International Runway Friction Index (IRFI) versus Aircraft Braking Coefficient (Mu)

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ABSTRACT

This paper reports the results of the Joint Winter Runway Friction Measurement Program (JWRFMP). The program includes research and data collection with aircraft and ground friction measurement Devices (GFMD) 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 the 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, Czech Republic, Canada, France, Germany, Japan, Norway, Scotland, Sweden, Switzerland, and the United States.

The data was used to compare the International Runway Friction Index determined from the GFMD's data to the aircraft braking coefficient (Mu) data collected from six different aircraft. During the year 2000, the ASTM E 2100 standard "The International Runway Friction Index", IRFI, was drafted and approved. The use of the IRFI reduced the standard error in measured GFMD friction from as high as 0.2 (without IRFI), to an average under 0.05. Correlations to the aircraft reduced the variations of the slopes of the correlations by 50% as compared to the GFMD without IRFI.

INTRODUCTION

Measuring the capability of a runway surface to provide aircraft tire braking action is fundamental to airport aviation safety, especially under winter conditions. The different seasons, mainly winter, result in the possibility of the runway having contaminants of varying natures and qualities that contribute to reduced braking friction capabilities [1-5][1]. No satisfactory method or technique had been developed before the Joint Winter Runway Friction Measurement Program (JWRFMP) to predict the tire braking action of aircraft by using friction data collected by ground vehicles

This paper gives the results of using the International Runway Friction Index (IRFI) to predict the tire braking action of aircraft by using friction data collected by ground vehicles.

An 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), Avinor (formerly 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 United States, Austria, Czech Republic, England, France, Germany, Japan, 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

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 [6] 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.

After eight years of testing, with the participation of experts from several countries, a systematic, standardized approach has been developed to achieve harmonized friction measurements. This leads 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

1. Numbers in brackets denote references

Runways, held in Montreal on October 20-22, 1996 [7].

EQUIPMENT TESTED

Since the beginning of the Joint Winter Runway Friction Measurement Program in January 1996, 10 aircraft and 42 different ground devices collected friction data at North Bay, Ontario; Sawyer Airbase, Gwinn; MI, NASA Wallops Flight Facility, Virginia; Oslo, Norway; Munich, Germany; Erding Air Force Base, Germany; Prague Airport. Czech Republic: and New Chitose, Japan. A total of over 450 aircraft runs and over 15,000 ground vehicle runs (over 41,000 data points) were conducted on nearly 40 different runway conditions. Over 300 individuals from nearly 50 organizations in 12 different countries have participated with personnel, equipment, facilities and data reduction/analysis techniques. The Canadian Runway Friction Index (CRFI) and the International Runway Friction Index (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 [7] and Nov. 1999 [8]) to disseminate the test results and obtain recommendations for future testing. Data from the ten 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 to not only 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, the 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 participated in the JWRFMP and made sufficient runs with aircraft to allow correlations with the aircraft.

Table 1. List of Test Aircraft that Participated in the JWRFMP, 1996 to 2001

AIRCRAFT TYPE	OWNER/OPERATOR	MANUFACTURER
Falcon-20	National Research Council of 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 CAN	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/Donier

* data not avalable

Table 2. Ground friction measuring devices that participated in the JWRFMP and made sufficient correlation runs with aircraft, 1996 to 2001

Owner	Device Name	Manufacturer
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
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
Norwegian Air Traffic and Airport Management	RUNAR Prototype Trailer	Norsemeter AS, Norway
FAA Technical Center	Runway Friction Tester (RFT)	Dynatest, Inc., USA
FAA Technical Center	Surface Friction Tester (SFT)	SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1979 Ser #99	SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1985	SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1985 Turbo	SAAB GM, Sweden
Department of National Defense	GripTester	Findley Irvine, Ltd.

At all test sites, NRC provided ice and snow specialists who classified the winter contaminant. Typically the water content, density, air and surface temperature, and depth of the contaminant were measured. Observations on the tire tracks produced by the test aircraft and ground vehicles were recorded. Data along with the hourly flight weather have also been included in the database

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 winter 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 if measurements are made at different speeds. Then, texture information or speed gradient is needed in the correlation equation as specified in ASTM Standard E 1960 [9] is recommended.

The field test data sampling for the model includes ice and snow surfaces, as well as winter wet and dry surfaces, in order to create a data set of sufficient range to enable linear regressions.

A simple linear regression, called the statistical IRFI [10], can be applied by the aviation community now. This model is a linear regression of the data for each device to 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 less exact.
This change in time is critical when regressions are being made, but once the regression constants have been determined, their use in calculating IRFI during operating conditions is not time critical.

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 [11]. This study concluded 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.

IRFI Correlations

The tables in the 2002 report [5] give the IRFI correlation constants *a* and *b* for each of the years 1996 to 2002. However the 1996 and 1997 values came from a reference of 0.95 IMAG torque. Between 1997 and 1998 the IMAG was modified and thus was a different device. Thus, the 1996-97 correlations are generally discarded. Table 3 is a summary of the harmonizing values all devices from 1998 to 2002.

Table 3 A Summary of the Harmonizing Values.

Year	*a* Min.	*a* Max.	*a* Ave.	*b* Min.	*b* Max.	*b* Ave.	St. Error
1998	-.05	.08	.03	.7	1.01	.82	.04
1999	0	.17	.09	.21	1.14	.67	.04
2000	.04	.25	.15	.28	.99	.62	.07
2001	.02	.21	.09	.61	.93	.74	.07
2002	.01	.19	.1	.52	.85	.68	.05

Errors of Fitted IRFI Values

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, in 2001 the R^2 ranged from 0.41 to 0.98 with an average of 0.83, and in 2002 the R^2 ranged from 0.42 to 0.94 with an average of 0.80.

In looking at these values, it appears the correlations were not as good in 1999 and 2000 as in other years. On the average this is true for 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 tests included tests in deep snow and more tests were conducted with some loose snow on the ice and packed snow making the sites more variable and subject to test location of each run. In 2000, tests 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 when collecting correlation data.

It should also be noted that devices that tested at all sites generally had better R^2 and a better standard error of estimate than those that 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 a great improvement when compared to correlations without the IRFI harmonization applied where the error was as much as 0.2.

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.

The harmonization paired data collected has a sufficient range in friction levels and surface textures and includes representative operational runway characteristics; the error is 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.

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 the accuracy.

STABILITY OF THE HARMONIZATION METHOD

When several friction measuring devices of the same standard type are brought together to measure the same surface condition, 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 [12 to 15] have demonstrated that reproducibility of two different kinds of continuous friction measuring devices were 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 BV11's configured with ASTM E1551 [16] 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 surfaces ranged from 0.3 to 2.5 mm mean texture depth as measured by the sand patch method according to ASTM E 965 [17] and the corresponding International Friction Index speed numbers ranged from 24 km/h to more than 260 km/h. 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.

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 number 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

In order to evaluate the time stability of the individual devices, a year-by-year comparison of the IRFI constants in JWRFMP was made. 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 results clearly show that not only are there differences within a class of devices, but that an individual device changes from year to year. Based on the findings, the ASTM standard was modified to require at least annual determination of the IRFI harmonization coefficients.

IRFI CORRELATIONS WITH AIRCRAFT BRAKING PERFORMANCE

Conditions for Data Used for Correlations

The analysis converts ground friction measuring devices (GFMD) to IRFI using the harmonization constants *a* and *b*, and plots the aircraft braking coefficients of friction, Mu, against IRFI for all of the 275 aircraft test points from different aircraft [18]. The results are compared to aircraft Mu plotted against IRV and 0.95*IMAG when IRV data is not available. The correlation constants with aircraft to GFMD and their IRFI are called “zero intercept” and “slope multiplier” to distinguish them from the correlations for IRFI calibration of GFMD to the reference, IRV, which are called *a* and *b*. Values of harmonization constants *a* and *b* as determined during each year of testing were used.

IRFI was investigated for the following devices: ERD Blazer, IMAG, ITTV, RUNAR, FAA RFT, SFT212, SFT99, SFT79, and SFT85. Other devices were excluded since they did not have many runs with aircraft. Correlations of ground friction devices with three or less runs with aircraft are not used

Analysis with International Reference Vehicle (IRV)

Figure 1 gives the aircraft versus IRV or 0.95 of IMAG correlation with all data points. For the reasons stated previously, 1996 and 1997 data is then removed and the correlation is redone as shown in Figure 2. This increases the R^2 from 0.60 to 0.70 and increases the slope multiplier and decreases the zero intercept. Finally, Figure 3 shows the same analysis with some obvious outliers removed, and as expected, this increased R^2 to 0.86. The results from Figure 2 are then used as the reference to compare results with the other GFMD. Data is mostly in two clusters which is true of winter surfaces. It is recommended that more data in the 0.45 to 0.65 range be collected were feasible.

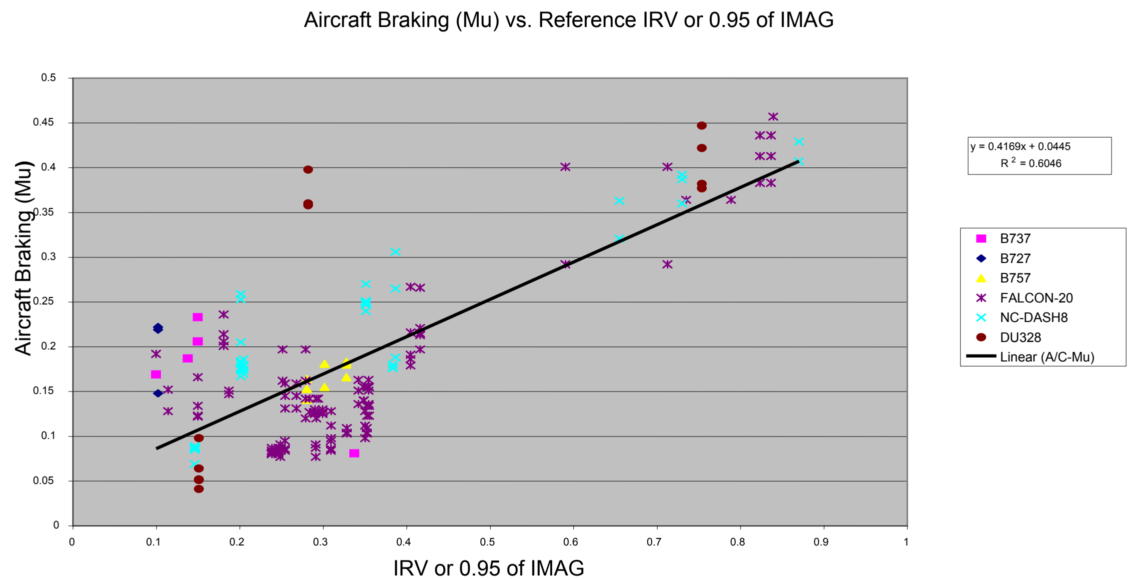

Figure 1. Aircraft Braking (Mu) versus International Reference Vehicle (IRV) friction or 0.95 of IMAG friction measurements

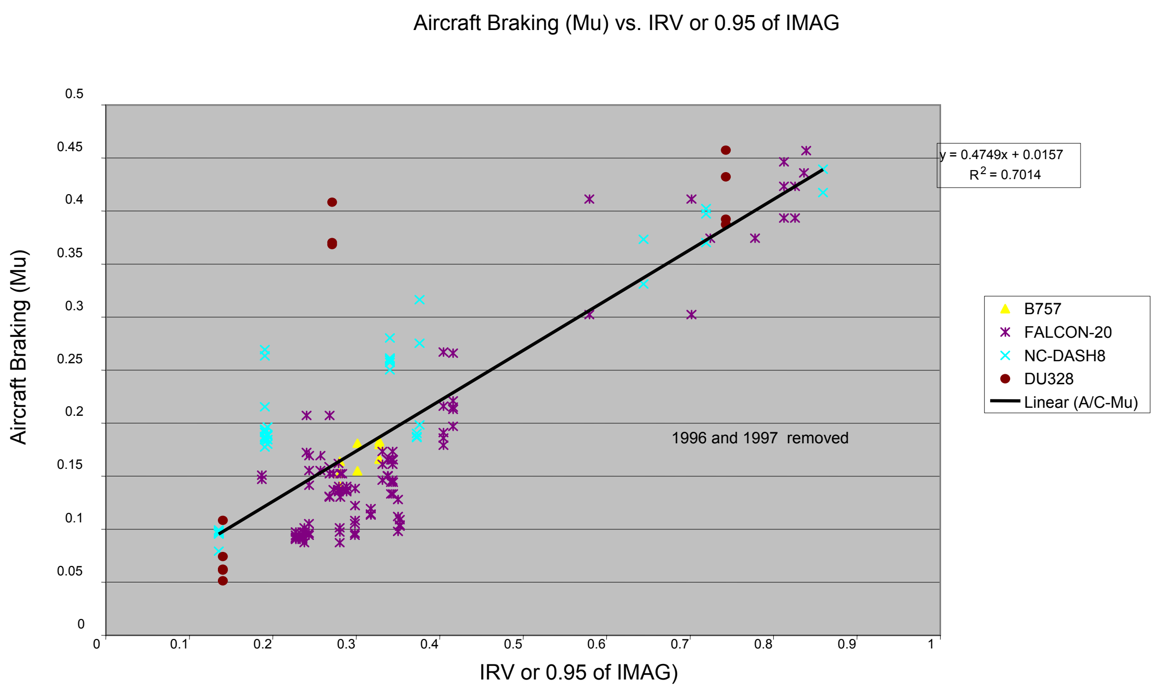

Figure 2 Aircraft Braking (Mu) versus IRV or 0.95 of IMAG friction measurements with 1996 and 1997 removed.

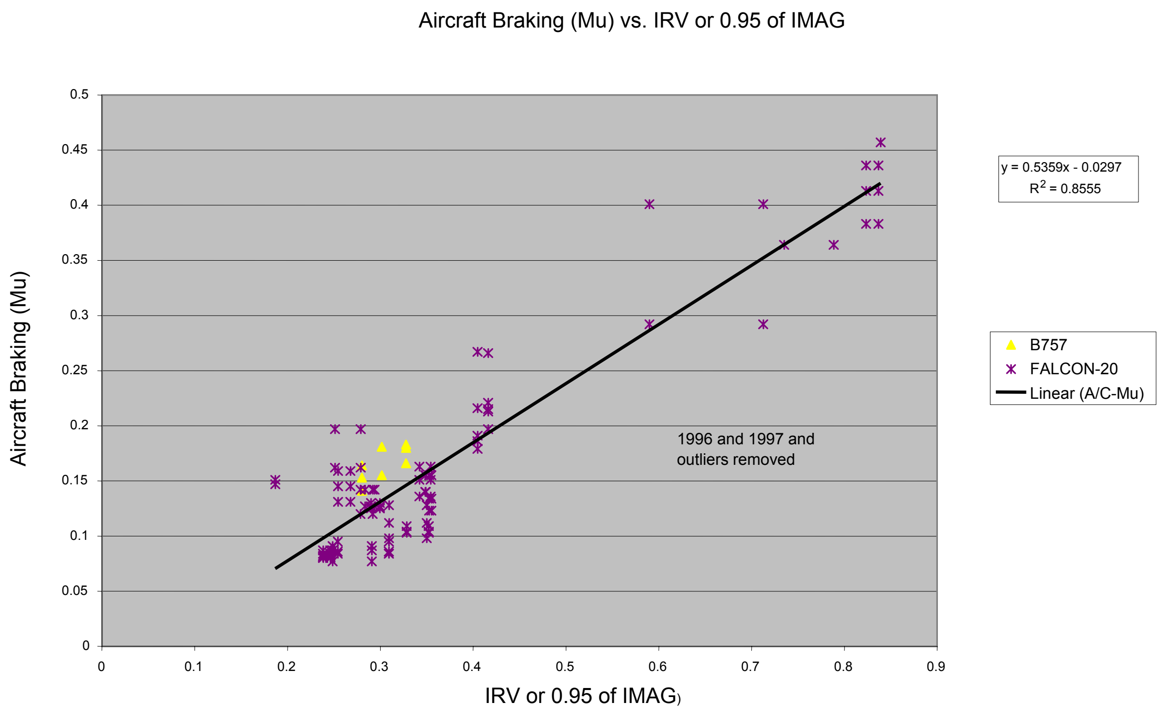

Figure 3. Aircraft Braking (Mu) versus IRV or 0.95 of IMAG friction measurements with 1996 and 1997 and outliers removed

Analysis with Electronic Recording Decelerometer (ERD)

Both ERD-Blazer and ERD-23 are used in the analysis because the Blazer was used in Europe one year and many runs were made with just the ERD-23 and the Falcon 20 while the Blazer was gone.

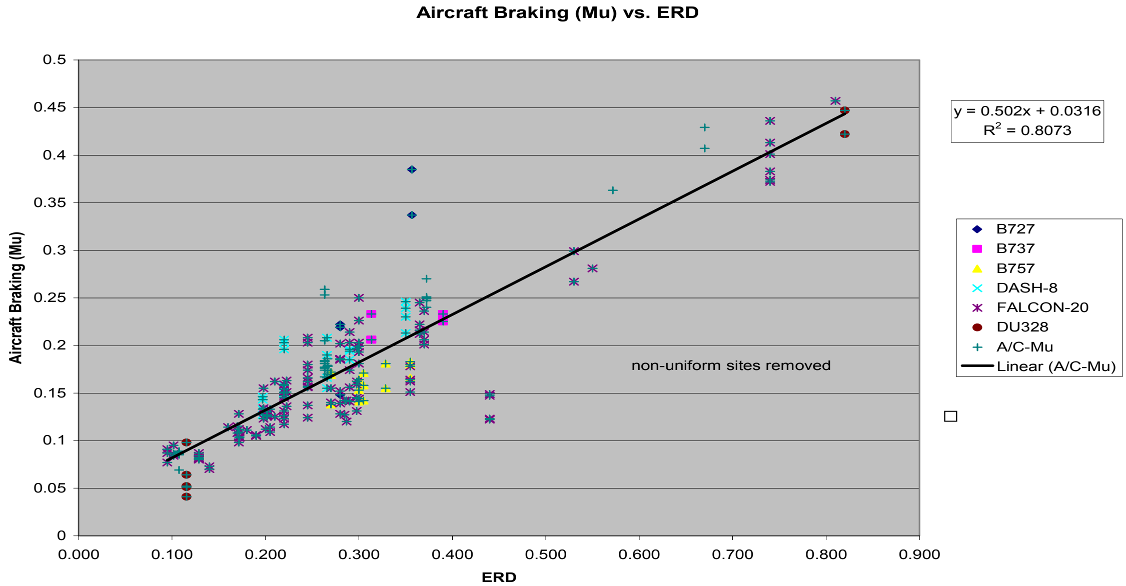

Figure 4a. Aircraft Braking (Mu) versus Electronic Recording Deccelerometer (ERD) friction measurements with non uniform sites removed

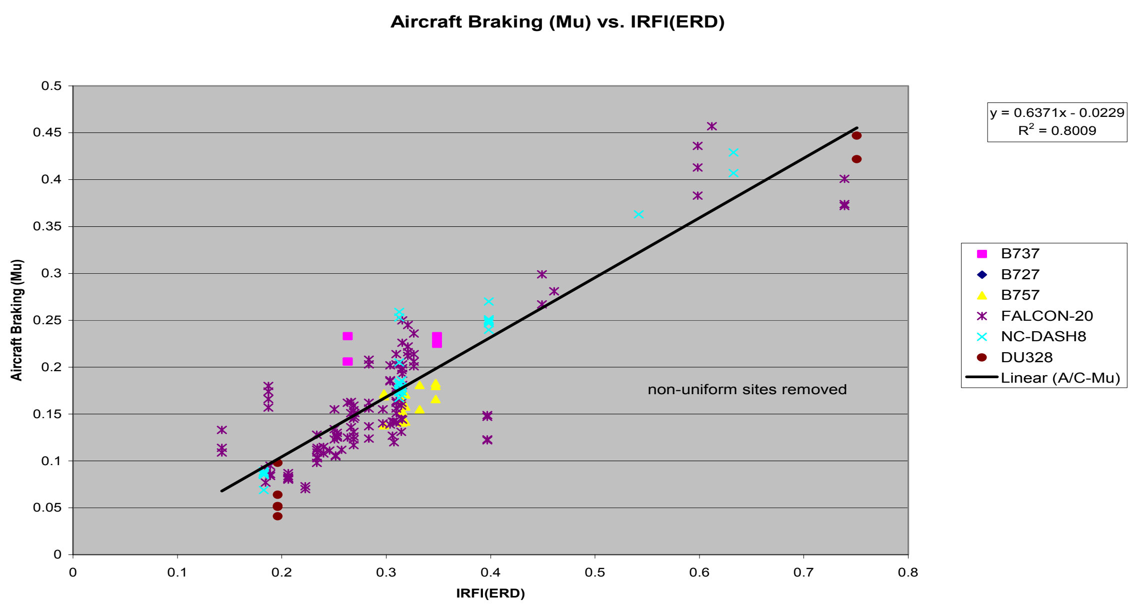

Figure 4b. Aircraft Braking (Mu) versus IRFI(ERD) with non uniform sites removed

Analysis with IMAG

Figure 5a and 5b show the IMAG correlations to aircraft without and with IRFI applied.

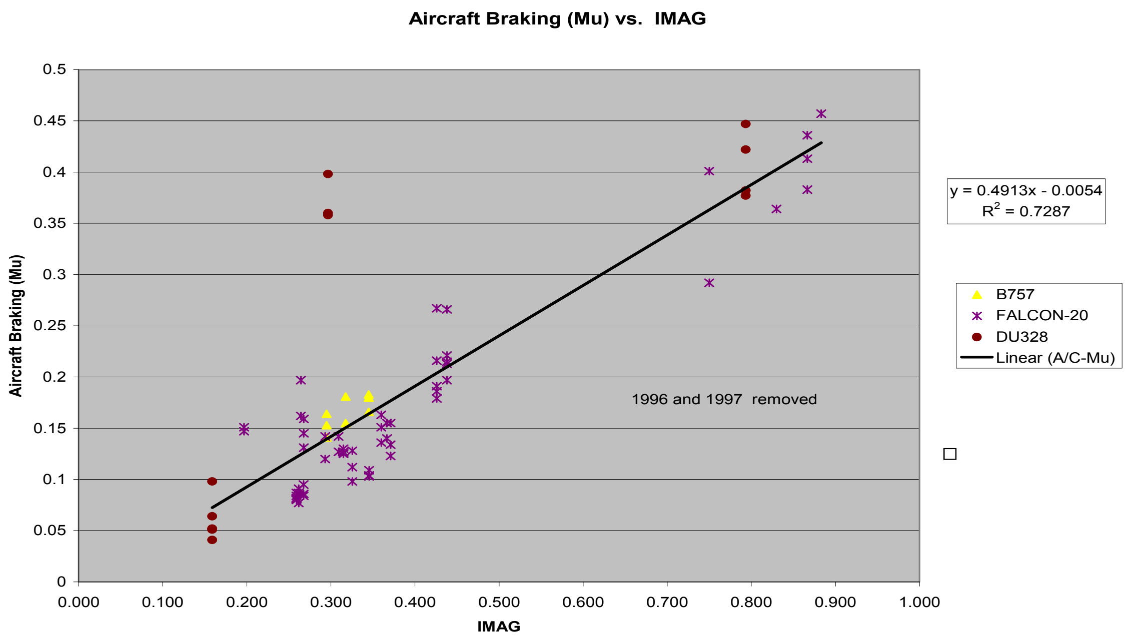

Figure 5a. Aircraft Braking (Mu) versus IMAG force measurements with 1996 and 1997 removed

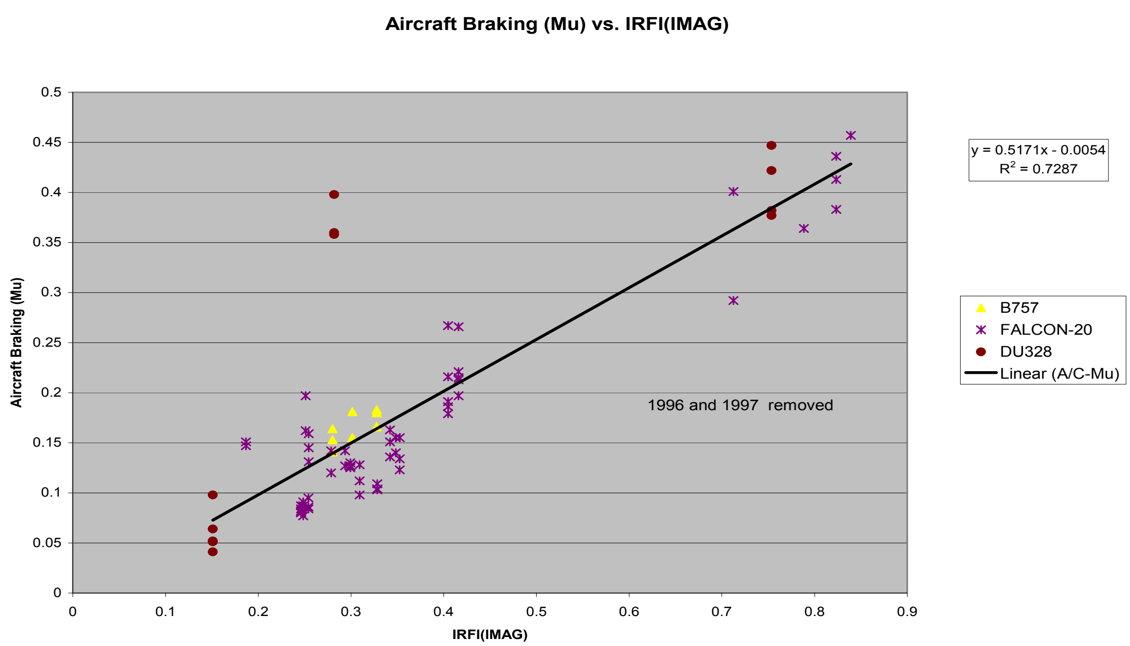

Figure 5b. Aircraft Braking (Mu) versus IRFI(IMAG) with 1997 and 1997 removed

Other Ground Friction Measuring Devices (GFMD)

All other correlations of the aircraft with GFMD are given in the report [10], first without IRFI applied and then with IRFI applied for the GripTester, Runway Friction Tester, ITTV, and Surface Friction Testers (SFT79, SFT85, SFT212, and SFT99). The R^2's vary from a low of 0.50 up to 0.88. The ITTV correlations have been discounted due to many mechanical problems and as a result a correlation that must be considered an outlier.

In summary, Table 4 compares the zero intercepts and slope multiplier values of the GFMD before and after IRFI is applied.

Table 4 Summary of Aircraft Correlations

	Device			IRFI(Device)		
Device	Zero Intercept	Slope Multiplier	R^2	Zero Intercept	Slope Multiplier	R^2
Reference	0.016	0.48	0.7	0.016	0.48	0.7
ERD	0.03	0.5	0.81	-0.023	0.64	0.8
IMAG	-0.005	0.49	0.73	-0.005	0.52	0.73
RUNAR	0.07	0.26	0.56	0.103	0.36	0.51
GT-DND	0.064	0.33	0.62	0.108	0.32	0.6
RFT	0.06	0.33	0.87	0.04	0.64	0.88
SFT79	0.07	0.34	0.6	0.08	0.39	0.61
SFT85	0.126	0.25	0.75	0.119	0.3	0.71
SFT212	0.178	0.23	0.52	0.13	0.37	0.89
SFT99	0.08	0.37	0.81	0.13	0.54	0.94

Table 4 clearly shows that: a) the correlation coefficient (R^2) between aircraft Mu and device friction does not change much when converted to IRFI, meaning that the correlation depends on the device, not the IRFI conversion, b) the four SFT's all have very high zero intercepts caused by their having problems measuring friction in significant depths of snow, c) the devices with the best correlations, namely the ERD, IMAG, and RFT are also the closest to the reference device for both zero intercept and slope multiplier.

To see how the IRFI reduces the difference of each GFMD when compared to the reference, Figure 6 shows the slope multipliers versus the reference graphically. Ideally one would want all the IRFI values to approach the reference. Figure 7 shows the difference of the slope multipliers from the reference. The average error is 0.14 without IRFI and the average is reduced to 0.05 with IRFI (absolute error of 0.1) or a 64% reduction in the error.

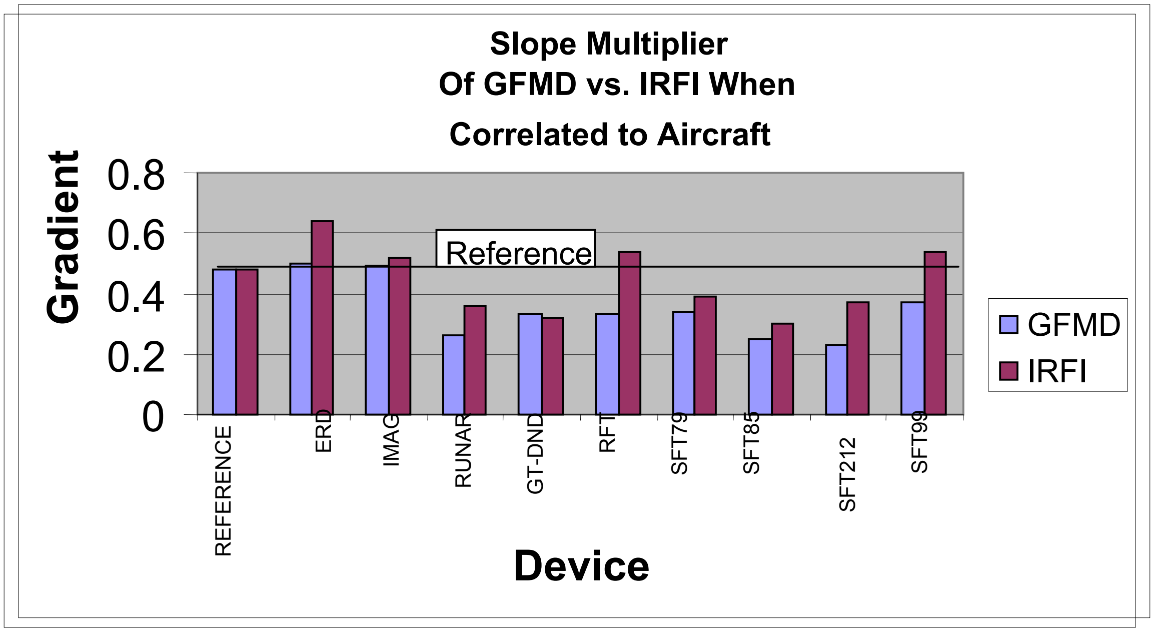

Figure 6 Slope Multpliers of Ground Friction Measuring Devices Versus their IRFI Correlations to Aircraft

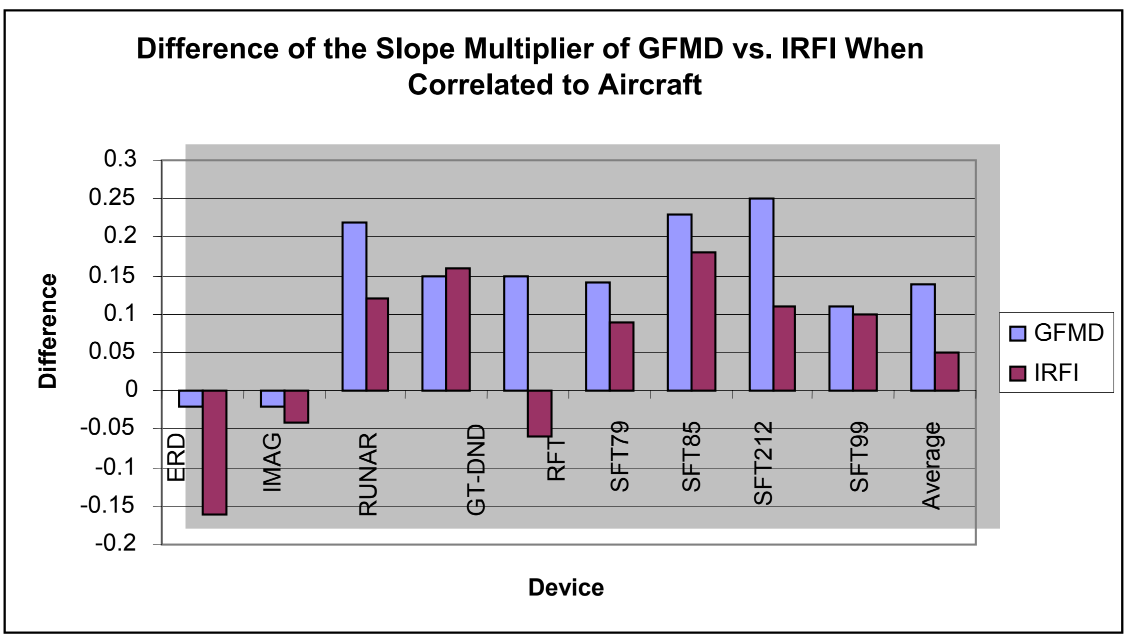

Figure 7 Error of the slope mutiplier of Ground Friction Measuring Devices Versus their IRFI Correlations to Aircraft

Figure 8 shows the zero intercepts. The SFT99, 85 and 212 are omitted since they had very few points and their intercepts are outliers.

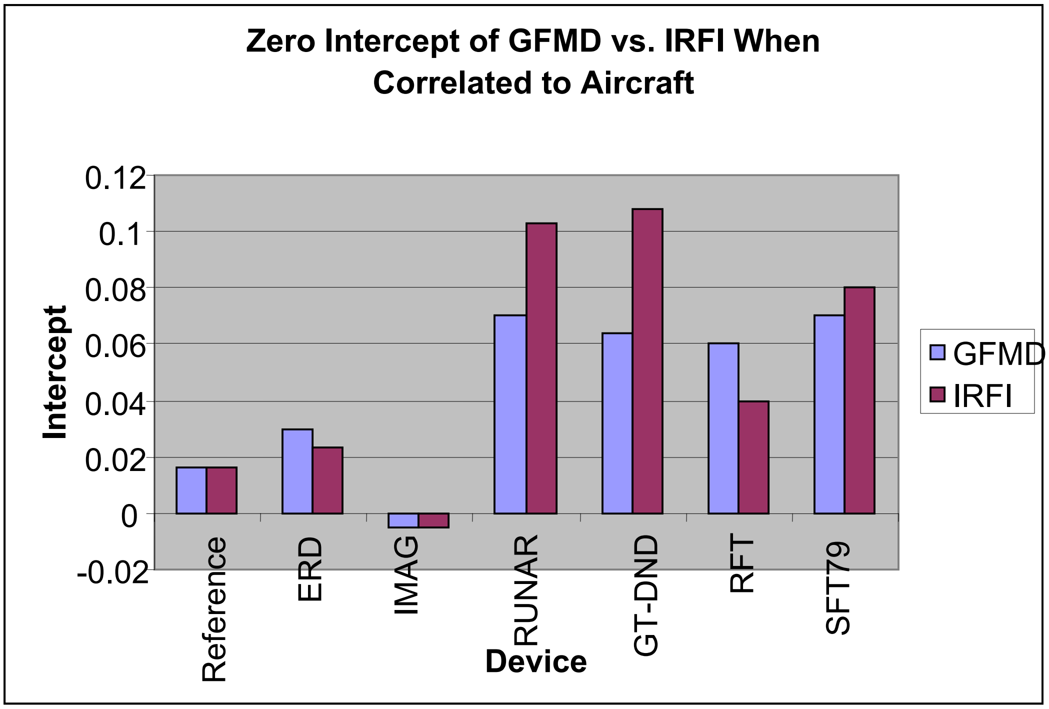

Figure 8. Zero Intercepts of Ground Friction Measuring Devices Versus their IRFI Correlations to Aircraft

The zero intercepts shown are reasonable for the IRV, ERD, IMAG (slightly negative), and the RFT,

CONCLUSIONS AND RECOMMENDATIONS

The ASTM Standard E 2100 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. Since many aircraft tests were run on prepared surfaces, more actual operational should be included in future tests.

The IRFI method typically reduces the present variations among different GFMD 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. It is recommended that a reference device should include the following:

- Measure both force and torque
- Have a high footprint contact pressure, greater than 500kPa
- Have variable or adjustable slip ratios up to 100%
- Have a standard tire that is reproducible from tire to tire
- Possibly be equipped with an anti-skid system, and
- Preferably be a trailer device that is compact for shipping and can be towed with most any truck.

The IRFI does help reduce the differences between GFMD when correlated to aircraft. The average difference is 0.14 without IRFI and the average is reduced to 0.05 with IRFI (absolute error of 0.1) or a 64% reduction in the difference. The IRFI does not significantly affect the degree of correlation between the individual GFMD's and aircraft Mu as would be expected with a linear correlation. The project has shown that IRFI can be used to predict aircraft braking performance.

REFERENCES

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

2. Wambold, J.C., et al “Joint Winter Runway Friction Measurement Program (JWRFMP) 1997-98 Testing and Data Analysis,” Transportation Development Centre, Transport Canada, TP 13836E, October 1999

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

4. Wambold, J.C., et al “Joint Winter Runway Friction Measurement Program (JWRFMP) 2000 Testing and Data Analysis,” Transportation Development Centre, Transport Canada, TP 140626E, October 2001

5. Wambold, J.C., et al “Joint Winter Runway Friction Measurement Program (JWRFMP) 2001 Testing and Data Analysis,” Transportation Development Centre, Transport Canada, TP 14192E, June 2002

6. ASTM (2000): "Practice for Calculating the International Runway Friction Index", Standard No. E2100-00, *American Society for Testing and Materials Book of Standards Part 04.03,* Philadelphia, PA.

7. Boccanfuso, A,” Proceedings of the International Meeting on Aircraft Performance on Contaminated Runways: IMAPCR ’96”, Transport Canada, TP 12943E, Montreal, 1996.

8. Boccanfuso, A,”Proceedings of the International Meeting on Aircraft Performance on Contaminated Runways: IMAPCR ’99”, Transport Canada, TP 13579E, Montreal, 1999.

9. ASTM (1998): "Practice for Calculating International Friction Index of a Pavement Surface", Standard No. E1960-98, *American Society for Testing and Materials Book of Standards Part 04.03,* Philadelphia, PA.

10. Wambold, J.C., et al “International Runway Friction Index (IRFI): Development Technique and Methodology” Transportation Development Centre, Transport Canada, TP14061E, September 2001

11. Henry, J.J. and Wambold, J.C., “Comparison of the IRV and the IMAG on Winter Contaminated Surfaces,” Transportation Development Centre, Transport Canada, TP 13791E, May 2001

12. Norwegian Air Traffic and Airport Management, Report TT991, “Harmonizing Friction Measures of NCAA Operated GripTesters 1999”, ISBN 82-91156-21-2.

13. Norwegian Air Traffic and Airport Management, Report TT2000-1, “Harmonizing Friction Measures of NATAM Operated BV11's in June 2000”, ISBN 82-91156-23-9.

14. Norwegian Air Traffic and Airport Management, Report TT983, “Results from a Calibration Workshop,” 25-29 May 1998.

15. Norwegian Air Traffic and Airport Management, Report OKK2000-1, OKK Friction Profiles of NATAM Operated Friction Measuring Devices 1998-2000,” ISBN 82-91156-22-0.

16. ASTM (1998): "Specification for special Purpose, Smooth-Tread Tire, Operated on Fixed Braking Slip Continuous Friction Measuring Equipment", Standard No. E1551-98, *American Society for Testing and Materials Book of Standards Part 04.03,* Philadelphia, PA.

17. ASTM (1996): "Standard Test Method of Measuring Surface Macrotexture Depth using a Volumetric Technique", Standard No. E965-96, *American Society for Testing and Materials Book of Standards Part 04.03,* Philadelphia, PA.

18. Croll, J.B., et al “Evaluation of Aircraft Braking Performance on Winter Contaminated Runways and Prediction of Aircraft Landing Distance Using the Canadian Runway Friction Index.” National Research Council Canada, LTR-FR-183, TP 13943E, June 2002.