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Evaluation of Aircraft Braking Performance On Winter Contaminated Runways and Prediction of Aircraft Landing Distance Using the Canadian Runway Friction Index

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16. Abstract

The braking performance of eight aircraft (six different aircraft types), all with similar anti-skid braking systems, was evaluated on winter contaminated runway surface conditions under the Joint Winter Runway Friction Measurement Program over a six-year period between 1996 and 2001. The aircraft included an NRC-operated Falcon 20, a NASA-operated B737 and B757, FAA- and First Air-operated B727's, deHavilland- and Nav Canada-operated Dash 8's, and a Fairchild Dornier-operated DU328 turboprop. A total of 275 full anti-skid braking runs were made on more than 70 contaminated surface conditions, most of which occurred naturally during winter conditions, and some of which were man-made. For all aircraft tested, the aircraft braking coefficients during full anti-skid braking remained essentially independent of aircraft groundspeed on contaminated surfaces.

Aircraft braking coefficients were compared with runway friction indices measured by various devices, including the Transport Canada Electronic Recording Decelerometer (ERD), the SAAB Surface Friction Tester and a reference vehicle providing an interim International Runway Friction Index (IRFI). The correlation between aircraft braking coefficients and the Canadian Runway Friction Index (CRFI), provided by the ERD, was considered to be good enough to be used for the prediction of aircraft braking performance based on the measured CRFI. Tables of recommended landing distance, independent of specific aircraft type, were developed as a function of the CRFI and published in the Transport Canada Aeronautical Information Publication. It is recommended that the results of the tests on the ground friction measurement devices be analyzed expeditiously to provide an internationally acceptable IRFI, and that the CRFI tables then be converted into IRFI tables.

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16. Résumé

Le Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver, qui s'est étalé sur une période de six ans, soit de 1996 à 2001, a servi à évaluer la performance en freinage de huit avions (de six types différents) équipés de systèmes antidérapage semblables, sur des pistes contaminées par des précipitations hivernales. Les aéronefs étudiés comprenaient un Falcon 20 exploité par le CNRC, un B737 et un B757 exploités par la NASA, deux B727 exploités respectivement par la FAA et First Air, deux Dash 8 exploités respectivement par deHavilland et Nav Canada, et un DU328 à turbopropulseurs exploité par Fairchild Dornier. Au total, 275 essais de freinage ont été réalisés, sur plus de 70 pistes contaminées, la plupart dans des conditions de précipitations naturelles, mais quelques-uns sous précipitations artificielles. Pour l'essentiel, tous les coefficients de freinage, peu importe l'avion, se sont avérés indépendants de la vitesse au sol.

Ces coefficients de freinage ont été mis en rapport avec les indices de glissance des pistes mesurés par divers dispositifs, dont le décéléromètre électronique (ERD) de Transports Canada, le glissancemètre (SFT) de SAAB et un véhicule de référence utilisé pour établir, à titre provisoire, un indice international de la glissance des pistes (IRFI). La corrélation entre les coefficients de freinage et l'indice canadien de la glissance des pistes (CRFI), obtenu à l'aide de l'ERD, s'est révélée suffisante pour que le CRFI mesuré puisse être utilisé pour prédire la performance des avions en freinage. Des tables de distances d'atterrissage recommandées ont donc été élaborées et publiées dans la Publication d'information aéronautique de Transports Canada. Ces tables, établies en fonction du CRFI, ne tiennent pas compte du type d'avion. Il est recommandé de procéder dans les plus brefs délais à l'analyse des résultats des essais sur les dispositifs de mesure du frottement au sol, de façon que l'on dispose de valeurs IRFI acceptables internationalement et que les tables CRFI puissent être converties en tables IRFI.

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ABSTRACT

The braking performance of eight aircraft (six different aircraft types), all with similar anti-skid braking systems, was evaluated on winter contaminated runway surface conditions under the Joint Winter Runway Friction Measurement Program (JWRFMP) over a six year period between 1996 and 2001. The aircraft included an NRC operated Falcon 20, a NASA operated B737 and B757, FAA and First Air operated B727's, deHavilland and Nav Canada operated Dash 8's and a Fairchild Dornier operated DU328 turboprop. A total of 275 full anti-skid braking runs were made on over 70 contaminated surface conditions, most of which occurred naturally during winter conditions, and some of which were man-made. For all aircraft tested, the aircraft braking coefficients during full anti-skid braking remained essentially independent of aircraft groundspeed on contaminated surfaces. Aircraft braking coefficients were compared with runway friction indices measured by various devices, including the Transport Canada Electronic Recording Decelerometer (ERD), the SAAB Surface Friction Tester (SFT) and a reference vehicle providing an interim International Runway Friction Index (IRFI). The correlation between aircraft braking coefficients and the Canadian Runway Friction Index (CRFI), provided by the ERD, was considered to be good enough to be used for the prediction of aircraft braking performance based on the measured CRFI. Tables of recommended landing distance, independent of specific aircraft type, were developed as a function of the CRFI and published in the Transport Canada Aeronautical Information Publication. It is recommended that the results of the tests on the ground friction measurement devices be analyzed expeditiously to provide an internationally acceptable IRFI, and that the CRFI tables then be converted into IRFI tables.

RÉSUMÉ

L'efficacité de freinage de huit avions (six types d'aéronef différents), tous dotés de systèmes de freinage antidérapant, a été évaluée sur pistes contaminées en hiver dans le cadre du Projet conjoint de friction des pistes en hiver (PCFPH), sur une période de six ans s'échelonnant de 1996 à 2001. Les avions étaient un Falcon 20 exploité par le CNRC, un B737 et un B757 exploités par la NASA, des B727 exploités par la FAA et First Air, des Dash 8 exploités par de Havilland et Nav Canada ainsi qu'un avion turbopropulseur DU328 exploité par Fairchild Dornier. En tout, 275 freinages complets avec dispositif antidérapant ont été effectués sur 70 surfaces contaminées, la plupart de façon naturelle en hiver et certaines dans des conditions artificielles. Pour tous les avions testés, les coefficients de freinage avec système antidérapant ont été essentiellement indépendants de la vitesse sol des avions sur les surfaces contaminées. Les coefficients de freinage des avions ont été comparés aux indices de frottement sur piste mesurés par divers dispositifs, dont le décéléromètre à enregistrement électronique (ERD) de Transports Canada, l'appareil d'essai de friction des surfaces (SFT) de SAAB et un véhicule de référence fournissant le coefficient international provisoire de friction sur piste (IRFI). La corrélation entre les coefficients de freinage des avions et le coefficient canadien de frottement sur piste (CFRI), fourni par le ERD, a été jugé suffisamment satisfaisante pour servir à la prédiction de l'efficacité de freinage des avions à partir du CFRI mesuré. Des tableaux de distance d'atterrissage recommandées, quel que soit le type d'avion, ont été élaborées comme une fonction du CFRI et publiées dans la Publication d'information aéronautique (AIP) de Transports Canada. Il est recommandé que les résultats des essais sur les appareils de mesure de la friction au sol soient rapidement analysés pour pouvoir servir d'IRFI accepté à l'échelle internationale et que les tableaux CFRI soient convertis en tableaux IRFI.

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GLOSSARY OF TERMS

$ACCR_{AV}$	Average Acceleration During Braking (for Recommended LD)
AFM	Aircraft Flight Manual
AIP	Aeronautical Information Publication
ASTM	American Society for Testing and Materials
ATIS	Automatic Terminal Information System
BDR	Braking Distance Ratio
C_D	Aircraft Coefficient of Drag
C_L	Aircraft Coefficient of Lift
CPU	Computer Processor Unit
CRFI	Canadian Runway Friction Index
D	Aerodynamic Drag
DAS	Data Acquisition System
DAT	Digital Audio Tape
D_{CONTAM}	Contamination Drag
D_F	Friction Drag
DFIS	Digital Flight Inspection System
DGPS	Differential Global Positioning System
D1R	Recommended Air Distance (from 50 feet to touchdown)
D2R	Recommended Delay Distance (from touchdown to brake application)
D3R	Recommended Braking Distance (from brake application to a complete stop)
ERD	Electronic Recording Decelerometer
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
ft	Feet
g	Gravitational Constant
GPIP	Glide Path Intercept Point
GPS	Global Positioning System
HW	Headwind
IAR	Institute for Aerospace Research
ILS	Instrument Landing System
IMAG	Instrument de Mesure Automatique de Glissance
INS	Inertial Navigation System
IRFI	International Runway Friction Index
IRV	IRFI Reference Vehicle
JBI	James Brake Index
JWRFMP	Joint Winter Runway Friction Measurement Program

KEAS	Knots Equivalent Airspeed
KTGS	Knots True Groundspeed
kts	knots
L	Aerodynamic Lift
lbf	Pounds of force
LDR	Recommended Landing Distance
MOU	Memorandum of Understanding
Mu	Coefficient of friction
MuR	Recommended Braking Coefficient
NASA	National Aeronautics and Space Administration
NOTAM	Notice to Airmen
PA	Pressure Altitude
psi	pounds per square inch
R^2	Statistical Coefficient of Determination
RFI	Runway Friction Index
RMS	Root Mean Square
RTO	Rejected Takeoff
S	Wing reference area (ft^2)
SD	Standard Deviation
SDR	Stopping Distance Ratio
SFT	Surface Friction Tester
SG	Specific Gravity
t	Time
T	Aircraft Thrust
TCH	Threshold Crossing Height
T_{DISC}	Propeller Discing Thrust
T_{REV}	Reverse Thrust
TS	Test Section
TW	Tailwind
V	Aircraft velocity along the runway
V_{EAS}	Equivalent Airspeed
V_{EFB}	Equivalent Airspeed at Application of Full Brakes
V_{E50}	Equivalent Airspeed at 50 feet Above the Runway Surface
V_{GFB}	Groundspeed at Application of Full Brakes
V_{G50}	Groundspeed at 50 feet Above the Runway Surface
V_{REF}	Aircraft Approach Speed
V_{T50}	True Airspeed at 50 feet Above the Runway Surface
V_W	Wheel speed
W	Aircraft Weight
	Runway Slope (positive uphill)
$_1$	Standard deviation of air distance
$_2$	Standard deviation of delay distance
μ_B	Aircraft Braking Coefficient (= Braking Force/(W-L))
μ_R	Rolling Friction Coefficient (= Rolling Resistance/(W-L))
μ_S	Wheel slip ratio (= $(V-V_W)/V$)

EVALUATION OF AIRCRAFT BRAKING PERFORMANCE ON WINTER CONTAMINATED RUNWAYS AND PREDICTION OF AIRCRAFT LANDING DISTANCE USING THE CANADIAN RUNWAY FRICTION INDEX

1.0 INTRODUCTION

1.1 Background

The Joint Winter Runway Friction Measurement Program (JWRFMP) is a multi-year international initiative to study winter runway friction, with the goals of both standardizing its measurement and determining its effect on aircraft takeoff and landing performance. The program is well documented in an *"Overview of the Joint Winter Runway Friction Measurement Program,"* Reference 1. Under the JWRFMP, the braking performance of several different aircraft types was evaluated on winter contaminated runway test surfaces during the six year period between 1996 and 2001. Test data were obtained for eight aircraft (six different aircraft types) with similar anti-skid braking systems. In parallel with the aircraft tests, a considerable amount of testing was conducted on ground vehicle based friction measuring devices in order to develop a standardized International Runway Friction Index (IRFI).

The aircraft for which data was obtained included an NRC operated Falcon 20, a NASA operated B737 and B757, FAA and First Air operated B727's, de Havilland and Nav Canada operated Dash 8's and a Fairchild Dornier operated 328 turboprop. A total of 275 full anti-skid braking runs were made on over 70 contaminated surface conditions, most of which occurred naturally during winter conditions, and some of which were man-made. The results of the individual aircraft tests are reported in References 2 through 12, 16 and 19. All these reports describe the specific tests conducted on the different aircraft, and contain the detailed results of aircraft braking performance measured on the various contaminated test surfaces. Contamination drag is also computed where it is a significant factor in aircraft deceleration.

Following the first year of NRC Falcon 20 testing, a study of the relationship between aircraft deceleration during full anti-skid braking and runway friction index was published in *"Determination of Falcon 20 Landing Distances on Winter Contaminated Runways as a Function of the James Brake Index,"* Reference 13. This initial study approximated aircraft deceleration as a linear function of groundspeed for the specific aircraft type.

In order to expand the application of runway friction index to the prediction of aircraft landing distance for other aircraft types, the stopping performance of various aircraft was expressed in terms of braking coefficients, which were then plotted against the successor to the JBI, the Canadian Runway Friction Index (CRFI). The resulting relationship was used to refine the deceleration model into a second order function of equivalent airspeed. The model, in turn, was used to predict aircraft stopping distance.

The prediction of aircraft landing distance as a function of CRFI was reported in References 7 and 9, the results of which formed the basis for the "CRFI Tables of Recommended Landing Distance" published in the Transport Canada Aeronautical Information Publication (AIP). These tables were updated twice as different aircraft performance data were obtained, and methods for estimating the effects of reverse thrust or propeller discing were applied (Reference 8).

This report is intended to consolidate the landing performance data for all the aircraft tested under the JWRFMP, whose tests are now complete, and to show how these data were used to derive the current version of the CRFI tables of recommended landing distance.

1.2 Objectives and Scope

The JWRFMP test objectives were threefold: 1) standardise the outputs of the various friction measuring devices into an IRFI, 2) establish accurate aircraft performance data for a wide range of winter contaminated runway conditions, and 3) validate the JBI Tables of recommended landing distance. The test results pertaining to the first objective are still being analysed, although intermediate reports have been published (see References 14 and 18). A standard, entitled *"Standard Practice for Calculating the International Runway Friction Index,"* has been adopted under the American Society for Testing and Materials (ASTM). Harmonization constants are applied to the output of each friction measuring device to calculate the equivalent IRFI.

Because the harmonization constants are not yet in final form, no attempt will be made in this report to predict aircraft landing performance based on the IRFI. Aircraft braking coefficients will be compared with the output of the IRFI Reference Vehicle (IRV) for aircraft tests which were performed against both IRFI and CRFI readings. These include the NRC Falcon 20 tests in January 2000 and the Nav Canada Dash 8 and Dornier 328 aircraft tests in January – March 2001. However, since the CRFI measurements exhibited the best correlation with aircraft braking coefficients, this report will be limited to the prediction of landing distance as a function of the CRFI. It is expected that when the IRFI harmonization constants are established in a final standard, the conversion to IRFI can be made.

The second JWRFMP objective encompasses aircraft performance parameters including braking coefficients, contamination drag and crosswind handling qualities, all of which influence aircraft takeoff and landing performance. The referenced reports cover these topics, where applicable, for the individual aircraft tested. This report will focus only on aircraft braking performance as it applies to landing distance on contaminated runways, and the development of the CRFI tables of recommended landing distance.

2.0 EQUIPMENT UNDER TEST

The equipment under test included the ground friction measuring devices, notably the Transport Canada Electronic Recording Decelerometer (ERD) used to produce the CRFI, the SAAB Surface Friction Tester (SFT), and the IRV used to produce the interim IRFI. Eight different aircraft (six aircraft types) named in sub-section 1.1 were used to perform the flight testing or to validate the CRFI tables. The following paragraphs provide a brief description of this equipment and its role in the JWRFMP.

2.1 Ground Friction Measuring Devices

The original friction measuring device used in Canada was the James Brake Decelerometer (JBD), reporting a friction index called the James Brake Index (JBI). Several years ago this device was upgraded to the ERD, which is now the primary instrument used for runway friction measurement during winter operations at virtually all Canadian airports and military air bases. The ERD uses a piezo-electric accelerometer to measure deceleration. The device is rigidly mounted in the cab of an airport vehicle, and readings are taken by accelerating the vehicle to 50 km/hr and then applying the brakes to the point of wheel lockup. A number of spot measurements are taken at various intervals on each side of the runway centreline, and averaged to provide a single friction value for the entire runway surface. Readings generated by inconsistent deceleration are automatically rejected.

The term used for the friction index at Canadian airports has been changed from the JBI to the Canadian Runway Friction Index (CRFI) to reflect the diverse use of different makes of decelerometers. There has been no change in runway friction testing methods, procedures or calibration methods as a result of this change in terminology. The CRFI is a number from 0.0 to 1.0, with the top value being equivalent to the theoretical maximum deceleration on a dry surface, although it is rarely above 0.8 in practice, and the bottom number indicating zero vehicle deceleration. Runway surface condition reports, including CRFI values, are reported to aircrew by notices to airmen (NOTAM), automatic terminal information systems (ATIS), and tower advisories.

In contrast with the ERD, which is a relatively simple decelerometer device, other more complex friction measuring devices can record surface friction on a continuous basis. The SAAB SFT, for example, is a fixed slip continuous friction measurement device used in Canada and other countries primarily for runway maintenance purposes. The IRV is a variable slip continuous friction measurement device identical to the French Instrument de Mesure Automatique de Glissance (IMAG), except that its output is modified, by the application of harmonization constants, into an interim IRFI. Throughout this report, the term "IRFI" will be used to denote the output of the IRV, with the understanding that neither the IRFI nor the IRV are in final form. Because of the different mechanics of friction measurement between the ERD and the IRV, the conversion from CRFI to IRFI is not straight forward, because the harmonization constants may depend on the type of contamination (snow, ice, slush) as well as the surface friction.

2.2 NRC Falcon 20

The NRC operated Falcon 20 research aircraft, C-FIGD, was tested at the North Bay airport during the five consecutive winters between 1995/1996 and 1999/2000. The aircraft was built by Dassault Aviation and is typical of a small business jet with two General Electric CF700-2D-2 engines, a maximum takeoff weight of about 27,300 lbs and conventional hydraulically actuated flight controls. Leading and trailing edge wing flaps are used for lift augmentation, and wing mounted airbrake panels are hydraulically actuated to dump lift after aircraft touchdown. The aircraft does not have reverse thrust capability, but a drag chute is available for emergency stopping assistance.

The Falcon 20 landing gear is conventional with a steerable nose gear fitted with dual 14.5 x 5.5 14 P.R. aircraft tires which have side-mounted chines to deflect spray. Each main gear is fitted with dual 26 x 6.6 14 P.R. aircraft tires. Tire pressure for all tires is 136 psi. A three disc brake unit is flange mounted to each of the four main wheels, and receives pressure from two independent hydraulic systems.

The anti-skid system on the Falcon 20 is a fully adaptive modulating system which automatically controls applied brake pressure to achieve maximum braking effectiveness and safety under all runway conditions. Wheel speed is used to detect an impending skid. When a wheel deceleration exceeding a preset skid threshold is detected, the anti-skid system will immediately reduce brake pressure to allow the wheel to recover, and then reapply it at a level slightly below the level which caused the wheel deceleration. The system then allows the brake pressure to increase until another rapid wheel deceleration is sensed. If the runway friction coefficient should suddenly decrease, the system automatically becomes more sensitive so that a wheel decelerating at a higher rate will cause adjustment of the skid threshold to a lower value. The anti-skid system is inoperative at aircraft groundspeeds below about 17 knots.

Wheel speed sensors mounted in each wheel axle send signals to the anti-skid control box, which controls anti-skid valves to modulate the brake pressure. Full brake pressure, prior to anti-skid modulation, is 1200 psi. The Falcon 20 is somewhat unique in that both left main gear wheels are controlled by a single anti-skid control channel and associated anti-skid valve, and both right main gear wheels are controlled by a second anti-skid control channel and associated valve. Each channel of the anti-skid control box uses the wheel speed signal indicating the worst skid to control both wheels on that side. It is more usual to have opposite pairs of wheels (i.e. inners and outers) controlled by separate channels. The Falcon 20 anti-skid system is analogue and was developed in the 1960's. It is considered a "Mark II" system, although it has many of the features associated with "Mark III" systems.

The NRC Falcon 20 had an onboard data acquisition system (DAS) in a standard avionics rack mounted on the seat rails in the rear cabin of the aircraft. A NovAtel RT-20 differential global positioning system (DGPS) was the principal source of aircraft position and velocity measurement, and was also used to provide the precise real-time aircraft guidance required to fly consistent precision approaches to landing on the contaminated test sections.

The DAS included all interfaces for the acquisition and recording of typical flight mechanics parameters, including accelerations, angles and rates in three axes, static and dynamic pressures, left and right brake pressures, four main wheel speeds, flight control, trim and throttle positions, and pilot event discrete. Data were recorded at a sample rate of 10 Hz on digital audio tape (DAT) using the onboard data recording system. This was supplemented by manual recording of some parameters such as type of test, configuration, fuel, reported wind direction/speed and pilot qualitative comment.

2.3 NASA B737

The NASA operated B737-100, registration number N-515, was tested at the North Bay airport during the first winter of the JWRFMP in 1995/1996. The aircraft was based at the NASA Langley Research Center, Hampton, Virginia, and was retired following the acquisition of the B757 research aircraft. The B737-100 is a short range narrow body jetliner, fitted with two Pratt and Whitney JT8D-7 turbofan engines with reverse thrust capability. The aircraft has a maximum takeoff weight of about 110,000 lbs, and a maximum authorized landing weight of 89,700 lbs with 40 landing flaps.

The B737 landing gear is conventional with a steerable nose gear fitted with dual 24 x 7.7 16 P.R. type VII aircraft tires. Each dual wheel main gear uses 40 x 14 24 P.R. type VII aircraft tires. Tire inflation pressure is maintained at 155 psi for the main gear tires and 135 psi for the nose gear tires. Anti-skid braking is available on this aircraft in two operational modes, “manual” and “automatic.” For manual anti-skid braking, the pilot uses full brake pedal deflection, in a manner similar to that discussed for the Falcon 20. This permits the anti-skid system to modulate brake pressure to the maximum level commensurate with the tire-surface friction level available. In the automatic mode, the pilot can select one of three levels of deceleration - minimum, medium or maximum, and the brake pressure will be automatically controlled to maintain the constant deceleration level selected. During the JWRFMP, only the manual anti-skid mode was used, with the pilots always attempting to hold full brake pedal deflection.

An extensive instrumentation package was used on board the NASA B737 to monitor the position of flight control surfaces, brake system performance, engine speed and throttle settings, and aircraft acceleration, heading, attitude and forward speed. Although the NASA instrumentation system could provide a maximum data sample rate of 100 samples/sec, most data were recorded and evaluated at 40 samples/sec. A more detailed description of this aircraft and its instrumentation, along with a discussion of previous tests conducted on contaminated runways, can be found in Reference 15.

2.4 FAA B727

The FAA operated B727-100QC, registration number N-40, was tested at the North Bay airport during the second winter of the JWRFMP in 1996/1997 (Reference 6). The aircraft is based at the William J. Hughes Technical Center in Atlantic City, N.J., and is maintained in the cargo configuration to allow for the installation of numerous project equipment racks. The B727-100 is a medium range narrow body jetliner, fitted with three Pratt and Whitney JT8D7 turbofan engines with reverse thrust capability. The aircraft has a maximum takeoff weight of about 160,000 lbs, and a maximum authorized landing weight of 142,500 lbs with 30 landing flaps.

The B727 landing gear is conventional with a steerable nose gear fitted with dual 32 x 11.5-15 12 P.R. type VII aircraft tires. Each dual wheel main gear uses 49 x 17 26 P.R. type VII aircraft tires. Tire inflation pressure is maintained at 145 psi for the main gear tires and 100 psi for the nose gear tires. Anti-skid braking is available on all three gear assemblies, although the nose gear braking system was not utilised during the tests carried out.

The aircraft data acquisition system recorded aircraft accelerations in three axes, commanded and actual brake pressures for all wheels, and positions of flight control surfaces, throttles and nosewheel steering. In addition, both the main and nose gear assemblies were fitted with strain gauges which provided a direct measurement of the forces encountered on each gear assembly. With this installation, the aircraft was limited to ground operations only.

2.5 De Havilland Dash 8

The de Havilland operated Dash 8 Series 200 aircraft was tested at the North Bay airport during the second and third winters of the JWRFMP in 1996/1997 (Reference 4) and in 1997/1998 (Reference 5). This was a developmental flight test aircraft operated by de Havilland (Bombardier Aerospace), fitted with Pratt and Whitney PW123D engines and Hamilton Standard four-bladed 14SF variable pitch propellers. Maximum takeoff weight was 33,000 lbs, and maximum landing weight was 32,400 lbs. All tests were performed with 15 flap.

The Dash 8 aircraft main gear is equipped with dual wheels fitted with Dunlop H31 x 9.75 13P.R. tubeless tires at 86 psi. The nose gear is also equipped with dual wheels which are fitted with 22 x 6.50 10 P.R. tires at 50 psi. The aircraft braking system is a Mark III Hydroair fully adaptive anti-skid braking system which operates in a similar manner to the systems described in the previous paragraphs. The anti-skid system cuts out below about 12 knots.

The data acquisition system on the Dash 8 was an Aydin Vector Programmable Master Unit (PMU) which recorded a series of parameters on hard disc. The aircraft position, provided by a NovAtel RT-20 DGPS, was used to calculate aircraft groundspeed and deceleration.

2.6 NASA B757

The NASA operated B757-200 was tested at the Sawyer airport at Gwinn, Michigan during the winter of 1998/1999, the fourth winter of JWRFMP research. The aircraft is based at the NASA Langley Research Center, Hampton, Virginia. The B757-200 is a medium range narrow body jetliner, fitted with two Pratt and Whitney 2037 turbofan engines with reverse thrust capability. The aircraft has a maximum takeoff weight of 220,000 lbs, and a maximum authorized landing weight of 165,000 lbs with 40 landing flaps.

The B757 landing gear is conventional with a steerable nose gear fitted with dual H31 x 13.0-12 20 P.R. type VII aircraft tires. Each tandem mounted dual wheel main gear truck uses four H40 x 14.5-19 24 P.R. type VII aircraft tires. Tire inflation pressure is maintained at 175 psi for the main gear tires and 150 psi for the nose gear tires. The B757 anti-skid braking system was a digitally implemented, fully adaptive modulating Mark IV system. As with the NASA B737 aircraft, anti-skid braking was available in two operational modes, “manual” and “automatic,” although only the manual anti-skid mode was used during the JWRFMP tests.

An extensive instrumentation package was used on board the NASA B757 to monitor the position of flight control surfaces, brake system performance, engine speed and throttle settings, and aircraft acceleration, heading, attitude and forward speed. Like the NASA B737, the instrumentation system could provide a maximum data sample rate of 100 samples/sec, although most data were recorded and evaluated at 40 samples/sec. A “quick look” capability was also available, with the application of one second averaging to selected data output files. A more detailed description of this aircraft and its instrumentation is given in Reference 12.

2.7 Nav Canada Dash 8

The Nav Canada operated Dash 8 series 100 flight inspection aircraft, registration number C-GCFK, was tested at the North Bay airport during the winter of 2000/2001 (Reference 19). The configuration of this aircraft and the anti-skid braking system is similar to that for the de Havilland Dash 8 described in sub-section 2.5 above.

The test aircraft contained two data acquisition systems (DAS). Nav Canada had a custom DAS, called the Digital Flight Inspection System (DFIS), for the flight inspection role. The DFIS contained interfaces to a real-time differential GPS, a Litton 92 Inertial Navigation System (INS) and Distance Measuring equipment (DME). A second NRC DAS was installed for the purpose of measuring aircraft performance. This DAS consisted of a VME based M68040 system and a PC laptop. The VME computer contained interfaces to the onboard INS, DFIS GPS, Flight Management System (FMS), and anti-skid wheel speed transducers and brake pressures. These data were recorded at a rate of 64hz. The laptop was used as a terminal for the VME computer and for displaying real-time data.

2.8 First Air B727

The First Air operated B727-100, registration number C-GFRB, was similar to the FAA B727 described in paragraph 2.4 above. The landing performance of the First Air B727 was not tested specifically under a dedicated test program, but was recorded under operational conditions at Canadian Arctic airports. Landing data were recorded during the winters of 1998/1999 and 1999/2000 to validate the "CRFI Tables of Recommended Landing Distance" in the Transport Canada AIP. The results of this project are reported in Reference 16.

The instrumentation used to record the landing data was the basic Flight Data Recorder (FDR) and an extended storage quick access recorder (EQAR) built by Dassault. The EQAR was used to record the existing FDR parameters as well as selected parameters from the aircraft GPS, a Trimble 8100.

2.9 Fairchild Dornier 328 Turboprop

The Fairchild Dornier 328-130 Turboprop prototype aircraft (S/N 3003) was tested at the Munich International airport in Germany during the winter of 1999/2000 and at the Erding military airport in Germany during the winter of 2000/2001. This was a developmental flight test aircraft operated by Fairchild Dornier, fitted with Pratt and Whitney PW119B engines. Maximum takeoff weight was 30,840 lbs, and maximum landing weight was 29,160 lbs. All tests were performed in the landing configuration.

The aircraft was fitted with an instrumentation system which recorded flight control surface positions, brake system performance, engine speed and throttle settings, individual wheel speeds, and aircraft acceleration, heading, attitude and forward speed. A minimum data sample rate of 16 samples/sec was available for all recorded parameters. A Honeywell Inertial Reference System and a differential GPS position reference system were also used for these tests.

3.0 ANALYSIS METHODS

The general analysis method used was to compute the aircraft braking coefficient from the equation for aircraft deceleration along the runway during full anti-skid braking runs. The braking coefficients obtained (also called "Mu effective" for full anti-skid braking) were compared to aircraft groundspeed for all runs on each surface condition to determine how the braking coefficients varied with groundspeed on contaminated runway surfaces. The average braking coefficient for each run was then plotted against runway friction index (RFI) to establish an empirical relationship between the two variables. The relationship exhibiting the best correlation, that between braking coefficient and CRFI, was used in the aircraft deceleration equation to establish an aircraft deceleration model as a function of aircraft weight, equivalent airspeed, and CRFI.

The aircraft deceleration model was used for the aircraft with the most test points, namely the Falcon 20 and the Dash 8, to determine aircraft stopping distances for representative aircraft weights, approach speeds and CRFI's. Air distances and delay distances (with safety factors) were added to these stopping distances to obtain the aircraft recommended landing distances. With the same aircraft weights and approach speeds being used to determine aircraft flight manual (AFM) landing distances on uncontaminated surfaces (bare and dry), the recommended landing distances could be determined simply as a function of AFM landing distance and CRFI, thus forming the basis of the CRFI charts.

The following paragraphs contain the equations and aircraft parameters used for the analysis.

3.1 Aircraft Braking Coefficient

The general equation for aircraft acceleration along the runway is:

$$\frac{W}{g}\frac{dV}{dt} = T - D - D_{CONTAM} - W\sin\varepsilon - D_F\,, \text{ and } \; D_F = \mu(W\cos\varepsilon - L)\,,$$

where:

L : Aerodynamic Lift

W : Aircraft Weight

T : Engine Thrust (assumed along the same axis as drag)

D : Aerodynamic Drag

D_{CONTAM} Contamination Drag

D_F : Friction Drag

μ : Friction Coefficient

: Runway Slope (+ve uphill)

V : Velocity Along Runway

g : Gravitational Constant

For small : cos ~ 1, sin ~ , and the general equation for acceleration, in "g" units, becomes:

$$\frac{1}{g}\frac{dV}{dt} = \frac{T}{W} - \frac{D}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \mu(1 - \frac{L}{W}) \tag{1}$$

Setting $\mu = \mu_B$ = aircraft braking coefficient for maximum anti-skid braking, the equation for aircraft braking coefficient becomes:

$$\mu_B = (\frac{T}{W} - \frac{D}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \tag{2}$$

The parameter D_{CONTAM}/W in equation (2) can be set to zero for braking runs on shallow contamination with insignificant drag, but for deep contamination with appreciable drag the parameter D_{CONTAM}/W can be calculated as follows:

$$\frac{D_{CONTAM}}{W} = \frac{T}{W} - \frac{D}{W} - \varepsilon - \mu_R (1 - \frac{L}{W}) - \frac{1}{g}\frac{dV}{dt} \qquad (3)$$

where μ_R is the aircraft rolling friction coefficient with no braking.

Equations for Aerodynamic Lift and Drag are as follows:

$$\begin{aligned} L &= \frac{1}{2}\rho_o V_{EAS}{}^2 S C_L \\ D &= \frac{1}{2}\rho_o V_{EAS}{}^2 S C_D \end{aligned} \qquad (4)$$

where: $_o = 0.002377 slug/ft^3$

V_{EAS} = Equivalent Airspeed (ft/sec) = $1.688 V_{EAS}$ ($knots$)

C_L = Lift Coefficient in Ground Effect, Ground Attitude

C_D = Drag Coefficient in Ground Effect, Ground Attitude, and

S = Wing reference area (ft^2)

For the Falcon 20, S = 441.1 ft^2, and C_L and C_D are 0.30 and 0.132 respectively in the landing configuration (flaps 40 , airbrakes out) and 0.10 and 0.076 respectively in the rejected takeoff (RTO) configuration (flaps 15 , airbrakes out). Also for the Falcon 20, engine thrust at idle power was modelled as a linear function of V_{EAS} (knots):

$$T = 600 - 4.62\, V_{EAS} \quad (lbf) \qquad (5)$$

For the Dash 8 aircraft, S = 585.0 ft^2, and C_L and C_D are 0.0767 and 0.1287 respectively in the landing configuration (flaps 15 , spoilers deployed) with power at flight idle, and 0.0460 and 0.1287 respectively in the landing configuration with discing power. For the Dash 8, engine thrust at idle and with discing power was modelled as a function of V_{EAS} (knots) as follows:

$$\begin{aligned} T_{IDLE} &= 3501.4 - 35.056\, V_{EAS} - 0.32580\, V_{EAS}^2 \quad (lbf) \\ T_{DISCING} &= 662.48 - 18.166\, V_{EAS} - 0.70523\, V_{EAS}^2 \quad (lbf) \end{aligned} \qquad (6)$$

3.2 Aircraft Landing Distance

The aircraft landing distance is defined as the horizontal distance necessary to land and come to a complete stop from a point 50 ft above the landing surface. The runway threshold crossing height (TCH) may be greater or less than 50 ft depending on the glide path intercept point (GPIP) on the runway and the pilot technique in flying the approach. The landing distance (LD) is usually expressed as the sum of three segments: D1, the air distance from 50 feet to aircraft touchdown; D2, the delay (or transition) distance from touchdown to the application of full wheel braking after deployment of lift dump devices; and D3, the braking distance (or stopping distance) from the application of full wheel braking to a complete stop.

Since safety factors are included in the calculation of all landing distances, including individual segments, for the CRFI tables, the notation in this report will include an "R" for "recommended." All quantities annotated with “R” contain safety factors. The equations for the recommended landing distance, LDR, and its segments are as follows:

$$LDR = D1R + D2R + D3R$$

$$\begin{aligned} D1R &= 1.55 \times (V_{G50} - 80)^{1.35} + \mathit{fixed\ distance} + 2 \times \sigma_1 \qquad (\mathit{ft}) \\ D2R &= (V_{G50} - 9.98) \times 1.688 \times 2.96 + 2 \times \sigma_2 \quad (\mathit{ft}) \\ D3R &= (V_{GFB} \times 1.688)^2 \div (64.348 \times ACCR_{AV}) \qquad (\mathit{ft}) \end{aligned} \tag{7}$$

where: V_{G50} = Aircraft V_{REF} groundspeed at 50 ft (knots),

$_1$ = standard deviation of air distance,

$_2$ = standard deviation of delay distance,

V_{GFB} = Aircraft ground speed at the application of full wheel braking (knots), and

$ACCR_{AV}$ = “Recommended” average deceleration (in g units) as a function of W and CRFI at the root mean square (RMS) of the start V_{EAS} and end speed (zero) for full braking, or:

$$ACCR_{AV} = F_1(W, CRFI) + F_2(W, CRFI) \times \frac{V_{EFB}}{\sqrt{2}} + F_3(W, CRFI) \times \frac{V_{EFB}^2}{2} \tag{8}$$

where: F_1, F_2, and F_3 are functions of W and CRFI, and

V_{EFB} = Aircraft equivalent airspeed at the application of full wheel braking (knots)

The actual values of the functions F_1, F_2, and F_3 in equation (8) for average (recommended) deceleration, $ACCR_{AV}$, are dependent on the relationship between aircraft braking coefficient and CRFI, and on the thrust model chosen for the aircraft. The empirical relationship between braking coefficient and CRFI is chosen on the conservative side, and will be shown in sub-section 4.2.1 to have a confidence level of at least 95%. Therefore, the safety factor for the recommended braking distance, D3R, is embedded in the value of $ACCR_{AV}$, and not included as a separate standard deviation. Specific values of this parameter will be shown in section 5.

In determining the recommended air distance, D1R, and the recommended delay distance, D2R, the two sigma safety factor is derived from the distribution of performance landings accomplished with the Falcon 20 during the test periods between 1996 and 1999. Assuming a normal distribution of data, the two sigma safety factor would give an approximate 97.5% confidence level (with only the exceedance part of the curve of concern) for the individual values of D1R and D2R. This means that the probability of exceeding either D1R or D2R would be about 2.5% or 0.025.

Segments D1R, D2R and D3R along with their safety factors are added in equation (7) to give the recommended landing distance LDR. The overall confidence level of landing within the predicted LDR is difficult to determine without making some assumptions on the inter-dependence of exceeding one or more segment distances. For approaches where V_{REF} is high, a strong tailwind component exists, or the runway TCH is well above 50 ft, the root cause of exceeding D1R may also apply to exceeding D2R. If all three segments were totally dependent, the probability of exceeding LDR would be 0.025*1.0*1.0 = 0.025. If all three segments were totally independent, the probability of exceeding LDR would be

0.025*0.025*0.05 = 0.00003. Assuming partial dependence of segment distances, the confidence level of LDR is likely to be at least 99%.

4.0 TEST RESULTS AND DISCUSSION

The following paragraphs present the aircraft test results for all the full anti-skid braking runs carried out during the course of the testing. Appendices A, B and C of this report contain a summary of all the braking runs by aircraft type, with Appendix A covering the NRC Falcon 20, Appendix B covering the Boeing aircraft (NASA B737 and B757, FAA B727), and Appendix C covering the Dash 8 aircraft operated by de Havilland and Nav Canada and the Fairchild Dornier 328 turboprop aircraft. The data in Appendix A is taken from the various reports on the Falcon 20 tests, References 2,3,7,9 and 10; the data in Appendix B is taken from References 6, 11 and 12, and the various flight test notes accompanying the NASA tests; and the data in Appendix C is taken from References 4, 5 and 19.

For each runway surface condition tested, Appendices A, B and C contain a brief surface description, the mean D_{CONTAM}/W parameter where applicable, and the mean CRFI. During the early years of testing (1996 through 1998) the CRFI was measured just prior to, and immediately following aircraft testing, so the mean CRFI shown is the identical number for all of the aircraft test points on that particular surface condition. During the 1999 and 2000 test periods the CRFI was often measured between each aircraft test point, in an attempt to achieve the most accurate comparison, so the mean CRFI shown is specific to the mean aircraft braking coefficient and groundspeed for that test point.

In the next section, the aircraft braking coefficients are shown plotted against aircraft groundspeed to determine the relationship between the two parameters for runway surface conditions which are contaminated, bare and wet, or bare and dry.

4.1 Aircraft Braking Coefficients – Variation with Ground Speed

Extensive tests were performed by NASA in the 1980's with the B727 and B737 aircraft on several types of wet and contaminated runways, reported in Reference 15. For these aircraft, the effective friction coefficient ($_{eff}$) with full application of anti-skid braking (equivalent to the term "aircraft braking coefficient" or "Mu braking" in this report) was measured and compared to aircraft groundspeed for compacted snow and ice covered runway conditions. The results of the tests showed that the variation of $_{eff}$ with aircraft groundspeed was not considered significant. Similarly, for several types of grooved and non-grooved dry runway test surfaces, the aircraft groundspeed had little effect on tire friction performance. On the other hand, for wet surfaces, both aircraft speed and surface macrotexture significantly affected tire friction performance, with decreasing macrotexture and increasing speed generally decreasing the friction level.

The results of the JWRFMP tests on the various aircraft types were consistent with the NASA results. Figure 1 shows the variation of Falcon 20 aircraft braking coefficient with groundspeed for five different surface conditions. From top to bottom, the curves show Mu braking values on a surface which was bare and dry with occasional ice patches, CRFI = 0.49; an ice covered surface with a double application of sand, CRFI = 0.26; a surface covered with compact snow and ice patches, CRFI = 0.25; an ice covered surface with a single application of sand, CRFI = 0.19; and an ice covered surface with no sand, CRFI = 0.10. Each data point represents a full anti-skid braking run, with the mean Mu braking plotted against the mean groundspeed.

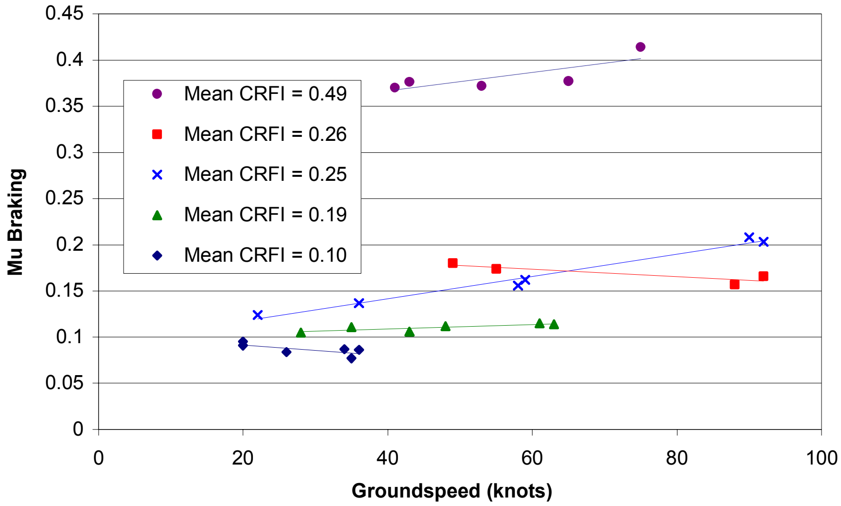

Figure 1 – Falcon 20 Braking Coefficient vs Groundspeed

As expected, the value of Mu braking in Figure 1 decreases with decreasing CRFI. The value of Mu braking does not vary significantly with groundspeed for the surface which is essentially bare and dry, CRFI = 0.49, and for three of the four contaminated surfaces shown. Mu braking decreases with decreasing groundspeed on the surface covered with compact snow and ice patches, CRFI = 0.25. This trend was observed for only three of the 28 contaminated surfaces on which at least four braking runs were done with the Falcon, and because of the low frequency of occurrence is not considered significant.

Figure 2 shows the variation of the NASA B757 aircraft braking coefficient with groundspeed for three contaminated surface conditions. These included a surface covered with one to 1½ inches of loose/ medium compacted snow, CRFI = 0.36; a surface covered with ¾ to one inch of loose moist snow, CRFI = 0.30; and a surface covered with ¼ inch of dry compacted snow, CRFI = 0.28. The curves show the Mu braking values to be consistent, between 0.14 and 0.18, for similar snow covered surface conditions and CRFI values. The value of Mu braking remains constant or decreases slightly with decreasing groundspeed in all three cases.

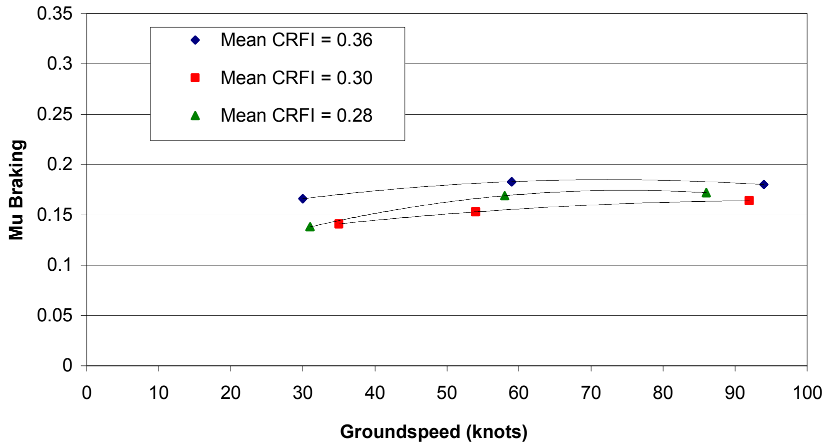

Figure 2 – NASA B757 Braking Coefficient vs Groundspeed

Tests conducted on the de Havilland Dash 8 aircraft in 1997, reported in Reference 4, showed that braking coefficient increased very slightly as groundspeed was reduced on a surface covered with 1½ inches of loose snow, CRFI = 0.29; and that braking coefficient decreased slightly as groundspeed was reduced on a surface covered with 1½ inches of hard packed snow, CRFI = 0.35. Further tests conducted on the de Havilland Dash 8 in 1998, reported in Reference 5, showed that braking coefficient decreased as groundspeed was reduced on a rough ice surface, CRFI = 0.23, and on a sanded moderately smooth ice surface, CRFI = 0.28; and that braking coefficient remained roughly constant with changing groundspeed on a moderately smooth ice surface, CRFI = 0.21.

Figure 3 shows the variation of the Nav Canada Dash 8 aircraft braking coefficient with groundspeed for three contaminated surface conditions. From top to bottom, these include a surface formed of 40% compact snow and 40% ice patches covered with sand and loose snow, CRFI = 0.37; a surface formed of 40% compact snow and 40% ice patches without sand, CRFI = 0.27; and a surface covered with smooth dry ice, CRFI = 0.11. The curves show the Mu braking values to remain constant with changing groundspeed for the two lower friction surfaces, and to increase slightly with decreasing groundspeed for the sanded surface.

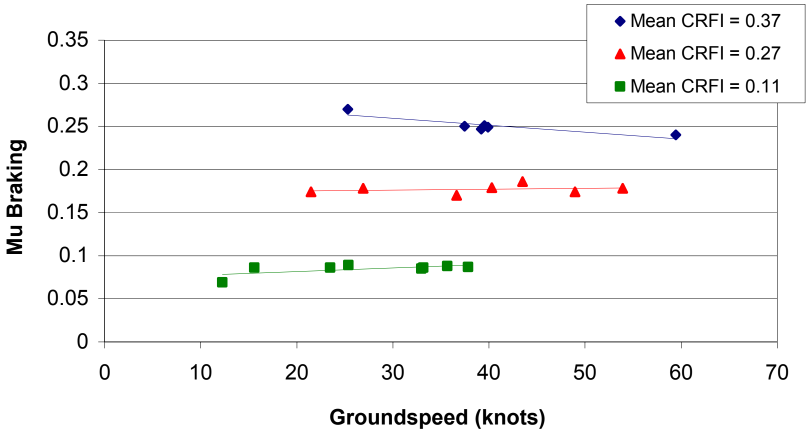

Figure 3 – Nav Canada Dash 8 Braking Coefficient vs Groundspeed

The purpose of the foregoing data review and discussion is to show that the braking coefficient during full anti-skid braking runs for several types of aircraft tested remained essentially independent of aircraft groundspeed on contaminated surfaces. Figure 4 is a summary chart which shows the change in braking coefficient (Mu braking for each test point minus the average Mu braking for each surface condition tested) plotted against groundspeed for all test points with the Falcon 20, Nav Canada and de Havilland Dash 8's and the Boeing aircraft. The fact that the deviations from average Mu braking collapse towards zero for all values of groundspeed is further proof of the invariance of Mu braking with groundspeed for the surfaces tested. The standard error for the y-axis variable in Figure 4 is 0.018, well within the standard error for the plots of Mu braking versus runway friction index (RFI) in the next section. The variation of Mu braking with the RFI will now be examined using a two dimensional analysis independent of groundspeed.

4.2 Aircraft Braking Coefficients – Variation with Runway Friction Index

For many years the use of the runway friction index (RFI) as a tool to predict aircraft braking performance was compounded by the many types of runway friction testers at airports around the world. The results of the JWRFMP tests to compare these friction testers and develop reliable harmonization constants will simplify this problem enormously. In this section, the aircraft braking coefficients obtained from the JWRFMP flight tests will be compared only to the actual RFI's measured by the ground vehicles on the test sections used by the aircraft. No attempt will be made to compare aircraft performance data to RFI's converted from one to another using as yet unfinalized harmonization constants, nor will any attempt be made to compare the RFI's to each other for the same surface condition.

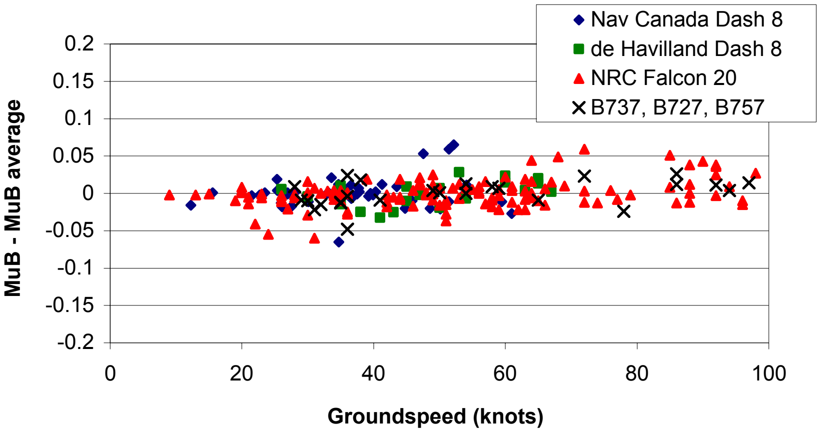

Figure 4 – Change in Braking Coefficient vs Groundspeed for all Aircraft

Direct comparisons were achieved between aircraft braking coefficients and three types of friction test vehicles: the ERD, SAAB SFT and IRV. The ERD was used during all the aircraft tests, so the data for each of the aircraft types tested will be compared to the CRFI. The SAAB SFT was used extensively alongside the Falcon 20 tests during the first four years of testing, but only partially with the other aircraft, so only the Falcon 20 data will be compared to the SFT RFI. The IRV was used with the Falcon 20, the Nav Canada Dash 8 and the Dornier 328 aircraft during the final two years of testing, so the data for these three aircraft will be compared to the IRFI.

Appendices A, B and C contain the tabular data for CRFI's and braking coefficients for all of the aircraft types tested. Appendix C also includes the IRFI data for the Nav Canada Dash 8 and Dornier 328 tests in 2001. Appendix D has been added to include the SFT data for the Falcon 20 tests between 1996 and 1999, and the IRFI data for the Falcon 20 tests in 2000.

4.2.1 Aircraft Braking Coefficient versus CRFI

Figure 5 shows the variation of the Falcon 20 braking coefficient with the measured CRFI. This plot includes 171 full anti-skid braking runs on 45 different test surfaces with CRFI ranging from 0.09 to 0.81. The braking coefficients shown are calculated using equation (2) in section 3.1, and averaged for each run. The contamination drag parameter, D_{CONTAM}/W, is included in equation (2) where applicable, and is calculated using equation (3).

The diamond symbols in Figure 5 depict test points on surfaces with a relatively uniform distribution of contamination, and show a good linear fit with a coefficient of determination $R^2 = 0.90$. The square symbols depict "other" test surface conditions falling into one of the following categories: 1) excessive depth of contamination, 2) highly variable contamination conditions, 3) surface conditions changing rapidly with time, or 4) the length of the aircraft test run was too short to provide consistent data. The square symbols are not included in the linear fit because they are not operationally realistic or they are recorded on variable surface conditions. Details will be provided in the following paragraphs.

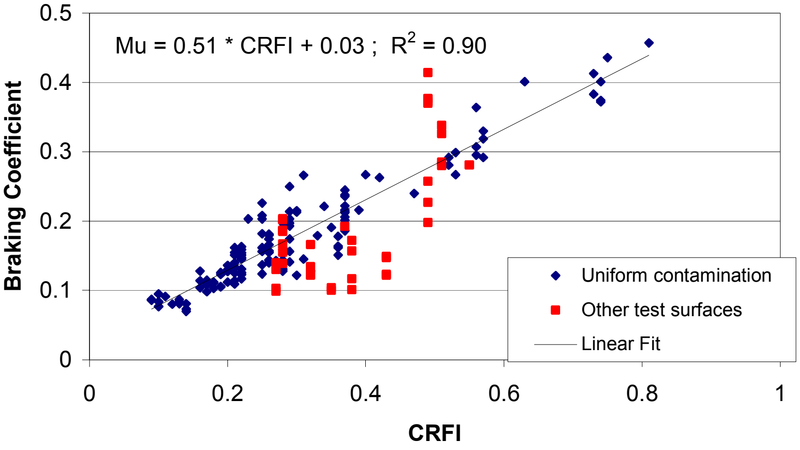

Figure 5 – Falcon 20 Braking Coefficient vs CRFI

Some of the square symbols in Figure 5 between CRFI values of 0.27 and 0.38 show a braking coefficient considerably below the linear fit line. These particular points correspond to tests done on surfaces covered with a deep layer of high density granular snow, specifically flights 96/09, 96/12, 96/21 and 97/07 where the value of D_{CONTAM}/W ranged from 0.072 to 0.110 (see Appendix A). If the value of the parameter D_{CONTAM}/W is added to the braking coefficient for all surfaces with any contamination drag, and this combined braking and drag parameter is plotted against the CRFI, Figure 6 results. The "offending" points have now relocated themselves on or even slightly above the linear fit line. Although the equation for the linear fit is unchanged, the coefficient of determination R^2 has increased to a value of 0.92, indicating a better linear fit for the "uniform" contamination points, some of which have a small amount of contamination drag. The deceleration of the Falcon 20 due to the combined effects of braking and contamination drag correlates well with the output of the ERD, a deceleration device.

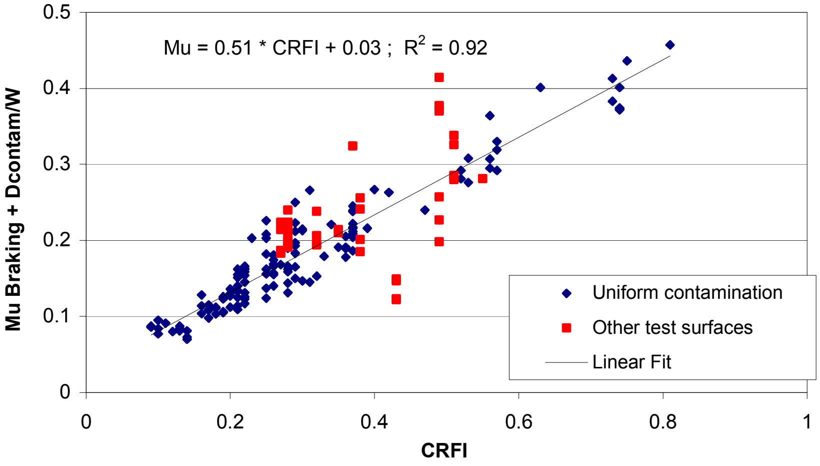

Figure 6 – Falcon 20 Braking Coefficient + D_{CONTAM}/W vs CRFI

Additional "outlying" points depicted by the squares in Figures 5 and 6 occur at CRFI's of 0.43, 0.49 and 0.51. The points well above the line of linear fit, at CRFI's of 0.49 and 0.51, were recorded on flights 97/06 and 98/01 on surfaces mainly bare and dry with a small percentage of ice patches and/or loose snow. In these cases, the CRFI values averaged by the ERD were much lower than the actual surface friction characteristics as seen by the aircraft anti-skid braking system. The CRFI value of 0.49, for example, was averaged from a total of ten ERD readings with a minimum of 0.29 (presumably on an ice patch) and a maximum of 0.68 (on a bare and dry surface). The actual aircraft braking was typical of a bare and dry surface, with braking coefficients from 0.37 to 0.41. This poor correlation illustrates one of the disadvantages of a spot measurement system on a widely varying contaminated surface. In this particular case the error is on the conservative side, with the actual aircraft braking performance better than predicted by the CRFI.

The points below the line of linear fit at a CRFI of 0.49 were recorded on flight 96/19 on a surface initially 70% bare and wet, changing to 70% ice patches. Rapidly changing conditions over the course of testing resulted in aircraft braking performance less than initially predicted by the CRFI. The points well below the line of linear fit at a CRFI of 0.43 were recorded on flight 98/10 on a surface 80% covered with wet snow and 20% bare and wet. Although it is not known for sure, this could be a case where the very poor aircraft braking performance was due to a layer of slush below the wet snow. The ability of the ERD to provide data which adequately predicts aircraft performance on slush covered and/or wet surfaces is not well known, because the ERD is not used operationally for these conditions. Insufficient data was obtained during the JWRFMP to assess the ERD on these types of surface conditions.

Figure 7 shows the variation of the braking coefficients for the Boeing series of aircraft against the measured CRFI. This plot includes 27 full anti-skid braking runs on 11 different test surfaces with the NASA B737 and B757, and the FAA B727. The braking coefficients for the B737 are provided by NASA in Reference 17, and the braking coefficients for the B757 and B727 are calculated using equation (2) in section 3.1, from data provided by NASA and the FAA. The contamination drag, where applicable, is calculated using equation (3) in section 3.1. To provide a direct comparison with the Falcon 20 data in Figure 6, the D_{CONTAM}/W parameter is added to the braking coefficients, even though its value is minimal for these runs.

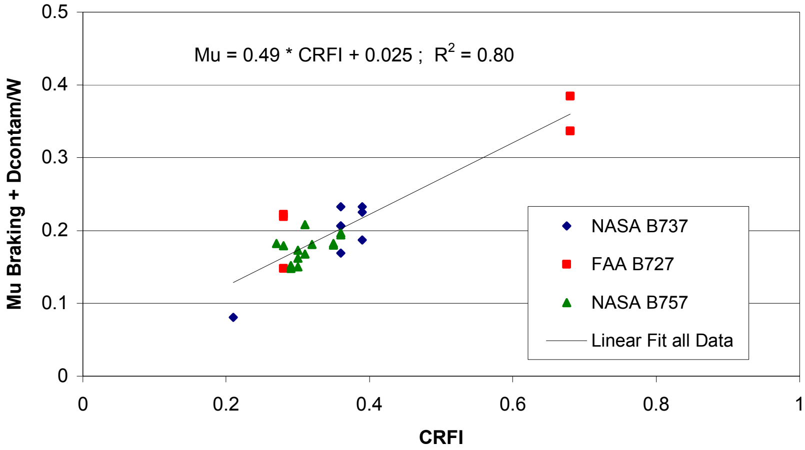

Figure 7 – Boeing Aircraft Braking Coefficient + D_{CONTAM}/W vs CRFI

Although the number of data points in Figure 7 is limited, and the coefficient of determination (R^2 = 0.80) is only fair, the relationship shown between Mu braking and CRFI for the Boeing aircraft is almost identical to that shown for the Falcon in Figure 6. This is not really surprising, considering the fact that these aircraft all have similar types of modulating, adaptive anti-skid braking systems, and the calculation of the braking coefficients removes configuration, aerodynamic and thrust effects unique to each aircraft.

Figure 8 shows the variation of the braking coefficients for the Dash 8 and Dornier 328 aircraft against the measured CRFI. This plot includes 20 full anti-skid braking runs on 5 different test surfaces with the de Havilland Dash 8, 45 full anti-skid braking runs on 10 different test surfaces with the Nav Canada Dash 8, and 12 full anti-skid braking runs on 4 different test surfaces with the Dornier 328. The braking coefficients for the de Havilland Dash 8 were converted by de Havilland from "percentage of dry" values in References 4 and 5 to absolute values in Appendix C and Figure 8. The braking coefficients for the Nav Canada Dash 8 and Dornier 328 were calculated using equation (2) in section 3.1. With the exception of de Havilland flight 2F1597, no turboprop aircraft braking tests were done on surfaces with significant depth of contamination, so the braking coefficients in Figure 8 do not include the effect of any contamination drag.

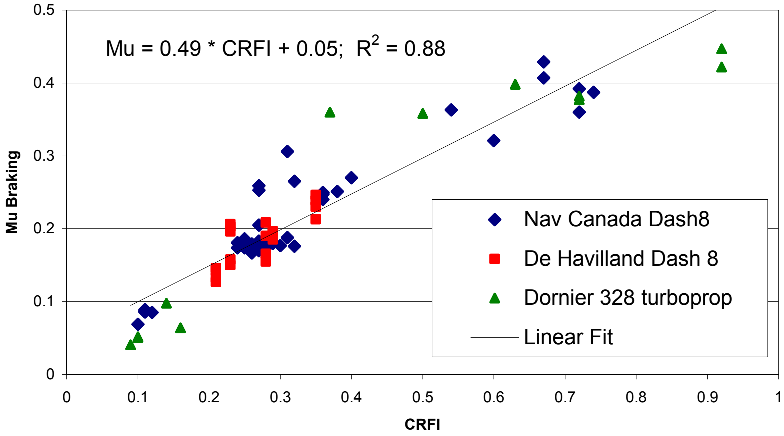

Figure 8 – Dash 8 and Dornier 328 Aircraft Braking Coefficients vs CRFI

The data points in Figure 8 show a good correlation with CRFI, with a coefficient of determination R^2 = 0.88. The relationship between Mu braking and CRFI is very close to that for the Falcon 20 and Boeing aircraft shown in Figures 6 and 7, with the vertical axis intercept slightly higher at 0.05 versus 0.03. The de Havilland Dash 8 data points are consistent with the Nav Canada Dash 8 data points on the surfaces tested with CRFI values between 0.21 and 0.35. The Dornier 328 data points for CRFI values below 0.16 are located below the line of linear fit, but considered to be within the data scatter range.

Figure 9 contains all the data shown in Figures 6, 7 and 8, and summarizes the variation of braking coefficients for all the test aircraft against the measured CRFI. This plot contains a total of 275 full anti-skid braking runs on over 70 different test surface conditions for six different aircraft types. The overall relationship between Mu braking and CRFI is almost identical to that for the individual aircraft, and the correlation is good, with a coefficient of determination R^2 = 0.89.

There are three main "clusters" of braking coefficient data in Figure 9. The first lies between CRFI values of 0.09 and 0.40, representative of winter contaminated surfaces covered with snow and/or ice. Because the large majority of the data lies in this region and correlates well with the CRFI, there is a high level of confidence that the value of the CRFI on snow or ice can be used to predict the aircraft braking coefficient. Note that there is more scatter in the value of Mu braking on surfaces covered with various depths of snow (CRFI between 0.25 and 0.40) than on various types of ice, sanded or unsanded (CRFI between 0.09 and 0.25). Despite this scatter, there is a fairly well defined line of minimum performance braking given by the equation MuR = 0.40 * CRFI + 0.02, where the letter "R" for "recommended" is added to Mu in accordance with the convention established for safety factors in section 3.2. With less than 5% of the 275 test points below the line, this equation provides a confidence level of better than 95% in predicting aircraft braking coefficient from CRFI.

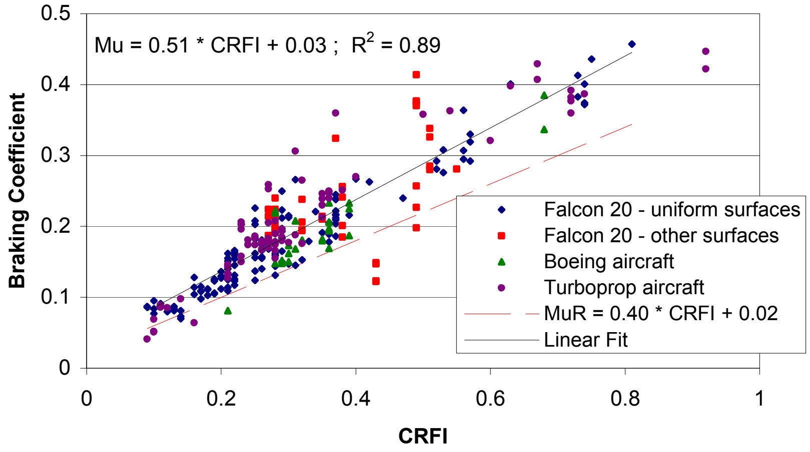

Figure 9 –Braking Coefficients for all Aircraft vs CRFI

The second cluster of data in Figure 9 lies between CRFI values of 0.51 and 0.57, and includes a few surfaces partially covered with compact or loose snow, and only two surfaces which were mostly bare and wet. This limited data appears to correlate well with the CRFI, but as pointed out previously, not enough data was obtained to confirm the ability of the ERD device to predict aircraft braking performance on surfaces covered with slush and/or various depths of water (damp, wet, flooded).

The third cluster of data lies between CRFI values of 0.67 and 0.92, and includes bare and dry surfaces, some with occasional ice patches. The limited number of data points in this region show a good correlation with the CRFI, and together with the results of previous tests conducted on bare and dry surfaces, result in a high level of confidence that the CRFI can at least be used to predict a conservative value of the aircraft braking coefficient on bare and dry surfaces.

Figure 9 can be thought of as a comparison of the braking performance between various anti-skid braking systems of similar vintage, exclusive of aircraft type, plotted against the CRFI. The value of the CRFI can be used to predict the minimum aircraft braking coefficient in general terms using the equation:

$$MuR = 0.40 \times CRFI + 0.02 \tag{9}$$

The "recommended" aircraft braking coefficient, MuR, to be used in the equation for stopping distance, is bounded by a conservative maximum value of 0.34 on a bare and dry surface (CRFI = 0.80) and a minimum value (rolling resistance) of 0.02 on a surface with nil braking (CRFI = 0.0).

Prior to continuing with the development of aircraft stopping distance and the CRFI tables, the relationship between aircraft braking coefficient and other forms of RFI will be shown.

4.2.2 Aircraft Braking Coefficient versus SAAB SFT RFI

Figure 10 shows the variation of the Falcon 20 braking coefficient with the RFI measured by the SAAB SFT. This plot includes 79 aircraft full anti-skid braking runs on 21 different test surfaces for which SFT friction data was available, summarized in Appendix D. It is emphasized that this data includes only the actual RFI's measured by the SFT on the test sections used by the Falcon 20, without any conversions or corrections from corresponding data measured by other friction testers. Some of the early SFT friction data was measured at a vehicle speed of 90 km/hr as opposed to the standard speed of 65 km/hr, but this speed difference is not considered to significantly affect the correlation with aircraft data (Reference 18).

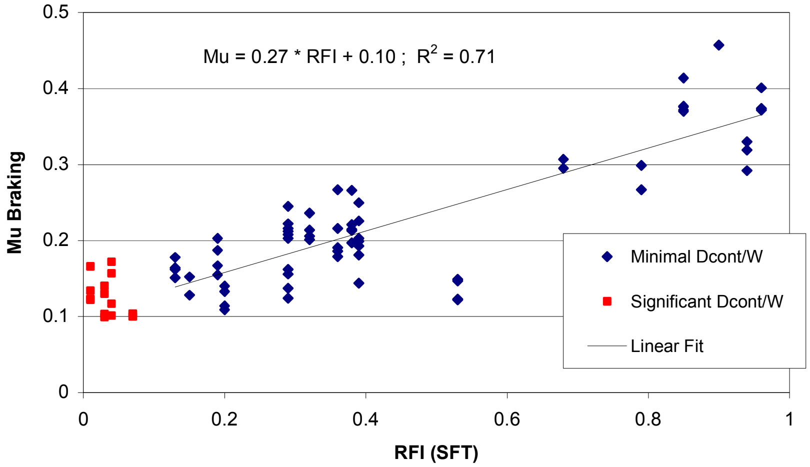

Figure 10 – Falcon 20 Braking Coefficient vs RFI from the SFT

The diamond symbols plotted in Figure 10 depict aircraft braking coefficients on surfaces with a minimal value of the contamination drag parameter, D_{CONTAM}/W, while the square symbols depict braking coefficients on surfaces with a significant value of D_{CONTAM}/W. The SAAB SFT was not a reliable vehicle for friction measurement on surfaces with significant contamination drag, measuring RFI values of only 0.01 to 0.07 on four different surfaces with D_{CONTAM}/W values between 0.072 and 0.110. Equivalent CRFI values were 0.27 to 0.28. These surfaces were all covered with at least one inch of loose granular snow. The data on the other surfaces tested, all with a minimal value of contamination drag, show a poor correlation with the RFI, with a coefficient of determination $R^2 = 0.71$.

The linear fit shown in Figure 10 gives a conservative value of 0.37 for Mu braking on a bare and dry surface (RFI = 1.0), but a poor approximation of 0.10 where no braking should exist at an RFI = 0.0. A second order fit to these data would slightly increase the value of R^2 to 0.73, but would increase the value of Mu braking to 0.15 at an RFI = 0.0. Because of the limited amount of SFT friction data obtained in parallel with the aircraft tests, and its poor correlation with Falcon 20 aircraft data, no attempt was made to predict aircraft stopping distance using the RFI measured by the SAAB SFT. Further work would have to be done to analyze the extensive data obtained during the comparisons of the various friction testers, in an attempt to transfer the good correlation between aircraft performance and ERD (CRFI) to one or more of the other friction testers.

4.2.3 Aircraft Braking Coefficient versus IRFI

Figures 11 and 12 compare correlations of the Falcon 20 braking coefficients with CRFI and IRFI respectively, with data taken from the Falcon 20 test results for the year 2000. The test data, also summarized in Appendix D, was the first raw IRFI data to be measured by the IRFI Reference Vehicle (IRV), and is compared only to the equivalent CRFI data taken in parallel with the aircraft test runs. Figure 11 shows an excellent correlation between Mu braking and CRFI, with a coefficient of determination $R^2 = 0.96$. The linear fit for this single year's data set is close to that obtained for all the aircraft, with only the slope being slightly steeper than that shown in Figure 9.

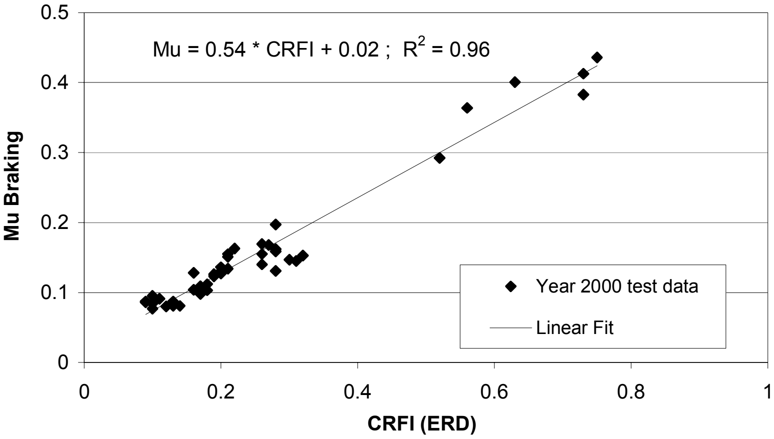

Figure 11 – Falcon 20 Braking Coefficient vs CRFI – Year 2000 Data

The identical set of Falcon 20 braking coefficients as shown in Figure 11 are now plotted against the IRFI in Figure 12. This time the correlation between Mu braking and IRFI is considered only fair, with a coefficient of determination $R^2 = 0.83$. The slope of the linear fit is identical to that shown in Figure 11, but the whole curve is shifted off to the right so that the vertical intercept at IRFI = 0.0 is a value of –0.04. Since negative braking coefficients do not exist in the real world, the only alternative to understanding this relationship is to define a braking coefficient equal to zero at an IRFI = 0.04/0.54 = 0.074. In other words, the minimum value of IRFI would be a slight positive value.

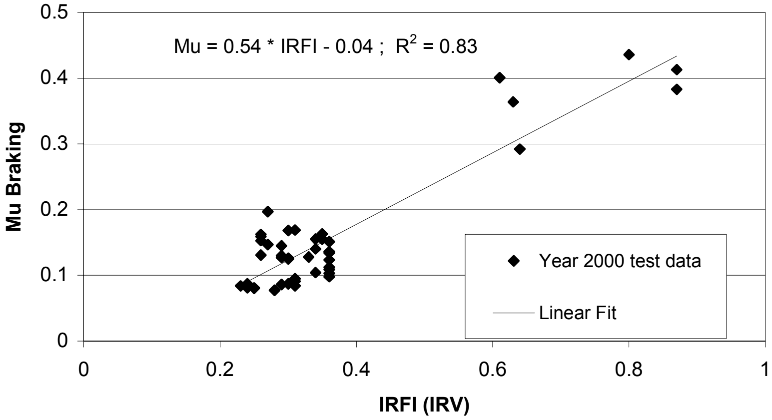

Figure 12 – Falcon 20 Braking Coefficient vs IRFI – Year 2000 Data

Another problem posed in Figure 12 is the range and distribution of IRFI values for the winter contaminated runway conditions at IRFI's below about 0.40. For these conditions, IRFI's range from a minimum of 0.23 to a maximum of 0.36, a range of only 0.13. In comparison, the CRFI's in Figure 11 range from a minimum of 0.09 to a maximum of 0.32, a range of 0.23, almost double that of the IRFI. There are also anomalies in the distribution of Mu braking values for IRFI's below 0.40. For example, the maximum value of Mu braking (0.197) occurs closer to the minimum rather than the maximum value of IRFI. By contrast, the same maximum value of Mu braking occurs at a CRFI only slightly below the maximum CRFI (CRFI's below 0.40), and the minimum value of Mu braking occurs at a CRFI very close to the minimum CRFI, as would be expected.

The correlation between Mu braking and IRFI in Figure 12 is almost totally dependent on the test points plotted for IRFI values above 0.40. If these points are removed from the plot, leaving only the points where IRFI < 0.40, the coefficient of determination R^2 drops to a value of 0.05, indicating essentially zero correlation. By comparison, if the test points plotted for CRFI values above 0.40 are removed from the plot in Figure 11, leaving only the points where CRFI < 0.40, the coefficient of determination R^2 drops to a value of 0.77, still indicating a fair correlation between Mu braking and CRFI for the isolated dataset.

Figure 13 shows the Nav Canada Dash 8 and Dornier 328 aircraft braking coefficients plotted against the IRFI for comparison with the identical braking coefficients plotted against the CRFI in Figure 8. Both IRFI and CRFI readings were taken in parallel with the aircraft tests at the North Bay and Erding airports during the winter of 2001. It is unknown whether or not the IRV was in the same configuration as it was during the 2000 test period with the Falcon, but it appears that the range and distribution of IRFI values for the winter contaminated runway conditions at IRFI's below 0.40 have improved considerably over those obtained for the Falcon 20. For the Dash 8 tests, the IRFI's range from a minimum of 0.13 to a maximum of 0.39, comparable to similar values for the CRFI's in Figure 8, and the maximum and minimum values of the Dash 8 and Dornier 328 braking coefficients are consistent with the maximum and minimum values of the IRFI. The correlation between Mu braking and IRFI is only fair, with an $R^2 = 0.80$, and the linear fit is reasonable, with a slightly high vertical axis intercept at 0.08.

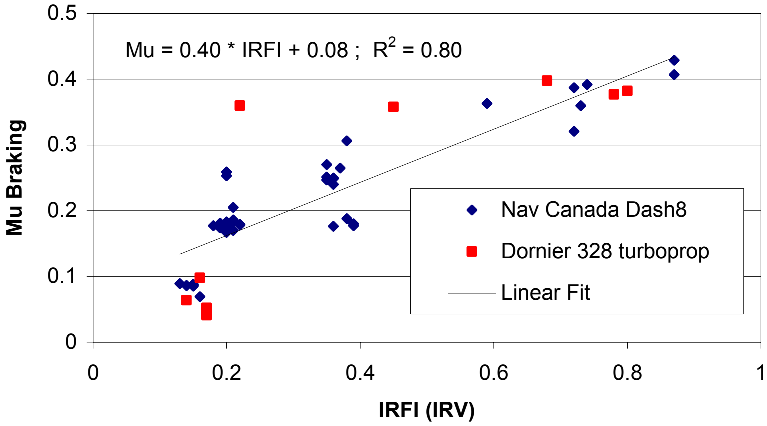

Figure 13 – Nav Canada Dash 8 and Dornier 328 Braking Coefficients vs IRFI

Based on the good correlation between aircraft braking coefficient and the value of the CRFI, the remainder of this report will address the prediction of aircraft stopping distance and landing distance based on the CRFI. Because of the limited amount of IRV measured data obtained with the aircraft tests, and the fact that further work will be accomplished to finalize the IRFI, any attempt to predict aircraft performance based on the IRFI at this time would be premature. However, once the final harmonization constants have been determined, the conversion of CRFI charts into IRFI charts can be accomplished.

5.0 LANDING DISTANCE PREDICTION

In this section, acceleration models will be developed for full anti-skid braking using the relationship between recommended aircraft braking coefficient, MuR, and CRFI given in equation (9). Models will be developed for three thrust conditions: 1) without reverse thrust, 2) with reverse thrust, and 3) with discing propeller thrust. Recommended aircraft braking distance, D3R, will be calculated using the average "recommended" acceleration, $ACCR_{AV}$, from the acceleration models and the aircraft groundspeed, V_{GFB}, at the application of full wheel braking, shown in equation (7). A ratio between the braking distances on contaminated runways and the braking distances on dry runways, called the braking distance ratio (BDR), will be developed and compared to the equivalent NASA stopping distance ratio (SDR), described in Reference 17. Finally, the recommended aircraft landing distance, LDR, will be calculated using equation set (7) over a range of typical aircraft gross weights and approach speeds. The comparison of these LDR's with equivalent AFM landing distances on dry runways will permit the prediction of recommended landing distance in terms of AFM landing distance and CRFI, which is the basis of the CRFI Tables.

5.1 Aircraft Acceleration Models

The acceleration model for an aircraft using full anti-skid braking without reverse thrust is taken from equation (1) with the assumption that the contamination drag, D_{CONTAM}, and runway slope, , are negligible (i.e. zero):

$$\frac{1}{g}\frac{dV}{dt} = \frac{T}{W} - \frac{D}{W} - \mu_B(1 - \frac{L}{W})$$

Substitutions are made into the above equation for Falcon 20 idle thrust T, equation (5); for lift L and drag D, equation (4), with the values of wing area S and C_L and C_D for the Falcon 20 in the landing configuration, and for recommended $_B$ (MuR) in equation (9). The acceleration, in "g" units, can now be expressed in terms of aircraft weight W in lbf, equivalent airspeed V_{EAS} in knots, and CRFI:

$$\frac{1}{g}\frac{dV}{dt} = (\frac{600}{W} - 0.02 - 0.40\times CRFI) + (\frac{-4.62}{W})\times V_{EAS} + (\frac{-0.197644}{W} + \frac{0.02\times 0.449191}{W} + \frac{0.40\times 0.449191\times CRFI}{W})\times V_{EAS}^2 \qquad (10)$$

The acceleration derived from equation (10) is plotted against V_{EAS} in Figure 14 for a representative aircraft weight of 22,000 lbf. Deceleration can be seen to increase with increasing CRFI, and to increase as a second order function of increasing V_{EAS} primarily due to the effects of aerodynamic drag. A slight acceleration occurs below about 20 knots at CRFI = 0.0 because the residual thrust at idle overcomes the rolling friction in this area.

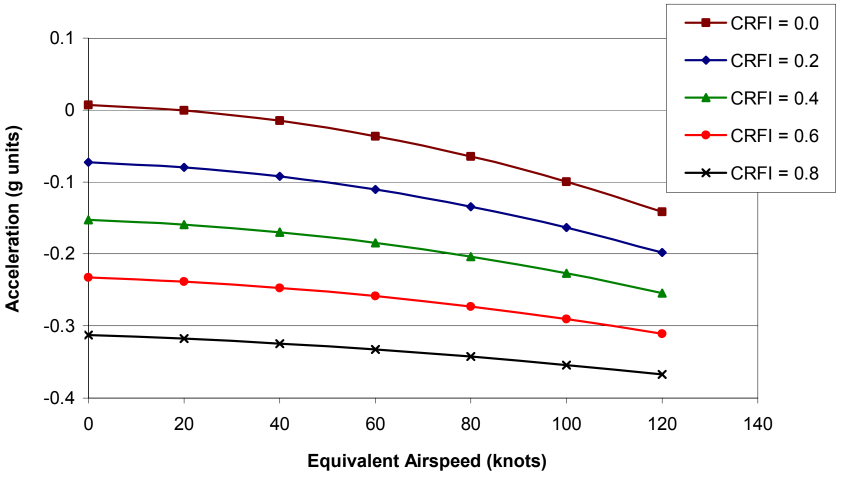

Figure 14 – Aircraft Acceleration Model for Full Anti-skid Braking with no Reverse Thrust, W = 22,000 lbf

The conservative relationship chosen between MuR and CRFI in equation (9) results in a conservative acceleration model which will be applied as a safety factor to the calculation of D3R. The maximum aircraft deceleration shown in Figure 14, for example, on a bare and dry runway (CRFI = 0.80) is about 0.32 to 0.37 g. The equivalent value of MuR, calculated from equation (9) at CRFI = 0.80, is 0.34. If the value of the aircraft braking coefficient had been chosen according to the linear fit in Figure 9, it would be closer to 0.42, and the deceleration on a bare and dry runway would be better than 0.40 g, more typical of actual aircraft performance, but without a safety factor.

The acceleration model for an aircraft using both full anti-skid braking and reverse thrust is taken from equation (1) with D_{CONTAM} and runway slope set to zero, and with reverse thrust T_{REV} expressed as a second order function of V_{EAS} in knots:

$$T_{REV} = 600 + 15 \times V_{EAS} - 0.4 \times V_{EAS}^2 \quad (lbf) \qquad (11)$$

This empirical relationship was chosen to match the results of the analysis in Reference 8, which determined the effect of reverse thrust on the stopping distance of a generic turbojet and turboprop aircraft by comparing the CRFI with the ratio of the stopping distance with reverse thrust to the stopping distance without reverse thrust. Equation (11) provides conservative thrust values of +600 lbf at $V_{EAS} = 0$, about zero lbf at $V_{EAS} = 60$ knots, and about –3300 lbf at $V_{EAS} = 120$ knots. Substitutions are made into equation (1) as before, except with reverse thrust T_{REV} from equation (11). The acceleration, in “g” units, is expressed again in terms of aircraft weight W in lbf, equivalent airspeed V_{EAS} in knots, and CRFI:

$$\frac{1}{g}\frac{dV}{dt} = (\frac{600}{W} - 0.02 - 0.40 \times CRFI) + (\frac{15}{W}) \times V_{EAS} + (\frac{-0.4}{W} + \frac{-0.197644}{W} + \frac{0.02 \times 0.449191}{W} + \frac{0.40 \times 0.449191 \times CRFI}{W}) \times V_{EAS}^2 \qquad (12)$$

Equation (12) expresses the aircraft acceleration for full anti-skid braking and the use of reverse thrust, and is plotted against V_{EAS} in Figure 15 for a representative aircraft weight of 22,000 lbf. Deceleration increases with increasing CRFI, and increases with increasing V_{EAS} up to about 60 knots in a similar manner to that shown for no reverse thrust in Figure 14. The effects of reverse thrust can be seen above 60 knots, where the deceleration increases significantly with increasing airspeed.

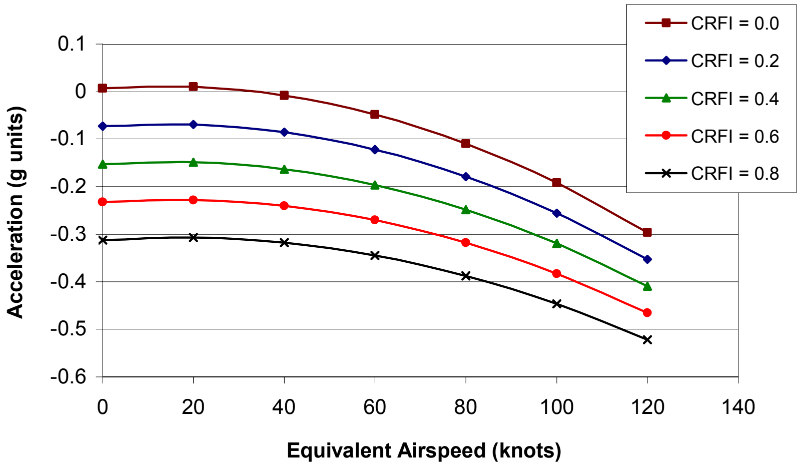

Figure 15 – Aircraft Acceleration Model for Full Anti-skid Braking and Reverse Thrust, W = 22,000 lbf

The third and final acceleration model will be for an aircraft using both full anti-skid braking and discing power from the turboprops. Again, equation (1) is used with D_{CONTAM} and runway slope set to zero, and with discing thrust T_{DISC} expressed as a second order function of V_{EAS} in knots:

$$T_{DISC} = 600 - 15\times V_{EAS} - 0.75\times V_{EAS}^{2} \quad (lbf) \tag{13}$$

Equation (13) for discing thrust is not exactly the same as equation (6) used for the Dash 8 aircraft, but very close to it. Equation (6) was used as a "best estimate" thrust model to extract braking coefficients during the flight test program, whereas equation (13) is a conservative form of discing thrust, accounting for variations in the measurements of discing propeller drag during the Dash 8 calibration flights. Figure 16 shows a comparison of the two.

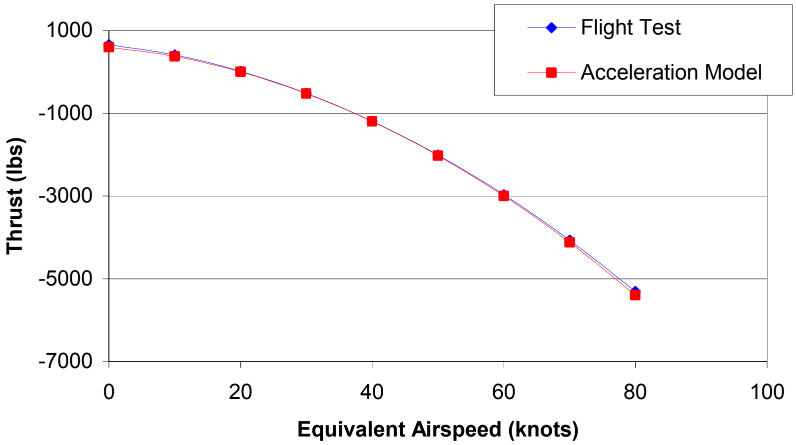

Figure 16 – Dash 8 Models for Discing Propeller Thrust

Substitutions are made into equation (1) as before, except with discing thrust T_{DISC} from equation (13), and with the values of wing area S and C_L and C_D for the Dash 8 aircraft in the landing configuration. The acceleration, in "g" units, is expressed again in terms of aircraft weight W in lbf, equivalent airspeed V_{EAS} in knots, and CRFI:

$$\frac{1}{g}\frac{dV}{dt} = (\frac{600}{W} - 0.02 - 0.40\times CRFI) + (\frac{-15}{W})\times V_{EAS} + (\frac{-0.75}{W} + \frac{-0.25557}{W} + \frac{0.02\times 0.091345}{W} + \frac{0.40\times 0.091345\times CRFI}{W})\times V_{EAS}^{2} \tag{14}$$

Equation (14) expresses the aircraft acceleration for full anti-skid braking and the use of discing power, and is plotted against V_{EAS} in Figure 17 for a representative aircraft weight of 25,000 lbf. The deceleration curves are similar to those with reverse thrust in Figure 15, except that the peak values of V_{EAS} are about 40 knots less.

5.2 Aircraft Braking Distance Ratio

The results of the aircraft acceleration model, without reverse thrust, will now be used to determine the recommended aircraft braking distance, D3R, and braking distance ratio (BDR) for comparison with NASA SDR (Reference 17). Since no credit is given for reverse thrust in the calculation of AFM landing distance on uncontaminated runways, BDR's are only applicable to operations without reverse thrust.

As noted in section 3.2, the "recommended" average acceleration, $ACCR_{AV}$, is calculated from the acceleration equation, in this case equation (10), at the root mean square (RMS) of the equivalent airspeed at the application of full braking, V_{EFB}. This average acceleration is used in equation (7) along with the aircraft ground speed at the application of full braking, V_{GFB}, to calculate D3R. Comparisons between D3R calculated using the average acceleration method and D3R using a numerical integration method showed agreement within a tolerance of less than five percent.

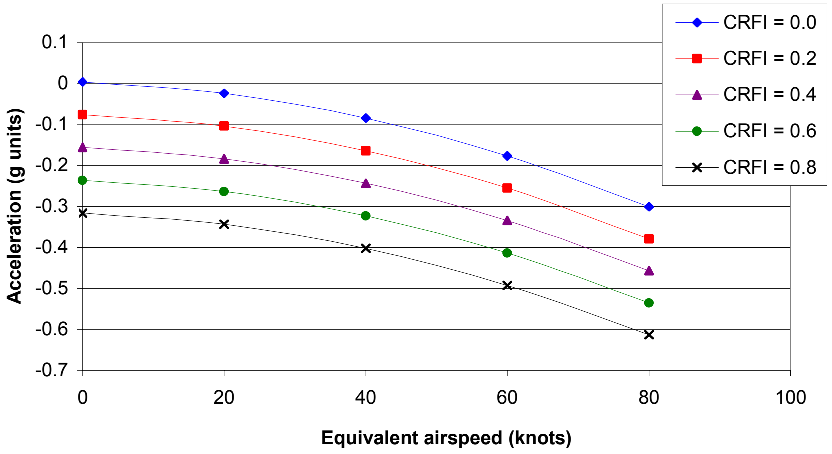

Figure 17 – Aircraft Acceleration Model for Full Anti-skid Braking and Discing Propeller Thrust, W = 25,000 lbf

Table 1 contains some of these calculations for CRFI's between 0.80 and 0.12 at an aircraft gross weight of 20,700 lbf and approach speed V_{E50} = 117.1 knots. The Falcon 20 approach speed, from the AFM, is a direct function of the square root of the aircraft weight in lbf, or:

$$V_{E50} = 0.8141 \times \sqrt{W} \quad (knots)$$

W (lbf)	CRFI	V_{E50} (kts)	PA (ft)	V_{T50} (kts)	HW (kts)	V_{G50} (kts)	AFMLD (ft)	V_{EFB} (kts)	V_{GFB} (kts)	$ACCR_{AV}$ (g)	D3R (ft)	BDR	MuR
20700	0.80	117.1	0	117.1	0	117.1	2400	104	104	-0.3392	1411.6	1.0	0.34
20700	0.70	117.1	0	117.1	0	117.1		104	104	-0.3038	1575.6	1.116	0.30
20700	0.60	117.1	0	117.1	0	117.1		104	104	-0.2685	1782.7	1.263	0.26
20700	0.55	117.1	0	117.1	0	117.1		104	104	-0.2509	1908.2	1.352	0.24
20700	0.50	117.1	0	117.1	0	117.1		104	104	-0.2332	2052.6	1.454	0.22
20700	0.45	117.1	0	117.1	0	117.1		104	104	-0.2156	2220.7	1.573	0.20
20700	0.40	117.1	0	117.1	0	117.1		104	104	-0.1979	2418.8	1.714	0.18
20700	0.35	117.1	0	117.1	0	117.1		104	104	-0.1803	2655.7	1.881	0.16
20700	0.30	117.1	0	117.1	0	117.1		104	104	-0.1626	2944.0	2.086	0.14
20700	0.27	117.1	0	117.1	0	117.1		104	104	-0.1520	3149.1	2.231	0.128
20700	0.25	117.1	0	117.1	0	117.1		104	104	-0.1450	3302.5	2.340	0.12
20700	0.22	117.1	0	117.1	0	117.1		104	104	-0.1344	3562.8	2.524	0.108
20700	0.20	117.1	0	117.1	0	117.1		104	104	-0.1273	3760.5	2.664	0.10
20700	0.18	117.1	0	117.1	0	117.1		104	104	-0.1202	3981.3	2.821	0.092
20700	0.15	117.1	0	117.1	0	117.1		104	104	-0.1097	4365.9	3.093	0.08
20700	0.12	117.1	0	117.1	0	117.1		104	104	-0.0991	4832.7	3.424	0.068

Table 1 – Braking Distance vs CRFI, Falcon 20 AFM LD = 2400 ft

With pressure altitude (PA) and headwind (HW) equal to zero in this case, the approach equivalent airspeed, V_{E50}, true airspeed, V_{T50}, and ground speed, V_{G50}, are all the same. The relationship between the approach speeds and the speeds at the application of full braking were determined from the performance landings accomplished with the Falcon 20 during the test periods between 1996 and 1999. The AFM landing distance (LD) of 2400 ft in Table 1 is defined only for a bare and dry runway with CRFI = 0.80.

The BDR is defined as the ratio of the braking distance on a contaminated runway to the braking distance on a bare and dry runway, or:

$$BDR = D3R_{CONTAM} / D3R_{DRY} \tag{15}$$

The BDR's calculated using equation (15) and corresponding MuR's calculated using equation (9) are shown in the last two columns of Table 1. BDR is plotted against MuR in Figure 18 for a Falcon 20 AFM landing distance of both 2400 ft and 3200 ft. Compared to these plots is a plot showing the NASA estimated stopping distance ratio (SDR) for a two engine transport aircraft taken from Reference 17. All three curves show very close agreement, indicating the BDR to be primarily dependent on the aircraft braking coefficient, and not significantly affected by the AFM landing distance or aircraft type.

Alternatively, BDR can be plotted against CRFI, as shown in Figure 19. The BDR can be seen to increase with decreasing CRFI from an initial value of 1.0 at CRFI = 0.80 to a value of almost 3.5 at CRFI = 0.12, typical of a runway surface covered with ice. Although the BDR concept provides useful information, it can only be used operationally if the dry runway braking distance is known. Since most AFM's provide only the total landing distance from a 50 foot screen height, without specifying the individual segment distances, the CRFI tables of recommended landing distance are considered to be more useful to pilots than BDR tables.

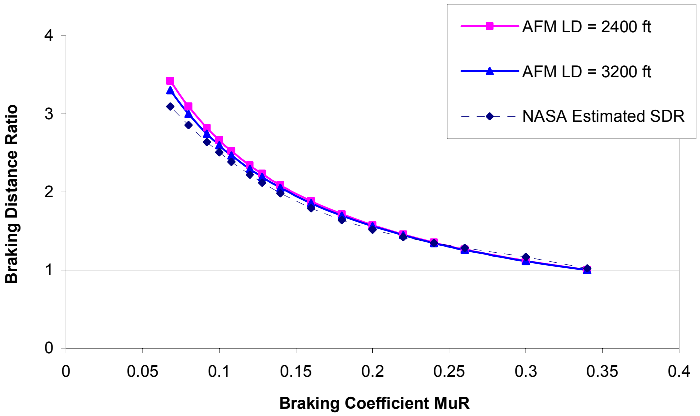

Figure 18 – Braking Distance Ratio vs Braking Coefficient, No Reverse Thrust

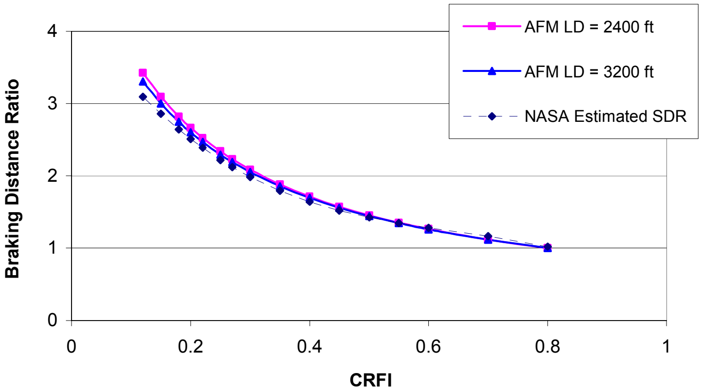

Figure 19 – Braking Distance Ratio vs CRFI, No Reverse Thrust

5.3 Recommended Landing Distance

A model for the prediction of aircraft landing distance on contaminated runways can now be developed by using equation set (7) in section 3.2 for each of the three segments D1R, D2R and D3R. The standard deviations applicable to the equations for D1R and D2R, based on the series of Falcon 20 performance landings, are the distance equivalents of 0.78 seconds at touchdown speed and 0.93 seconds at brake application speed respectively. The equations become:

$$\begin{aligned} D1R &= 1.55\times(V_{G50}-80)^{1.35}+964+(V_{G50}-6.52)\times1.688\times1.56 \quad (ft) \\ D2R &= (V_{G50}-9.98)\times1.688\times2.96+(V_{G50}-13.44)\times1.688\times1.86 \quad (ft) \end{aligned} \qquad (16)$$

The braking distance D3R will be based on the deceleration models shown in section 5.1 for no reverse thrust, reverse thrust, or propeller discing.

5.3.1 Recommended Landing Distance – No Reverse Thrust

Using equation (16) for D1R and D2R, equation (10) for $ACCR_{AV}$ at $V_{EAS} = V_{EFB}/\sqrt{2}$, and equation (7) for D3R and LDR, calculations are made for CRFI's between 0.80 and 0.12. Combinations of aircraft weight, approach speed, pressure altitude and surface wind are selected in the Falcon 20 AFM to give corresponding AFM dry landing distances from 1800 ft to 4000 ft. Table 2 is an example of the calculations made for an AFM LD = 3200 ft, defined only for CRFI = 0.80.

W (lbf)	CRFI	V_{E50} (kts)	PA (ft)	V_{T50} (kts)	HW (kts)	V_{G50} (kts)	AFMLD (ft)	V_{EFB} (kts)	V_{GFB} (kts)	$ACCR_{AV}$ (g)	D3R (ft)	D2R (ft)	D1R (ft)	LDR (ft)
25200	0.80	129.23	6000	141.4	0	141.4	3200	116.08	128.2	-0.3432	2120.4	1058	1720.8	4899.3
25200	0.70	129.23	6000	141.4	0	141.4		116.08	128.2	-0.3081	2362.7	1058	1720.8	5141.5
25200	0.60	129.23	6000	141.4	0	141.4		116.08	128.2	-0.2729	2667.4	1058	1720.8	5446.3
25200	0.55	129.23	6000	141.4	0	141.4		116.08	128.2	-0.2553	2851.3	1058	1720.8	5630.2
25200	0.50	129.23	6000	141.4	0	141.4		116.08	128.2	-0.2377	3062.5	1058	1720.8	5841.3
25200	0.45	129.23	6000	141.4	0	141.4		116.08	128.2	-0.2201	3307.4	1058	1720.8	6086.2
25200	0.40	129.23	6000	141.4	0	141.4		116.08	128.2	-0.2025	3594.8	1058	1720.8	6373.7
25200	0.35	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1849	3937.0	1058	1720.8	6715.9
25200	0.30	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1673	4351.2	1058	1720.8	7130.1
25200	0.27	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1567	4644.4	1058	1720.8	7423.3
25200	0.25	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1497	4862.8	1058	1720.8	7641.7
25200	0.22	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1391	5231.9	1058	1720.8	8010.8
25200	0.20	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1321	5510.8	1058	1720.8	8289.6
25200	0.18	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1250	5821.0	1058	1720.8	8599.9
25200	0.15	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1145	6357.9	1058	1720.8	9136.8
25200	0.12	129.23	6000	141.4	0	141.4		116.08	128.2	-0.1039	7004.0	1058	1720.8	9782.8

Table 2 – Recommended Landing Distance vs CRFI, Falcon 20 AFM LD = 3200 ft, No Reverse Thrust

The only columns in Table 2 which change as a function of CRFI are the acceleration parameter $ACCR_{AV}$, recommended braking distance D3R and recommended landing distance LDR, the other parameters not being dependent on changing runway surface conditions. As CRFI decreases from 0.80, LDR increases because of increases in D3R. D1R and D2R remain constant, because they are dependent only on approach ground speed, as shown in equation (16). The ratio of LDR at a CRFI of 0.12, about

9780 ft, to LDR at a CRFI of 0.80, about 4900 ft, is approximately 2.0, in contrast to the braking distance ratio of about 3.5 for the same CRFI values. The difference is due to the fact that D1R and D2R do not change with CRFI.

Figure 20 plots the LDR's in Table 2 against the corresponding CRFI values for an AFM LD = 3200 ft, and for other AFM LD's between 2000 ft and 4000 ft. This is the graphical representation of the CRFI table of recommended landing distance with no reverse thrust, shown in Table 3.

Table 3 provides recommended landing distances only for CRFI values between 0.60 and 0.18, since CRFI's are not usually measured operationally above 0.60 due to excessive wear and tear on the vehicle. CRFI measurements below 0.18 are normally of short duration, being used primarily as an indication that maintenance must be performed on the runway surface to increase the friction level, rather than being permitted to remain so slippery for any appreciable length of time. The data shown in Table 3 is identical to the data contained in "CRFI TABLE 1" in the latest amendment to the Transport Canada AIP, dated April 18, 2002, and is based on the final analysis of the aircraft test data as described in this report.

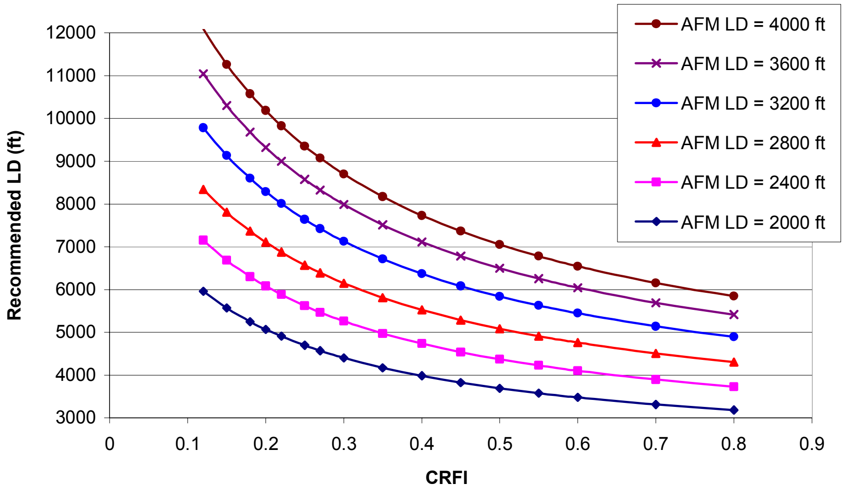

Figure 20 – Recommended Landing Distance vs CRFI, No Reverse Thrust

	Reported CRFI											
AFM LD	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.27	0.25	0.22	0.2	0.18
Unfactored	Recommended Landing Distance (ft), No Reverse Thrust											
1800	3120	3200	3300	3410	3540	3700	3900	4040	4150	4330	4470	4620
2000	3480	3580	3690	3830	3980	4170	4410	4570	4700	4910	5070	5250
2200	3720	3830	3960	4110	4280	4500	4750	4940	5080	5310	5490	5700
2400	4100	4230	4370	4540	4740	4980	5260	5470	5620	5880	6080	6300
2600	4450	4590	4750	4940	5160	5420	5740	5960	6130	6410	6630	6870
2800	4760	4910	5090	5290	5530	5810	6150	6390	6570	6880	7110	7360
3000	5070	5240	5430	5650	5910	6220	6590	6860	7060	7390	7640	7920
3200	5450	5630	5840	6090	6370	6720	7130	7420	7640	8010	8290	8600
3400	5740	5940	6170	6430	6740	7110	7550	7870	8100	8500	8800	9130
3600	6050	6260	6500	6780	7120	7510	7990	8330	8580	9000	9320	9680
3800	6340	6570	6830	7130	7480	7900	8410	8770	9040	9490	9840	10220
4000	6550	6780	7050	7370	7730	8170	8700	9080	9360	9830	10180	10580

Table 3 – CRFI Table of Recommended Landing Distance, No Reverse Thrust

The recommended landing distances shown in the column for CRFI = 0.60 in Table 3 are very close to the factored AFM landing distance for a dry runway, or AFM LD/0.6, also referred to as the landing field length. The consistency between the more traditional method of applying a safety factor of 0.6 to the unfactored AFM LD and the results of the JWRFMP flight tests, with safety factors added, lends credibility to the use of the data in Table 3. This applies at least to a runway surface with a CRFI above 0.60, which is mostly bare and dry, or in the worst case damp.

For runways which are wet, the traditional method of applying a safety factor of AFM LD 1.15/0.6, or AFM LD 1.92, comes closest to the recommended landing distances shown in the column for CRFI = 0.45 in Table 3. Although landing distances on wet surfaces can vary considerably as a function of surface macrotexture and water depth, a CRFI value of 0.45 in the AIP is considered representative of a moderate water depth of 0.02 inches on an asphalt or concrete surface, again showing some consistency between accepted methods and JWRFMP test results.

Although the data in Table 3 has been developed using landing distances from the Falcon 20 AFM, it is considered to be applicable to jet transport aircraft in general for a variety of reasons. First and foremost, the primary relationship used to model the braking distance, shown in equation (9), is applicable to all the aircraft types tested under the JWRFMP, and is more typical of an anti-skid braking system than an aircraft type. Second, the equations used to model the air and delay distances, equation (16), are typical of most aircraft types, being dependent only on approach groundspeed and flare technique to a certain extent. Third, the braking distance ratio comparisons in Figure 19, which are simply another method of showing the same aircraft performance results, are consistent between the NASA tests and the JWRFMP tests. Fourth, the data in Table 3 is consistent with traditional methods of applying safety factors to jet transport landing distances. Finally, major differences between aircraft types are accounted for by entering Table 3 with the specific aircraft AFM LD, and making adjustments for runway friction as a ratio to that quantity.

5.3.2 Recommended Landing Distance – With Reverse Thrust

The acceleration model for an aircraft using reverse thrust is described in section 5.1 and shown in equation (12). This equation, along with equation (16), is used to calculate recommended landing distances with reverse thrust for CRFI's between 0.80 and 0.12. The same combinations of Falcon 20 aircraft parameters, with corresponding AFM landing distances from 1800 ft to 4000 ft, are used for these calculations, the difference this time being that the values of D3R and LDR include the deceleration effects of reverse thrust whereas the AFM landing distances do not.

Table 4 is an example of the calculations made for an AFM LD = 3200 ft, and is the same as Table 2, except that the three columns for PA, V_{T50} and HW have been deleted, and three columns have been added for $ACCR_{AV}$ (Rev), D3R (Rev) and LDR (Rev), the notation (Rev) meaning the inclusion of reverse thrust. A direct comparison can be made between these parameters and the corresponding parameters calculated without reverse thrust. At a CRFI = 0.80, for example, the LDR with reverse thrust is only about 240 feet less than the LDR with no reverse thrust, whereas for a CRFI = 0.12, the LDR with reverse thrust is over 2000 feet less than the LDR with no reverse thrust.

W (lbf)	CRFI	VE50 (kts)	VG50 (kts)	AFMLD (ft)	VEFB (kts)	VGFB (kts)	ACCRAV (g)	D3R (ft)	D2R (ft)	D1R (ft)	LDR (ft)	ACCRAV Rev (g)	D3R Rev (ft)	LDR Rev (ft)
25200	0.80	129.2	141.4	3200	116.1	128.2	-0.3432	2120.4	1058	1720.8	4899.3	-0.3863	1884.2	4663.0
25200	0.70	129.2	141.4		116.1	128.2	-0.3081	2362.7	1058	1720.8	5141.5	-0.3511	2073.0	4851.9
25200	0.60	129.2	141.4		116.1	128.2	-0.2729	2667.4	1058	1720.8	5446.3	-0.3159	2304.0	5082.8
25200	0.55	129.2	141.4		116.1	128.2	-0.2553	2851.3	1058	1720.8	5630.2	-0.2983	2439.9	5218.8
25200	0.50	129.2	141.4		116.1	128.2	-0.2377	3062.5	1058	1720.8	5841.3	-0.2807	2592.9	5371.7
25200	0.45	129.2	141.4		116.1	128.2	-0.2201	3307.4	1058	1720.8	6086.2	-0.2631	2766.3	5545.2
25200	0.40	129.2	141.4		116.1	128.2	-0.2025	3594.8	1058	1720.8	6373.7	-0.2455	2964.6	5743.5
25200	0.35	129.2	141.4		116.1	128.2	-0.1849	3937.0	1058	1720.8	6715.9	-0.2279	3193.5	5972.4
25200	0.30	129.2	141.4		116.1	128.2	-0.1673	4351.2	1058	1720.8	7130.1	-0.2103	3460.7	6239.6
25200	0.27	129.2	141.4		116.1	128.2	-0.1567	4644.4	1058	1720.8	7423.3	-0.1998	3643.7	6422.5
25200	0.25	129.2	141.4		116.1	128.2	-0.1497	4862.8	1058	1720.8	7641.7	-0.1927	3776.8	6555.6
25200	0.22	129.2	141.4		116.1	128.2	-0.1391	5231.9	1058	1720.8	8010.8	-0.1822	3995.7	6774.5
25200	0.20	129.2	141.4		116.1	128.2	-0.1321	5510.8	1058	1720.8	8289.6	-0.1751	4156.3	6935.2
25200	0.18	129.2	141.4		116.1	128.2	-0.1250	5821.0	1058	1720.8	8599.9	-0.1681	4330.4	7109.2
25200	0.15	129.2	141.4		116.1	128.2	-0.1145	6357.9	1058	1720.8	9136.8	-0.1575	4620.7	7399.5
25200	0.12	129.2	141.4		116.1	128.2	-0.1039	7004.0	1058	1720.8	9782.8	-0.1470	4952.7	7731.5

Table 4 – Recommended Landing Distance vs CRFI, Falcon 20 AFM LD = 3200 ft, with Reverse Thrust

As mentioned in sub-section 5.1, an analysis was done in Reference 8 to determine the effect of reverse thrust on the stopping distance of a generic turbojet and turboprop aircraft. This analysis was based on the fact that the ratio of the stopping distance with reverse thrust to the stopping distance without reverse thrust varied predictably with the CRFI. Since the reverse thrust acceleration model in this report was patterned after this analysis, the aircraft stopping distances resulting from both methods agree well. However, the results of the reverse thrust acceleration model are used in the final CRFI table because they are slightly more conservative at the lower CRFI's than those obtained using the other method.

Figure 21 plots the LDR (Rev) values in Table 4 against the corresponding CRFI values for an AFM LD = 3200 ft, and for other AFM LD's between 2000 ft and 4000 ft. This is the graphical representation of the CRFI table of recommended landing distance with reverse thrust, shown in Table 5.

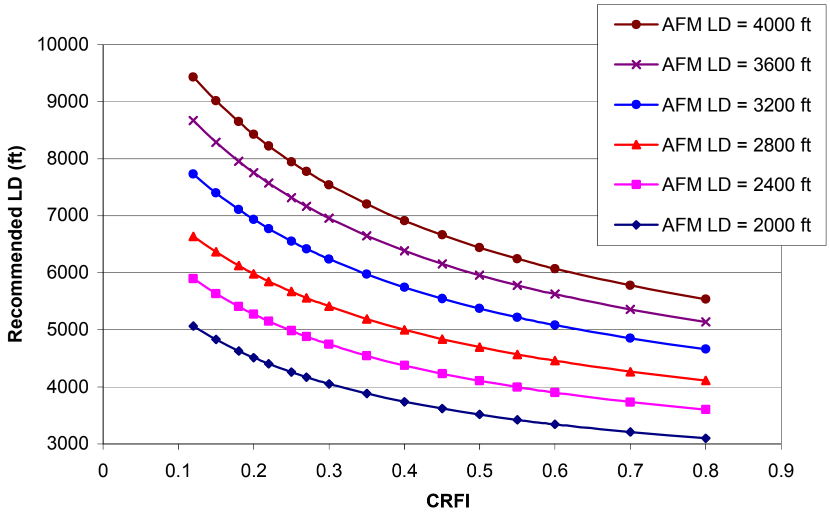

Figure 21 – Recommended Landing Distance vs CRFI, with Reverse Thrust

A direct comparison between Figures 20 and 21 (and between Tables 3 and 5) shows the effect of reverse thrust on recommended landing distances for equivalent values of AFM LD and CRFI. As noted above, the use of reverse thrust does not significantly reduce the LDR for uncontaminated runways with high CRFI values. The effect of reverse thrust becomes more evident as the CRFI values decrease and the AFM LD values increase.

	Reported CRFI											
AFM LD	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.27	0.25	0.22	0.2	0.18
Unfactored	Recommended Landing Distance (ft), With Reverse Thrust											
1800	3010	3080	3160	3250	3350	3480	3630	3730	3810	3930	4030	4130
2000	3340	3420	3520	3620	3740	3880	4050	4170	4260	4400	4510	4630
2200	3570	3660	3760	3880	4020	4170	4360	4490	4590	4750	4870	5000
2400	3900	4000	4110	4230	4380	4550	4750	4880	4980	5150	5270	5410
2600	4200	4300	4420	4560	4710	4890	5100	5240	5350	5520	5650	5790
2800	4460	4570	4700	4840	5000	5190	5410	5560	5670	5850	5980	6130
3000	4740	4860	5000	5160	5340	5550	5790	5950	6070	6270	6420	6580
3200	5080	5220	5370	5550	5740	5970	6240	6420	6560	6770	6940	7110
3400	5350	5500	5660	5850	6060	6310	6590	6790	6930	7170	7340	7530
3600	5620	5780	5960	6160	6390	6650	6960	7170	7320	7570	7750	7950
3800	5890	6060	6250	6460	6700	6980	7310	7540	7700	7970	8160	8380
4000	6070	6250	6440	6660	6910	7210	7540	7780	7950	8220	8430	8650

Table 5 – CRFI Table of Recommended Landing Distance, With Reverse Thrust

5.3.3 Recommended Landing Distance – With Propeller Discing

The aircraft acceleration model for full anti-skid wheel braking with discing power for a turboprop aircraft is given in equation (14) and shown in Figure 17. The "recommended" average acceleration with discing power, $ACCR_{AV}$ (Disc), is calculated from equation (14), at $V_{EAS} = V_{EFB}/\sqrt{2}$, and used in equation (7) along with the aircraft ground speed at the application of full braking, V_{GFB}, to calculate the braking distance with discing, D3R (Disc). Equation (16) is again used for D1R and D2R.

Recommended landing distances, LDR (Disc), are calculated for CRFI's between 0.80 and 0.12, using combinations of aircraft weight, approach speed, pressure altitude and surface wind, selected this time from the Dash 8 AFM to give corresponding AFM landing distances from 1200 ft to 2000 ft. Table 6 is an example of the calculations made for an AFM LD = 1800 ft, using an aircraft gross weight of 33,500 lbf and approach speed V_{E50} = 100.7 knots. The Dash 8 approach speed, from the AFM, is a direct function of the square root of the aircraft weight in lbf, or:

$$V_{E50} = 0.55 \times \sqrt{W} \quad (knots)$$

W (lbf)	CRFI	VE50 (kts)	PA (ft)	VT50 (kts)	HW (kts)	VG50 (kts)	AFMLD (ft)	VEFB (kts)	VGFB (kts)	ACCRAV Disc (g)	D3R Disc (ft)	D2R (ft)	D1R (ft)	LDR Disc (ft)
33500	0.80	100.7	6000	110.1	0	110.1	1800	87.5	97	-0.4612	902.6	803.8	1390.4	3096.9
33500	0.70	100.7	6000	110.1	0	110.1		87.5	97	-0.4216	987.3	803.8	1390.4	3181.6
33500	0.60	100.7	6000	110.1	0	110.1		87.5	97	-0.3820	1089.6	803.8	1390.4	3283.9
33500	0.55	100.7	6000	110.1	0	110.1		87.5	97	-0.3622	1149.2	803.8	1390.4	3343.4
33500	0.50	100.7	6000	110.1	0	110.1		87.5	97	-0.3425	1215.6	803.8	1390.4	3409.8
33500	0.45	100.7	6000	110.1	0	110.1		87.5	97	-0.3227	1290.1	803.8	1390.4	3484.4
33500	0.40	100.7	6000	110.1	0	110.1		87.5	97	-0.3029	1374.4	803.8	1390.4	3568.7
33500	0.35	100.7	6000	110.1	0	110.1		87.5	97	-0.2831	1470.5	803.8	1390.4	3664.8
33500	0.30	100.7	6000	110.1	0	110.1		87.5	97	-0.2633	1581.1	803.8	1390.4	3775.3
33500	0.27	100.7	6000	110.1	0	110.1		87.5	97	-0.2514	1655.8	803.8	1390.4	3850.0
33500	0.25	100.7	6000	110.1	0	110.1		87.5	97	-0.2435	1709.6	803.8	1390.4	3903.8
33500	0.22	100.7	6000	110.1	0	110.1		87.5	97	-0.2316	1797.2	803.8	1390.4	3991.5
33500	0.20	100.7	6000	110.1	0	110.1		87.5	97	-0.2237	1860.8	803.8	1390.4	4055.1
33500	0.18	100.7	6000	110.1	0	110.1		87.5	97	-0.2158	1929.1	803.8	1390.4	4123.4
33500	0.15	100.7	6000	110.1	0	110.1		87.5	97	-0.2039	2041.4	803.8	1390.4	4235.7
33500	0.12	100.7	6000	110.1	0	110.1		87.5	97	-0.1920	2167.7	803.8	1390.4	4361.9

Table 6 – Recommended Landing Distance vs CRFI, Dash 8 AFM LD = 1800 ft, with Discing Power

Because of the limited range of AFM LD's for the Dash 8, a separate CRFI chart is not needed. Instead, the results of the JWRFMP testing on the Dash 8 aircraft can be integrated quite well into the CRFI chart for jet aircraft with reverse thrust (Table 5). At the lower CRFI values, the LDR's with discing power are very close to the LDR's with reverse thrust, at equivalent AFM LD's. Figure 22 shows this to be the case at a CRFI = 0.18 for AFM LD's of 1800 ft and 2000 ft. At the higher CRFI values, on the other hand, the LDR's with discing power are higher than the LDR's with reverse thrust, at equivalent AFM LD's. At a CRFI of 0.6, for example, Figure 22 shows the LDR with discing power to be about 300 ft higher than the LDR with reverse thrust for AFM LD's of 1800 ft and 2000 ft.

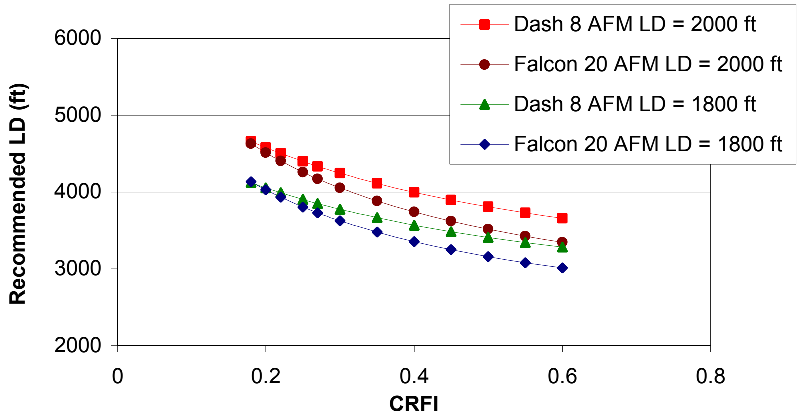

Figure 22 – Comparison of Recommended Landing Distances for Discing vs Reverse Thrust

The differences between the LDR's calculated with discing power as opposed to reverse thrust are partly due to differences in the acceleration models used, and partly due to the fact that the AFM LD itself contains the effects of discing power for propeller aircraft, but not the effects of reverse thrust for jet aircraft. In any case, the differences are small, and can be resolved by setting the LDR's with discing power at CRFI = 0.60 approximately equal to the factored AFM LD for jet aircraft, consistent with the trend noted in sub-section 5.3.1, and shown in Table 7. The LDR's with discing power for CRFI values between 0.60 and 0.18 are adjusted slightly to provide a smooth transition from the corrected value at CRFI = 0.60 to the uncorrected value at CRFI = 0.18 and lower.

	Reported CRFI											
AFM LD	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.27	0.25	0.22	0.2	0.18
Unfactored	Recommended Landing Distance (ft), With Reverse/Discing Thrust											
1200	2000	2040	2080	2120	2170	2220	2280	2340	2380	2440	2490	2540
1400	2340	2390	2440	2500	2580	2660	2750	2820	2870	2950	3010	3080
1600	2670	2730	2800	2880	2970	3070	3190	3280	3360	3460	3540	3630
1800	3010	3080	3160	3250	3350	3480	3630	3730	3810	3930	4030	4130
2000	3340	3420	3520	3620	3740	3880	4050	4170	4260	4400	4510	4630
2200	3570	3660	3760	3880	4020	4170	4360	4490	4590	4750	4870	5000
2400	3900	4000	4110	4230	4380	4550	4750	4880	4980	5150	5270	5410
2600	4200	4300	4420	4560	4710	4890	5100	5240	5350	5520	5650	5790
2800	4460	4570	4700	4840	5000	5190	5410	5560	5670	5850	5980	6130
3000	4740	4860	5000	5160	5340	5550	5790	5950	6070	6270	6420	6580
3200	5080	5220	5370	5550	5740	5970	6240	6420	6560	6770	6940	7110
3400	5350	5500	5660	5850	6060	6310	6590	6790	6930	7170	7340	7530
3600	5620	5780	5960	6160	6390	6650	6960	7170	7320	7570	7750	7950
3800	5890	6060	6250	6460	6700	6980	7310	7540	7700	7970	8160	8380
4000	6070	6250	6440	6660	6910	7210	7540	7780	7950	8220	8430	8650

Table 7 – CRFI Table of Recommended Landing Distance, With Reverse/Discing Thrust

The result of the above calculations is the CRFI Table of Recommended Landing Distance, with Reverse /Discing Thrust shown in Table 7. The data in Table 7 is identical to the data contained in "CRFI TABLE 2" in the latest amendment to the Transport Canada AIP, dated April 18, 2002.

5.3.4 Limitations of the CRFI Tables

As stated in the Transport Canada AIP, the recommended landing distances in the CRFI Tables are based on standard pilot techniques for a minimum distance landing from a screen height of 50 feet. These techniques include a stabilized approach at V_{REF} using a three degree glideslope to 50 feet or less, a firm touchdown, minimum delay to nose lowering and deployment of ground lift dump devices, and sustained application of full anti-skid wheel braking until stopped. Significant deviations to these landing techniques, such as a high approach speed or extended flare, may result in actual landing distances in excess of the CRFI table distances, even with the built-in safety factors.

On the other hand, and because of the inclusion of safety factors, minor deviations in landing techniques, such as a *slightly* extended flare, late application of reverse thrust or less than full anti-skid braking will result in landing distances longer than optimal, but still within the CRFI table of recommended distances. This was demonstrated during the First Air B727 aircraft landings (Reference 16), where 25 out of 26 operational landings were within the CRFI table recommended landing distance, with the only exception being a landing with a very extended flare.

The downside of the CRFI tables for some aircraft types may be that the safety factors provide recommended landing distances which are overly conservative, resulting in some additional economic penalties. Any changes made to the safety factors applied to air distance D1R and delay distance D2R should be carefully considered in view of the fact that the CRFI table landing distances are approximately equal to the factored AFM landing distances at CRFI's of 0.60 and above. Any reductions made to the CRFI table safety factors and recommended landing distances could not be used for aircraft dispatch, for example, where the governing requirement is the landing field length (factored AFM landing distance) at the destination.

The safety factor applied to the recommended braking distance, D3R, is embedded in the relationship between the "recommended" braking coefficient, MuR, and CRFI shown in equation (9). The question may be asked "how much of a safety factor is applied to the recommended braking distance D3R over and above the braking distance D3 which would be obtained by using the linear fit relationship for Mu versus CRFI?" The answer can be obtained by examining Figure 9 and using Table 2 to obtain the comparative braking distances.

In Figure 9, for example, a horizontal line at Mu = 0.18 would cross the linear fit line (Mu = 0.51*CRFI + 0.03) at CRFI = 0.3, and would cross the "recommended" line (MuR = 0.40*CRFI + 0.02) at CRFI = 0.4. This means that the braking performance without a safety factor at CRFI = 0.3 would be the same as the braking performance with a safety factor at CRFI = 0.4. From Table 2, the braking distance D3R for the latter condition at CRFI = 0.4 would be 3595 ft, also equal to the braking distance D3 for the former condition (no safety factor) at CRFI = 0.3. But the recommended braking distance D3R at CRFI = 0.3, also from Table 2, is 4351 ft. The safety factor, at least for an AFM LD = 3200 ft and CRFI = 0.3, is (4351-3595)/3595 = 21%. When applied to the overall landing distance, LDR, the safety factor is only about 12%, 7130 ft vs 6374 ft.

The point of the foregoing analysis is to show that there is a relatively small price to pay for a safety factor which increases the confidence level of landing within the recommended distance from about 50% to well over 95%, and any attempt to make adjustments to the CRFI table safety factors is not recommended.

6.0 CONCLUSIONS

The braking performance of eight aircraft (six different aircraft types), all with similar anti-skid braking systems, was evaluated on winter contaminated runway surface conditions under the JWRFMP over the six year period between 1996 and 2001. A total of 275 full anti-skid braking runs were conducted on over 70 different runway surface conditions.

For all aircraft tested, the aircraft braking coefficient during full anti-skid braking remained essentially independent of aircraft groundspeed on contaminated surfaces.

Comparisons were made between aircraft braking performance and various methods of measuring runway friction index. The best correlation obtained was between the aircraft braking coefficients and the CRFI, measured by the Transport Canada ERD. This correlation was considered to be good enough to used for the prediction of aircraft braking performance based on measured CRFI.

Each of the three major classes of aircraft tested (business jet, medium transport and turboprop), showed a similar relationship between aircraft braking coefficient and the CRFI.

Insufficient data was obtained during the JWRFMP on slush covered and/or wet runway surfaces to verify the ability of the ERD, or other friction measurement devices, to predict aircraft braking performance on these surfaces.

For the limited data collected, the Falcon 20 aircraft braking coefficients did not correlate well with the runway friction index measured by the SAAB Surface Friction Tester.

The correlation between the Falcon 20 aircraft braking coefficients and the interim IRFI, measured by the IRV during the year 2000 test period, was poor. The correlation between the Dash 8 and Dornier 328 aircraft braking coefficients and the interim IRFI, measured by the IRV during the year 2001 test period, was fair. Pending further analysis of the test results of the various ground friction measurement devices, the IRFI has the potential to be used as a basis for the prediction of aircraft braking performance.

Based on a conservative relationship selected between aircraft braking coefficient and CRFI, acceleration models were developed for full anti-skid braking with and without reverse thrust, and with propeller discing.

The braking distance ratio chart developed using the acceleration model without reverse thrust was almost identical to the equivalent chart developed by NASA from tests in the 1980's.

The CRFI tables of recommended landing distance with and without reverse thrust were developed using Falcon 20 AFM data and a generic reverse thrust model. The CRFI table with reverse thrust was expanded to include the effects of propeller discing, using data for the Dash 8 aircraft. Based on the methods used to develop the CRFI tables, they are considered to be independent of aircraft type.

7.0 RECOMMENDATIONS

Analysis of all the existing data for the ground friction measurement devices should be expedited to determine the final configuration of the IRV and the final version of the IRFI. After acceptance of the IRFI by the JWRFMP member countries, the CRFI tables should be converted into IRFI tables by analysis or further flight testing as required.

8.0 ACKNOWLEDGEMENTS

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APPENDIX A - SUMMARY OF FULL ANTI-SKID BRAKING TEST RUNS FOR THE FALCON 20 AIRCRAFT, ALL TEST PERIODS BETWEEN 1996 AND 2000

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
96/04 17/01/96	9 14:10	26	LDG	Bare and Wet		0.56	64	0.295
	10 14:26	26	LDG	“		"	66	0.307
96/07 20/01/96	5 14:44	31TS	RTO	1/8 to ¼ inch loose granular snow, SG=0.53	-0.001	0.37	47	0.245
	6 14:57	31TS	LDG	“	"	"	79	0.222
	7 15:04	31TS	LDG	“	"	"	44	0.216
	8 15:13	31TS	LDG	“	"	"	72	0.212
96/07 20/01/96	9 15:27	26	RTO	Bare and Dry		0.74	63	0.401
	10 15:41	26	LDG	“		"	63	0.374
	11 15:58	26	LDG	“		“	65	0.372
96/08 21/01/96	5 12:10	31TS	RTO	1 to 11/4 inch loose granular snow, SG=0.53	0.027	0.36	47	0.178
	6 12:27	31TS	LDG	“	"	"	86	0.151
	7 12:33	31TS	LDG	“	"	"	48	0.162
	8 12:48	31TS	LDG	“	"	"	88	0.164
96/09 21/01/96	5 16:39	31TS	RTO	13/4 to 2 inch loose granular snow, SG=0.53 *	0.084	0.38	42	0.172
	6 16:52	31TS	LDG	“	"	"	86	0.117
	7 16:57	31TS	LDG	“	"	"	42	0.157
	8 17:06	31TS	LDG	“	"	"	85	0.101
96/11 24/01/96	1 11:38	08	LDG	60% bare and dry, 30% compact snow, 10% 1/8 inch loose snow		0.57	59	0.292
	2 11:56	08	LDG	“		"	59	0.319
	3 12:15	08	RTO	“		"	64	0.330
96/12 24/01/96	5 16:48	31TS	RTO	1 to 11/4 inch loose/medium compact snow, SG=0.55 *	0.084	0.27	44	0.140
	6 17:04	31TS	LDG	“	"	"	63	0.099
	7 17:10	31TS	LDG	“	"	"	43	0.130
	8 17:21	31TS	LDG	“	"	"	71	0.103
96/13 25/01/96	5 10:17	31TS	RTO	½ to 11/2 inch medium/hard compact snow, SG=0.57 *	0.037	0.28	43	0.167
	6 10:25	31TS	LDG	“	"	"	80	0.187
	7 10:33	31TS	LDG	“	"	"	39	0.155
	8 10:46	31TS	LDG	“	"	"	73	0.203
96/14 25/01/96	1 15:19	31TS	RTO	50% ice, 50% thin ice over compact snow		0.21	57	0.140

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
	2 15:23	31TS	LDG	“		"	56	0.133
	3 15:35	31TS	LDG	“		"	96	0.114
	4 15:45	31TS	LDG	“		"	96	0.109
96/14 25/01/96	5 16:15	31TS	RTO	50% ice, 50% thin ice over compact snow, double sand application		0.26	55	0.174
	6 16:19	31TS	LDG	“		"	49	0.180
	7 16:32	31TS	LDG	“		"	92	0.166
	8 16:43	31TS	LDG	“		"	88	0.157
96/19 04/03/96	1 16:01	26	RTO	70% bare and wet, 20% slush, 10% ice, changing to 70% ice patches, 30% bare and dry *		0.49	59	0.257
	2 16:14	26	LDG	“		"	62	0.198
	3 16:33	26	LDG	“		"	54	0.227
96/20 06/03/96	2 11:00	08TS	RTO	1/8 to 3/8 inch loose snow, SG= 0.44	0.003	0.37	60	0.236
	3 11:16	08TS	LDG	“	"	"	74	0.201
	4 11:24	08TS	LDG	“	"	"	56	0.214
	5 11:39	08TS	LDG	“	"	"	77	0.206
96/21 07/03/96	5 10:08	08TS	RTO	2 inch loose snow, SG= 0.52, becoming heavily rutted. *	0.072	0.32	55	0.166
	6 10:24	08TS	LDG	“	"	"	49	0.123
	7 10:29	08TS	LDG	“	"	"	56	0.134
	8 10:48	08TS	LDG	“	"	"	72	0.122
96/22 07/03/96	5 15:08	08TS	RTO	3 inch loose snow, SG= 0.53, becoming heavily rutted. *	0.132	0.37	69	0.192
97/06 23/01/97	1 10:24	08	RTO	Bare and dry with occasional ice patches *		0.49	41	0.370
	2 10:29	08	LDG	“		"	43	0.376
	3 10:48	08	LDG	“		"	65	0.377
	4 11:08	08	LDG	“		“	53	0.372
	5 11:29	08	RTO	“		"	75	0.414
97/07 24/01/97	5 17:05	08TS	LDG	1.5 inch loose granular snow, SG= 0.67 *	0.110	0.35	42	0.100
	6 17:20	08TS	LDG	“	"	"	59	0.104
97/08 26/01/97	8 11:48	08TS	LDG	0.8 inch loose granular snow, SG= 0.35	0.038	0.28	88	0.152
	9 11:56	08TS	LDG	“	"	"	42	0.128
98/01 21/01/98	6 15:25	31TS	LDG	60% bare and dry, 40% 1/8 inch loose snow and ice patches *		0.51	42	0.326
	7 15:32	31TS	LDG	“		“	67	0.285

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
	8 15:36	31TS	RTO	“		“	46	0.338
	9 15:52	31TS	LDG	“		“	92	0.280
98/02 26/01/98	5 15:59	31TS	LDG	100% 0.4 inch loose snow on 60% asphalt, 40% ice patches	0.009	0.29	51	0.141
	6 16:15	31TS	LDG	“	“	“	92	0.203
	7 16:25	31TS	LDG	“	“	“	63	0.156
	8 16:36	31TS	LDG	“	“	“	92	0.214
	9 16:43	31TS	RTO	“	“	“	64	0.174
98/03 28/01/98	5 13:09	31TS	LDG	100% 1.6 inch loose snow, SG= 0.13	0.015	0.22	56	0.151
	6 13:15	31TS	LDG	“	“	“	42	0.147
98/04 29/01/98	1 10:11	08	LDG	40% bare and wet, 60% ice patches treated with chemical deicer to 80% bare and wet, 20% ice patches.		0.37	42	0.238
	2 10:19	08	LDG	“		0.42	52	0.263
	3 10:25	08	LDG	“		0.47	66	0.240
	4 10:30	08	RTO	“		0.52	49	0.281
98/06 30/01/98	1b 14:30	31TS	RTO	100% 1.2 inch loose snow, SG= 0.31 *	0.027	0.28	57	0.186
	2b 14:38	31TS	LDG	“	0.052	“	58	0.139
	3b 14:52	31TS	LDG	“	0.013	“	88	0.185
	4b 15:07	31TS	RTO	“	0.013	“	104	0.202
98/08 13/02/98	1 11:52	31TS	LDG	100% compact snow with ice patches		0.25	22	0.124
	2 11:57	31TS	LDG	“		“	36	0.137
	3 12:02	31TS	LDG	“		“	58	0.156
	4 12:18	31TS	LDG	“		“	92	0.203
	5 12:25	31TS	RTO	“		“	59	0.162
	6 12:40	31TS	LDG	“		“	90	0.208
98/09 03/03/98	3 14:48	31TS	LDG	50% bare and wet, 25% slush, 25% snow changing to 75% bare and wet, 25% snow	0.009	0.53	30	0.299
	4 14:52	31TS	LDG	“	“	“	50	0.267
98/10 04/03/98	1 09:18	08	LDG	1/8 inch sanded snow over ice changing to bare and wet *		0.55	47	0.281
	2 09:57	31TS	LDG	80% ½ inch loose snow, 20% bare and wet *		0.43	52	0.123
	3 10:03	31TS	LDG	“		“	63	0.122
	4 10:10	31TS	LDG	“		“	45	0.149
	5 10:15	31TS	LDG	“		“	32	0.147

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
99/01 225/01/99	6 12:15	31TS	LDG	100% bare and dry		0.81	61	0.457
99/03 28/01/99	1a 10:48	08	LDG	50% bare and dry, 50% loose snow drifts of 1.2 inch depth changing to 30% bare and dry, 70% loose snow drifts		0.33	30	0.179
	2a 11:01	08	LDG	“		0.35	46	0.191
	3a 11:14	08	LDG	“		0.37	62	0.186
	4a 11:28	08	LDG	“		0.39	85	0.216
	5a 11:42	08	RTO	“		0.40	72	0.267
99/04 28/01/99	1 14:38	31	LDG	60% ¼ inch loose snow, 20% compact snow, 20% bare and dry		0.29	36	0.197
	2 14:42	31	LDG	“		0.30	53	0.215
	3 14:49	31	LDG	“		0.31	64	0.266
	5 15:15	31	RTO	“		0.30	49	0.213
	6 15:36	31	LDG	“		0.34	49	0.221
99/05 29/01/99	1 10:21	31TS	LDG	100% thin ice with roughness from pavement texture		0.28	24	0.144
	2 10:28	31TS	LDG	“		0.29	53	0.193
	3 10:34	31TS	RTO	“		0.23	76	0.203
	4 10:59	31TS	LDG	“		0.25	98	0.226
	5 11:06	31TS	RTO	“		0.26	58	0.181
	6 11:29	31TS	LDG	“		0.29	85	0.250
	7 11:35	31TS	LDG	“		0.28	64	0.199
99/06 29/01/99	1 15:34	31TS	LDG	100% ice with one application of sand		0.19	28	0.105
	2 15:40	31TS	LDG	“		0.18	35	0.111
	3 15:46	31TS	LDG	“		0.20	48	0.112
	4 15:56	31TS	LDG	“		0.17	61	0.115
	5 16:06	31TS	RTO	“		0.16	63	0.114
	6 16:12	31TS	RTO	“		0.19	43	0.106
99/07 09/03/99	1 08:45	31TS	LDG	100% smooth ice, unsanded		0.14	36	0.073
	2 08:54	31TS	LDG	“		0.14	13	0.070
	3 09:35	31TS	LDG	100% smooth ice, double sand application		0.17	21	0.108
	4 09:47	31TS	LDG	“		0.22	30	0.123
	5 10:02	31TS	LDG	“		0.22	61	0.131
	6 10:19	31TS	LDG	“		0.22	34	0.126

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
	7 10:46	31TS	RTO	“		0.21	35	0.125
	8 11:00	31TS	RTO	“		0.22	21	0.117
99/08 23/03/99	1 16:24	31TS	LDG	30%slush, 50% moist snow, depth ¼ to ½ inch, 20% bare and wet		0.25	19	0.182
	2 16:30	31TS	LDG	80% moist snow, 20% slush, depth ¼ to ½ inch		0.22	34	0.154
	3 16:39	31TS	LDG	“		0.22	46	0.159
	4 16:46	31TS	LDG	“		0.22	19	0.145
	5 16:50	31TS	RTO	“		0.21	54	0.162
2000/02 18/01/00	1 15:52	31TS	RTO	60% ice, 40% compact snow over ice, scarified longitudinally		0.18	20	0.112
	2 15:58	31TS	LDG	“		0.18	23	0.103
	3 16:12	31TS	LDG	“		0.17	26	0.098
	4 16:23	31TS	RTO	“		0.17	36	0.109
	5 16:33	31TS	RTO	“		0.16	39	0.128
	6 16:41	31TS	LDG	“		0.16	44	0.104
2000/03 18/01/00	1 17:08	08	LDG	100% bare and dry, occasional ice patches		0.75	66	0.436
2000/04 19/01/00	1 13:59	26TS	LDG	100% thin loose snow changing to 60% loose snow, 20% compact snow, 20% bare & dry		0.28	51	0.131
	2 14:13	26TS	LDG	“		0.28	72	0.162
	3 14:20	26TS	RTO	“		0.28	48	0.159
	4 14:35	26TS	RTO	“		0.28	88	0.197
	5 14:43	26TS	LDG	“		0.31	57	0.145
2000/05 20/01/00	1 14:56	31TS	RTO	100% ice with occasional bare spots		0.14	9	0.081
	2 15:02	31TS	LDG	“		0.13	15	0.082
	3 15:32	31TS	LDG	“		0.13	20	0.084
	4 15:38	31TS	RTO	“		0.13	28	0.081
	5 15:54	31TS	RTO	“		0.13	35	0.087
	6 16:01	31TS	LDG	“		0.12	34	0.080
2000/06 20/01/00	1 16:40	08	LDG	100% bare and dry with occasional ice patches		0.73	51	0.383
	2 17:02	08	RTO	“		0.73	67	0.413
2000/07 21/01/00	1 08:26	31TS	RTO	100% ice with occasional bare spots		0.10	20	0.095
	2 08:32	31TS	LDG	“		0.11	20	0.091
	3 08:43	31TS	LDG	“		0.10	26	0.084

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
	4 08:50	31TS	RTO	“		0.09	34	0.087
	5 09:00	31TS	RTO	“		0.09	36	0.086
	6 09:08	31TS	LDG	“		0.10	35	0.077
2000/08 21/01/00	1 13:15	31TS	RTO	100% ice with double sand application, occasional bare spots		0.20	26	0.136
	2 13:21	31TS	LDG	“		0.19	27	0.123
	3 13:48	31TS	LDG	“		0.22	44	0.163
	4 13:55	31TS	RTO	“		0.21	47	0.155
	5 14:10	31TS	RTO	“		0.21	50	0.151
	6 14:16	31TS	LDG	“		0.21	51	0.134
2000/09 24/01/00	1 12:12	26TS	RTO	70% bare and dry, 30% light dusting of snow		0.52	31	0.292
	2 12:20	26TS	LDG	“		0.56	53	0.364
	3 12:40	26TS	LDG	“		0.63	68	0.401
2000/10 25/01/00	3 12:56	26TS	RTO	100% ¾ inch loose snow changing to 60% compact snow, 40% ¾ inch loose snow	0.026	0.32	58	0.127
	4 13:04	26TS	LDG	“	“	0.30	61	0.120
	5 13:33	26TS	LDG	“	“	0.27	94	0.142
	6 13:43	26TS	RTO	“	“	0.26	69	0.142
2000/11 27/01/00	1 11:24	31	RTO	100% ice, longitudinally scarified		0.19	23	0.126
	2 11:30	31	LDG	“		0.19	28	0.125
	3 11:36	31	LDG	“		0.20	32	0.127
	4 11:44	31	RTO	“		0.20	33	0.130
2000/12 27/01/00	2 12:51	36	LDG	90% sanded ice, 10% bare and dry		0.26	31	0.155
	3 12:55	36	LDG	“		0.26	34	0.140

* Annotated surface condition data not used in determination of correlation between $_B$ and CRFI due to one or more of the following conditions: a) excessive depth of contamination, b) highly variable contamination conditions, c) surface conditions changing rapidly with time, or d) length of aircraft test run too short to provide consistent data.

APPENDIX B - SUMMARY OF FULL ANTI-SKID BRAKING TEST RUNS FOR THE NASA B737/B757 AND FAA B727 AIRCRAFT

NASA B737 - 1996 TEST PERIOD

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
790 06/03/96	3 13:51	08TS	LDG	1/4 inch loose snow, SG= 0.44		0.39	36	0.225
	5 15:32	08TS	LDG	“		“	49	0.233
791 07/03/96	2 09:56	08TS	LDG	2 inches loose snow, SG= 0.52, becoming heavily rutted		0.36	29	0.206
	5 10:26	08TS	LDG	“		“	38	0.233
	8 10:58	08TS	LDG	“		“	65	0.206
791 07/03/96	10 14:32	08TS	LDG	3 inches loose snow, SG= 0.53, becoming heavily rutted		0.39	28	0.187
	13 15:03	08TS	LDG	“		0.36	41	0.169
792 08/03/96	3 11:33	26TS	LDG	Patchy thin ice		0.21	55	0.081

FAA B727 - 1997 TEST PERIOD

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
97/02 24/01/97	8 11:05	08TS	LDG	100% bare and dry		0.68	36	0.385
	9 11:45	08TS	LDG	“		“	78	0.337
97/07 29/01/97	27 11:30	08TS	RTO	½ to 1 inch loose snow, mean SG= 0.50		0.28	36	0.148
	29 12:03	08TS	RTO	“		“	72	0.219
	31 12:37	08TS	RTO	“		“	86	0.222

NASA B757 - 1999 TEST PERIOD

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B
R093 02/02/99	4 16:52	19	LDG	2 inches loose moist snow	0.027	0.35	35	0.155
	5 17:36	19	LDG	“	“	0.31	54	0.181
R095 04/02/99	2 16:14	19	LDG	1 to 11/2 inches of loose/ medium compacted snow	0.014	0.35	30	0.166
	4 16:51	19	LDG	“	“	0.36	94	0.180
	6 17:10	19	LDG	“	“	0.36	59	0.183

FLT/ DATE	**RUN/ TIME**	**RW**	**CONFIG**	**SURFACE DESCRIPTION**	**MEAN D_{CONTAM}/W**	**MEAN CRFI**	**MEAN SPEED (KTGS)**	**MEAN μ_B**
R096A 06/02/99	2A 11:06	19	LDG	¾ to 1 inch loose moist snow, SG= 0.36	0.009	0.30	35	0.141
	3A 11:27	19	LDG	“	“	“	54	0.153
	5A 11:48	19	LDG	“	“	“	92	0.164
R096B 06/02/99	2B 15:32	19	LDG	½ inch dry, compacted snow	0.010	0.29	32	0.142
	3B 15:49	19	LDG	“	“	0.31	50	0.158
	5B 16:07	19	LDG	“	“	0.32	97	0.171
R097 07/02/99	2 10:35	19	LDG	¼ inch dry compacted snow	0.010	0.29	31	0.138
	3 10:52	19	LDG	“	“	0.28	58	0.169
	4 11:08	19	LDG	“	“	0.27	86	0.172

APPENDIX C - SUMMARY OF FULL ANTI-SKID BRAKING TEST RUNS FOR THE de HAVILLAND and NAV CANADA DASH 8 AIRCRAFT, AND FAIRCHILD DORNIER DU328 TURBO-PROP AIRCRAFT

De Havilland DASH 8 – 1997 and 1998 TEST PERIOD

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN CRFI	MEAN SPEED (KTGS)	MEAN μ_B *
2F1597 03/03/97	H 11:51	31	LDG	1 ½ inches loose snow	0.016	0.29	54	0.185
	I 12:04	31	LDG	“	“	“	67	0.194
	J 12:11	31	LDG	“	“	“	63	0.196
2F1599 05/03/97	O 12:06	31	LDG	1 ½ inch hard packed snow		0.35	50	0.213
	P 12:17	31	LDG	“		“	47	0.230
	R 12:23	31	LDG	“		“	50	0.239
	S 12:30	31	LDG	“		“	60	0.246
2F1653 14/02/98	K 14:09	31	LDG	100% rough ice		0.23	65	0.196
	M 14:24	31	LDG	“		“	60	0.206
	O 14:35	31	LDG	“		“	65	0.203
	P 14:45	31	LDG	“		“	41	0.150
	R 15:05	31	LDG	“		“	43	0.158
2F1654 15/02/98	H 10:11	13	LDG	100% moderately smooth ice		0.21	26	0.143
	J 10:17	13	LDG	“		“	30	0.133
	N 10:31	13	LDG	“		“	45	0.127
	R 10:44	13	LDG	“		“	45	0.146
2F1655 15/02/98	C 13:15	13	LDG	100% moderately smooth ice with sand application		0.28	35	0.166
	F 13:28	13	LDG	“		“	38	0.155
	J 13:41	13	LDG	“		“	53	0.208
	N 13:56	13	LDG	“		“	35	0.190

* Converted by deHavilland from $_B$ (% of Dry) in References 4 and 5 to Mean $_B$

NAV CANADA DASH 8 - 2001 TEST PERIOD, LANDING CONFIGURATION

FLT/ DATE	RUN/ TIME	RW	POWER	SURFACE DESCRIPTION	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN μ_B
2001/01 29/01/01	8 15:42	26	IDLE	100% bare and dry	0.67	0.87	51.44	0.407
	9 15:53	26	IDLE	“	0.67	0.87	54.13	0.429

FLT/ DATE	**RUN/ TIME**	**RW**	**POWER**	**SURFACE DESCRIPTION**	**MEAN CRFI**	**MEAN IRFI**	**MEAN SPEED (KTGS)**	**MEAN μ_B**
2001/02 31/01/01	5 14:45	31TS	IDLE	1/8 inch loose dry snow over 40% compact snow, 40% ice patches, 20% bare and dry	0.28	0.19	21.47	0.174
	6 15:03	31TS	IDLE	“	0.28	0.20	26.92	0.178
	7 15:13	31TS	IDLE	“	0.27	0.21	36.62	0.170
	8 15:20	31TS	IDLE	“	0.27	0.22	53.91	0.178
	9 15:32	31TS	DISC	“	0.26	0.22	40.28	0.179
	10 15:38	31TS	DISC	“	0.25	0.21	43.5	0.186
	11 15:43	31TS	DISC	“	0.24	0.20	48.96	0.174
	13 16:04	08TS	IDLE	1/8 inch loose dry snow over bare pavement	0.31	0.38	47.56	0.306
	16 16:25	08TS	DISC	“	0.31	0.38	34.71	0.188
	18 16:39	08TS	IDLE	“	0.32	0.37	41.28	0.265
2001/03 01/02/01	1 10:47	36N	IDLE	1/8 to ½ inch loose snow over bare pavement	0.27	0.18	27.56	0.177
	2 10:52	36N	IDLE	“	0.26	0.20	26.1	0.176
	3 11:02	36N	IDLE	“	0.25	0.21	45.84	0.184
	4 11:09	36N	DISC	“	0.27	0.21	36.57	0.205
	5 11:52	31TS	IDLE	¼ inch loose snow over 40% ice patches, 40% compact snow, 20% bare and dry	0.24	0.19	25.95	0.181
	6 11:58	31TS	IDLE	“	0.25	0.19	48.56	0.174
	7 12:04	31TS	IDLE	“	0.26	0.20	60.94	0.167
	8 12:15	31TS	IDLE	“	0.26	0.20	50.59	0.177
	9 12:22	31TS	DISC	“	0.27	0.20	52.14	0.259
	10 12:26	31TS	DISC	“	0.27	0.20	51.43	0.253
	11 12:31	31TS	DISC	“	0.27	0.20	30.11	0.183
2001/04 01/02/01	1 14:46	31TS	IDLE	Sanded loose snow over 40% ice patches, 40% compact snow, 20% bare and dry	0.40	0.35	25.32	0.270
	2 14:50	31TS	IDLE	“	0.38	0.35	39.52	0.251
	3 14:54	31TS	IDLE	“	0.36	0.36	59.46	0.240
	4 15:02	31TS	IDLE	“	0.36	0.36	39.9	0.249
	5 15:08	31TS	DISC	“	0.36	0.36	37.47	0.250
	6 15:15	31TS	DISC	“	0.36	0.35	39.21	0.247
2001/05 21/03/01	1 14:11	31N	IDLE	70% wet snow and slush, 30% water puddles	0.32	0.36	22.71	0.176
	2 14:24	31N	IDLE	“	0.30	0.39	26.91	0.177
	4 14:42	31N	IDLE	“	0.29	0.39	28.16	0.180
2001/06 22/03/01	1 07:25	31N	DISC	100% smooth dry ice	0.10	0.16	12.25	0.069

FLT/ DATE	RUN/ TIME	RW	POWER	SURFACE DESCRIPTION	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN μ_B
	2 07:30	31N	DISC	“	0.11	0.15	15.58	0.086
	3 07:40	31N	DISC	“	0.11	0.14	23.48	0.086
	4 07:45	31N	DISC	“	0.11	0.13	25.38	0.089
	5 07:55	31N	IDLE	“	0.11	0.14	33.17	0.086
	6 08:00	31N	IDLE	“	0.12	0.15	32.98	0.085
	7 08:13	31N	IDLE	“	0.11	0.15	35.67	0.088
	8 08:17	31N	IDLE	“	0.11	0.15	37.83	0.087
2001/07 22/03/01	1 10:08	31N	IDLE	80% bare and damp with patches of standing water, 20% bare and dry	0.54	0.59	33.59	0.363
	2 10:12	31N	IDLE		0.60	0.72	50.13	0.321
2001/08 23/03/01	1 11:28	31TS	IDLE	100% bare and damp on a coarse texture, with 10 to 20% standing water	0.74	0.72	37.73	0.387
	2 11:32	31TS	IDLE	“	0.72	0.74	34.66	0.392
	3 12:02	31TS	IDLE	100% bare and damp on a coarse texture, with 20 to 40% standing water	0.72	0.73	44.75	0.360

DORNIER 328 AIRCRAFT - 2001 TEST PERIOD, LANDING CONFIGURATION

FLT/ DATE	RUN/ TIME	RW	POWER	SURFACE DESCRIPTION	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN μ_B
T30916-41 28/02/01	6 14:12	26	Ground Idle	100% Bare and Dry	0.92	N/A	43	0.447
T30916-42 28/02/01	7 14:29	26	Ground Idle	100% Bare and Dry	0.92	N/A	39	0.422
T30916-61 28/02/01	8 15:09	26	Ground Idle	!00% Bare and Wet	0.72	0.80	45	0.382
T30916-62 28/02/01	9 15:28	26	Ground Idle	100% Bare and Wet	0.72	0.78	47	0.377
T30919-21 01/03/01	1 08:26	26	Ground Idle	100% Smooth Ice	0.09	0.17	24	0.041
T30919-22 01/03/01	2 08:32	26	Ground Idle	100% Smooth Ice	0.10	0.17	44	0.051
T30919-23 01/03/01	3 08:36	26	Ground Idle	100% Smooth Ice	0.10	0.17	57	0.052
T30919-24 01/03/01	4 09:15	26	Ground Idle	100% Smooth Ice	0.14	0.16	45	0.098
T30919-25 01/03/01	5 08:58	26	Ground Idle	100% Smooth Ice	0.16	0.14	39	0.064
T30919-41 01/03/01	6 10:12	26	Ground Idle	100% Smooth Ice with Chemicals	0.37	0.22	20	0.360
T30919-42 01/03/01	7 10:15	26	Ground Idle	100% Smooth Ice with Chemicals	0.50	0.45	26	0.358
T30919-43 01/03/01	8 10:26	26	Ground Idle	100% Smooth Ice with Chemicals	0.63	0.68	20	0.398

APPENDIX D - SUMMARY OF FALCON 20 BRAKING COEFFICIENTS FOR FULL ANTI-SKID BRAKING COMPARED TO RUNWAY FRICTION INDICES MEASURED BY DIFFERENT FRICTION MEASUREMENT DEVICES

FALCON 20 μ_B vs ERD AND SFT, TEST PERIODS BETWEEN 1996 AND 1999

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN RFI (ERD)	MEAN RFI (SFT)	MEAN μ_B
96/04 17/01/96	9 14:10	26	LDG	Bare and Wet		0.56	0.68	0.295
	10 14:26	26	LDG	“		"	“	0.307
96/07 20/01/96	5 14:44	31TS	RTO	1/8 to ¼ inch loose granular snow, SG=0.53	-0.001	0.37	0.29	0.245
	6 14:57	31TS	LDG	“	"	"	“	0.222
	7 15:04	31TS	LDG	“	"	"	“	0.216
	8 15:13	31TS	LDG	“	"	"	“	0.212
96/07 20/01/96	9 15:27	26	RTO	Bare and Dry		0.74	0.96	0.401
	10 15:41	26	LDG	“		"	“	0.374
	11 15:58	26	LDG	“		“	“	0.372
96/08 21/01/96	5 12:10	31TS	RTO	1 to 11/4 inch loose granular snow, SG=0.53	0.027	0.36	0.13	0.178
	6 12:27	31TS	LDG	“	"	"	“	0.151
	7 12:33	31TS	LDG	“	"	"	“	0.162
	8 12:48	31TS	LDG	“	"	"	“	0.164
96/09 21/01/96	5 16:39	31TS	RTO	13/4 to 2 inch loose granular snow, SG=0.53 *	0.084	0.38	0.04	0.172
	6 16:52	31TS	LDG	“	"	"	“	0.117
	7 16:57	31TS	LDG	“	"	"	“	0.157
	8 17:06	31TS	LDG	“	"	"	“	0.101
96/11 24/01/96	1 11:38	08	LDG	60% bare and dry, 30% compact snow, 10% 1/8 inch loose snow		0.57	0.94	0.292
	2 11:56	08	LDG	“		"	“	0.319
	3 12:15	08	RTO	“		"	“	0.330
96/12 24/01/96	5 16:48	31TS	RTO	1 to 11/4 inch loose/medium compact snow, SG=0.55 *	0.084	0.27	0.03	0.140
	6 17:04	31TS	LDG	“	"	"	“	0.099
	7 17:10	31TS	LDG	“	"	"	“	0.130
	8 17:21	31TS	LDG	“	"	"	“	0.103
96/13 25/01/96	5 10:17	31TS	RTO	½ to 11/2 inch medium/hard compact snow, SG=0.57 *	0.037	0.28	0.19	0.167
	6 10:25	31TS	LDG	“	"	"	“	0.187
	7 10:33	31TS	LDG	“	"	"	“	0.155

FLT/ DATE	**RUN/ TIME**	**RW**	**CONFIG**	**SURFACE DESCRIPTION**	**MEAN D_{CONTAM}/W**	**MEAN RFI (ERD)**	**MEAN RFI (SFT)**	**MEAN μ_B**
	8 10:46	31TS	LDG	“	"	"	“	0.203
96/14 25/01/96	1 15:19	31TS	RTO	50% ice, 50% thin ice over compact snow		0.21	0.20	0.140
	2 15:23	31TS	LDG	“		"	“	0.133
	3 15:35	31TS	LDG	“		"	“	0.114
	4 15:45	31TS	LDG	“		"	“	0.109
96/20 06/03/96	2 11:00	08TS	RTO	1/8 to 3/8 inch loose snow, SG= 0.44	0.003	0.37	0.32	0.236
	3 11:16	08TS	LDG	“	"	"	“	0.201
	4 11:24	08TS	LDG	“	"	"	“	0.214
	5 11:39	08TS	LDG	“	"	"	“	0.206
96/21 07/03/96	5 10:08	08TS	RTO	2 inch loose snow, SG= 0.52, becoming heavily rutted. *	0.072	0.32	0.01	0.166
	6 10:24	08TS	LDG	“	"	"	“	0.123
	7 10:29	08TS	LDG	“	"	"	“	0.134
	8 10:48	08TS	LDG	“	"	"	“	0.122
97/06 23/01/97	1 10:24	08	RTO	Bare and dry with occasional ice patches *		0.49	0.85	0.370
	2 10:29	08	LDG	“		"	“	0.376
	3 10:48	08	LDG	“		"	“	0.377
	4 11:08	08	LDG	“		“	“	0.372
	5 11:29	08	RTO	“		"	“	0.414
97/07 24/01/97	5 17:05	08TS	LDG	1.5 inch loose granular snow, SG= 0.67 *	0.110	0.35	0.07	0.100
	6 17:20	08TS	LDG	“	"	"	“	0.104
97/08 26/01/97	8 11:48	08TS	LDG	0.8 inch loose granular snow, SG= 0.35	0.038	0.28	0.15	0.152
	9 11:56	08TS	LDG	“	"	"	“	0.128
98/08 13/02/98	1 11:52	31TS	LDG	100% compact snow with ice patches		0.25	0.29	0.124
	2 11:57	31TS	LDG	“		“	“	0.137
	3 12:02	31TS	LDG	“		“	“	0.156
	4 12:18	31TS	LDG	“		“	“	0.203
	5 12:25	31TS	RTO	“		“	“	0.162
	6 12:40	31TS	LDG	“		“	“	0.208
98/09 03/03/98	3 14:48	31TS	LDG	50% bare and wet, 25% slush, 25% snow changing to 75% bare and wet, 25% snow	0.009	0.53	0.79	0.299
	4 14:52	31TS	LDG	“	“	“	“	0.267

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN RFI (ERD)	MEAN RFI (SFT)	MEAN μ_B
98/10 04/03/98	2 09:57	31TS	LDG	80% ½ inch loose snow, 20% bare and wet *		0.43	0.53	0.123
	3 10:03	31TS	LDG	“		“	“	0.122
	4 10:10	31TS	LDG	“		“	“	0.149
	5 10:15	31TS	LDG	“		“	“	0.147
99/01 225/01/99	6 12:15	31TS	LDG	100% bare and dry		0.81	0.90	0.457
99/03 28/01/99	1a 10:48	08	LDG	50% bare and dry, 50% loose snow drifts of 1.2 inch depth changing to 30% bare and dry, 70% loose snow drifts		0.33	0.36	0.179
	2a 11:01	08	LDG	“		0.35	“	0.191
	3a 11:14	08	LDG	“		0.37	“	0.186
	4a 11:28	08	LDG	“		0.39	“	0.216
	5a 11:42	08	RTO	“		0.40	“	0.267
99/04 28/01/99	1 14:38	31	LDG	60% ¼ inch loose snow, 20% compact snow, 20% bare and dry		0.29	0.38	0.197
	2 14:42	31	LDG	“		0.30	“	0.215
	3 14:49	31	LDG	“		0.31	“	0.266
	5 15:15	31	RTO	“		0.30	“	0.213
	6 15:36	31	LDG	“		0.34	“	0.221
99/05 29/01/99	1 10:21	31TS	LDG	100% thin ice with roughness from pavement texture		0.28	0.39	0.144
	2 10:28	31TS	LDG	“		0.29	“	0.193
	3 10:34	31TS	RTO	“		0.23	“	0.203
	4 10:59	31TS	LDG	“		0.25	“	0.226
	5 11:06	31TS	RTO	“		0.26	“	0.181
	6 11:29	31TS	LDG	“		0.29	“	0.250
	7 11:35	31TS	LDG	“		0.28	“	0.199

FALCON 20 μ_B vs ERD AND IRV, 2000 TEST PERIOD

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN RFI (ERD)	MEAN RFI (IRV)	MEAN μ_B
2000/02 18/01/00	1 15:52	31TS	RTO	60% ice, 40% compact snow over ice, scarified longitudinally		0.18	0.36	0.112
	2 15:58	31TS	LDG	“		0.18	0.36	0.103
	3 16:12	31TS	LDG	“		0.17	0.36	0.098

FLT/ DATE	RUN/ TIME	RW	CONFIG	SURFACE DESCRIPTION	MEAN D_{CONTAM}/W	MEAN RFI (ERD)	MEAN RFI (IRV)	MEAN μ_B
	4 16:23	31TS	RTO	“		0.17	0.36	0.109
	5 16:33	31TS	RTO	“		0.16	0.33	0.128
	6 16:41	31TS	LDG	“		0.16	0.34	0.104
2000/03 18/01/00	1 17:08	08	LDG	100% bare and dry, occasional ice patches		0.75	0.8	0.436
2000/04 19/01/00	1 13:59	26TS	LDG	100% thin loose snow changing to 60% loose snow, 20% compact snow, 20% bare & dry		0.28	0.26	0.131
	2 14:13	26TS	LDG	“		0.28	0.26	0.162
	3 14:20	26TS	RTO	“		0.28	0.26	0.159
	4 14:35	26TS	RTO	“		0.28	0.27	0.197
	5 14:43	26TS	LDG	“		0.31	0.29	0.145
2000/05 20/01/00	1 14:56	31TS	RTO	100% ice with occasional bare spots		0.14	0.25	0.081
	2 15:02	31TS	LDG	“		0.13	0.24	0.082
	3 15:32	31TS	LDG	“		0.13	0.23	0.084
	4 15:38	31TS	RTO	“		0.13	0.24	0.081
	5 15:54	31TS	RTO	“		0.13	0.24	0.087
	6 16:01	31TS	LDG	“		0.12	0.25	0.080
2000/06 20/01/00	1 16:40	08	LDG	100% bare and dry with occasional ice patches		0.73	0.87	0.383
	2 17:02	08	RTO	“		0.73	0.87	0.413
2000/07 21/01/00	1 08:26	31TS	RTO	100% ice with occasional bare spots		0.10	0.31	0.095
	2 08:32	31TS	LDG	“		0.11	0.31	0.091
	3 08:43	31TS	LDG	“		0.10	0.31	0.084
	4 08:50	31TS	RTO	“		0.09	0.3	0.087
	5 09:00	31TS	RTO	“		0.09	0.29	0.086
	6 09:08	31TS	LDG	“		0.10	0.28	0.077
2000/08 21/01/00	1 13:15	31TS	RTO	100% ice with double sand application, occasional bare spots		0.20	0.36	0.136
	2 13:21	31TS	LDG	“		0.19	0.36	0.123
	3 13:48	31TS	LDG	“		0.22	0.35	0.163
	4 13:55	31TS	RTO	“		0.21	0.35	0.155
	5 14:10	31TS	RTO	“		0.21	0.36	0.151
	6 14:16	31TS	LDG	“		0.21	0.36	0.134
2000/09 24/01/00	1 12:12	26TS	RTO	70% bare and dry, 30% light dusting of snow		0.52	0.64	0.292
	2 12:20	26TS	LDG	“		0.56	0.63	0.364

FLT/ DATE	**RUN/ TIME**	**RW**	**CONFIG**	**SURFACE DESCRIPTION**	**MEAN D_{CONTAM}/W**	**MEAN RFI (ERD)**	**MEAN RFI (IRV)**	**MEAN μ_B**
	3 12:40	26TS	LDG	“		0.63	0.61	0.401
2000/10 25/01/00	3 12:56	26TS	RTO	100% ¾ inch loose snow changing to 60% compact snow, 40% ¾ inch loose snow	0.025	0.32	0.26	0.128
	4 13:04	26TS	LDG	“	“	0.30	0.27	0.122
	5 13:33	26TS	LDG	“	“	0.27	0.3	0.143
	6 13:43	26TS	RTO	“	“	0.26	0.31	0.144
2000/11 27/01/00	1 11:24	31	RTO	100% ice, longitudinally scarified		0.19	0.3	0.126
	2 11:30	31	LDG	“		0.19	0.3	0.125
	3 11:36	31	LDG	“		0.20	0.29	0.127
	4 11:44	31	RTO	“		0.20	0.29	0.130
2000/12 27/01/00	2 12:51	36	LDG	90% sanded ice, 10% bare and dry		0.26	0.34	0.155
	3 12:55	36	LDG	“		0.26	0.34	0.140

* Annotated surface condition data not used in determination of correlation between $_B$ and CRFI due to one or more of the following conditions: a) excessive depth of contamination, b) highly variable contamination conditions, c) surface conditions changing rapidly with time, or d) length of aircraft test run too short to provide consistent data.