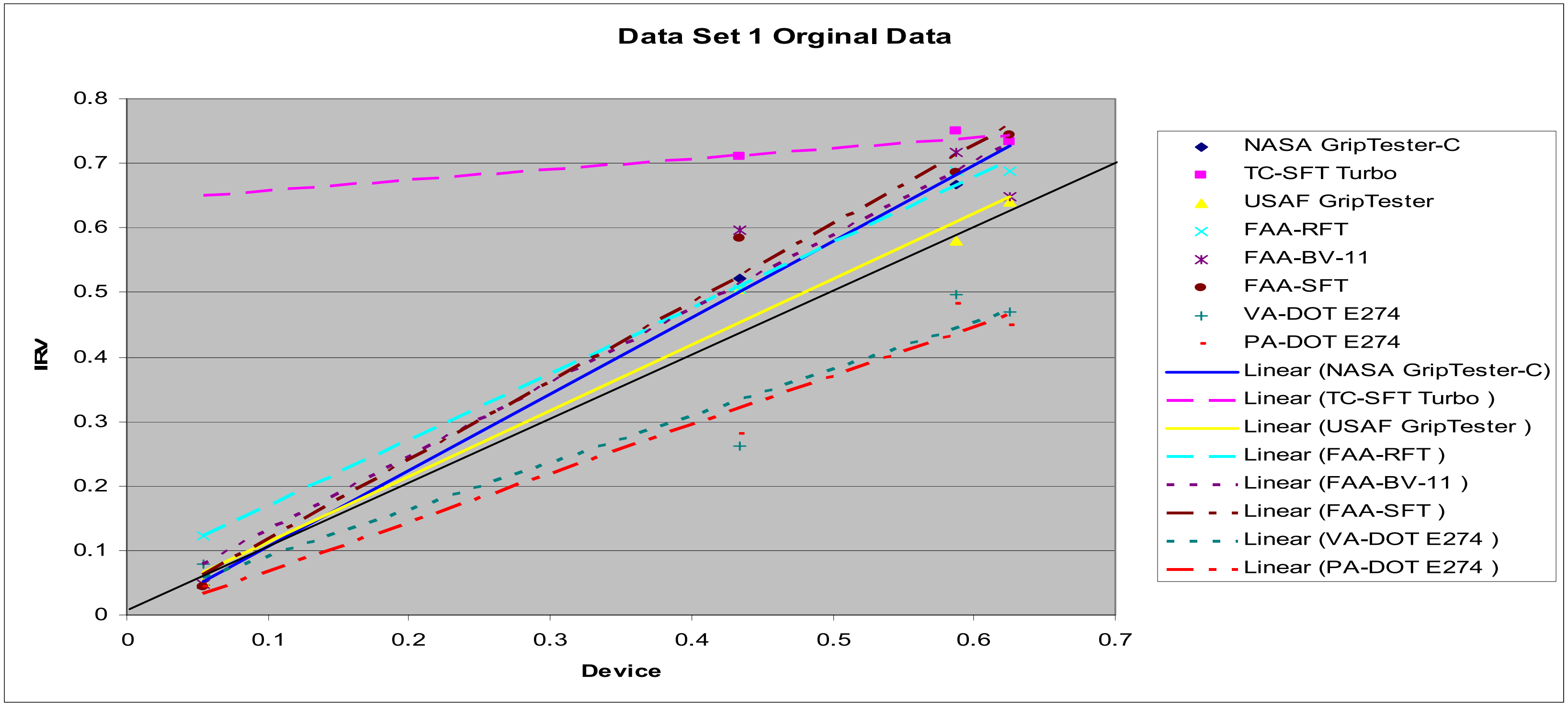
1. A. Andresen and J.C. Wambold, “Friction Fundamentals, Concepts and Methodology”, TP 13837E, Transportation Development Centre of Transport Canada, Montreal, October 1999.

2. J.C. Wambold, C.E. Antle, J.J. Henry, and Z. Rado, “International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements”, Final Report, World Road Association (PIARC), Paris, 1995.

Appendix A Data of Set 1 and Set 2

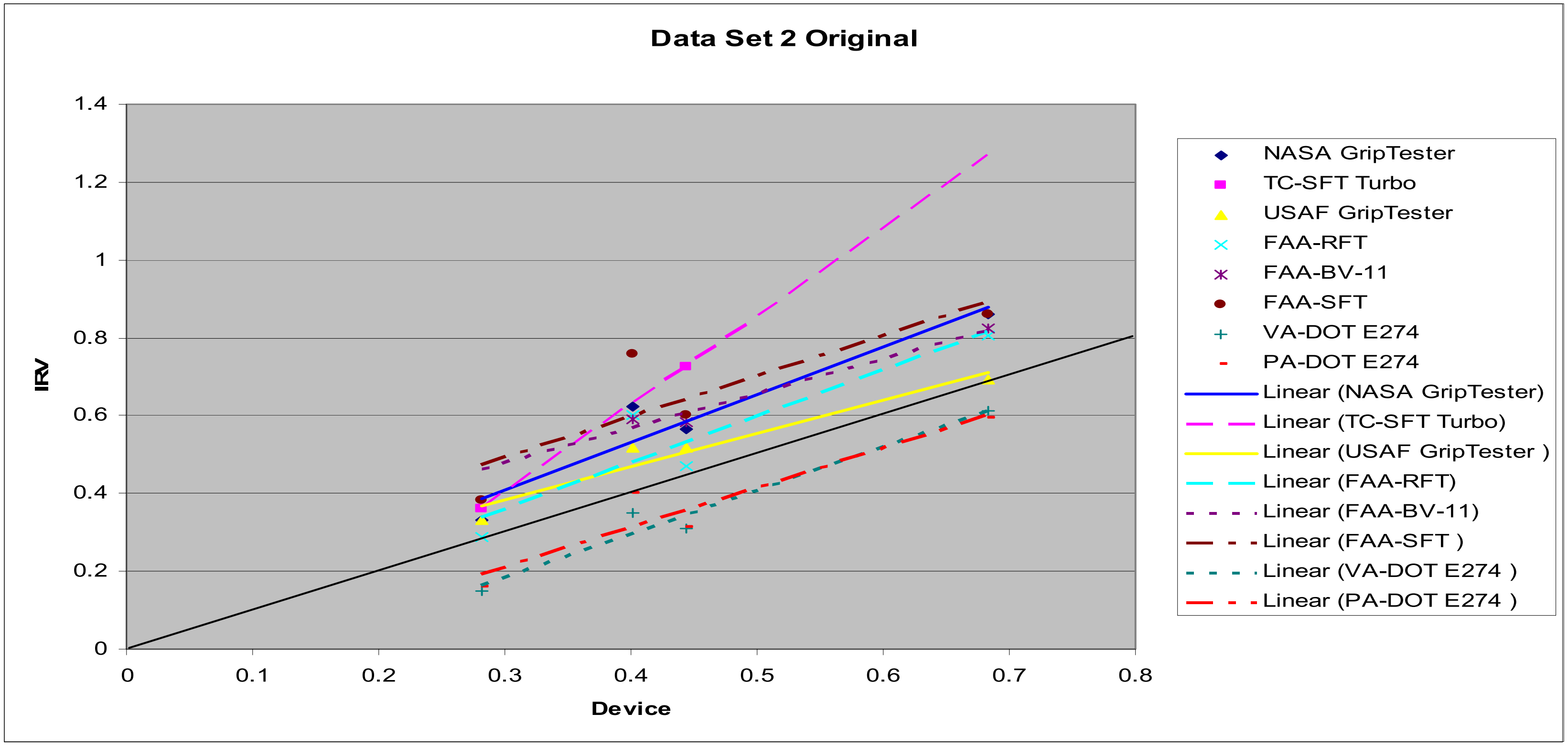
Data Set 1 Original Data

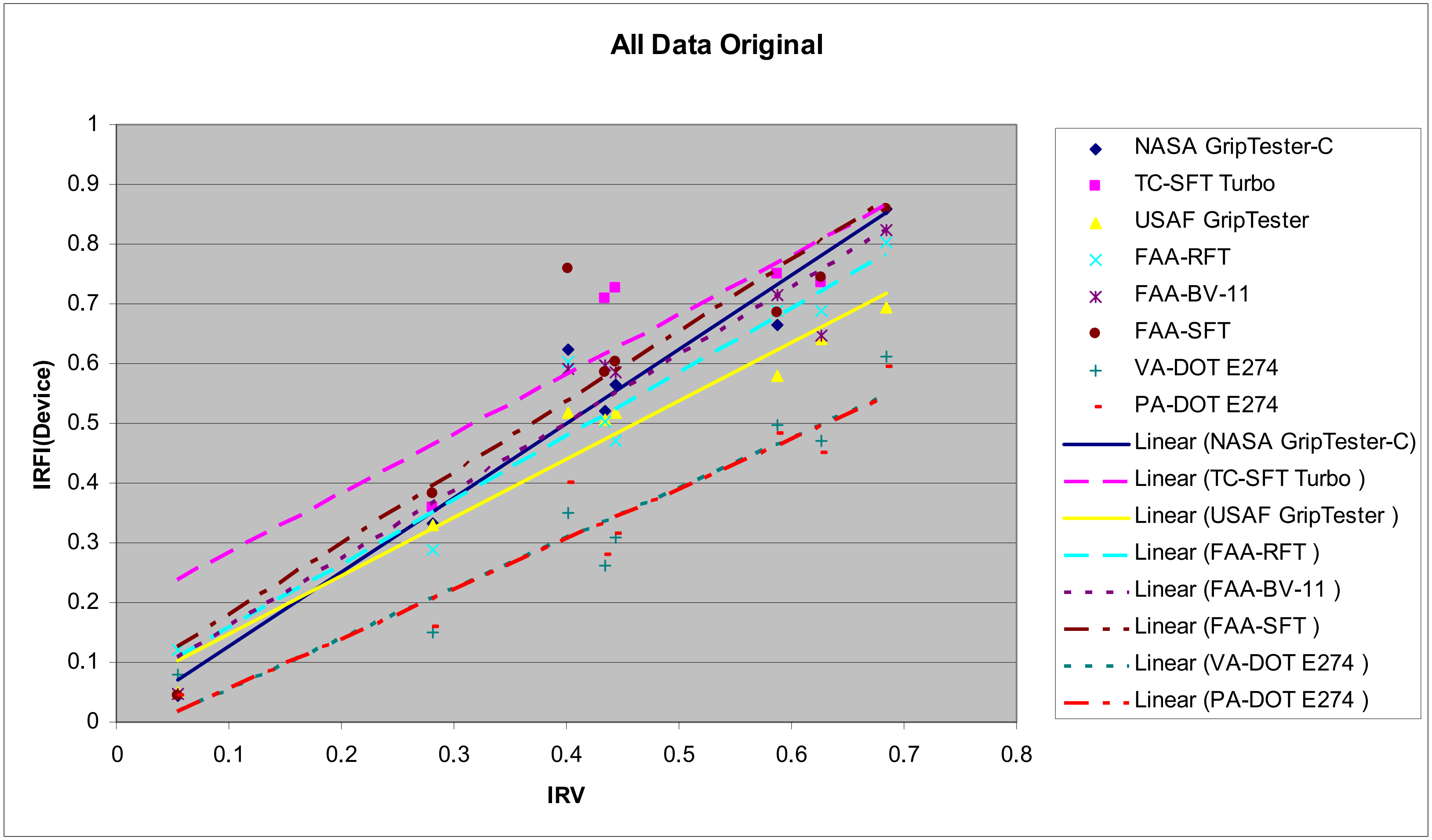
IRV	NASA GT	USAF GT	FAA-RFT	FAA-BV-11	FAA-SFT	VA-DOT E274	PA-DOT E274
0.434	0.452364	0.681611	0.428858	0.503328	0.481722	0.342394	0.382273
0.588	0.573871	0.720175	0.608645	0.602676	0.5642	0.642897	0.640468
0.626		0.704749	0.608645	0.546379	0.611098	0.61048	0.599444
0.054	0.049721	-0.0029	0.055606	0.049639	0.045078	0.106211	0.079721



Data Set 2 Original Data

IRV	NASA GT	TC-SFT Turbo	USAF GT	FAA-RFT	FAA-BV-11	FAA-SFT	VA-DOT E274	PA-DOT E274
0.444	0.564	0.726	0.517176	0.47	0.584	0.602	0.3084	0.3134
0.402	0.623468		0.516396	0.602	0.59	0.76	0.3512	0.4002
0.684	0.859019		0.69302	0.804	0.824	0.86	0.613	0.5936
0.282	0.332413	0.36	0.330588	0.288		0.382	0.151	0.1602




All Data Original
IRFI(Device)
IRV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
NASA GripTester-C
TC-SFT Turbo
USAF GripTester
FAA-RFT
FAA-BV-11
FAA-SFT
VA-DOT E274
PA-DOT E274
Linear (NASA GripTester-C)
Linear (TC-SFT Turbo)
Linear (USAF GripTester)
Linear (FAA-RFT)
Linear (FAA-BV-11)
Linear (FAA-SFT)
Linear (VA-DOT E274)
Linear (PA-DOT E274)