FALCON 20 AIRCRAFT PERFORMANCE TESTING ON CONTAMINATED RUNWAY SURFACES DURING THE WINTER OF 1999/2000

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16. Abstract

The landing performance of the NRC Falcon 20 research aircraft was tested on winter contaminated runway surfaces at the North Bay airport during the month of January 2000. This was the final year of a five-year collaborative test program involving Transport Canada, NASA, NRC and the FAA. The aircraft braking performance during full anti-skid braking runs on snow covered runway surfaces agreed very well with data from previous testing. Additional data was gathered on runway surfaces with very low friction indices, such as those covered with smooth ice and having a Canadian Runway Friction Index (CRFI) as low as 0.09. The aircraft braking performance was also tested against a vehicle that measured the International Runway Friction Index (IRFI). The aircraft braking coefficient did correlate as well as the IRFI as it did with the CRFI, the notable exception being on a smooth ice surface. The aircraft landing data obtained was used to verify landing data from the previous four years of testing. No further recommendations were made to update the CRFI table of recommended landing distances published in the Transport Canada Aeronautical Information Publication (AIP). No data points were obtained for contamination drag, due to very few instances of natural snow in North Bay during the available test period.

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16. Résumé

En janvier 2000, les performances à l'atterrissage de l'avion de recherche Falcon 20 du CNRC ont été évaluées sur des pistes d'atterrissage recouvertes de précipitations hivernales à l'aéroport de North Bay. Il s'agissait de la dernière année d'un programme d'essai quinquennal conjoint auquel participaient Transports Canada, la NASA, le CNRC et la FAA. La qualité du freinage de l'avion pendant les essais de freinage avec utilisation du système antidérapage sur des pistes recouvertes de neige ont très bien concordé avec les données des essais antérieurs. Des données additionnelles ont été recueillies sur des pistes présentant de très faibles indices de freinage sur piste, comme sur celles recouvertes de glace lisse et présentant un indice Canadien de freinage sur piste (CRFI) de 0,09. La qualité du freinage de l'avion a aussi fait l'objet d'essais par rapport à un véhicule qui mesurait l'indice international de freinage sur piste (IRFI). Le coefficient de freinage de l'avion correspondait tout aussi bien à l'IRFI qu'au CRFI, la seule exception notable étant sur une surface de glace lisse. Les données d'atterrissage de l'avion obtenues ont été utilisées pour permettre de vérifier les données d'atterrissage des quatre années d'essai précédentes. Aucune autre recommandation n'a été formulée pour mettre à jour la table CRFI des distances d'atterrissage recommandées, figurant dans la Publication d'information aéronautique (AIP) de Transports Canada. Aucun point n'a été attribué à la traînée causée par les précipitations en raison des très rares cas de neige naturelle à North Bay pendant la période d'essai.

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GLOSSARY OF TERMS

AIP	Aeronautical Information Publication
ATIS	Automatic Terminal Information System
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
DC	Direct Current
D_{CONTAM}	Contamination Drag
DEC	Digital Equipment Corporation
DGPS	Differential Global Positioning System
ERD	Electronic Recording Decelerometer
EWD	Equivalent Water Depth
FAA	Federal Aviation Administration
ft	Feet
g	Gravitational Constant
GPIP	Glide Path Intercept Point
GPS	Global Positioning System
HW	Headwind
IAR	Institute for Aerospace Research

IFR	Instrument Flight Rules
ILS	Instrument Landing System
IRFI	International Runway Friction Index
JAA	Joint Aviation Authority
JBI	James Brake Index
knots	Nautical miles per hour
L	Aerodynamic Lift
lbf	Pounds of force
LSI	Large Scale Integration
Mu	Coefficient of friction
NASA	National Aeronautics and Space Administration
NOTAM	Notice to Airmen
RTO	Rejected Takeoff
SG	Specific Gravity
t	Time
T	Aircraft Thrust
TS	Test Section
TW	Tailwind
V	Aircraft velocity along the runway (groundspeed)
V_{EAS}	Equivalent Airspeed
VFR	Visual Flight Rules
V_w	Wheel speed
W	Aircraft Weight
	Runway Slope (positive uphill)
	Atmospheric Density Ratio (= / $_0$)
μ_B	Aircraft Braking Coefficient (= Braking Force/(W-L))
μ_R	Rolling Friction Coefficient (= Rolling Resistance/(W-L))
μ_S	Wheel slip ratio (= $(V-V_W)/V$)

The NRC Falcon 20 Research Aircraft

FALCON 20 AIRCRAFT PERFORMANCE TESTING ON CONTAMINATED RUNWAY SURFACES DURING THE WINTER OF 1999/2000

1.0 INTRODUCTION

1.1 Background

In December 1995, the Joint Winter Runway Friction Program (JWRFP) was initiated to determine the braking friction and contamination drag of various aircraft on winter contaminated runways, in an effort to provide a better correlation between aircraft performance parameters and data obtained by ground friction measuring vehicles. This five year agreement was signed by the National Aeronautics and Space Administration (NASA) and Transport Canada, with the National Research Council (NRC) and the Federal Aviation Administration (FAA) as additional collaborating agencies. The first four years of testing were conducted at the North Bay airport, Ontario, Canada during the winters of 1995/1996 through 1998/1999, and at the K.I. Sawyer airport in northern Michigan, 1998/1999. These deployments were successful in providing comparative data for five different types of aircraft (the NRC Falcon 20, the NASA B737 and B757, the FAA B727 and the deHavilland Dash 8) and several ground friction measuring vehicles. References 1 through 8 cover the test results for these aircraft.

This report describes results of the Falcon 20 aircraft flight tests carried out during the fifth winter of testing. The Falcon results are compared with the Canadian Runway Friction Index (CRFI) and the International Runway Friction Index (IRFI). Lastly, the influence of this additional data is compared to currently established performance models. The NRC Institute for Aerospace Research (IAR), in collaboration with the Transport Canada Civil Aviation Aircraft Certification Branch, conducted the tests during the month of January 2000.

1.2 Objectives and Scope

The test objectives for the ground friction measuring vehicles were to assess the effectiveness of these devices on various winter contaminated runway surfaces, and to standardize their outputs into an IRFI. The results of the ground vehicle tests will be published in a separate report, and will not be referred to in this report except to compare the Falcon 20 braking performance with the friction index measured by the Transport Canada Electronic Recording Decelerometer (ERD) device and the IRFI.

The objectives of the aircraft tests were as follows:

a. Determine the aircraft braking coefficients on various winter contaminated runway surfaces.

b. Determine the aircraft contamination drag on various winter contaminated runway surfaces.

c. Compare the aircraft braking coefficient with the International Runway Friction Index (IRFI).

d. Obtain additional data to refine the Canadian Runway Friction Index (CRFI) tables for recommended landing distances recently published in the Transport Canada Aeronautical Information Publication (AIP).

e. Obtain additional data towards the establishment of more accurate models for the effect of contamination on continued takeoff and rejected takeoff performance.

2.0 EQUIPMENT DESCRIPTION

2.1 Ground Friction Measuring Devices

The ERD is the primary instrument used for runway friction measurement at virtually all Canadian airports and military air bases. Its development was preceded by a series of pendulum-based mechanical decelerometers used since the 1960's, including the James Brake Decelerometer, Tapley Meter, and Bowmonk Dynameter. 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 lockup. A number of readings 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 friction index now reported in Canada by the ERD is called the Canadian Runway Friction Index (CRFI), replacing the old James Brake Index (JBI). This 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 being representative of zero braking. Runway surface condition reports, including CRFI values, are reported to aircrew by notices to airmen (NOTAM), automatic terminal information systems (ATIS), and tower advisories.

Currently under development is the establishment of the International Runway Friction Index (IRFI) standard. This work is being done under the auspices of the American Society of Testing and Materials (ASTM). In the past year, a reference vehicle has been adopted for the standardization of the IRFI and is based on the French vehicle, the Instrument de Mesure Automatic de Glissance (IMAG).

The "CRFI Table of Recommended Landing Distances" is published in the Transport Canada AIP. The most recent version of this table is based primarily on the results of the Falcon 20 performance tests conducted during the previous four test periods (References 2, 3, 7 and 8).

2.2 Falcon 20 Research Aircraft

The test aircraft was the NRC Falcon 20D, C-FIGD, S/N 109, designed and built by Dassault Aviation. With two General Electric CF700-2D-2 engines, the maximum takeoff weight is 27,337 lbf and maximum landing weight is 26,036 lbf. The flight controls are conventional hydraulically actuated ailerons, elevators and rudder with artificial feel, and electrical trim via the feel system for the ailerons and rudder. Pitch trim is by an electrically actuated moving horizontal stabiliser. Leading edge wing flaps (slats) and trailing edge wing flaps are used for lift augmentation. Airbrake panels (one panel per wing) are hydraulically actuated and electrically signalled by a cockpit lever. There are only two airbrake positions, retracted or extended.

The landing gear is conventional, with a hand tiller steerable nose gear fitted with dual 14.5 x 5.5 14 PR tires. The nosegear tires have side-mounted chines to deflect spray. Each main gear is fitted with dual 26 x 6.6 14 PR tires. Tire pressure for all tires is 136 lbf/in^2. A three disc brake unit is flange-mounted to each of the four main wheels, and receives pressure from two independent hydraulic systems for normal (anti-skid assisted or manual), or emergency (manual only) operation. The brake energy limit is 7.27 10^{6} ft-lbf per brake.

Goodyear (now Aircraft Braking Systems Corporation) manufactures the anti-skid system on the Falcon 20. It 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, and rapid wheel deceleration above a fixed maximum rate is interpreted as the initiation of a skid. When a wheel deceleration exceeding a pre-set skid threshold is detected, the 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 lbf/in^2. 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., inner and outer) controlled by separate channels. The Falcon 20 anti-skid system is analog and was developed in the 1960's. It is considered a "Mark 2" system, although it has many of the features associated with "Mark 3" systems.

2.3 Aircraft Instrumentation

The NRC Falcon 20 has an onboard data acquisition system (DAS) in a standard 19 inch avionics rack mounted on the seat rails in the rear cabin of the aircraft. The DAS uses a Digital Equipment Corporation (DEC) LSI 11/73 as a central processing unit (CPU), and includes all interfaces for the following specially mounted instrumentation sensors:

a. Differential GPS latitude, longitude and height;
b. Longitudinal, lateral and vertical accelerometers;
c. Pitch, roll and heading attitude gyros;
d. Pitch, roll and yaw rate gyros;
e. Static and dynamic (total-static) pressure sensors;
f. Total temperature probe;
g. Left and right brake pressure sensors;
h. Weight on wheels switch;
i. Flap and airbrake positions;
j. Left and right, inner and outer wheel speeds (4);
k. Nose wheel steering position;
l. Elevator, aileron and rudder positions;
m. Pitch, aileron and rudder trim positions;
n. Left and right throttle positions; and
o. Pilot event discrete.

The NovAtel RT-20 differential global positioning system (DGPS) was the principal source of aircraft x, y, z position measurement and velocity measurement. It was also used to provide precise real-time aircraft guidance required to fly consistent precision approaches to the runway. This system is more fully described in Reference 1.

An equipment rack and project operator's station is located in the aircraft cabin. The rack contained a NovAtel RT-20 GPS receiver, Dell 486 host computer and monitor, and a VHF receiver and modem used for a real-time DGPS data link. The operator's station was used to initialise and control the airborne software program, and to troubleshoot the DAS when required. Data were recorded at a sample rate of 10 Hz on digital audiotape (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.

3.0 TEST PROCEDURES

3.1 Test Site Description

The North Bay airport has three runways suitable for Falcon 20 operations. The preferred runway for Falcon 20 testing, Runway 13/31, was closed to normal airport traffic and, thus, could be allowed to accumulate a significant amount of undisturbed natural snow or other contaminant prior to testing. The operational runway, Runway 08/26, was also used for aircraft testing but had the constraint that its full length had to be kept open for night and IFR operations. This meant that any test section contamination had to be cleared at the end of each day, and the entire runway had to be kept free of contamination overnight. This made it difficult to acquire any significant natural snow accumulation for testing on Runway 08/26. Runway 18/36 is too short for high speed testing but was used for some low speed test points.

The practice of taking snow from the snow banks along the edges of the runway to create a test section was discontinued for two reasons. The first is due to an incident involving the ingestion of snow into the Falcon 20 engines during the 1997/1998 test period (Reference 7). Secondly, the process of moving various quantities of snow onto the test section via a blower or grader from the edges of the runway, and grooming the snow in place with ground equipment, gave the manipulated snow an unnaturally high density. Instead, only natural snow was used for testing. Natural snow was allowed to accumulate to a desired depth of snow, the test section was then formed by removing the snow from around the edges. As in previous years, the Runway 13/31 test section was about 1200 ft long, starting at 1000 ft from the threshold of Runway 31 and ending short of the intersection between Runway 13/31 and Runway 08/26. The 3500 ft of Runway 31 remaining beyond the intersection was kept clear for effective aircraft braking following the exit from the test section. The test section was 80 ft wide, allowing about 40 ft of cleared pavement on each runway edge to regain control of the aircraft in the event of a lateral departure from the test section.

The location of the test section on Runway 31 allowed both accelerate/stop manoeuvres and landings to be performed. Starting at the threshold of Runway 31, the aircraft could be accelerated to a maximum of about 70 knots prior to entering the test section, resulting in mid-speed or low-speed test points. Landings could be made in the 1000 ft clear area prior to the test section, with high-speed points conducted through the test section. With no published approaches to Runway 31 in North Bay, approaches for landings were made under Visual Flight Rules (VFR) only, using DGPS precision guidance to Runway 31. A 3 degree glidepath was used, with a Glide Path Intercept Point (GPIP) of 400 ft from the threshold of Runway 31 needed to allow the aircraft nose to be lowered and the airbrakes to be extended prior to entering the test section.

Although there was no particular test section designated for Runway 08 during the 1999/2000 test period, the runway could be used in its existing operational condition for aircraft tests. An Instrument Landing System (ILS) approach to Runway 08 was available for operations under Instrument Flight Rules (IFR).

3.2 Tests Conducted

Since no thrust parameter instrumentation or engine thrust calibration data were available, all test runs were done with idle thrust. Coasting runs with no pilot braking were done to verify the rolling friction coefficient and idle thrust, and to determine the contamination drag. Full pilot braking effort (maximum anti-skid braking) runs were done to determine the braking coefficient. The test plan sequence was arranged to allow for periodic airborne brake cooling with the landing gear extended. The following aircraft configurations were tested:

a. Continued takeoff configuration (flaps 15 , airbrakes in)
b. Rejected takeoff configuration (flaps 15 , airbrakes out)
c. Landing configuration (flaps 40 , airbrakes out).

The sequence of events for each contaminated surface was as follows. First, the test surface was prepared and documented to the satisfaction of the various test teams. Ground vehicle runs were made to determine the surface friction prior to the aircraft runs. When applicable, aircraft test runs were made for the determination of contamination drag. Aircraft braking test runs were then made for the determination of the braking friction coefficient. Finally, ground vehicle runs were made to record the surface friction following the aircraft runs. In some cases, ground vehicle runs were made between aircraft test runs to account for changing runway surface conditions. The following test plans were used for the Falcon 20 test points:

YYBFJF00/01: Aerodynamic, Idle Thrust and Rolling Friction Parameter Determination (on a bare and dry runway surface). This plan consisted of taxi tests down the full length of Runways 08/26 and 13/31, and a landing/coast run in the continued takeoff configuration;

YYBFJF00/02: Contamination Drag Determination. This plan consisted of accelerate/ coast and landing/coast runs through the test section in the continued takeoff configuration;

YYBFJF00/03: Braking Friction Coefficient Determination. This plan consisted of accelerate/stop and landing/stop runs through the test section in the rejected takeoff and landing configurations; and

YYBFJF00/04: Integrated Contamination Drag and Braking Friction Coefficient Determination. This plan consisted of accelerate/coast/stop and landing/coast/stop runs through the test section in all three configurations listed above.

Based on the incident involving the ingestion of snow into the Falcon 20 engines during the 1997/98 test period, a detailed ground test plan was developed to incorporate the procedural changes recommended in Reference 7, namely:

a. Maximum water equivalent depth of contamination limited to 0.75 inches for test operations.

b. No free gravel or grit in a contaminated test section of slush or snow (hard packed snow or ice surfaces may be sanded).

c. Average depth of contamination, variations in depth, and specific gravity to be measured and relayed to the test team prior to the start of testing. Ground test co-ordinator to be designated to maintain the consistency of the contaminated test section and observe the aircraft test runs.

d. Test only one aircraft at a time on snow or slush, and minimise test section regrooming between runs.

e. Discontinue the use of mechanically blown or plowed snow and emphasize data collection on runways covered with natural snow.

The condition of each test section was recorded and included both qualitative and analytical descriptions. The analytical description contained depth of contamination at various intervals along and across the test section, specific gravity (SG) of contamination, ambient conditions including temperature and wind, contamination and ground temperatures, and the ERD readings (CRFI) prior to the start of testing and following completion of testing. In addition, the changes in contamination depth adjacent to the aircraft tire tracks, along with any other changes to the test section, were recorded between each aircraft run. Initial test section conditions, any significant changes in the test section parameters, and clearance for each run were relayed via radio from the ground test co-ordinator to the aircraft pilots.

All Falcon 20 test runs were recorded using a video camera from a position adjacent to the test section. Still photographs were taken of the aircraft, and also of the main wheel and nose wheel tracks after each run through loose contamination. Still photographs were also used to document the characteristics of the test sections, particularly those with widely varying conditions.

3.3 Analysis Methods

The analysis methods are fully described in Appendix A of Reference 2, but will be summarised in this section for easy reference. Essentially, the methods involve calculating the balance of forces necessary to obtain the measured aircraft acceleration. Using the general equation for aircraft acceleration along the runway, specific equations can be derived for rolling friction coefficient, braking friction coefficient and contamination drag as shown in the following paragraphs:

a. The general equation for aircraft acceleration along the runway is:

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

$$D_F = \mu(W\cos\varepsilon - L)$$

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

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

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

c. Setting $\mu = \mu_R$ = Rolling Friction Coefficient (no aircraft braking), and $D_{CONTAM} = 0$, the equation for rolling friction coefficient on a runway surface with negligible contamination drag becomes:

$$\mu_R = (\frac{T}{W} - \frac{D}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \tag{3}$$

d. Setting $\mu = \mu_B$ = Aircraft Braking Coefficient (maximum anti-skid braking), and $D_{CONTAM} = 0$, the equation for aircraft braking coefficient on a runway surface with negligible contamination drag becomes:

$$\mu_B = (\frac{T}{W} - \frac{D}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \tag{4}$$

e. Setting $\mu = \mu_R$ = Rolling Friction Coefficient (no aircraft braking), the contamination drag parameter D_{CONTAM}/W can be calculated as a direct indication of the deceleration component due to the contamination drag:

$$\frac{D_{CONTAM}}{W} = \frac{T}{W} - \frac{D}{W} - \varepsilon - \mu_R(1 - \frac{L}{W}) - \frac{1}{g}\frac{dV}{dt} \tag{5}$$

f. Setting $\mu = \mu_B$ = Aircraft Braking Coefficient (maximum anti-skid braking), and retaining the contamination drag parameter D_{CONTAM}/W, the equation for aircraft braking coefficient on a runway surface with appreciable contamination drag becomes:

$$\mu_B = \left(\frac{T}{W} - \frac{D}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}\right) \Big/ \left(1 - \frac{L}{W}\right) \qquad (6)$$

g. Equations for Aerodynamic Lift and Drag, and Engine Thrust at idle power, modelled as a linear function of V_{EAS}, as described in Reference 3, are as follows:

$$L = \frac{1}{2}\rho_o V_{EAS}^2 S C_L$$
$$D = \frac{1}{2}\rho_o V_{EAS}^2 S C_D \qquad (7)$$
$$T = 600 - 4.62 V_{EAS} \quad (lbf)$$

where $S = 441.1 ft^2$ for the Falcon 20

$_o = 0.002377 slug/ft^3$

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

C_L = Lift Coefficient in Ground Effect, Ground Attitude, and

C_D = Drag Coefficient in Ground Effect, Ground Attitude

The revised values of lift coefficient and drag coefficient determined during the 1996 tests (Reference 2), and used for the 1997 tests, were also used for the analysis of the current test results. These are:

	C_L	C_D
Flaps 15 , airbrakes in	0.2	0.05
Flaps 15 , airbrakes out	0.1	0.076
Flaps 40 , airbrakes out	0.3	0.132

Angular wheel speed was determined from the anti-skid system wheel driven DC tachometer generators mounted in the main landing gear axles. The output voltage is given in the maintenance manual as 7.75 (+/- 0.35) VDC per 1000 rpm, from 100 to 3500 rpm. The angular wheel speeds were calibrated as linear fits against the DGPS groundspeed prior to the test flights. In this report, wheel speed is considered to be the same as tire speed. The slip ratio (μ_S) is determined from the equation:

$$\mu_S = (V - V_W)/V; \qquad (8)$$

where V is the aircraft groundspeed in knots and V_W is the wheel speed in knots.

4.0 TEST RESULTS AND DISCUSSION

4.1 Summary of Test Runs

During the winter of 1999/2000, a total of eleven different contaminated runway surfaces were tested during nine separate test sessions in North Bay. An additional session was conducted on bare and dry runway surfaces to evaluate rolling friction coefficients and maximum performance landings to a full stop. A single deployment was flown to North Bay in January 2000.

Test section surface conditions evaluated during the period included naturally occurring patchy snow over a compacted base, with a variable distribution of contamination, and man-made ice surfaces with various levels of roughness (scarification) and applications of sand. Lower CRFI values were achieved this year compared to previous years, with a minimum CRFI = 0.09 tested on a smooth ice surface with no sand. The surface conditions and CRFI/IRFI were recorded between each test run, as adopted last year. This procedure took additional time, but provided a better comparison of aircraft performance data and runway surface friction by minimizing the effects of changing surface conditions over the duration of the test session.

Appendix A contains a description of all surfaces tested, a summary of all the test runs, and the time histories of selected aircraft parameters for each run. A total of 52 test runs were recorded on twelve test surfaces. These included 3 runs for rolling friction, 1 for mapping the test section on runway 36, 4 runs for combined contamination drag/braking coefficient, and 46 runs for braking friction coefficient. Other than the combination runs, no tests were specifically conducted to measure contamination drag, due to a lack of any significant depth of snowfall in North Bay during the winter. On five out of the twelve test surfaces (flights 2000/02, 2000/05, 2000/07, 2000/08 and 2000/11), surface conditions were too slippery to allow safe operation of the aircraft at high speed. As a result, only low and mid-speed data were obtained for these test surfaces. Each of the figures in Appendix A (pages A4 through A21) is annotated with the runway surface description, the aircraft configuration, together with time histories of ground speed (from DGPS), acceleration (from accelerometer data for all runs except the coasting runs on flights 2000/01 and 2000/02 where the derivative of DGPS ground speed was used), left brake pressure and right brake pressure. All runs shown in Appendix A are either coasting runs (no braking) or maximum anti-skid braking runs.

All test were conducted on either runways 08/26/31, with the exception of test flight 2000/12. A target of opportunity arose on runway 36, a surface which had not been tested in the previous four years, and hence required the first test run to be a slow speed taxi run to map the runway slope.

4.2 Verification of Rolling Friction Coefficient and Idle Thrust

Two taxi runs and one landing/coast run were performed on surfaces with negligible contamination drag on flight 2000/01 to confirm the aircraft rolling friction coefficient (μ_R) and the idle thrust. The table on page B1 of Appendix B summarises these three test runs. Individual test runs are shown on page B2, with each data point of Mu Rolling (μ_R) plotted against aircraft groundspeed. These were calculated using equation (3) in section 3.3 paragraph c. Data from the 1996 through 1999 test periods are also shown on page B3.

A good correlation can be seen in the data on page B3 between the 2000 data points and the data points obtained during previous tests. This verifies the relationship (originally derived in Reference 2) between μ_R and aircraft ground speed to be:

$\mu_R = 0.010 + 0.00012$ V: where V is the groundspeed in knots.

In addition to verifying the equation for μ_R above, the taxi runs also confirmed the equation for idle thrust shown in section 3.3, and the landing/coast run confirmed the adopted values of aerodynamic lift coefficient and drag coefficient determined during previous tests and also listed in section 3.3.

4.3 Anti-skid Braking Slip Ratio

Falcon 20 slip ratio data were obtained to provide a better understanding of aircraft anti-skid braking performance as a function of aircraft ground speed and runway surface condition. Appendix C summarizes the braking test runs for which the anti-skid slip ratio ($_S$) was determined, and lists the mean slip ratios for each main wheel in the table on pages C1 and C2. Pages C3 through C47 show the time histories of several parameters, with one braking run per page. The parameters plotted for each run are the aircraft ground speed, left and right outer wheel speeds, left and right inner wheel speeds, left and right brake pressures, left and right outer wheel slip ratios, and left and right inner wheel slip ratios.

As an aircraft decelerates and slows down (i.e., on the ground) it will reach a point where the rudder is no longer effective to steer the aircraft, and the nose wheel steering must be used for directional control. On the Falcon 20, the rudder is no longer effective below about 80 knots. On a bare and dry surface the cornering friction of the nose wheel is effective up to 80 knots and above; hence, throughout the ground roll period the pilot is in full directional control of the aircraft. However, as the runway surface friction decreases, so does the cornering friction of the nose wheel. There can exist a dangerous speed band where the aircraft is too fast for effective nose wheel steering due to a lack of cornering friction, but too slow for rudder effectiveness, and the pilot cannot steer the aircraft. Hence, on very slippery surfaces only slow speed tests were conducted. The data from all five years of testing has shown the braking coefficient to be independent of ground speed and, therefore, slow speed test data is considered appropriate for the determination of aircraft braking performance.

Flight 2000/02 runs 1 to 6 (pages C3 to C8) were full anti-skid braking runs on a runway surface, which was 60% ice, 40% compacted snow over ice, scarified longitudinally with average CRFI's of 0.18 to 0.16. On this low friction surface, the anti-skid system is very active, modulating the brake pressures from between 100 to 600 psi, well below the system maximum of 1200 psi. The wheel speeds essentially vary from zero up to the aircraft ground speed, indicating that the wheels are either in a state of free-wheeling or in a deep skid (i.e., wheel lockup). Braking action can be considered to be close to nil and, hence, only low speed test points were taken on this surface. The maximum ground speed attained was 55 knots.. Throughout the six runs the left-outer and right-outer wheels are causing the anti-skid system to modulate. The right-inner brake exhibits significantly lower slip ratios than the other wheels, the same for all of this year's testing. This will be discussed in detail following the presentation of the 11 test surfaces.

Flight 2000/03 run 1 (page C9) was a full anti-skid braking run on a runway surface 100% bare and dry, with occasional ice patches and an average CRFI of 0.75. For most of the test the brake pressures are at the maximum of 1200 psi, indicating that the system is torque limited. On the left hand side there is one instance of the anti-skid system cycling and two on the right. These would be due to ice patches or centerline paint markings encountered. The average slip ratio is about 8% and is very constant, with the right-inner brake being a notable exception as already mentioned.

Flight 2000/04 runs 1 to 5 (pages C10 to C14) were full anti-skid braking runs on a runway surface of 100% thin 1/2 inch loose snow, changing to a thin layer of loose snow with tracks, average CRFI's between 0.28 and 0.31. It appears that the two outer wheels are driving the anti-skid system, which is very active. The average slip ratio is around 10%, which is quite good. The wheel speeds are very well modulated and none of the wheels enter into a deep skid. This indicates that the anti-skid system had adapted very well to this surface condition. A careful examination of the brake pressures for the first two runs seems to reveal a beat frequency of around 0.5 Hz. This phenomenon is not present for the last three runs. A review of the data from all years of testing reveals only one other (marginal) case of this phenomenon (Flight 2000/10 run 3, Page C38 of this report). There are three possible explanations for this behavior. One is that it is a function of the adaptive modulation technique employed by the anti-skid controller. Secondly, this could simply be a function of the surface conditions, perhaps due to wind blown ridging of the light snow cover. Lastly, this could be evidence of brake pressure sampling anti-aliasing. The data system normally samples the analogue brake pressures at 10 Hz. However, some tests were conducted at 32 Hz to assess the suitability of the 10 Hz sampling rate. These tests revealed the frequency response of the anti-skid system to be 4 Hz, just below the Nyquist frequency of 5 Hz. This leads to the conclusion that 10 Hz sampling of the brake pressures is adequate, but is the minimum acceptable.

Flight 2000/05 runs 1 to 6 (pages C15 to C20) were carried out on a surface which was 100% ice with occasional bare spots, with average CRFI's from 0.14 to 0.12. Runs 1 to 3 show the behavior of the anti-skid system below the cutoff speed. The Falcon's anti-skid system is set to cut out at speeds below 17 knots where full brake pressure is supplied to the brakes. From wheel speed plots it appears that the ground speed trace has not been plotted when, in fact, the wheels are locked up and the ground speed is zero. Looking at the slip ratio plots, one can see that the anti-skid system on the left side of the aircraft cuts out at the correct value of 17 knots; however, the right side seems to modulate right down to 8 knots. This represents an operational hazard. Should the left wheel encounter a bare patch, the aircraft could lurch to the left and depart the test section, albeit at very low speeds. On runs 4 to 6, the aircraft speeds are higher and do not drop below the anti-skid cutoff speeds; however, due to safety considerations, no high-speed test points were conducted. On these test runs, the anti-skid system exhibits typical behavior.

Flight 2000/06 runs 1 and 2 (pages C21 and C22) were carried out on a surface which was 100% bare and dry with occasional ice patches, with an average CRFI of 0.73. These two runs exhibit typical bare and dry behaviour, and the comments from Flight 2000/03 apply. From the traces it can be seen that the ice patches appear to be concentrated in the second half of the test section, as this is where brake pressure modulation occurred on both test runs.

Flight 2000/07 runs 1 to 6 (pages C23 to C28) were carried out on a surface which was 100% ice with occasional bare spots, with average CRFI's from 0.11 to 0.09. This surface represents the lowest friction value tested on. Comments for flight 2000/06 apply for this test. On run 1 the left-hand anti-skid system has some odd behavior where the cutoff speed is reached and the brake pressure is no longer modulated; however, at 15 knots it starts to modulate again. No explanation is offered to describe this behavior. Interesting behavior can be seen of the left-hand inner wheel for runs 3 to 6. For most of the tests, the wheel speeds are typical for very low friction surfaces, where the wheel speeds alternate between zero and the aircraft ground speed. However, for periods of two to four seconds the wheel speeds cycle well below the aircraft ground speed (i.e., high slip ratio). It would appear that, on this extremely low surface friction, the anti-skid system is unable to effectively adapt to the conditions.

Flight 2000/08 runs 1 to 6 (pages C29 to C34) were carried out on a runway surface of 100% ice with sand application and occasional bare spots, with average CRFI's from 0.19 to 0.21. For the test runs, the anti-skid system on the aircraft behaved consistently with previous runs. Despite the low friction and the relatively poor braking, the pilots indicated that the nose wheel directional control was good, due to the application of sand to the test surface.

Flight 2000/09 runs 1 to 3 (pages C35 to C 37) were carried out on a runway surface of 70% bare and dry, 30% light dusting of snow, with average CRFI's from 0.52 to 0.63. With each run the CRFI increased, indicating that the light dusting of snow was being progressively blown off the test section. This is also evident in the brake pressure traces, where for the first run the brake pressure is cycling just below the maximum torque limited pressure. With the two subsequent test runs, the brake pressures are operating close to the max system brake pressure for longer periods of time, typical of a bare and dry surface.

Flight 2000/10 runs 3 to 6 (page C38 to C41) were carried out on a runway surface of 100% 3/4" loose snow changing to 60% packed snow, 40% 3/4" loose snow, with average CRFI's from 0.33 to 0.26. Surprisingly, the surface friction decreases as the loose snow is compacted over the duration of the testing. The anti-skid system is very active on all runs, with the very notable exception of the right inner wheel. The left outer wheel speed trace for run 3 (page C38) shows a very distinct harmonic beat frequency, particularly during the last five seconds of the test run. See comments for flight 2000/03 for possible explanations.

Flight 2000/11 runs1 to 4 (pages C42 to C45) were carried out on a runway surface of 100% longitudinally scarified ice, with average CRFI's of 0.19 and 0.20. For safety considerations, only slow speed tests were conducted on this surface. On the first two runs the entry speed into the test section was at or below 40 knots and the wheel speeds essentially cycled between zero and the aircraft ground speed. However, on the last two runs the aircraft entered the test sections at 55 knots and the behavior of the anti-skid system is quite different. The anti skid system does not allow the wheels to go into deep skids as in the previous two lower speed runs. It is only when the wheel speeds drop below 20 knots that the wheels start to lock up. It appears that the higher entry speed into the test section has placed the anti-skid system into a different operating mode. In fact it, is arguable that in the low speed run cases the anti-skid system never stabilizes and, hence, the wheels are either freewheeling or locked up.

Flight 2000/12 runs 2 and 3 (pages C46 and C47) were carried out on a runway surface of 90% sanded ice, 10% bare and dry, with average CRFI's of 0.26. From the brake pressure traces it is evident when the wheels encounter a bare and dry patch as the anti-skid system responds by spiking the pressure up to near maximum. It appears that it is the two outer wheels that are primarily driving the anti-skid system to cycle.

In the entire set of appendix C graphs the right inner brake consistently showed signs of not cycling correctly. Flight 2000/12 run 3 (page C47) shows this clearly. This also becomes glaringly obvious when we plot all of the average slip ratios against the ground speed of the aircraft (page C48). The graph shows that the slip ratio of right inner wheel (solid squares) is significantly lower than that of the other three wheels. A review of the maintenance records and the current wear limits on the brakes reveal that the right inner wheel is not wearing at the rates that the other wheels are. The right inner brakes were replaced in March of 1998, after that winter of testing. The other three brake units were all replaced subsequent to this date and, yet, the right inner brake shows less wear than the others. A review of last year's data (Ref. 8, page C 40) indicates that the right inner brakes were functioning at a level just below the others and, presumably, only starting to malfunction. The aircraft maintenance crew chief offers two possible explanations for this behaviour. The first is a malfunctioning brake caliper unit and the second is a malfunctioning brake metering valve. Despite the reduced braking effectiveness of the right inner brake unit, the overall aircraft braking coefficient was not reduced by any significant amount.

Page C48 of appendix C shows the average slip ratio for each run plotted against the average ground speed of the aircraft. It is evident that the slip ratio increases with decreasing aircraft ground speed and that this relationship follows a power law. Typical braking technique employed by pilots is to initially apply heavy braking action and, as the aircraft slows down, to ease off the brakes. Hence, if one looks only at the data from 40 knots and up, the relationship between the slip ratio and groundspeed is essentially linear. In this speed range the four wheels are all braking at essentially the same efficiency, thus supporting the reason why the reduced efficiency of the right inner brake does not significantly reduce the overall braking coefficient of the aircraft. An energy budget of a braking run reveals that the speed band of 40 knots down to 0 knots represents only 11% of the energy required to stop an aircraft from 120 knots. For the Falcon, the 40 knot point marks the break point where, below this speed, the slip ratios increase exponentially. The conclusion is that the efficiency of the anti-skid system below 40 knots is relatively insignificant to the overall braking performance of an aircraft. One must, therefore, be careful when drawing conclusions about the efficiency of the anti-skid system from only low speed braking runs.

4.4 Aircraft Braking Coefficient on Runway Surfaces with no or Negligible Contamination Drag

Appendix D summarises the test runs to determine the aircraft braking coefficient (μ_B) on runway surfaces with no or negligible contamination drag. Eleven such surfaces were tested during the January 2000 test period as follows:

a. Flight 2000/02, 60% ice, 40% compacted snow over ice, ice scarified longitudinally, average CRFI from 0.16 to 0.18,
b. Flight 2000/03, 100% bare and dry, occasional ice patches, average CRFI 0.75,
c. Flight 2000/04, 100% thin loose snow with tracks, 20% bare and dry, 20% compressed snow, 60% loose snow, average CRFI from 0.28 to 0.31,
d. Flight 2000/05, 100% ice with occasional bare spots, average CRFI from 0.12 to 0.14,
e. Flight 2000/06, 100% bare and dry with occasional ice patches, average CRFI 0.73,
f. Flight 2000/07, 100% ice with occasional bare patches, average CRFI from 0.09 to 0.10,
g. Flight 2000/08, 100% ice with sand application and occasional bare spots, average CRFI from 0.19 to 0.22,
h. Flight 2000/09, 70% bare and dry, 30% light dusting of snow, average CRFI from 0.52 to 0.63,
i. Flight 2000/10, 100% 3/4 inch loose snow changing to 60% packed snow, 40% ¾ inch loose snow, average CRFI from 0.26 to 0.33,
j. Flight 2000/11, 100% longitudinally scarified ice, average CRFI from 0.19 to 0.20,
k. Flight 2000/12, 90% sanded ice, 10% bare and dry, average CRFI from 0.26 to 0.28.

On pages D3 to D18 the results for each individual test run are graphically plotted. The following is a discussion of the noteworthy test data.

Flight 2000/02, shown on page D3 and D4, shows a test surface of 60% longitudinally scarified ice and 40% compacted snow over ice. The data shows the typical variations associated with calculation of the μ_B. Since the aircraft deceleration is the predominant term that affects the calculation of the μ_B, the variations are associated with variations in the deceleration. This, in turn is due to the rapid cycling of the anti-skid system of the aircraft and is not due to sensor noise. This is why the data has not been filtered or averaged prior to presentation. Due to the low CRFI values measured by the ground vehicle, the aircraft did not perform any high-speed tests on this surface for safety purposes.

Flight 2000/04, shown on pages D6 and D7, shows a test surface of 100% 1/2" loose snow changing to loose snow with tracks, 20% bare and dry, 20% compacted snow and 60% loose snow. As the tests progress and the surface becomes more compacted and bare and dry, there is a corresponding increase in the μ_B of the aircraft. Coincidentally, the aircraft test speeds also increase with each run, leading to possible false interpretations. This will be discussed in further detail shortly.

Flight 2000/06 shown on page D10, shows a test surface of 100% bare and dry with occasional ice patches. At the higher speeds (above 50 knots) this test surface does not show the typical data scatter that the other surfaces do. This is due to the aircraft brakes being torque limited, meaning that the aircraft braking system cannot apply enough braking force to the wheels to induce a skid, hence the anti skid system is inactive during this portion. The aircraft brakes are only torque limited at the higher speeds. As the aircraft slows, the brakes can apply sufficient force to cause the wheels to skid and, hence, the anti-skid system to cycle. When the brakes are no longer torque limited the anti-skid system starts to cycle and the aircraft deceleration shows the typical scatter. Pages A12, C21 and C22 show the deceleration, brake pressures and wheel speeds for these two test runs.

Flight 2000/09, shown on page D15, shows a test surface of 70% bare and dry with a 30% light dusting of snow. The first run shows a wildly varying μ_B, whereas the second run shows a variation of μ_B consistent with other data runs. The third run shows a scatter pattern consistent with that described in the previous paragraph. The conclusion is that the surface condition is changing throughout the test sequence. The surface starts out as an inhomogeneous surface with the dusting of snow giving the varying results. The presence of the aircraft then starts to blow the light dusting of snow off the test section such that, by the end of the test, the condition reflects that of a bare and dry surface.

On pages D19 to D21 the average μ_B of the aircraft is plotted against ground speed for each test surface. In nine of the eleven graphs shown there is clearly no trend observed between the μ_B of the aircraft and the ground speed. This is consistent with the entire previous data collected on the Falcon. The two notable exceptions are flights 2000/04 and 2000/09 where there appears to be a linear relationship with the aircraft ground speed. As previously noted, both of these cases represent surface conditions that changed significantly with each pass of the aircraft through the test section. Therefore, the apparent relationship between the aircraft μ_B and ground speed is merely coincidental and is really a reflection of a changing test surface friction.

The graph on page D22 shows the mean μ_B plotted against the mean CRFI for each of the runs contained in Appendix D (2000 data), together with the data obtained from previous years (1996 through 1999). The dashed line shows the linear fit for the 1996 and 1997 tests, currently used as a basis for the CRFI tables of recommended landing distance. The 2000 data adds five full braking points on a bare and dry surface at the upper right side of the chart, and adds a number of braking points at the lower CRFI levels down to 0.09 at the lower left side. The solid line shows the linear fit for all data points shown. The 2000 data falls within the scatter of the data from previous years and, hence, there is almost no change in the linear fit of μ_B and CRFI. In the development of the CRFI tables, a safety factor was used that took into account the scatter in the data. Therefore, the 2000 test data does not significantly change or influence the CRFI tables of recommended landing distance published in the AIP.

4.5 Contamination Drag

Appendix E summarizes the test runs to determine the contamination drag for only one surface condition, which occurred during the 2000 test period. This was 100% 3/4" loose snow changing to 60% packed snow, 40% 3/4" loose snow, on Flight 2000/10. The table shown on page E1 contains the summary information for the two test runs. Page E2 shows the variation of the drag parameter D_{CONTAM}/W (calculated using equation (5) in section 3.3 paragraph e) with ground speed for the two individual runs, where D_{CONTAM} is the contamination drag and W is the aircraft weight. Page E3 shows the mean D_{CONTAM}/W plotted against the mean ground speed for the two runs.

The two graphs on page E2 reveal that the mean D_{CONTAM}/W are very low (0.025 and 0.026 respectively). These values are close enough to zero that this test case can be considered to have negligible contamination drag. The subsequent braking runs discussed in the following section (4.6) were treated as having contamination drag.

On page E3 the graphs of mean D_{CONTAM}/W versus mean aircraft ground speed reveal that there is no correlation between the two. This supports the conclusions made in the four previous NRC reports that the contamination drag is independent of ground speed. This is in contradiction to the currently accepted methodology (JAA AMJ25X1591) that has a speed relationship. However, it should be cautioned that the values obtained this year are close to nil and that they do not support this conclusion as strongly as previous years data did.

4.6 Aircraft Braking Coefficient on Runway Surfaces with Appreciable Contamination Drag

Appendix F summarizes the test runs to determine the aircraft braking coefficient (μ_B) on runway surfaces with appreciable contamination drag. Only one such surface was tested during the 2000 test period, and this was on Flight 2000/10, where the contamination drag was essentially zero, as described above.

Page F2 shows each individual test run (Mu Braking versus Ground Speed) for the test surface and page F3 summarizes these results. The data shows no correlation between the aircraft braking coefficient and the ground speed.

On page F4 the aircraft braking coefficient is compared with the Canadian Runway Friction Index (CRFI), as measured by the ERD. The solid line shows the relationship between the Mu braking and the CRFI on surfaces with no or negligible contamination drag from previous years. If one assumes that the model and methodology used for calculating the Mu braking on surfaces with and without contamination drag is valid, then it follows that the Mu's should compare very well with each other and, in fact, should be the same. From the graph on page F4 there is too little data to draw this conclusion. However, if one looks at the entire five year data (page F5) set, this is indeed so.

5.0 International Runway Friction Index (IRFI)

For the first time the International Runway Friction Index (IRFI) was available as a measured quantity by the international reference ground vehicle. This data is summarized in Appendix A on pages A1 through A3. In the past the IRFI has only been available in a virtual form as a conversion formula from other ground vehicles. This section summarizes the relationship of μ_B versus IRFI, and contrasts that with the comparison of the μ_B versus CRFI for the 2000 test data.

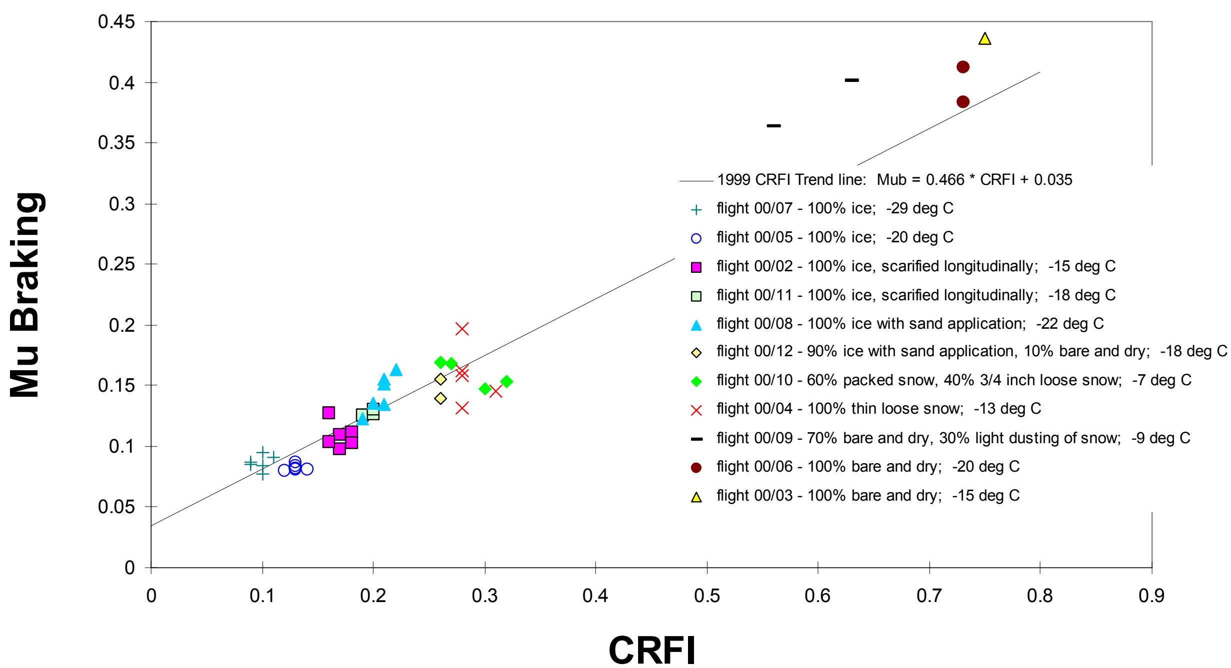


Figure 1
Falcon 20 Mu Braking versus CRFI, 2000 Data

Figure 1 shows the Falcon 20 Mu Braking coefficient versus the measured CRFI for the 2000 test data. The legend on the right shows the applicable flight number and runway surface contamination description. The relationship between the aircraft μ_B and CRFI shows a good linear relationship. The trend of increasing μ_B is consistent with the increasing friction associated with each test surface. For example, the 100% sanded ice surface has a higher friction than that of a 100% ice surface. This holds true for all the test surfaces from 100% ice all the way up to the bare and dry test surface.

Figure 2 shows the 2000 aircraft μ_B versus IRFI data. From this figure, it is evident that there are problems with the IRFI. There is a lack of a good correlation between the μ_B and the IRFI. If the three high friction value test surfaces are ignored, the data would suggest no correlation at all. There is also a lack of consistency between the IRFI and the surface conditions. For example flight 2000/02 was a 100% scarified ice surface was measured to have a higher IRFI than flight 2000/04 which was a 100% loose thin snow. There appears to be insufficient data measurement resolution to distinguish the different surfaces. For example, the data in figure 2 clusters around the range of 0.23 to 0.36 on the IRFI scale while, on the CRFI scale, the same data covers a range of 0.09 to 0.34. There remains, therefore, more work to be done by the IRFI team to better correlate with aircraft test results.

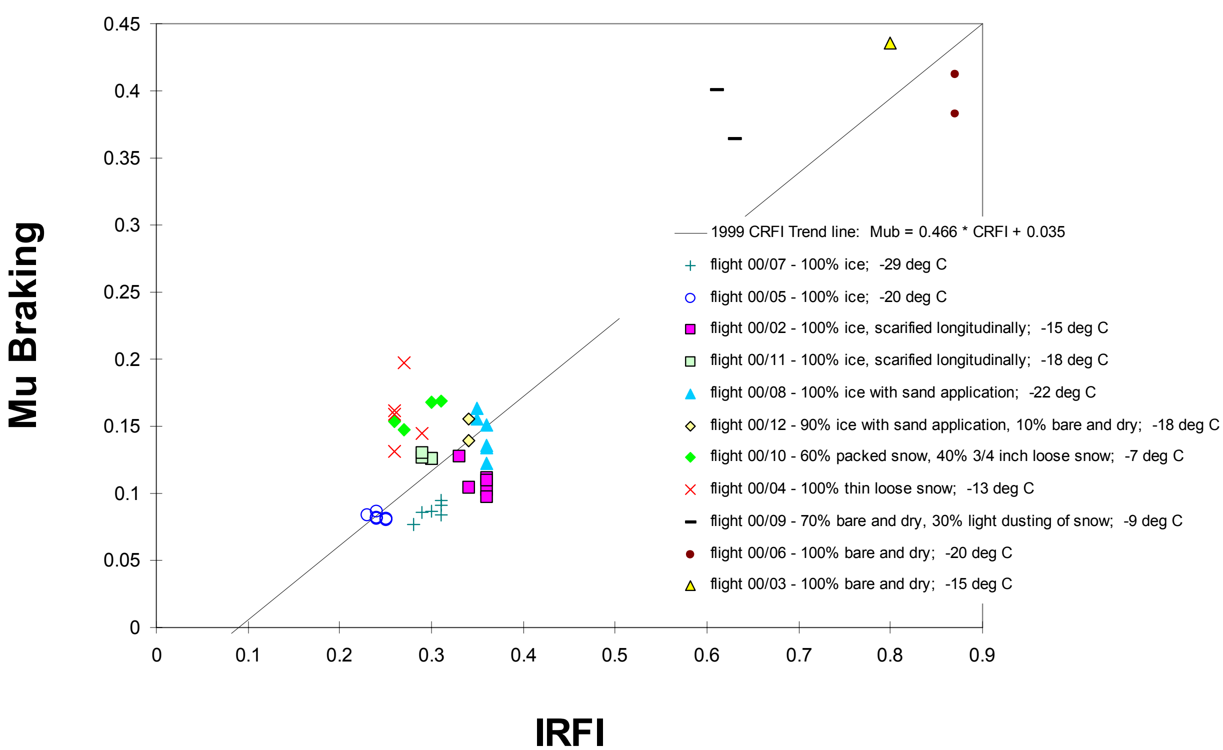


Figure 2
Falcon 20 Mu Braking versus IRFI, 2000 Data

6.0 CONCLUSIONS

During the winter of 1999/2000, a total of twelve different contaminated runway surfaces were tested during nine separate test sessions in North Bay. The tests provided some important additional information on aircraft braking performance on runway surfaces with very low CRFI values. The results from previous tests were also verified, and the test procedures and aircraft limitations evolving from those tests were validated. The following specific conclusions can be drawn from this phase of the test program:

a. The average slip ratio for full anti-skid braking increased linearly with decreasing groundspeed above 40 knots. Data below 40 knots lie outside the realistic operating range of the anti-skid system and, therefore, give little or no practical information for determination of anti skid system efficiency.

b. Low speed tests were, however, important to the assessment of the handling characteristics of the aircraft on very low friction surfaces, and hence the safety of the operation.

c. The aircraft braking coefficient was independent of ground speed. Therefore, on surfaces with only low speed test points, these results are valid for drawing conclusions for higher speeds.

d. The relationship of aircraft braking coefficient versus CRFI, as determined from past years, remains essentially unchanged.

e. The table of recommended landing distances (CRFI tables), based on the Mu Braking and CRFI relationship, remain unchanged from that contained in Reference 8.

f. The IRFI did not correlate well with the aircraft and was not consistent with test surface descriptions.

g. A defective right-inner brake unit did not perform to the level of the other three brake units. However, the overall aircraft braking performance was not significantly affected.

7.0 RECOMMENDATIONS

a. For the past five years of testing, the problem of aircraft landing has been examined in great detail and, has resulted in the creation of the “CRFI tables”. Aircraft performance for a rejected takeoff (RTO) has not yet been investigated.

b. As more aircraft continue to participate in the JWRFP, it would be beneficial for the aviation community to have a detailed comparison made of all these aircraft.

c. More work needs to be done on the IRFI. For the IRFI to be truly accepted as an international standard, it needs to correlate with aircraft breaking performance **at least** as well as the CRFI does.

d. More aircraft tests need to be done with large wide-bodied aircraft. The CRFI tables currently stop at an aircraft landing distance of 4000 ft. It is important for the aviation community to have the tables extended beyond this distance.

e. The right-inner brake unit of the Falcon 20 needs to be serviced before any further runway friction work is done with this aircraft.

8.0 ACKNOWLEDGEMENTS

The authors are indebted to the many people who contributed to the success of this project over the five years of testing so far completed. The NRC Falcon 20 test team and other NRC people who provided support during the aircraft deployments. The Transport Canada Operational Standards Branch who provided project guidance and much needed financial backing. The Transportation Development Centre project managers who provided project co-ordination and financial administration. The Transport Canada Airports Branch who co-ordinated the activities of the various test teams and ran the day-to-day operations during the test period, and the North Bay airport staff who handled the numerous support requirements and ensured the preparation of all the test sections to the specifications desired.

9.0 REFERENCES

1. J.B. Croll, J.C.T. Martin, M. Bastian — Determination of Falcon 20 Landing Distances on Winter Contaminated Runways as a Function of the James Brake Index, National Research Council Canada, IAR-AN-84, August 1996.

2. J.C.T. Martin, J.B. Croll, M. Bastian — Braking Friction Coefficient and Contamination Drag Obtained for a Falcon 20 Aircraft On Winter Contaminated Runway Surfaces, National Research Council Canada, LTR-FR-132, September 1996.

3. J.B. Croll, J.C.T. Martin, M. Bastian — Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1996/1997, National Research Council Canada, LTR-FR-137, August 1997.

4. M. Doogan, E. Herrmann, P. Lamont — Braking Friction Coefficient and Contamination Drag for the Dash 8 on Winter Contaminated Runways, de Havilland, Inc, DHC-D4547-97-09, September 1997.

5.	M. Doogan E. Herrmann P. Lamont	Dash 8 Aircraft Performance Testing on Contaminated Runway Surfaces (Winter 1997/1998), Bombardier Aerospace, DHC-D4547-98-06, June 1998.
6.	M. Bastian P. Lamont	Braking Friction Coefficient and Contaminated Drag of a B727 on Contaminated Runways, National Research Council Canada, LTR-FR-147, TP 13258E, June 1998.
7.	J.B. Croll J.C.T. Martin M. Bastian	Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1997/1998, National Research Council Canada, LTR-FR-151, TP 13338E, December 1998.
8.	J.B. Croll J.C.T. Martin M. Bastian	Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1998/1999, National Research Council Canada, LTR-FR-158, TP 13557E, December 1999.
9.	J.C.T. Martin	Proposed Amendment to the CRFI Recommended Landing Distance Table for Aircraft with Thrust Reverser or Propeller Reversing Systems, Transport Canada Aircraft Certification Flight Test Division, January 1999.

APPENDIX A - SUMMARY OF TEST RUNS

The following table shows the test conditions for all test runs. Pages A4 to A21 show the time histories of ground speed, acceleration, left brake pressure and right brake pressure for each run (up to 4 runs per page). Note: for coasting runs, the brake pressure is zero.

FLT/ DATE	RUN/ TIME	RW	TAXI/ RTO/ LAND	CONFIG (see Note 1)	WEIGHT (LB)	HW (KT)	SURFACE DESCRIPTION (see Note 2)	MEAN IRFI	MEAN IMAG
2000/01 17/01/00	1 13:57	08	TAXI	15/IN/NO	21220	-1	100% Bare and Dry, Occasional Ice Patches Air Temperature -25 C		
	2 14:05	26	TAXI	15/IN/NO	21120	2	"		
	3 14:34	08	LAND	15/IN/NO	20020	-4	"		
	4 14:42	26	RTO	15/OUT/B	19820	4	"		
2000/02 18/01/00	1 15:52	31TS	RTO	15/OUT/B	22590	-4	60% Ice, 40% Compacted Snow over Ice, Ice Scarified Longitudinally CRFI from 0.16 to 0.22, Average 0.18 Air Temperature -15 C Surface Temperature -12 C to -14 C	0.36	0.35
	2 15:58	31TS	RTO	40/OUT/B	22340	-4	CRFI from 0.16 to 0.22, Average 0.18	0.36	0.35
	3 16:12	31TS	RTO	40/OUT/B	22090	-4	CRFI from 0.13 to 0.20, Average 0.17	0.36	0.35
	4 16:23	31TS	RTO	15/OUT/B	21790	-4	CRFI from 0.13 to 0.20, Average 0.17	0.36	0.35
	5 16:33	31TS	RTO	15/OUT/B	21690	-3	CRFI from 0.14 to 0.20, Average 0.16	0.33	0.30
	6 16:41	31TS	RTO	40/OUT/B	21440	-4	CRFI from 0.14 to 0.20, Average 0.16	0.34	0.32
2000/03 18/01/00	1 17:08	08	LAND	40/OUT/B	20590	3	100% Bare and Dry, Occasional Ice Patches CRFI from 0.68 to 0.78, Average 0.75 Air Temperature -15 C Surface Temperature -14 C	0.80	0.83
2000/04 19/01/00	1 13:59	26TS	RTO	40/OUT/B	22990	6	100% Thin (~1cm)loose snow changing to thin layer of loose snow with tracks. 20% bare and dry, 20% compressed snow, 60% loose snow CRFI from 0.25 to 0.29, Average 0.28 Air Temperature -13 C Surface Temperature -9 C Specific Gravity of loose snow 0.08	0.26	0.26
	2 14:13	26TS	LAND	40/OUT/B	22490	7	CRFI from 0.25 to 0.29, Average 0.28	0.26	0.26
	3 14:20	26TS	RTO	15/OUT/B	22090	6	CRFI from 0.25 to 0.29, Average 0.28	0.26	0.26
	4 14:35	26TS	LAND	15/OUT/B	21690	3	CRFI from 0.25 to 0.35, Average 0.31	0.27	0.25
	5 14:43	26TS	RTO	40/OUT/B	21340	3	CRFI from 0.25 to 0.35, Average 0.31	0.29	0.25

FLT/ DATE	RUN/ TIME	RW	TAXI/ RTO/ LAND	CONFIG (see Note 1)	WEIGH T (LB)	HW (KT)	SURFACE DESCRIPTION (see Note 2)	MEAN IRFI	MEAN IMAG
2000/05 20/01/00	1 14:56	31T S	RTO	15/OUT/B	22290	0	100% ice with occasional bare spots CRFI from 0.11 to 0.15, Average 0.13 Air Temperature -20 C Surface Temperature -15 C	0.25	0.26
	2 15:02	31T S	RTO	40/OUT/B	22140	3	CRFI from 0.11 to 0.15, Average 0.13	0.24	0.26
	3 15:32	31T S	RTO	40/OUT/B	21590	2	CRFI from 0.11 to 0.15, Average 0.13	0.23	0.25
	4 15:38	31T S	RTO	15/OUT/B	21390	0	CRFI from 0.11 to 0.15, Average 0.13	0.24	0.25
	5 15:54	31T S	RTO	15/OUT/B	21190	2	CRFI from 0.10 to 0.15, Average 0.12	0.24	0.25
	6 16:01	31T S	RTO	40/OUT/B	20890	3	CRFI from 0.10 to 0.15, Average 0.12	0.25	0.25
2000/06 20/01/00	1 16:40	08	RTO	40/OUT/B	20390	2	100% bare and dry with occasional ice patches CRFI from 0.67 to 0.79, Average 0.73 Air Temperature -20 C	0.87	0.90
	2 17:02	08	LAND	15/OUT/B	19240	3	CRFI from 0.67 to 0.79, Average 0.73	0.87	0.90
2000/07 21/01/00	1 8:26	31T S	RTO	15/OUT/B	22590	-1	100% ice with occasional bare patches CRFI from 0.09 to 0.12, Average 0.10 Air Temperature -29 C	0.31	0.27
	2 8:32	31T S	RTO	40/OUT/B	22390	0	CRFI from 0.09 to 0.12, Average 0.10	0.31	0.27
	3 8:43	31T S	RTO	40/OUT/B	22190	0	CRFI from 0.08 to 0.12, Average 0.11	0.31	0.27
	4 8:50	31T S	RTO	15/OUT/B	22040	0	CRFI from 0.08 to 0.12, Average 0.11	0.30	0.26
	5 9:00	31T S	RTO	15/OUT/B	21790	2	CRFI from 0.08 to 0.10, Average 0.09	0.29	0.26
	6 9:08	31T S	RTO	40/OUT/B	21640	2	CRFI from 0.08 to 0.10, Average 0.09	0.28	0.26
2000/08 21/01/00	1 13:15	31T S	RTO	15/OUT/B	21090	6	100% ice with sand application and occasional bare spots CRFI from 0.17 to 0.22, Average 0.20 Air Temperature –22 C	0.36	0.36
	2 13:21	31T S	RTO	40/OUT/B	20990	5	CRFI from 0.17 to 0.22, Average 0.20	0.36	0.36
	3 13:48	31T S	RTO	40/OUT/B	20640	1	CRFI from 0.18 to 0.27, Average 0.22	0.35	0.38
	4 13:55	31T S	RTO	15/OUT/B	20340	2	CRFI from 0.18 to 0.27, Average 0.22	0.35	0.36
	5 14:10	31T S	RTO	40/OUT/B	20140	2	CRFI from 0.18 to 0.26, Average 0.21	0.36	0.36
	6 14:16	31T S	RTO	40/OUT/B	19990	1	CRFI from 0.18 to 0.26, Average 0.21	0.36	0.36
2000/09 24/01/00	1 12:12	26T S	RTO	15/OUT/B	22400	3	70% Bare and Dry, 30% light dusting of snow CRFI from 0.38 to 0.49, Average 0.42 Air Temperature –9	0.64	0.79
	2 12:20	26T S	RTO	40/OUT/B	22150	2	CRFI from 0.59 to 0.62, Average 0.61	0.63	0.80
	3 12:40	26T S	LAND	40/OUT/B	21400	3	CRFI from 0.65 to 0.66, Average 0.66	0.61	0.82

FLT/ DATE	RUN/ TIME	RW	TAXI/ RTO/ LAND	CONFIG (see Note 1)	WEIGHT (LB)	HW (KT)	SURFACE DESCRIPTION (see Note 2)	MEAN IRFI	MEAN IMAG
2000/10 25/01/00	1 12:32	26TS	TAXI	15/IN/NO	22480	-4	100% ¾ inch loose snow changing to 60% packed snow, 40% ¾ inch loose snow CRFI from 0.32 to 0.35, Average 0.33 Air Temperature –7	0.25	0.24
	2 12:43	26TS	TAXI	15/IN/NO	22230	-3	CRFI from 0.32 to 0.35, Average 0.33	0.25	0.24
	3 12:56	26TS	RTO	15/OUT/B	21980	-3	CRFI from 0.25 to 0.30, Average 0.27	0.26	0.25
	4 1:04	26TS	RTO	40/OUT/B	21630	-3	CRFI from 0.25 to 0.30, Average 0.27	0.27	0.28
	5 1:33	26TS	LAND	40/OUT/B	20780	-4	CRFI from 0.21 to 0.29, Average 0.26	0.30	0.32
	6 1:43	26TS	RTO	15/OUT/B	20580	-3	CRFI from 0.21 to 0.29, Average 0.26	0.31	0.34
2000/11 27/01/00	1 11:24	31	RTO	15/OUT/B	22340	0	100% Scarified Ice CRFT from 0.16 to 0.23, Average 0.19 Air Temperature –18	0.30	0.33
	2 11:30	31	RTO	40/OUT/B	22190	6-11	CRFT from 0.16 to 0.23, Average 0.19	0.30	0.33
	3 11:36	31	RTO	40/OUT/B	22040	0	CRFT from 0.16 to 0.25, Average 0.21	0.29	0.32
	4 11:44	31	RTO	15/OUT/B	21840	0	CRFT from 0.16 to 0.25, Average 0.21	0.29	0.31
2000/12 27/01/00	1 12:25	36	TAXI	15/OUT/NO	20590	7-15	90% Sanded Ice, 10% Bare and Dry CRFI from 0.26 to 0.29, Average 0.28 Air Temperature –18	0.36	0.39
	2 12:51	36	RTO	40/OUT/B	20340	8	CRFI from 0.21 to 0.30, Average 0.26	0.34	0.36
	3 12:55	36	RTO	40/OUT/B	20190	7-11	CRFI from 0.21 to 0.30, Average 0.26	0.34	0.36

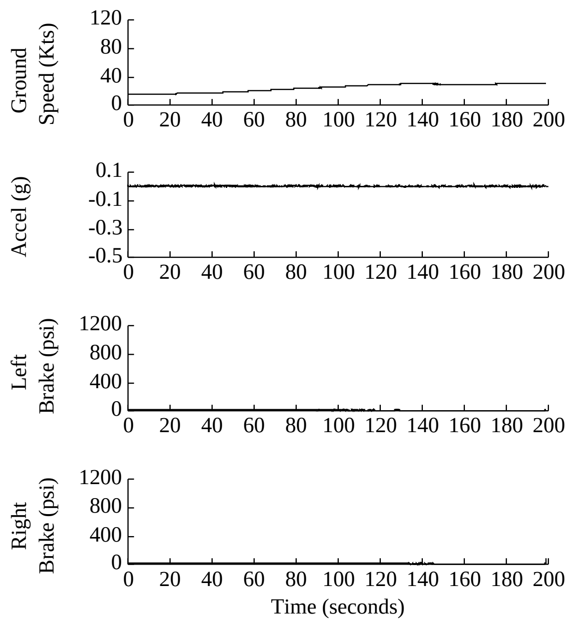
Note 1: Indicates flap setting (15 or 40), airbrake position (IN or OUT) and pilot braking (NO for no braking, B for maximum anti-skid braking)

Note 2: Temperatures in degrees Celsius.

Surface: 100% Bare and Dry, Occasional Ice Patches

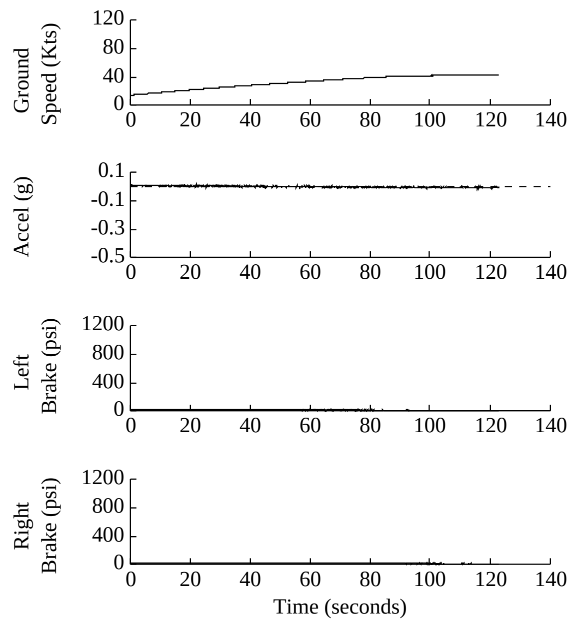
Flight 2000/01, Run Number 1

Configuration: Flaps 15, Air Brakes In, No Braking



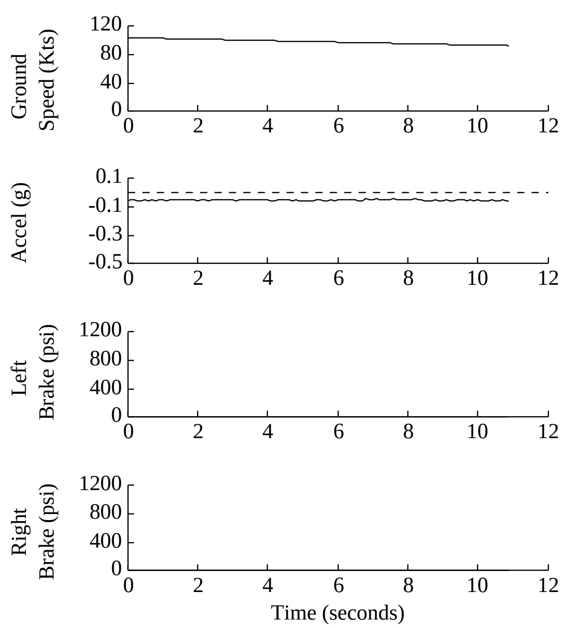
Flight 2000/01, Run Number 2

Configuration: Flaps 15, Air Brakes In, No Braking



Flight 2000/01, Run Number 3

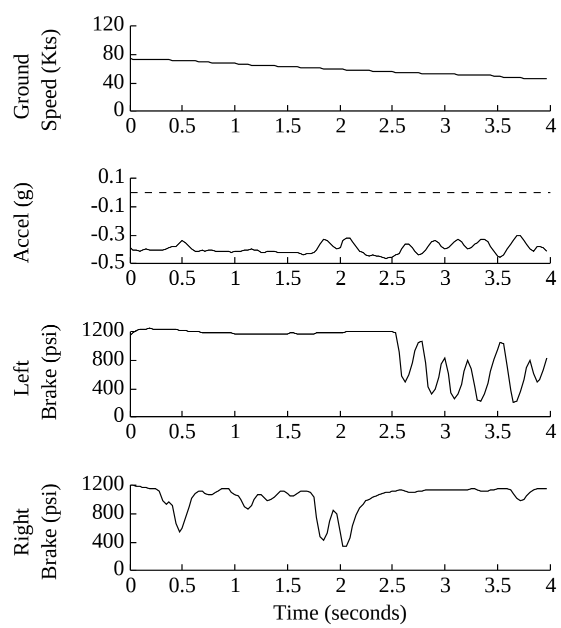
Configuration: Flaps 15, Air Brakes In, No Braking



Flight 2000/01, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Not Measured

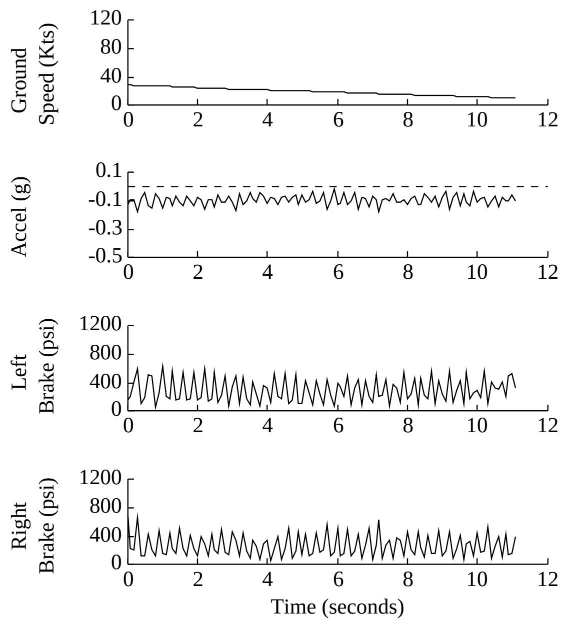


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

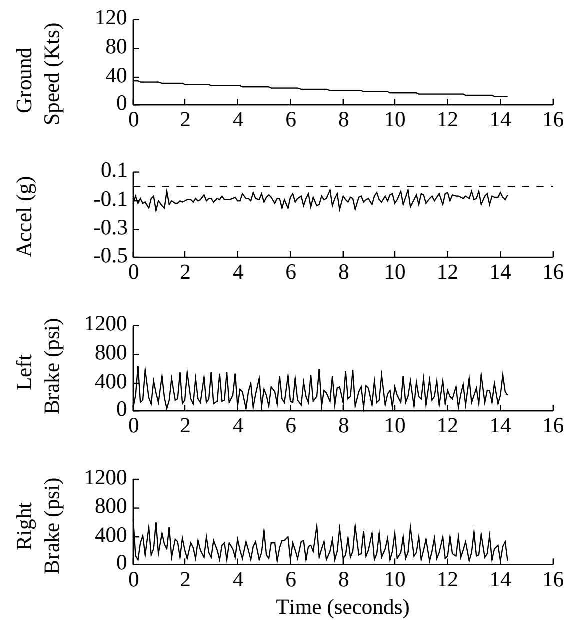
CRFI Average 0.18



Flight 2000/02, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

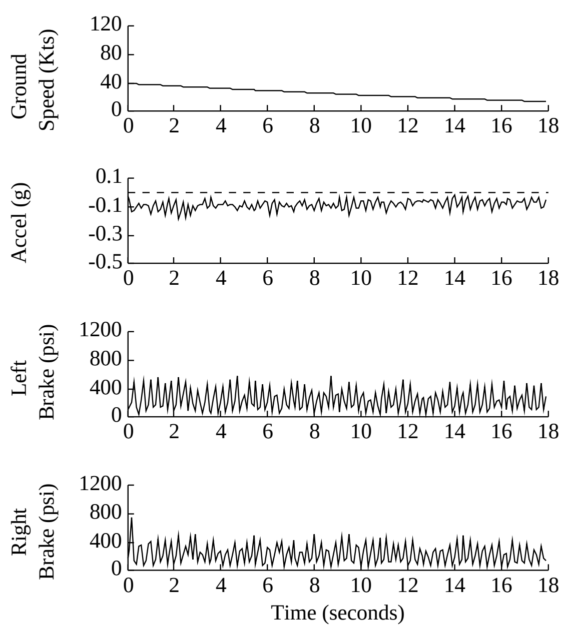
CRFI Average 0.18



Flight 2000/02, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

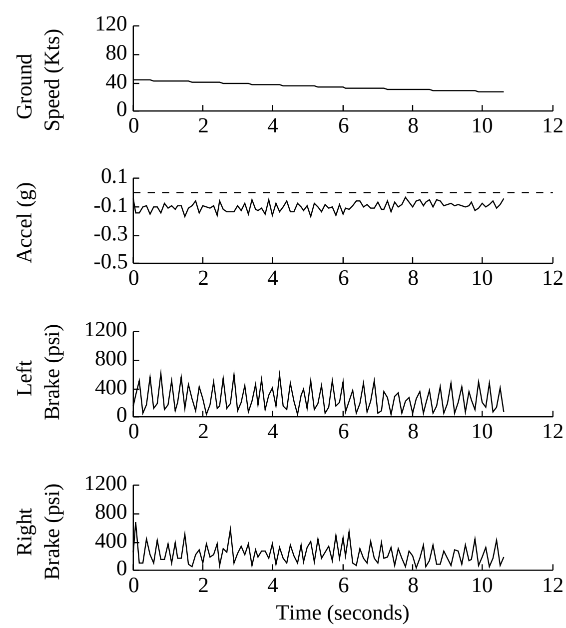
CRFI Average 0.17



Flight 2000/02, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.17

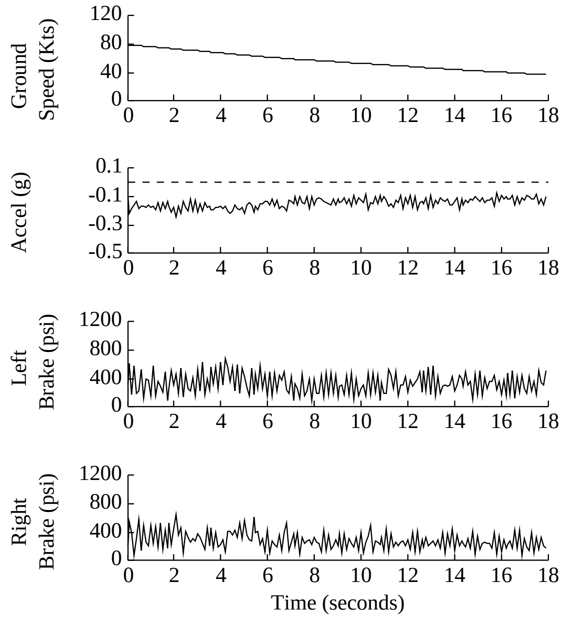


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

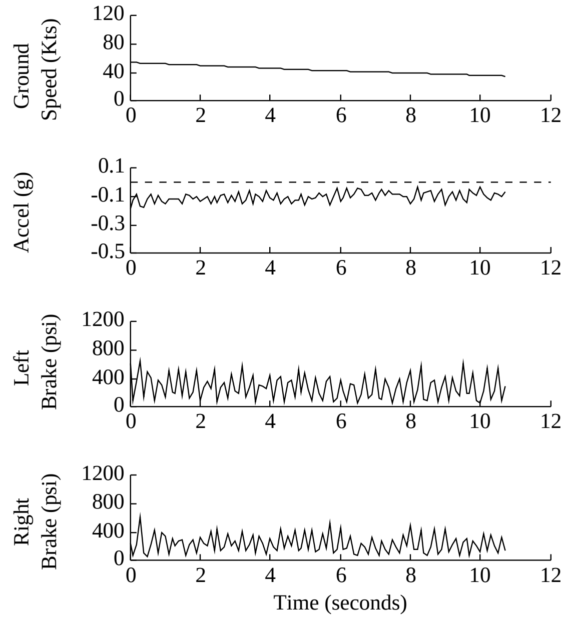
CRFI Average 0.16



Flight 2000/02, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.16

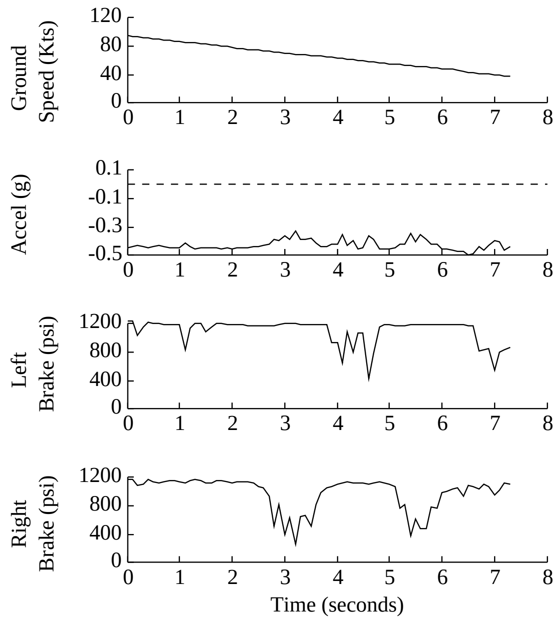


Surface: 100% Bare and Dry, Occasional Ice Patches

Flight 2000/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.75

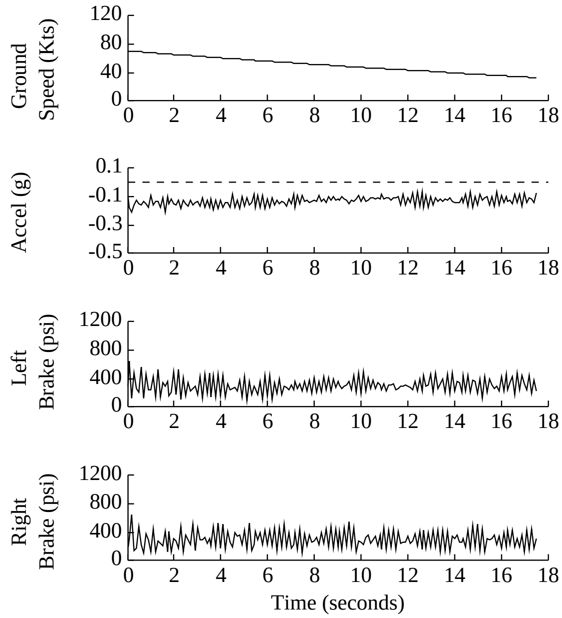


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow
Sg of snow 0.08

Flight 2000/04, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

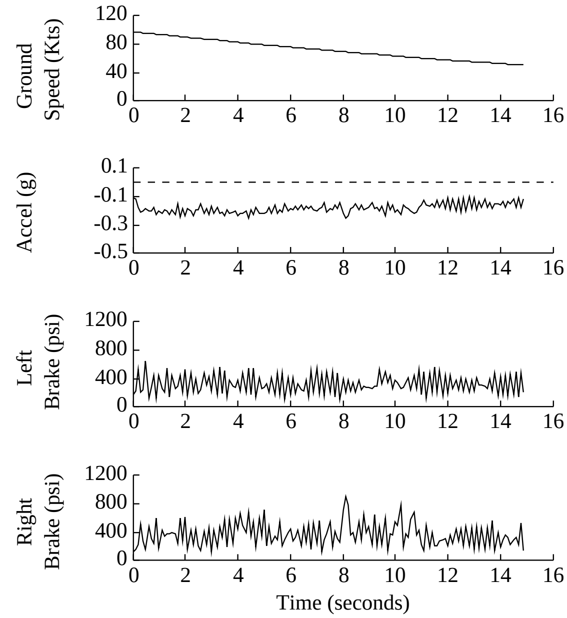
CRFI Average 0.28



Flight 2000/04, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

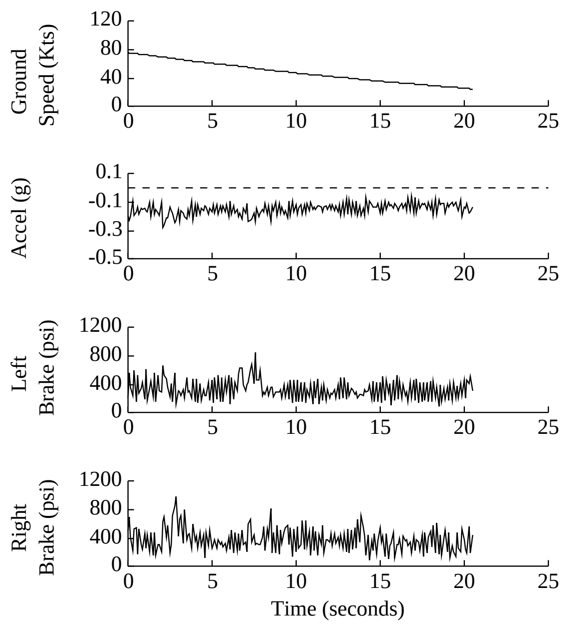
CRFI Average 0.28



Flight 2000/04, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

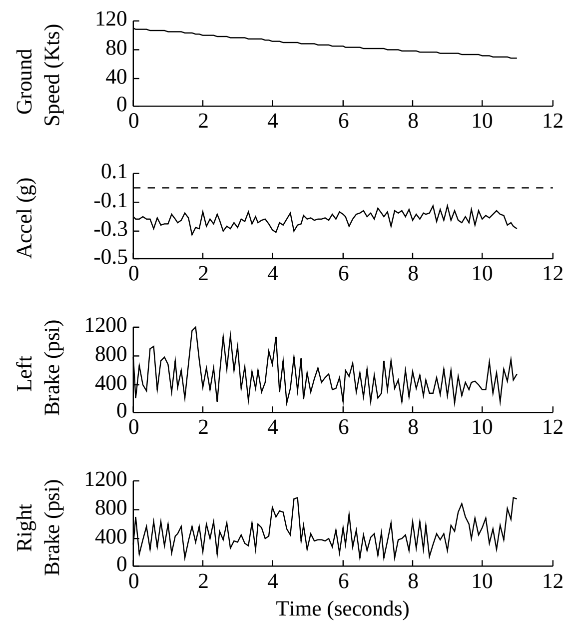
CRFI Average 0.28



Flight 2000/04, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.31

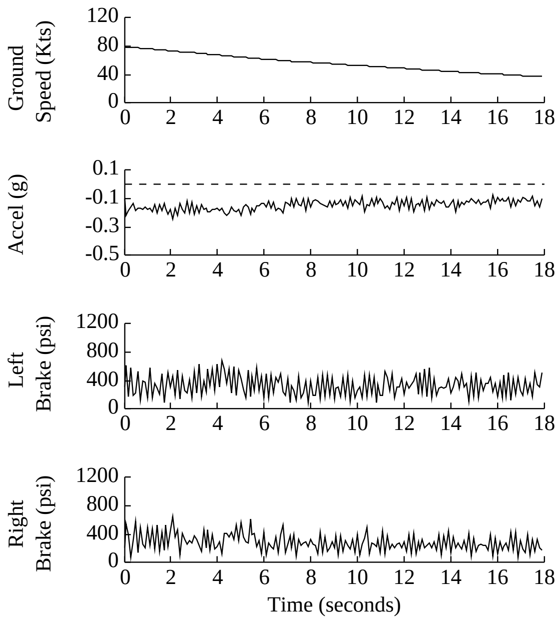


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow
Sg of snow 0.08

Flight 2000/04, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.31

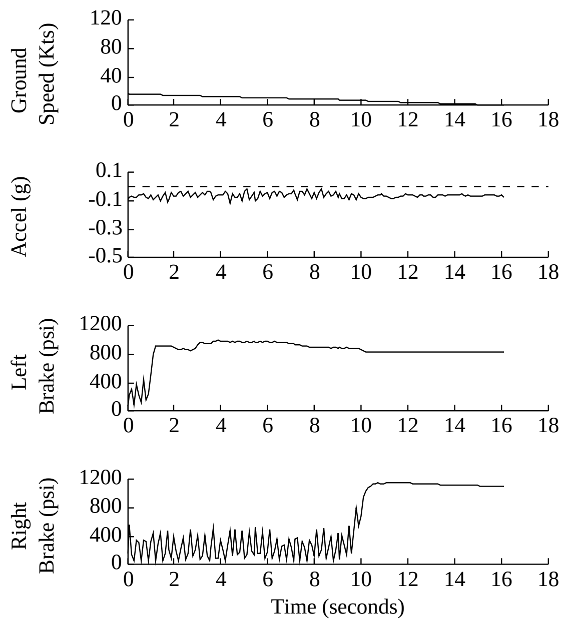


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

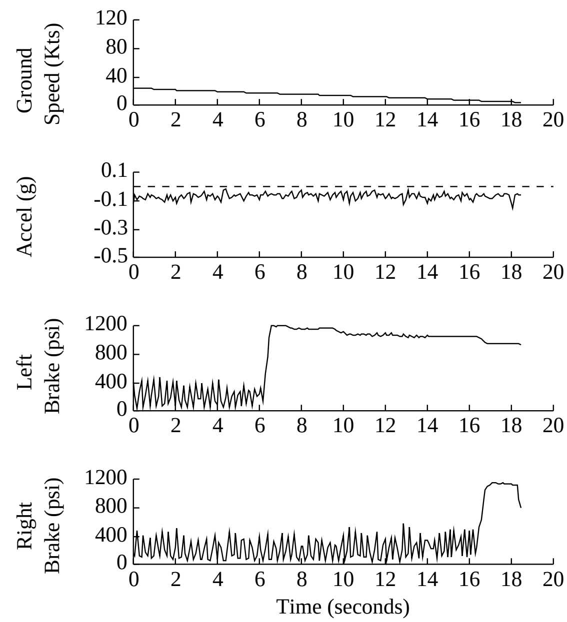
CRFI Average 0.13



Flight 2000/05, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

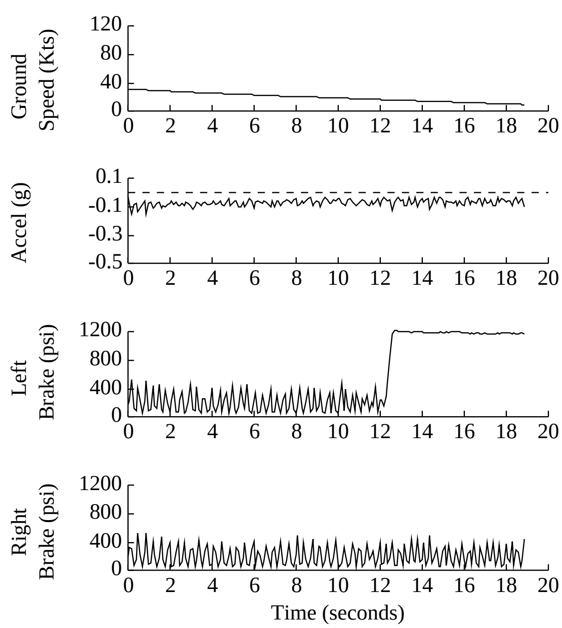
CRFI Average 0.13



Flight 2000/05, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

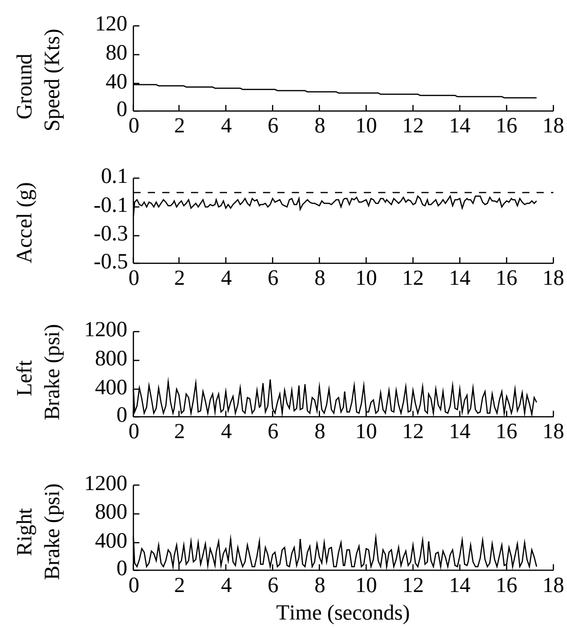
CRFI Average 0.13



Flight 2000/05, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.13

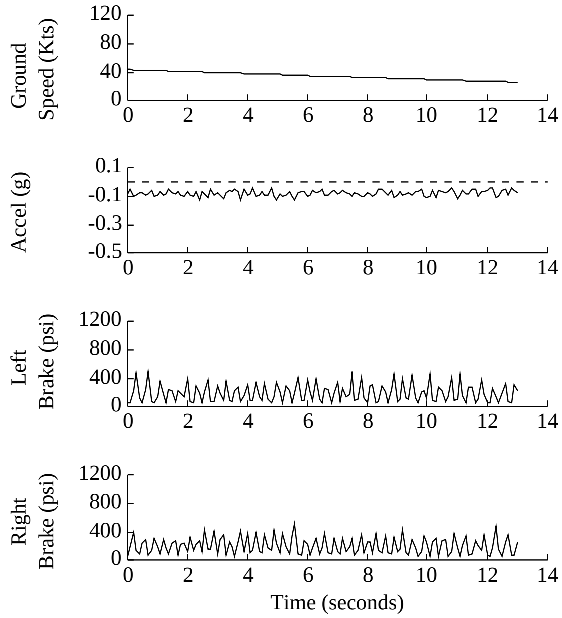


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

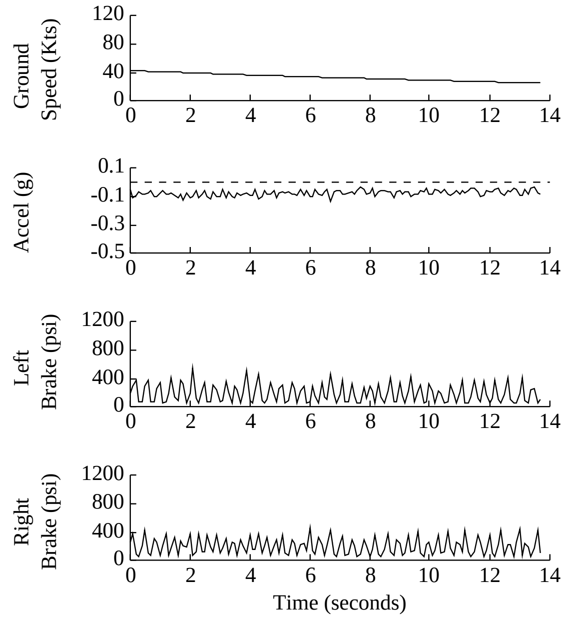
CRFI Average 0.12



Flight 2000/05, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.12

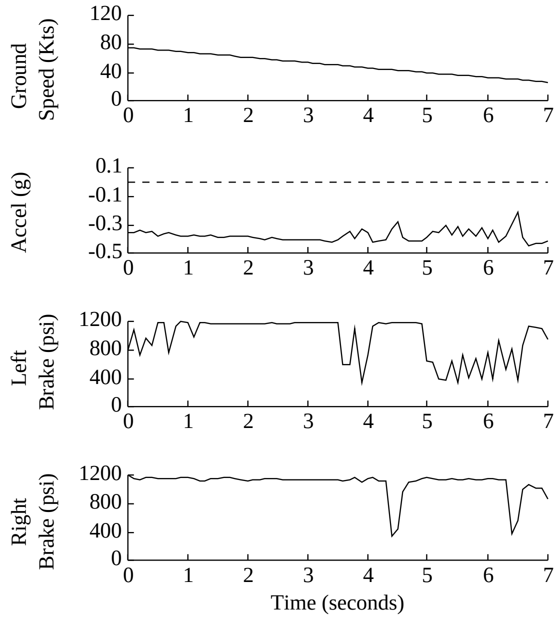


Surface: 100% Bare and Dry, With Occasional Ice Patches

Flight 2000/06, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

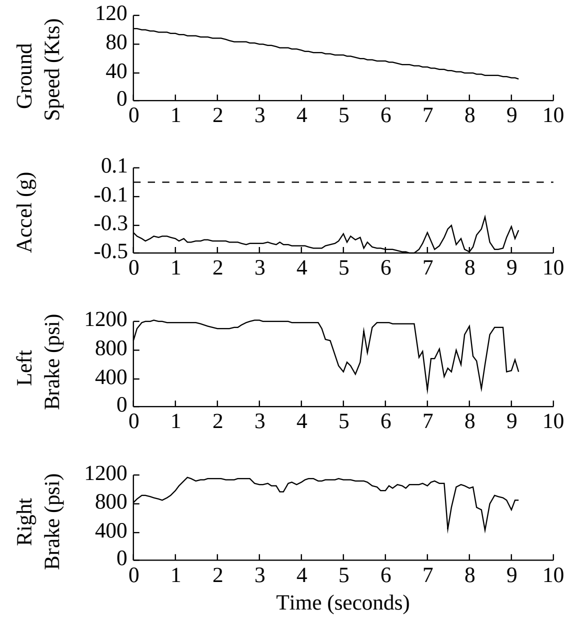
CRFI Average 0.73



Flight 2000/06, Run Number 2

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.73

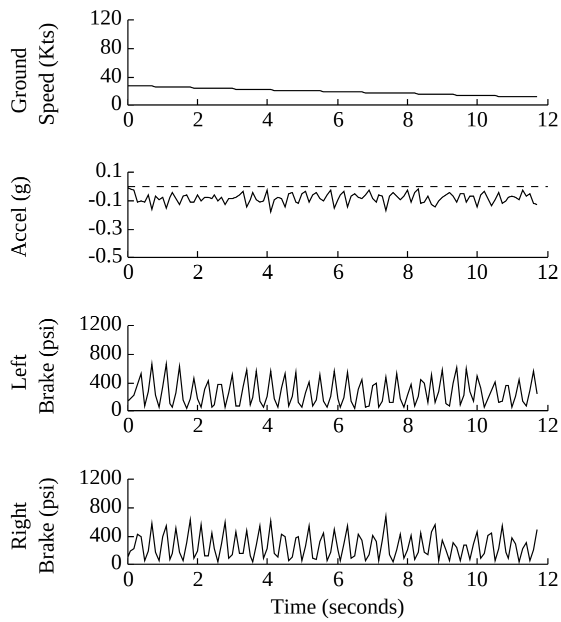


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

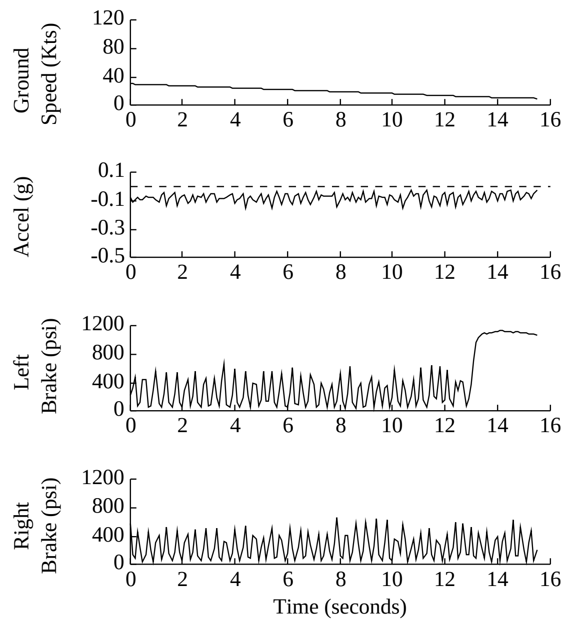
CRFI Average 0.10



Flight 2000/07, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

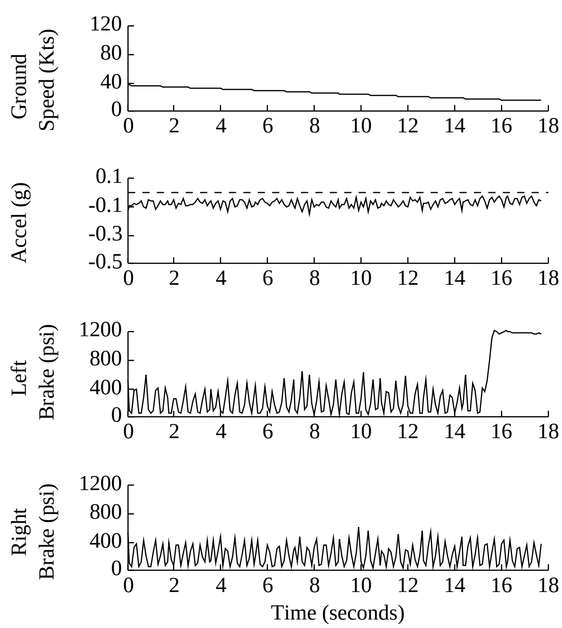
CRFI Average 0.10



Flight 2000/07, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

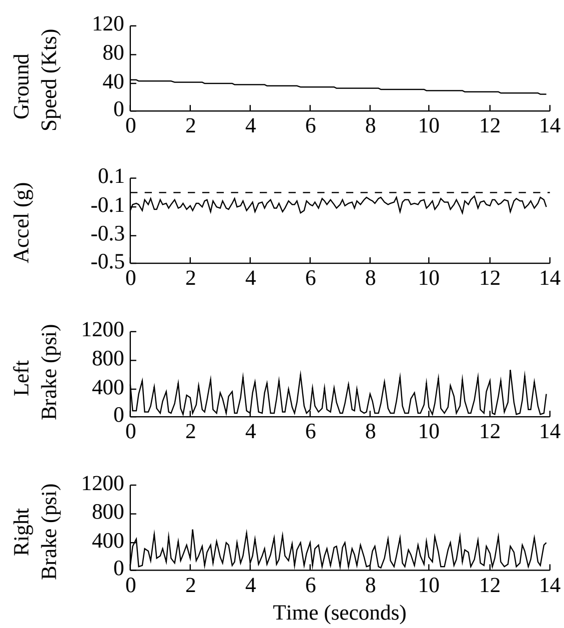
CRFI Average 0.11



Flight 2000/07, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.11

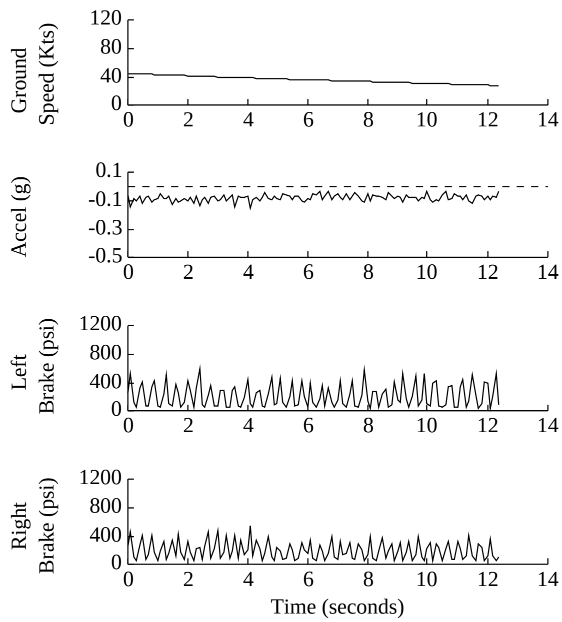


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

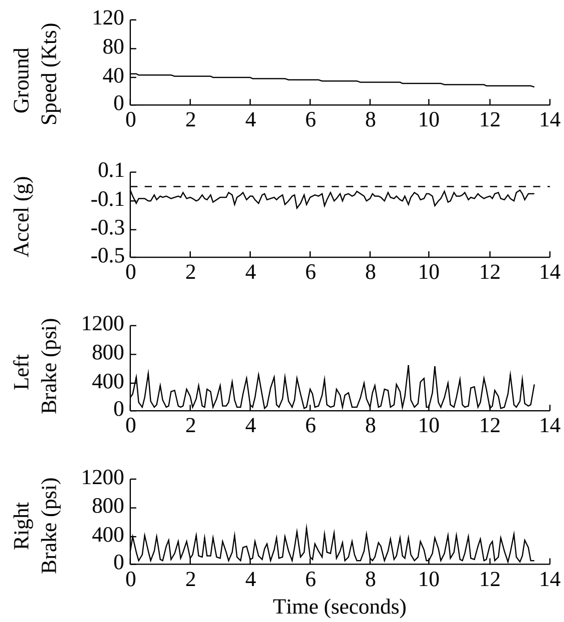
CRFI Average 0.09



Flight 2000/07, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.09

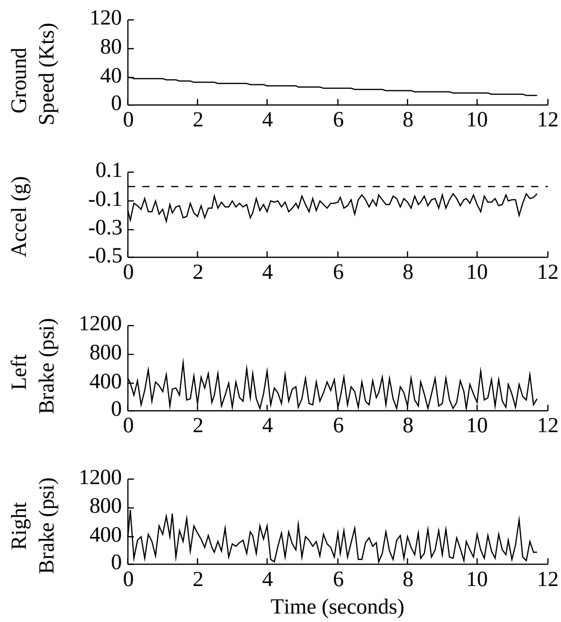


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

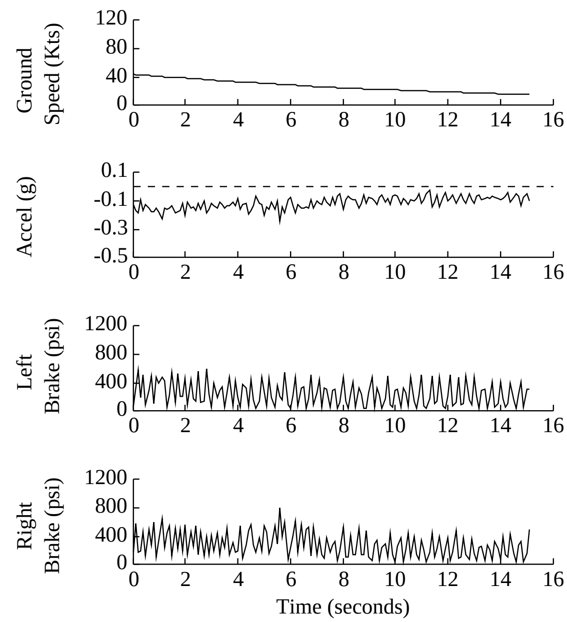
CRFI Average 0.20



Flight 2000/08, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

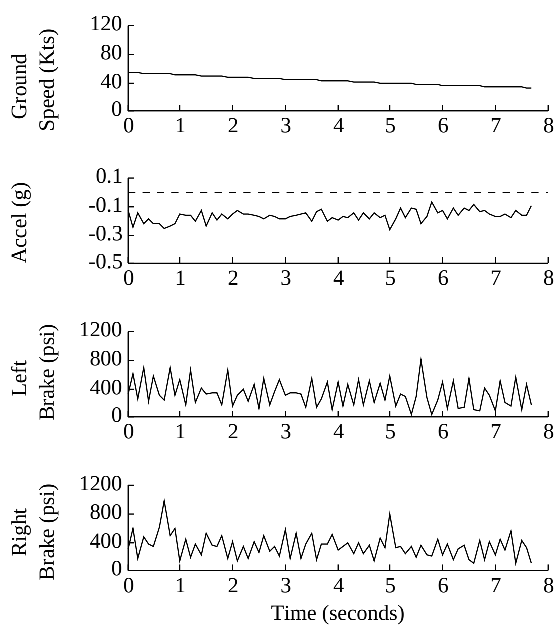
CRFI Average 0.20



Flight 2000/08, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

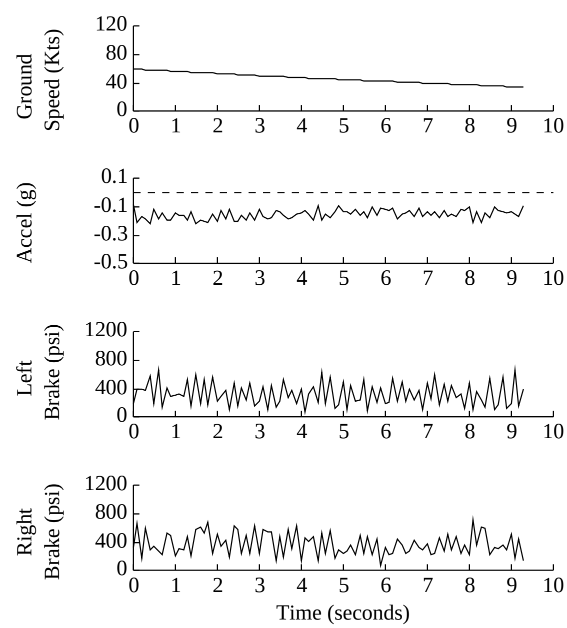
CRFI Average 0.22



Flight 2000/08, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.22

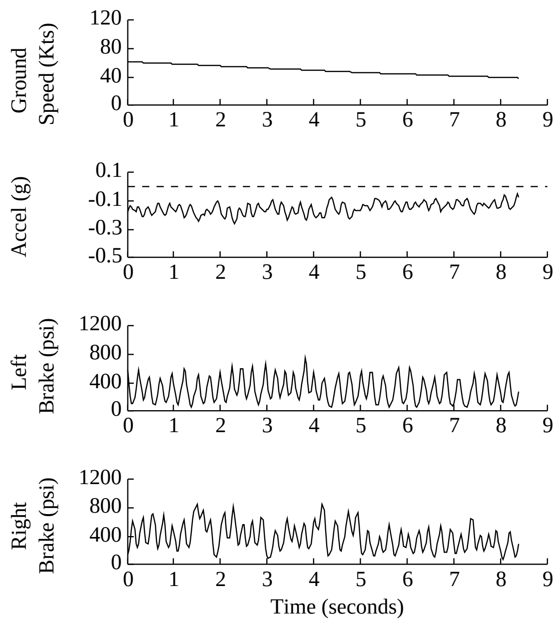


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

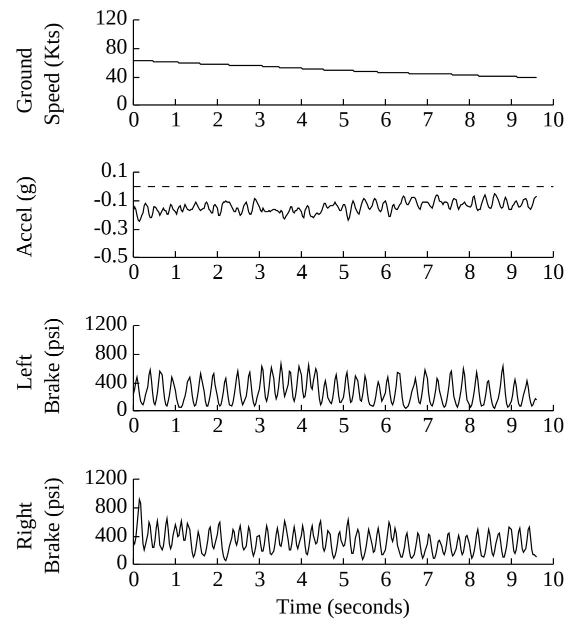
CRFI Average 0.21



Flight 2000/08, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.21

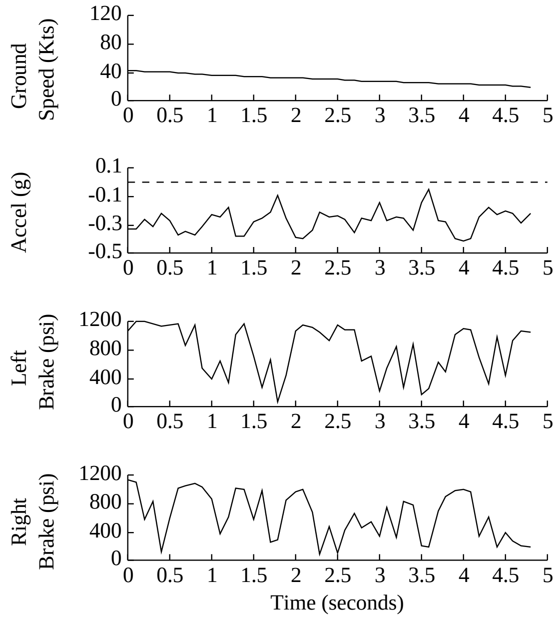


Surface: 70% Bare And Dry, 30% Light Dusting of Snow

Flight 2000/09, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

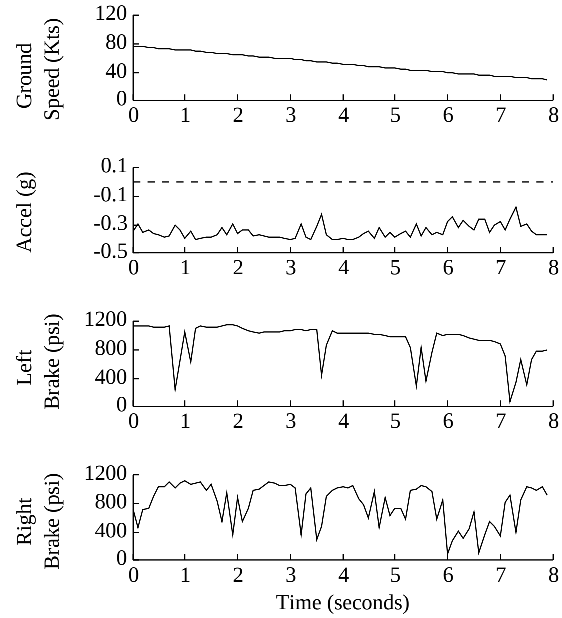
CRFI Average 0.42



Flight 2000/09, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

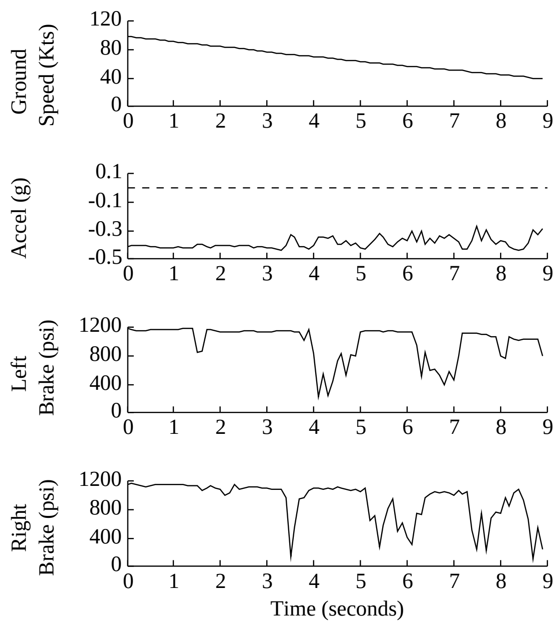
CRFI Average 0.61



Flight 2000/09, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.66

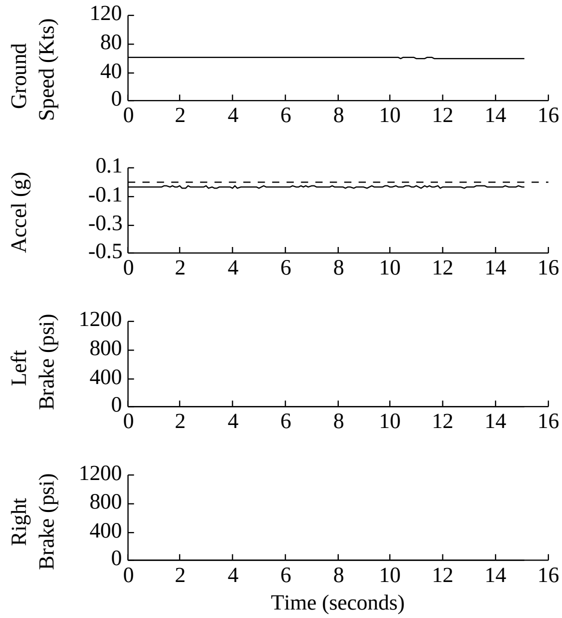


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 1

Configuration: Flaps 15, Air Brakes In, No Braking

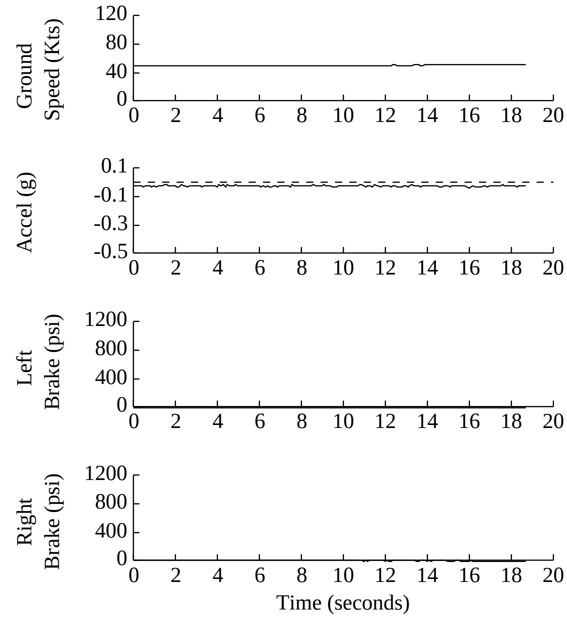
CRFI Average 0.33



Flight 2000/10, Run Number 2

Configuration: Flaps 15, Air Brakes In, No Braking

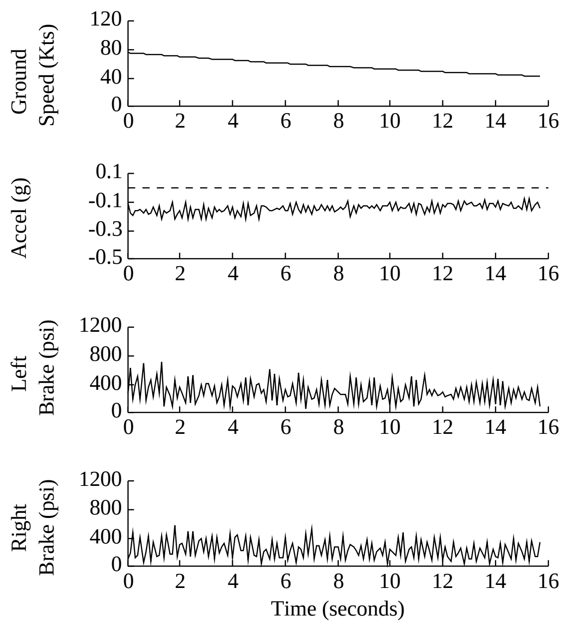
CRFI Average 0.33



Flight 2000/10, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

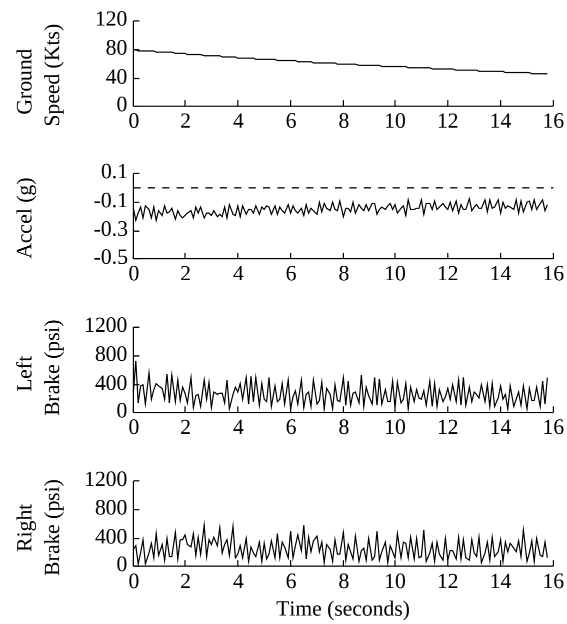
CRFI Average 0.27



Flight 2000/10, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.27

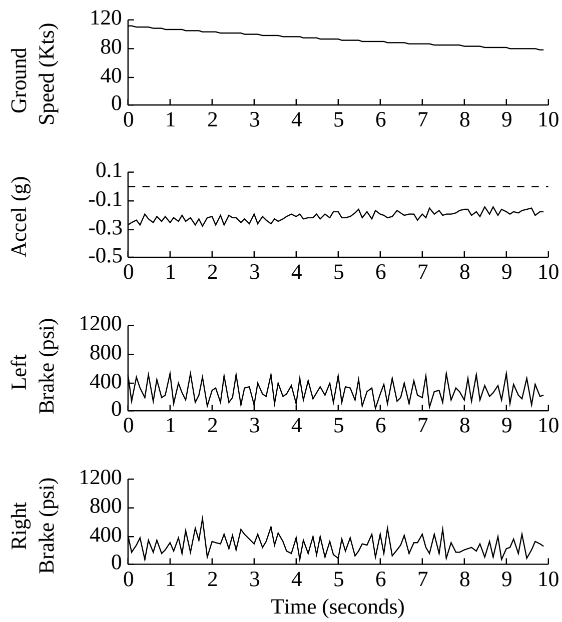


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

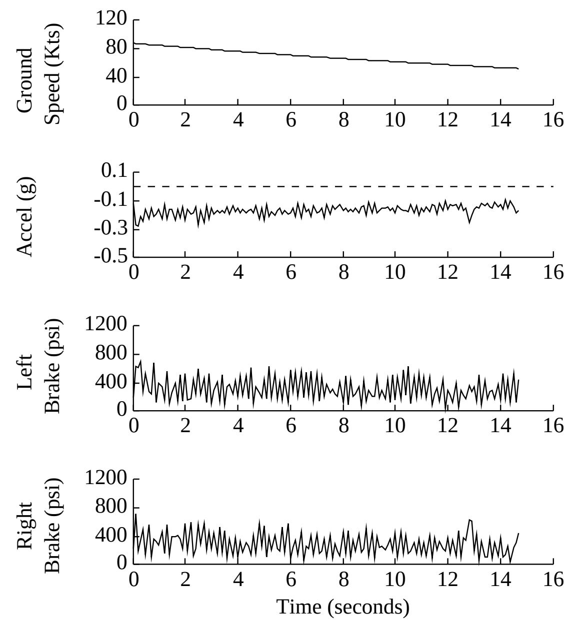
CRFI Average 0.26



Flight 2000/10, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.26

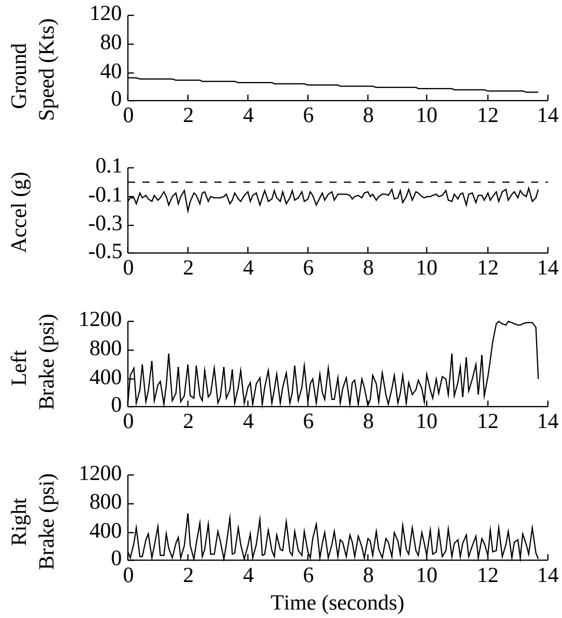


Surface: 100% Longitudinally Scarified Ice

Flight 2000/11, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

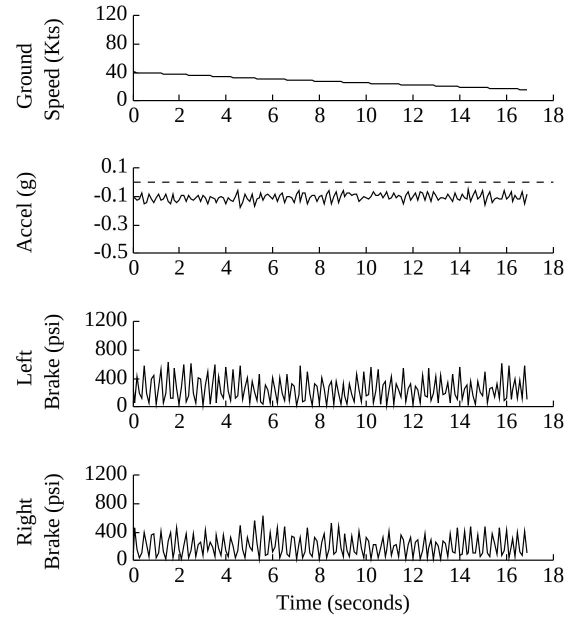
CRFI Average 0.19



Flight 2000/11, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

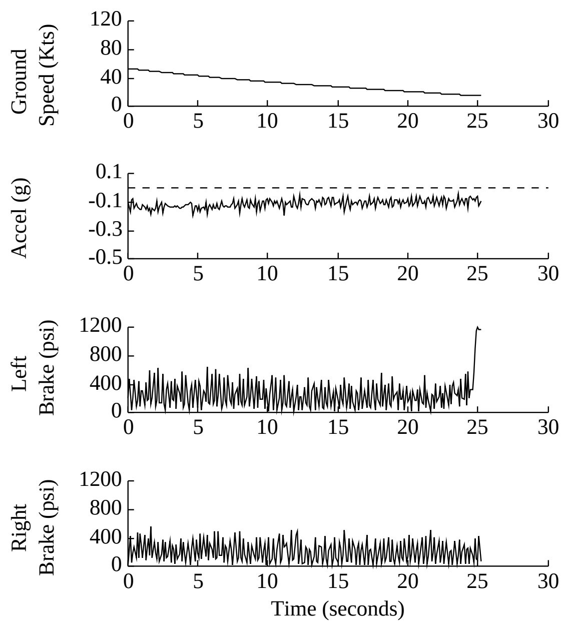
CRFI Average 0.19



Flight 2000/11, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

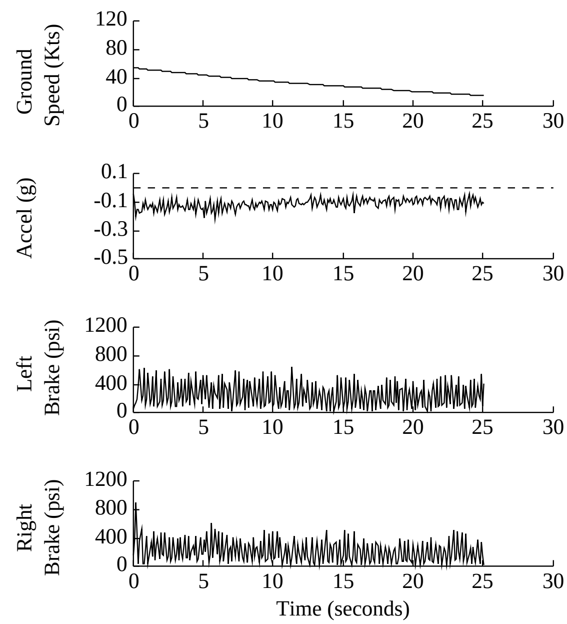
CRFI Average 0.21



Flight 2000/11, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21

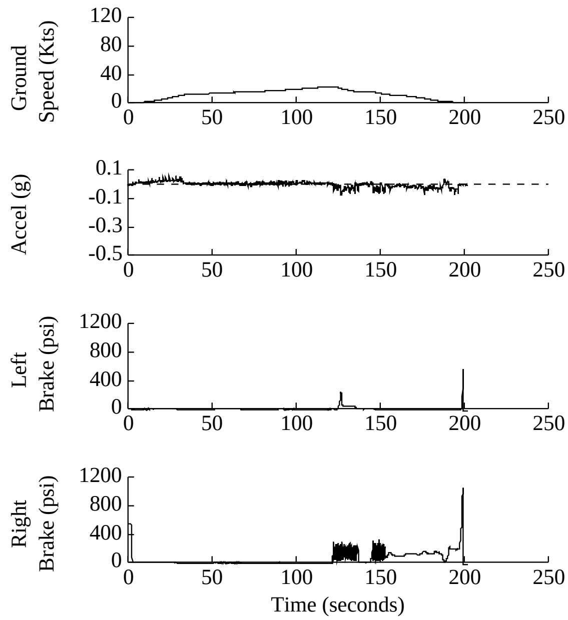


Surface: 90% Sanded Ice, 10% Bare and Dry

Flight 2000/12, Run Number 1

Configuration: Flaps 15, Air Brakes Out, No Braking

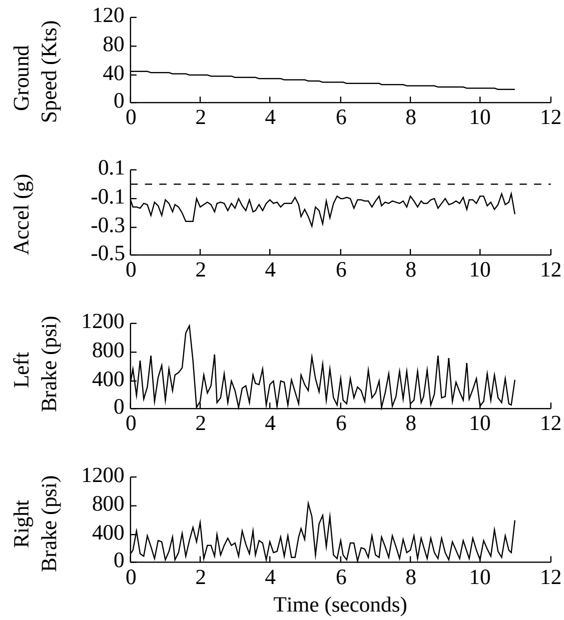
CRFI Average 0.26



Flight 2000/12, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

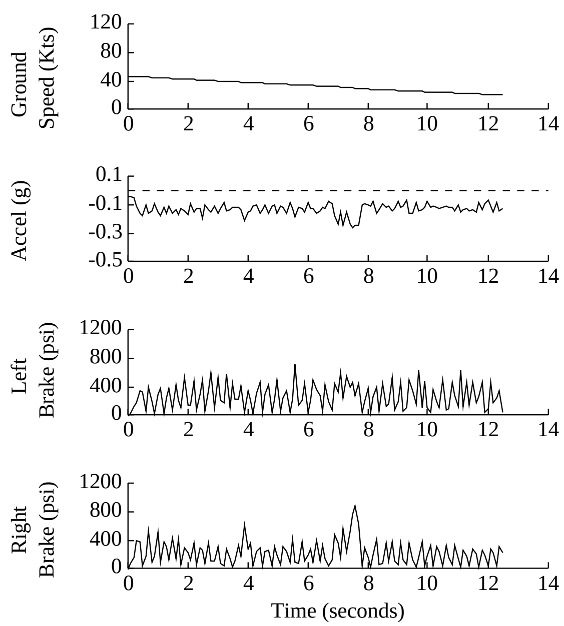
CRFI Average 0.26



Flight 2000/12, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.26



APPENDIX B - TEST RUNS FOR ROLLING FRICTION COEFFICIENT AND IDLE THRUST CALIBRATION

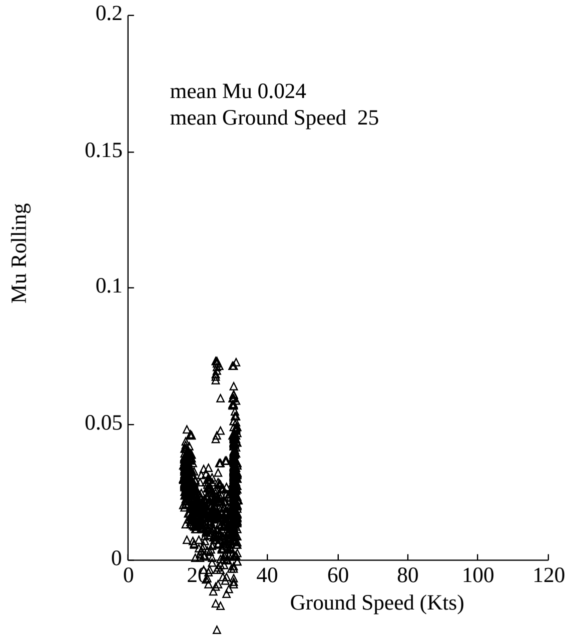
The following table shows the test runs used to verify the aircraft rolling coefficient ($_R$) and idle thrust on runway surfaces with no or negligible contamination drag. Page B2 shows the variation of $_R$ with ground speed for each run. The mean ground speed and mean $_R$ for each run is shown in the table and on Page B3 together with the results obtained in the 1996, 1997, 1998 and 1999 tests.

FLT	RUN	RWY	TAXI/ RTO/ LAND	CONFIG	WEIGHT (LB)	MEAN SPEED (KTGS)	MEAN $_R$
2000/01 17/01/00	1 13:57	08	TAXI	15/IN/NO	21220	25	0.024
	2 14:05	26	TAXI	15/IN/NO	21120	33	0.009
	3 14:34	08	LAND	15/IN/NO	20020	99	0.025

Surface: 100% Bare and Dry, Occasional Ice Patches

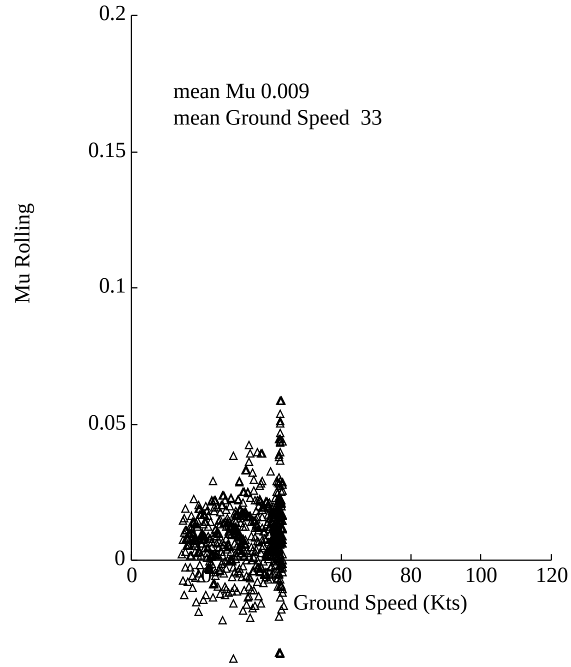
Flight 2000/01, Run Number 1

Configuration: Flaps 15, Air Brakes In, No Braking



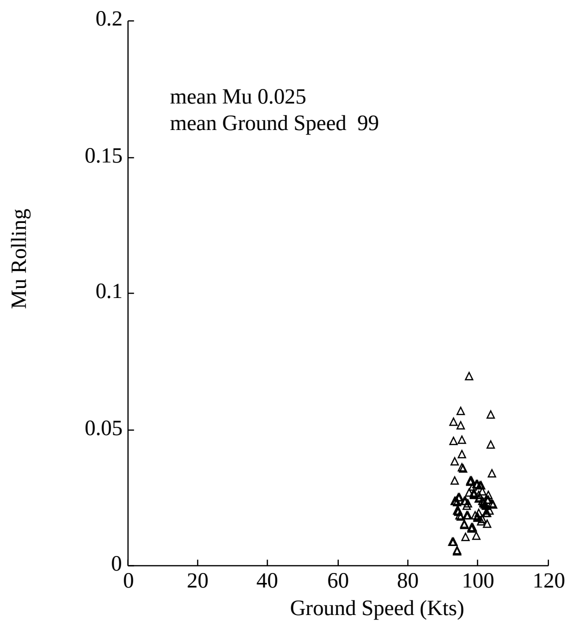
Flight 2000/01, Run Number 2

Configuration: Flaps 15, Air Brakes In, No Braking



Flight 2000/01, Run Number 3

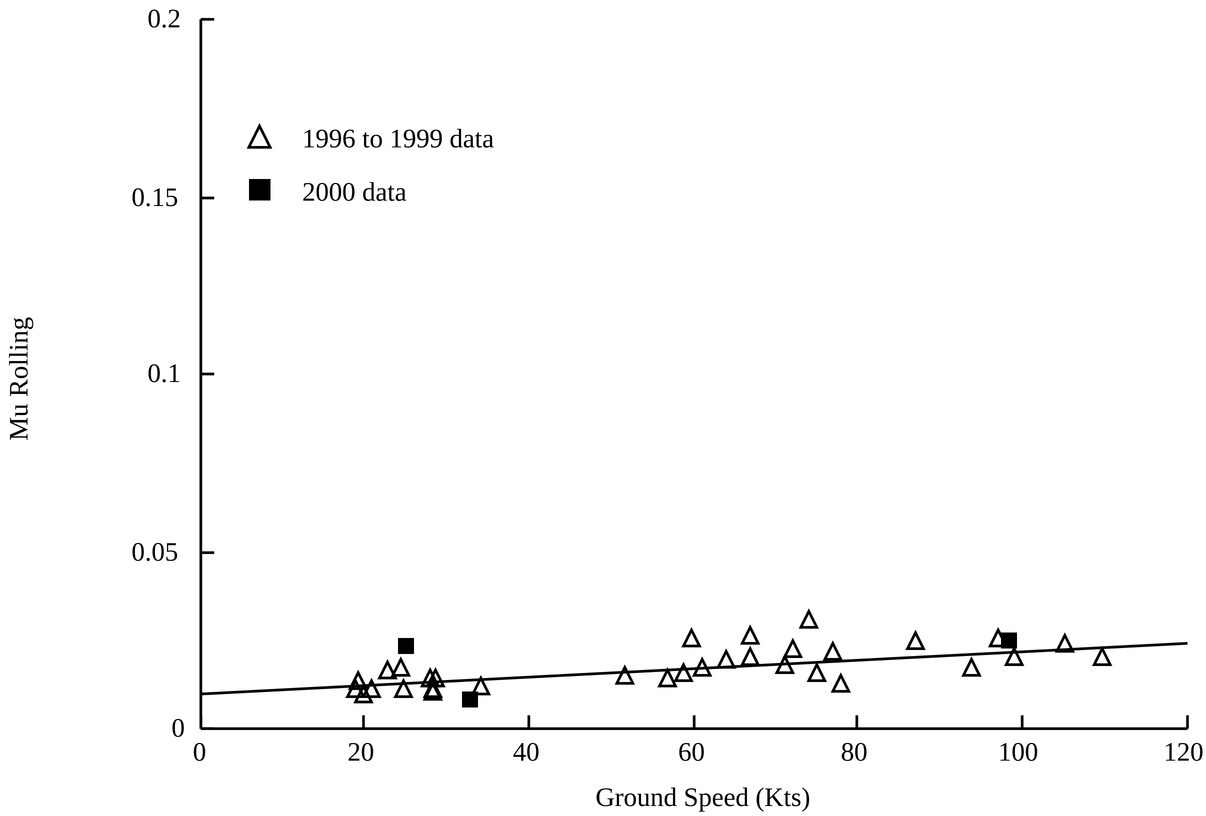
Configuration: Flaps 15, Air Brakes In, No Braking



Surface: No or Negligible Contamination

Flight 2000/01 runs 1 through 3

Mu Rolling = 0.0108 + 0.000127 * GroundSpeed



APPENDIX C - TEST RUNS FOR ANTI-SKID BRAKING SLIP RATIO

The following table shows the test runs used to determine the anti-skid braking wheel slip ratio ($_S$). Pages C3 to C47 show time histories of ground speed, left and right outer wheel speed, left and right inner wheel speed, left and right brake pressures. Also shown is the variation of the left outer and inner, and right outer and inner wheel slip ratios with ground speed. The average run value of ground speed and $_S$ for each wheel is shown in the table and on Page C48.

FLT	**RUN**	**RWY**	**TAXI/ RTO/ LAND**	**CONFIG**	**WEIGHT (LB)**	**MEAN SPEED (KTGS)**	**MEAN SLIP RATIO** $_S$			
							LO	**LI**	**RO**	**RI**
2000/02 18/01/00	1 15:52	31TS	RTO	15/OUT/B	22590	20	0.454	0.237	0.295	0.098
	2 15:58	31TS	RTO	40/OUT/B	22340	23	0.486	0.257	0.326	0.082
	3 16:12	31TS	RTO	40/OUT/B	22090	26	0.391	0.340	0.297	0.065
	4 16:23	31TS	RTO	15/OUT/B	21790	36	0.274	0.277	0.190	0.068
	5 16:33	31TS	RTO	15/OUT/B	21690	39	0.228	0.304	0.202	0.085
	6 16:41	31TS	RTO	40/OUT/B	21440	44	0.214	0.218	0.167	0.083
2000/03 18/01/00	1 17:08	08	LAND	40/OUT/B	20590	66	0.084	0.072	0.077	0.054
2000/04 19/01/00	1 13:59	26TS	RTO	40/OUT/B	22990	51	0.135	0.091	0.076	0.017
	2 14:13	26TS	LAND	40/OUT/B	22490	72	0.112	0.068	0.067	0.036
	3 14:20	26TS	RTO	15/OUT/B	22090	48	0.161	0.082	0.081	0.056
	4 14:35	26TS	LAND	15/OUT/B	21690	88	0.086	0.057	0.052	0.037
	5 14:43	26TS	RTO	40/OUT/B	21340	57	0.158	0.061	0.097	0.033
2000/05 20/01/00	1 14:56	31TS	RTO	15/OUT/B	22290	9	0.983	0.956	0.683	0.474
	2 15:02	31TS	RTO	40/OUT/B	22140	15	0.857	0.843	0.560	0.286
	3 15:32	31TS	RTO	40/OUT/B	21590	20	0.719	0.663	0.430	0.180
	4 15:38	31TS	RTO	15/OUT/B	21390	28	0.582	0.370	0.372	0.106
	5 15:54	31TS	RTO	15/OUT/B	21190	35	0.616	0.256	0.230	0.081
	6 16:01	31TS	RTO	40/OUT/B	20890	34	0.584	0.381	0.293	0.171
2000/06 20/01/00	1 16:40	31TS	RTO	40/OUT/B	20390	51	0.120	0.043	0.066	0.065
	2 17:02	08	LAND	15/OUT/B	19240	67	0.081	0.051	0.056	0.053

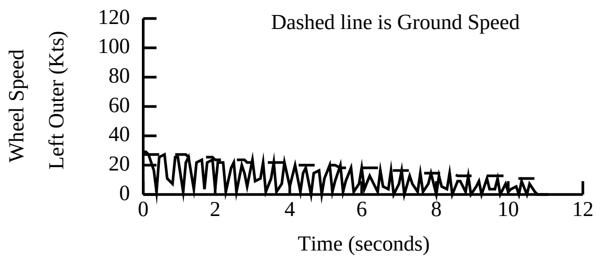
FLT	RUN	RWY	TAXI/ RTO/ LAND	CONFIG	WEIGHT (LB)	MEAN SPEED (KTGS)	MEAN SLIP RATIO S			
2000/07 21/01/00	1 8:26	31TS	RTO	15/0UT/B	22590	20	0.531	0.381	0.312	0.202
	2 8:32	31TS	RTO	40/0UT/B	22390	20	0.604	0.530	0.405	0.210
	3 8:43	31TS	RTO	40/0UT/B	22190	26	0.641	0.478	0.306	0.169
	4 8:50	31TS	RTO	15/0UT/B	22040	34	0.621	0.310	0.264	0.140
	5 9:00	31TS	RTO	15/0UT/B	21790	36	0.547	0.342	0.277	0.125
	6 9:08	31TS	RTO	40/0UT/B	21640	35	0.591	0.320	0.351	0.155
2000/08 21/01/00	1 13:15	31TS	RTO	15/OUT/B	21090	26	0.366	0.331	0.242	0.105
	2 13:21	31TS	RTO	40/OUT/B	20990	27	0.442	0.364	0.244	0.085
	3 13:48	31TS	RTO	40/OUT/B	20640	44	0.201	0.205	0.118	0.043
	4 13:55	31TS	RTO	15/OUT/B	20340	47	0.198	0.140	0.097	0.061
	5 14:10	31TS	RTO	40/OUT/B	20140	50	0.267	0.138	0.120	0.075
	6 14:16	31TS	RTO	40/OUT/B	19990	51	0.283	0.166	0.126	0.063
2000/09 24/01/00	1 12:12	26TS	RTO	15/OUT/B	22400	31	0.169	0.049	0.156	0.048
	2 12:20	26TS	RTO	40/OUT/B	22150	53	0.093	0.065	0.096	0.062
	3 12:40	26TS	LAND	40/OUT/B	21400	68	0.084	0.067	0.086	0.061
2000/10 25/01/00	3 12:56	26TS	RTO	15/OUT/B	21980	58	0.163	0.103	0.109	0.039
	4 1:04	26TS	RTO	40/OUT/B	21630	61	0.172	0.136	0.109	0.049
	5 1:33	26TS	LAND	40/OUT/B	20780	94	0.080	0.108	0.062	0.035
	6 1:43	26TS	RTO	15/OUT/B	20580	69	0.121	0.079	0.076	0.036
2000/11 27/01/00	1 11:24	31	RTO	15/OUT/B	22340	23	0.631	0.406	0.387	0.028
	2 11:30	31	RTO	40/OUT/B	22190	28	0.467	0.338	0.372	0.026
	3 11:36	31	RTO	40/OUT/B	22040	32	0.440	0.312	0.316	0.037
	4 11:44	31	RTO	15/OUT/B	21840	33	0.359	0.288	0.314	0.037
2000/12 27/01/00	2 12:51	36	RTO	40/OUT/B	20340	31	0.355	0.161	0.282	0.056
	3 12:55	36	RTO	40/OUT/B	20190	34	0.370	0.183	0.297	0.057

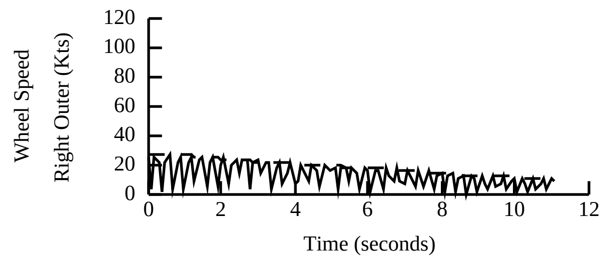
Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

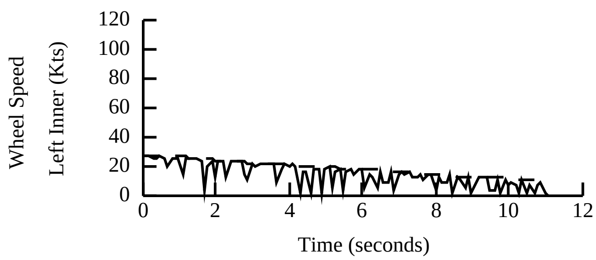
Flight 2000/02, Run Number 1

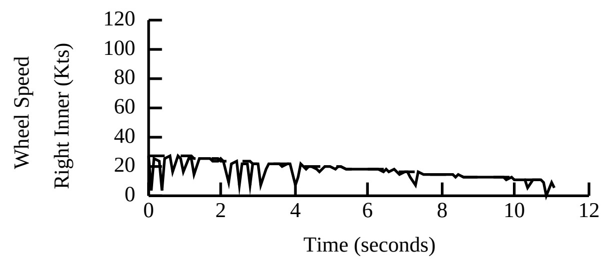
Configuration: Flaps 15, Air Brakes Out, Max Braking

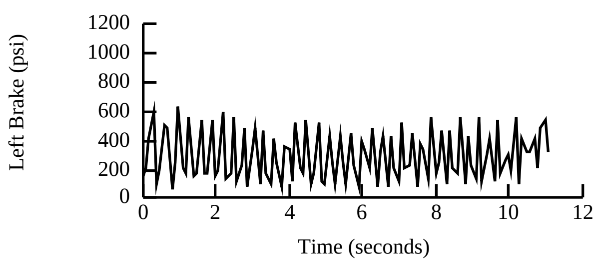
CRFI Average 0.18

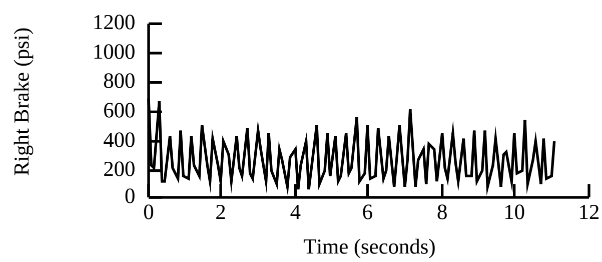


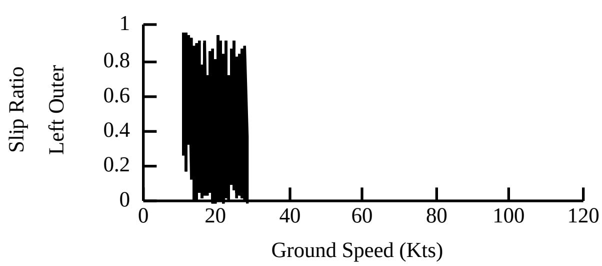


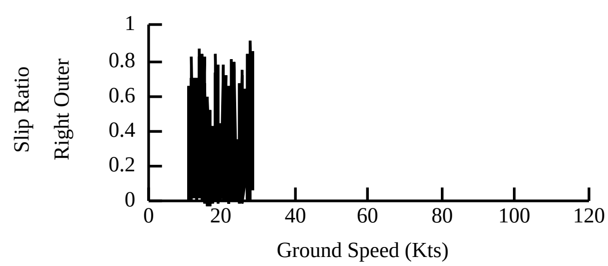


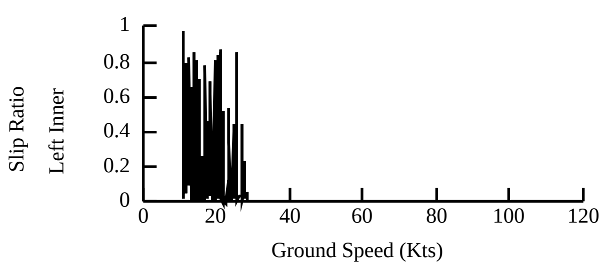


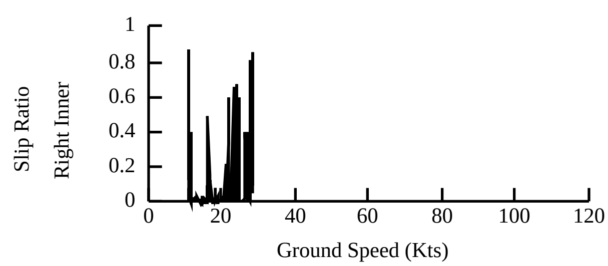










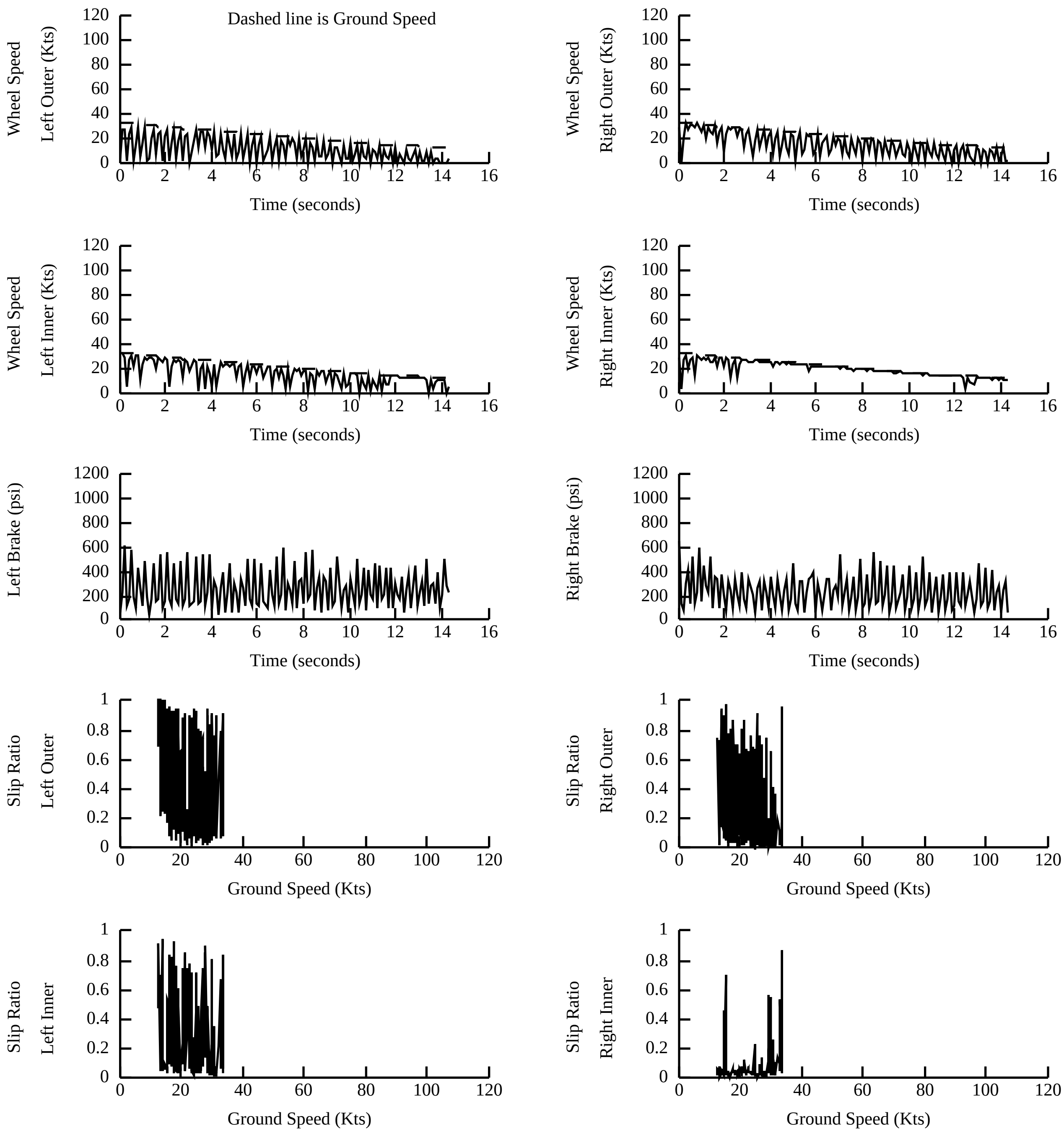


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.18

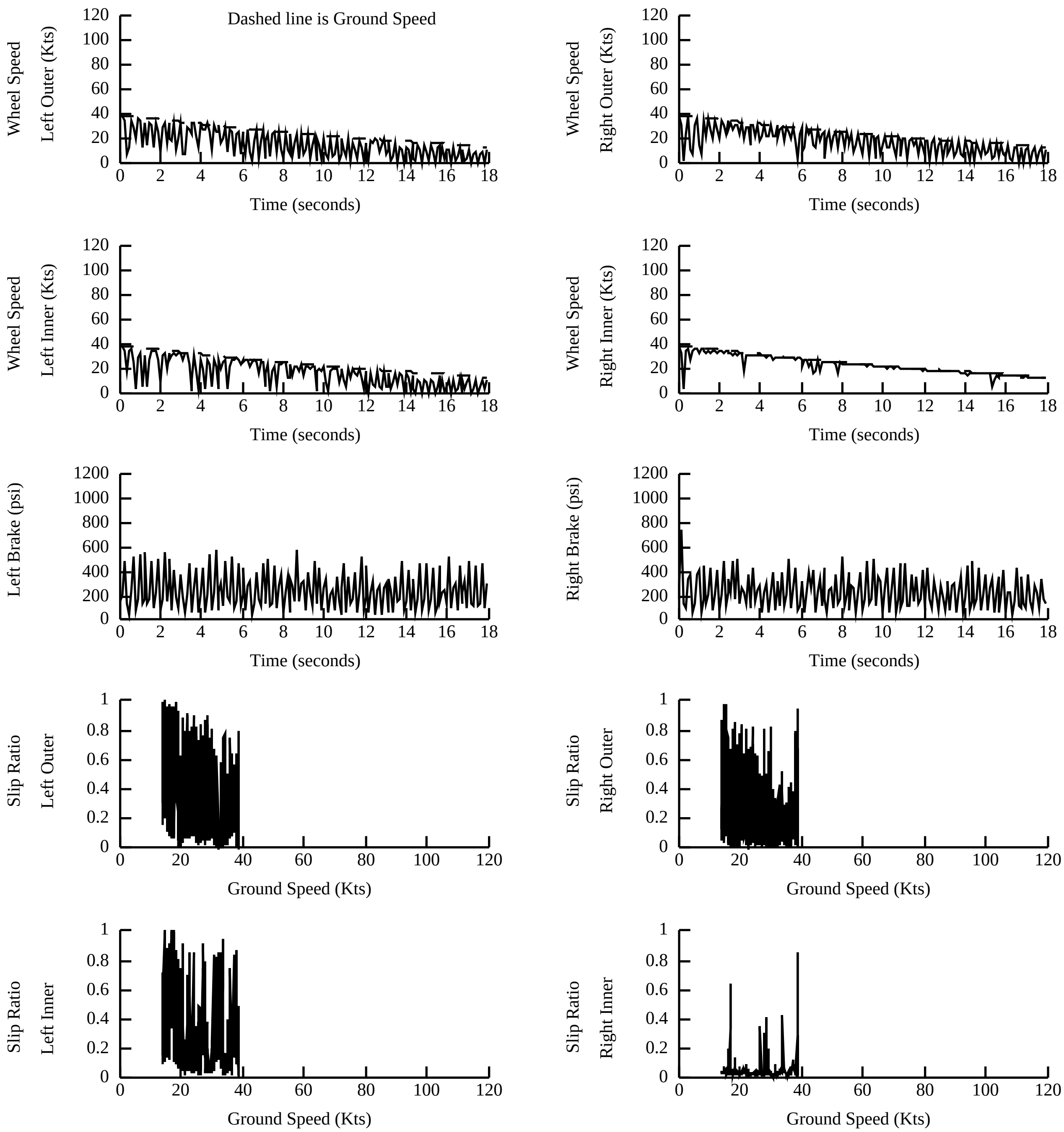


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.17

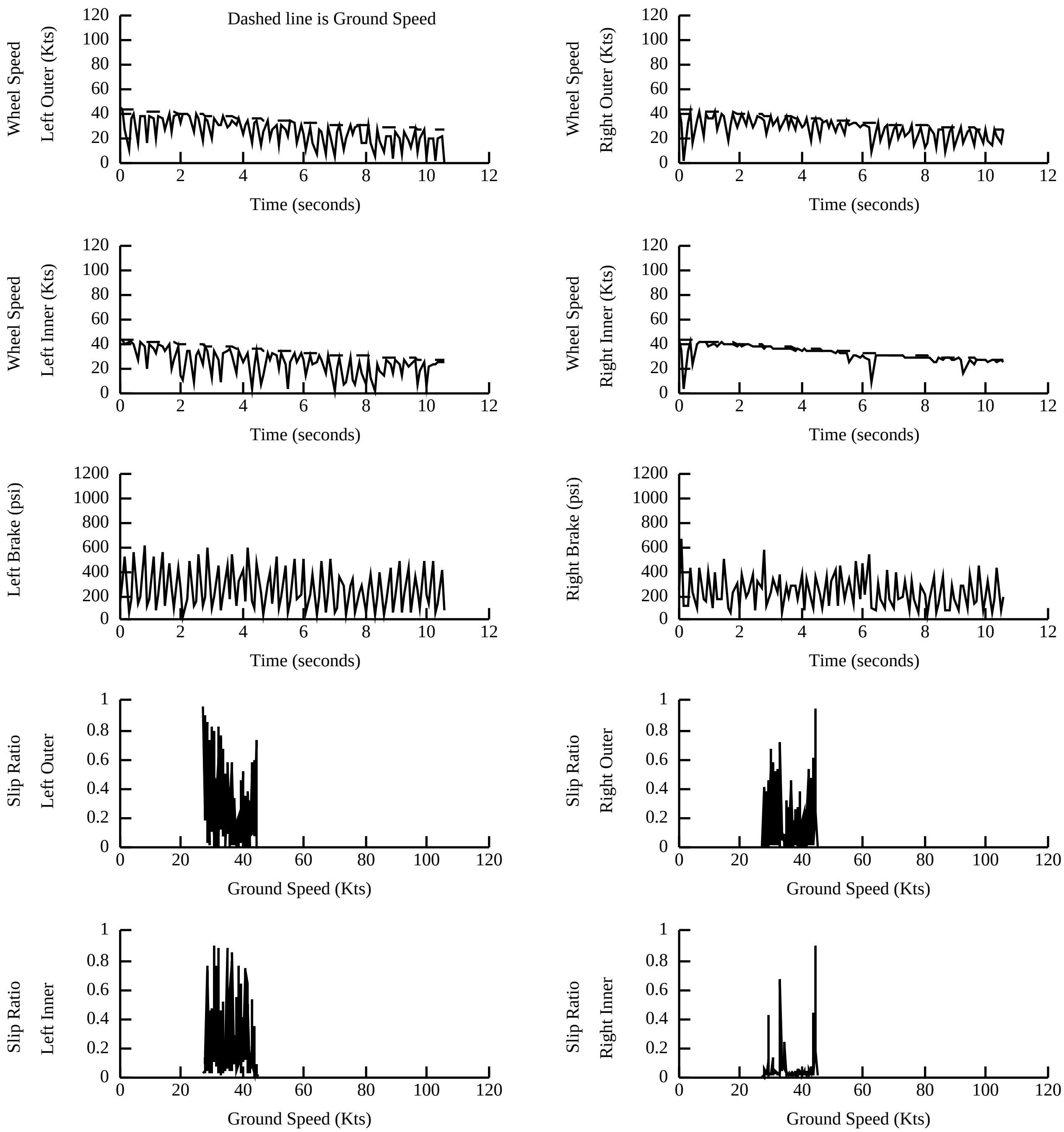


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.17

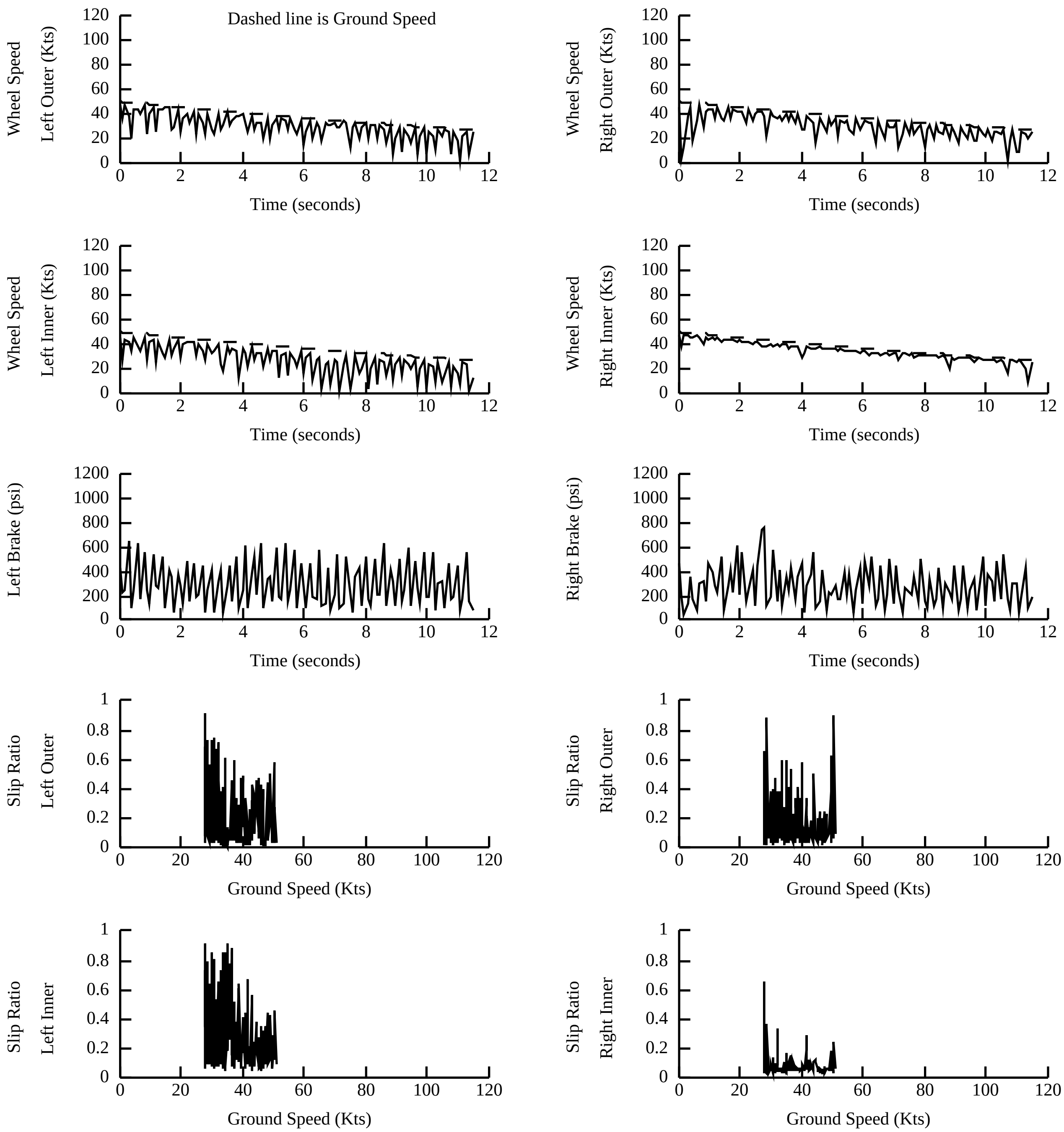


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.16

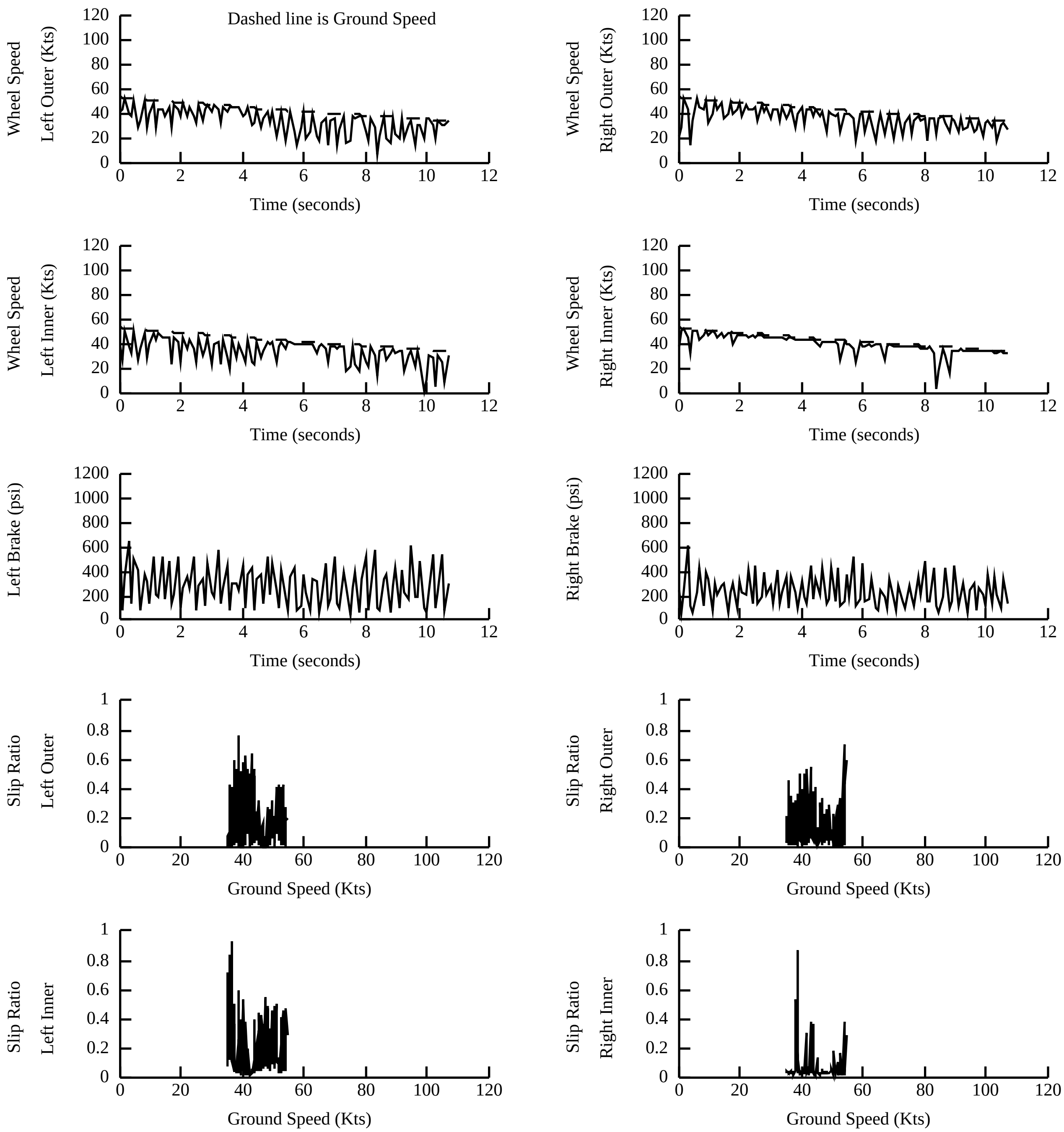


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.16

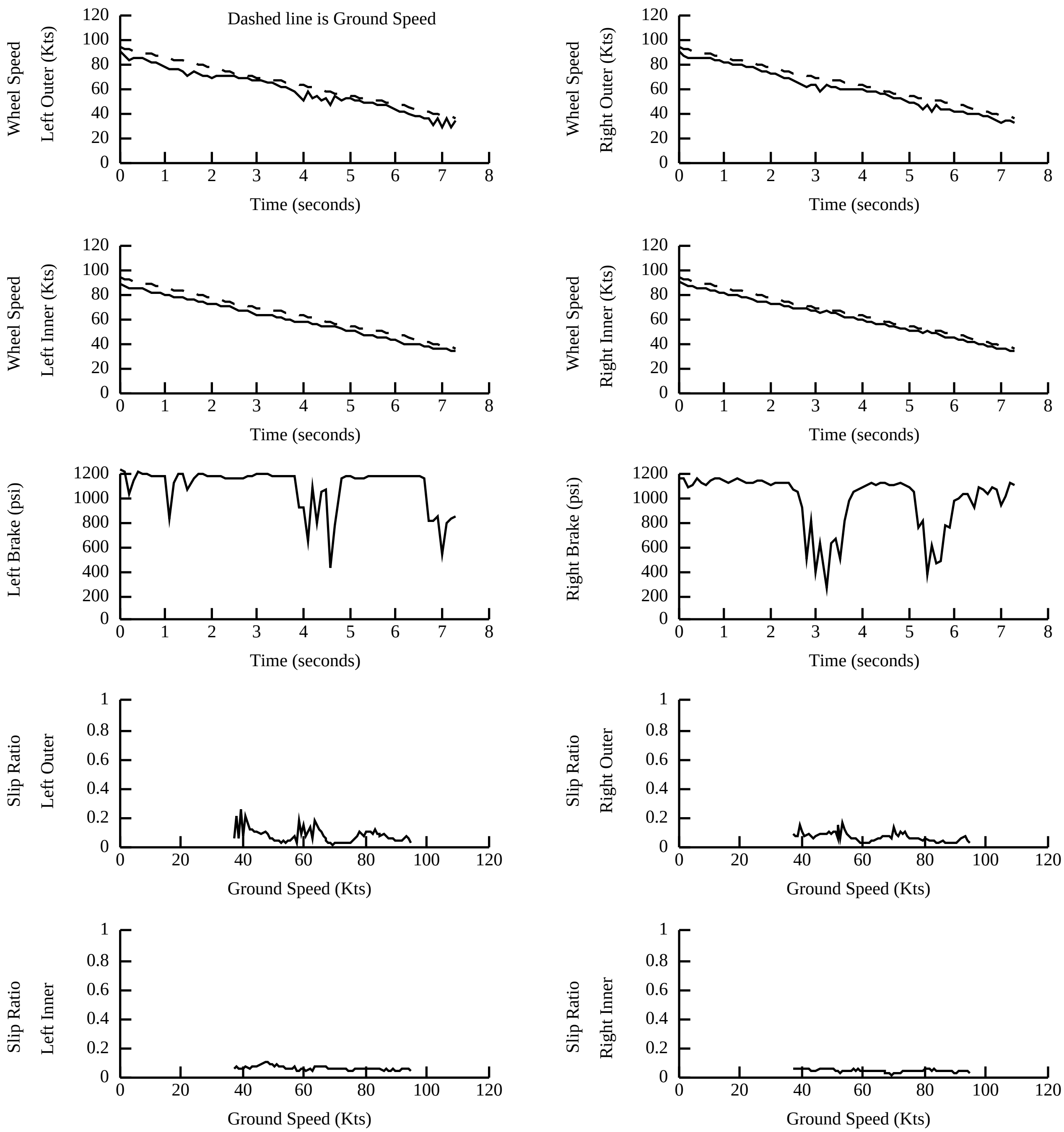


Surface: 100% Bare and Dry, Occasional Ice Patches

Flight 2000/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.75

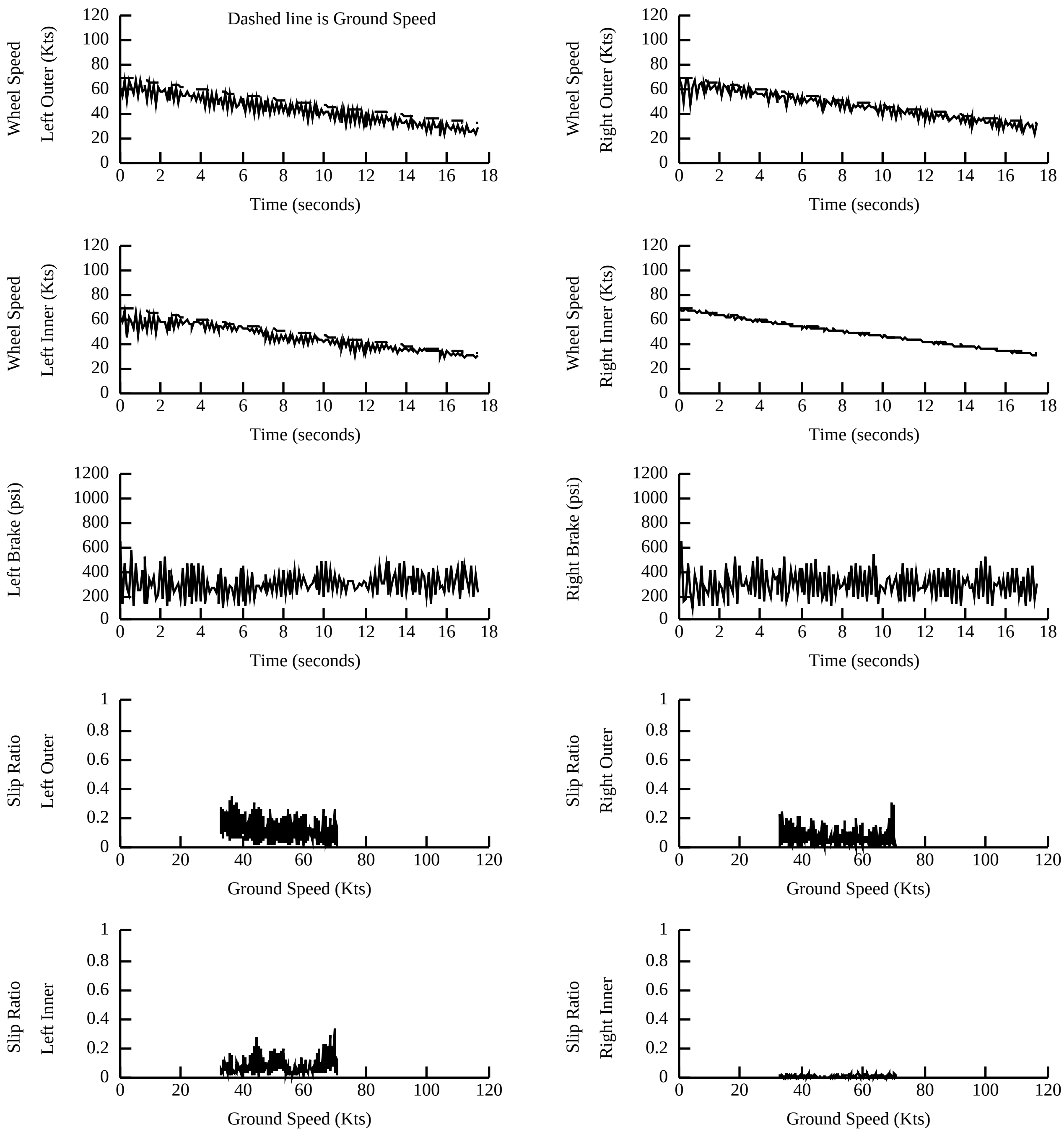


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow

Flight 2000/04, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.28

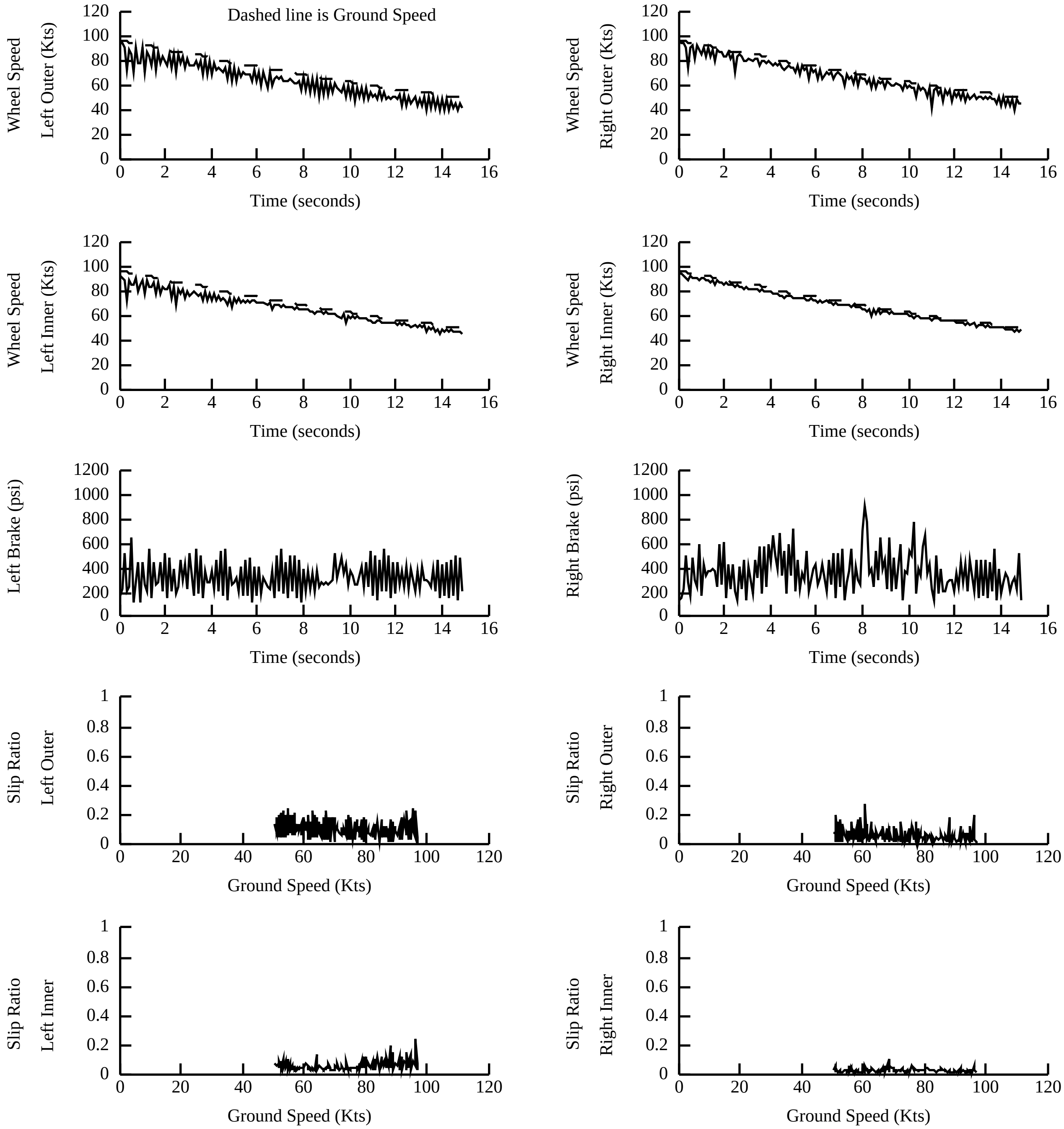


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow

Flight 2000/04, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.28

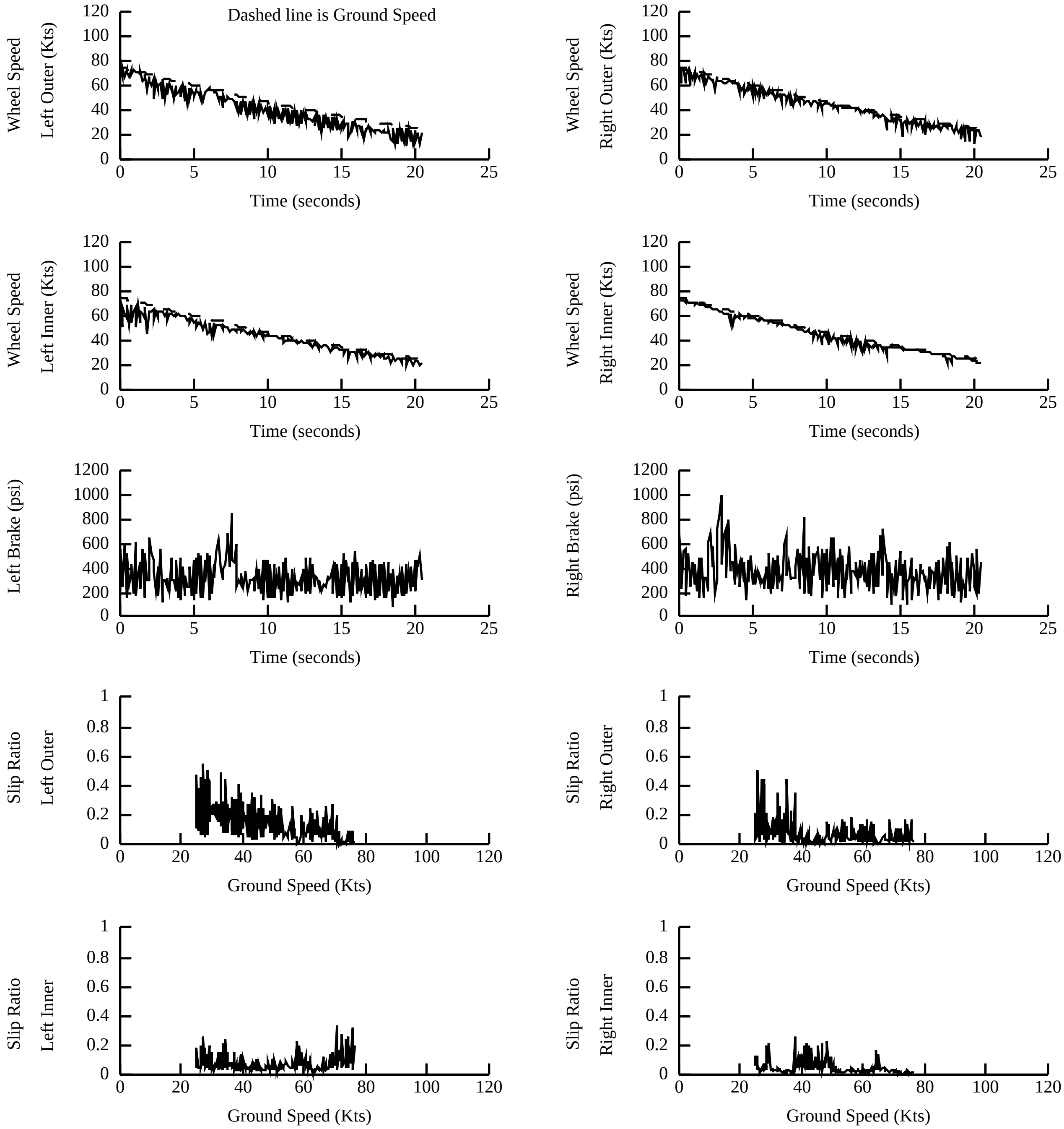


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow

Flight 2000/04, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.28

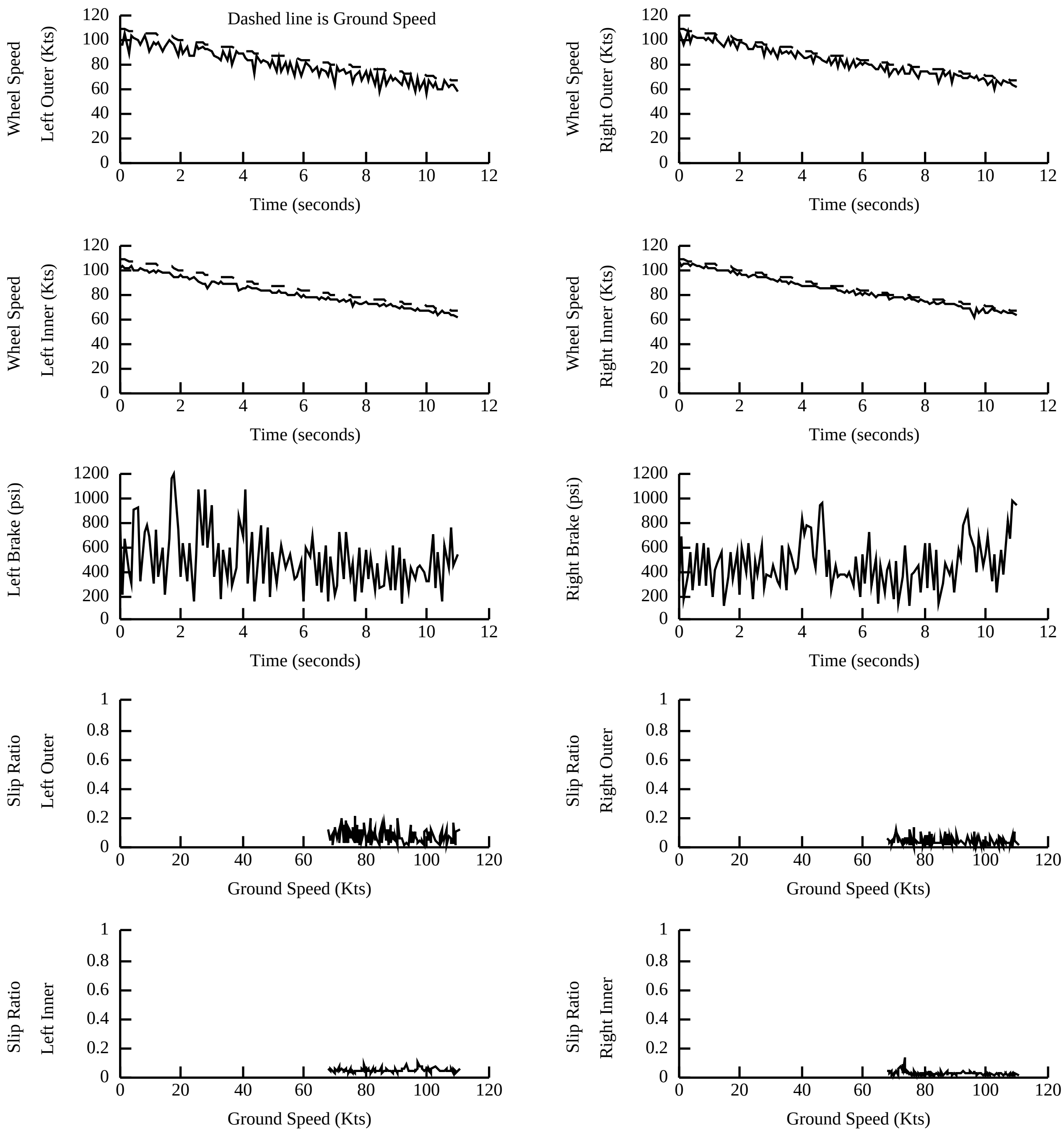


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow

Flight 2000/04, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.31

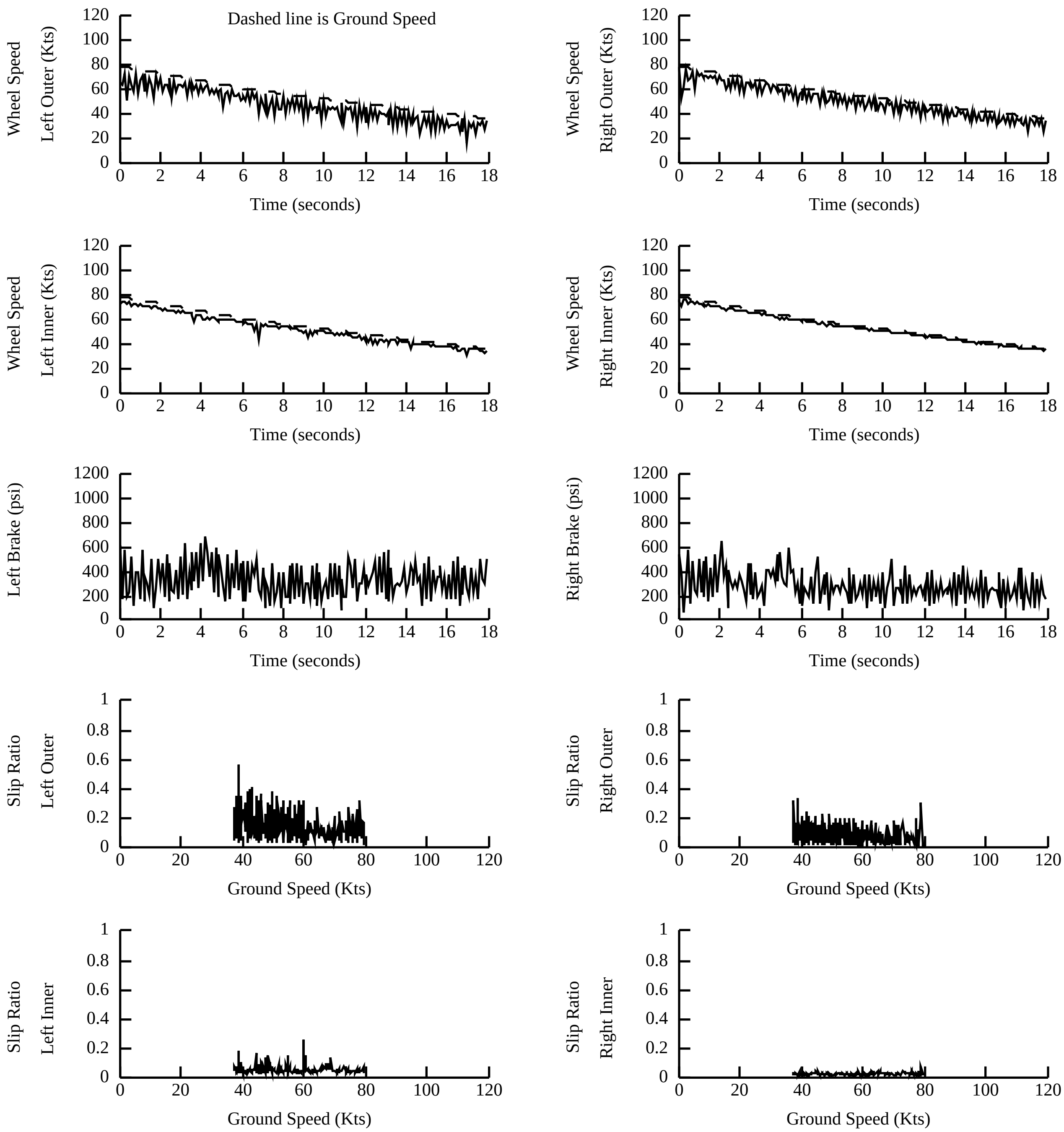


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow

Flight 2000/04, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.31

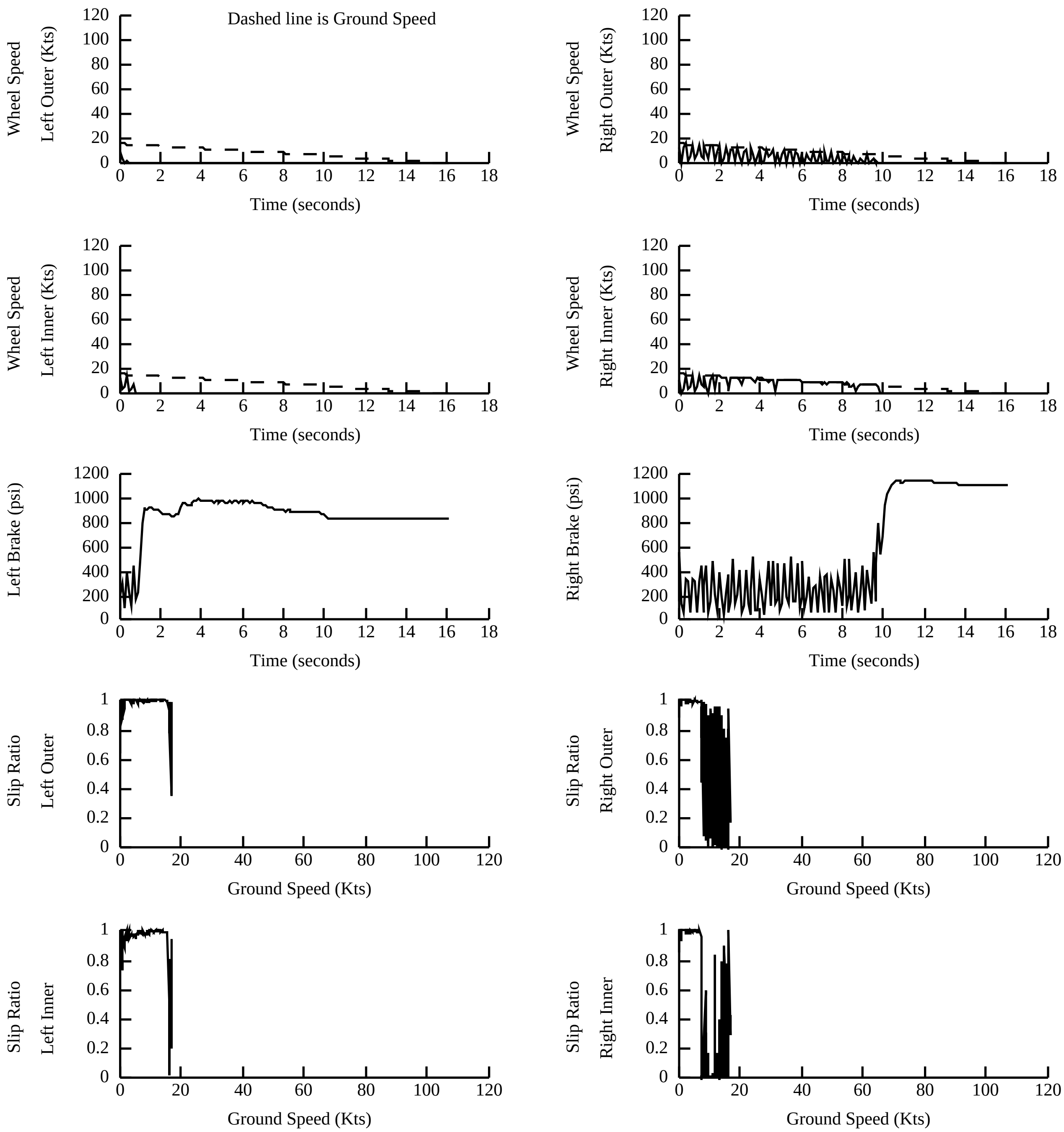


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.13

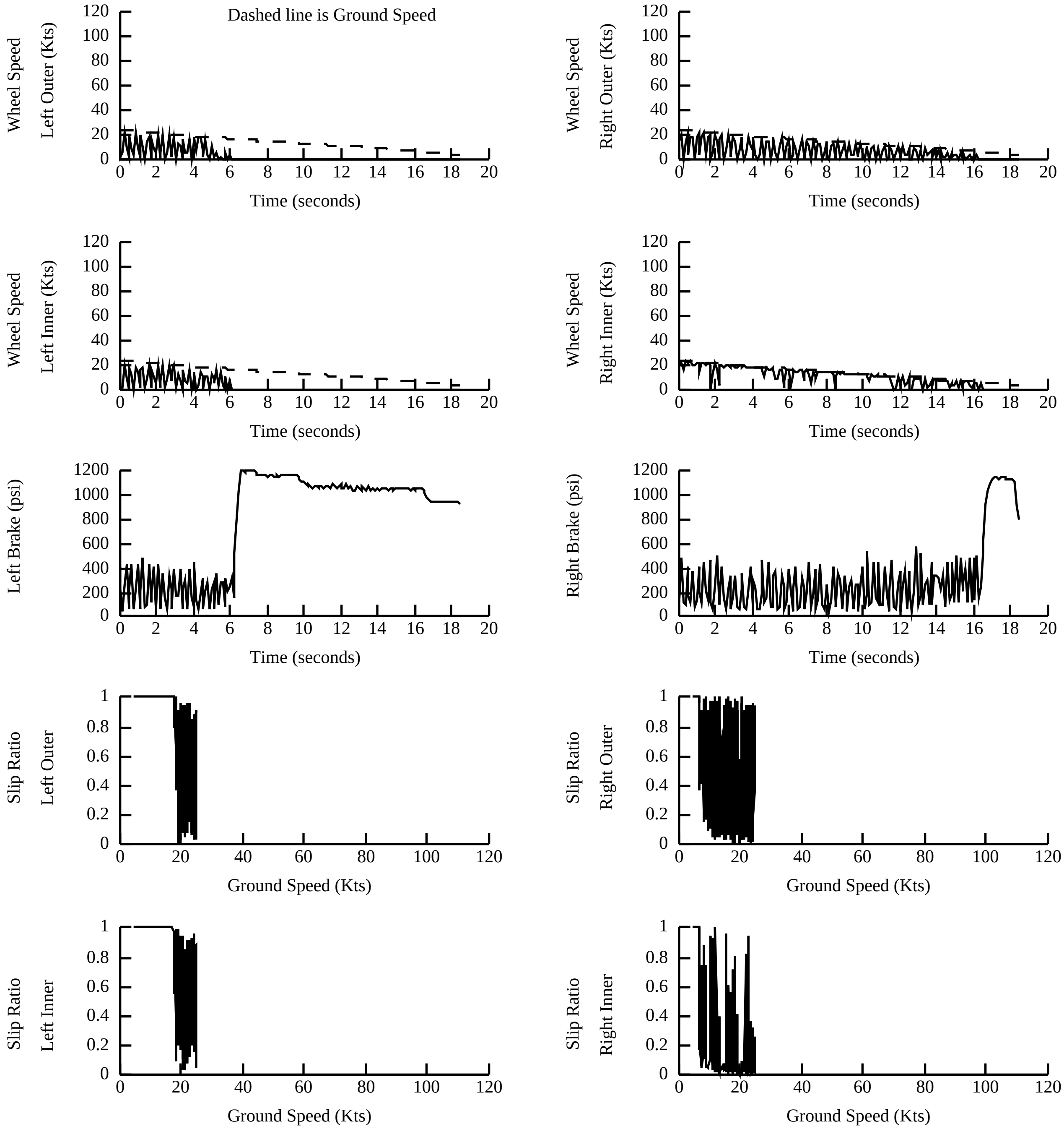


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.13

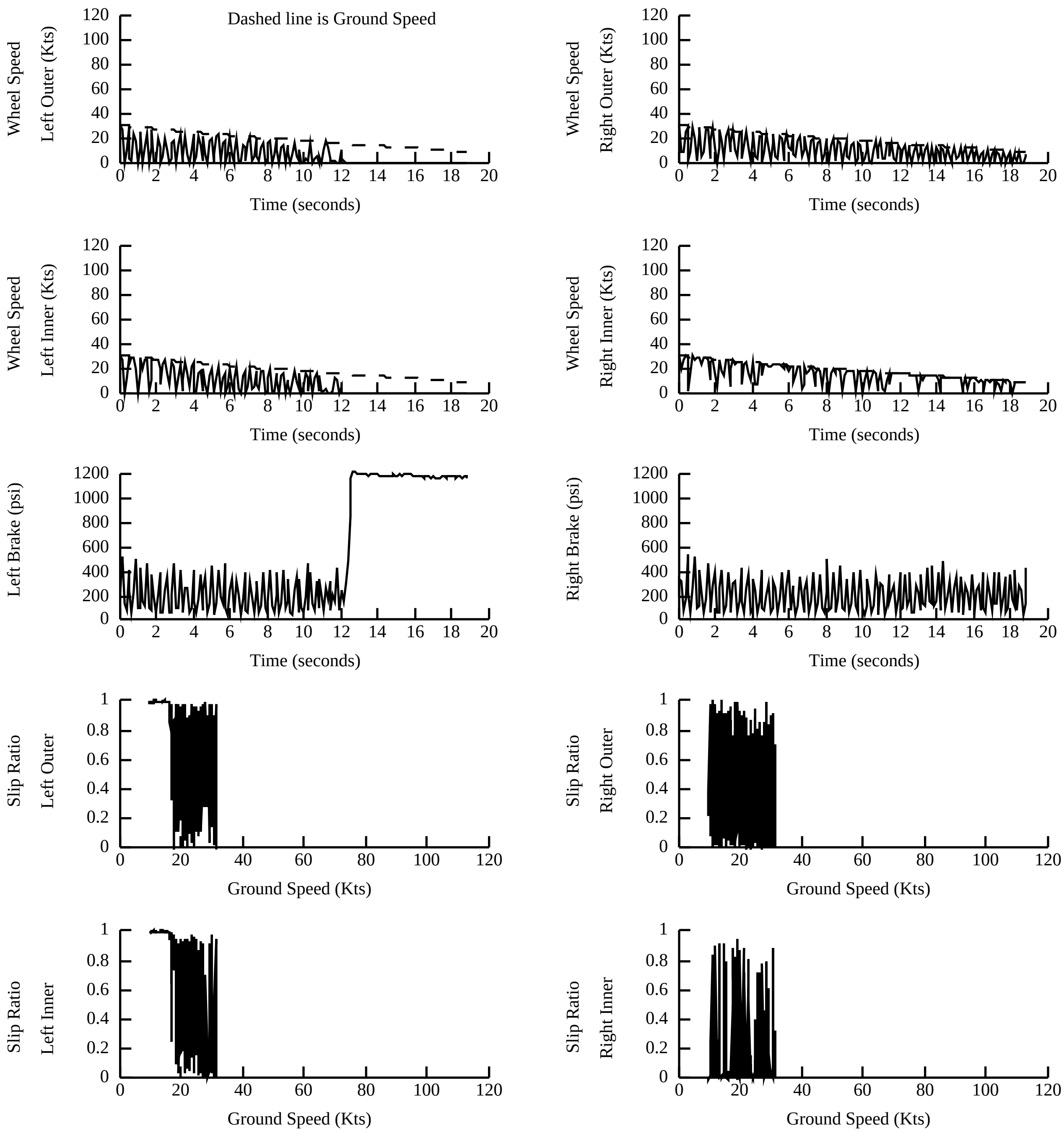


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.13

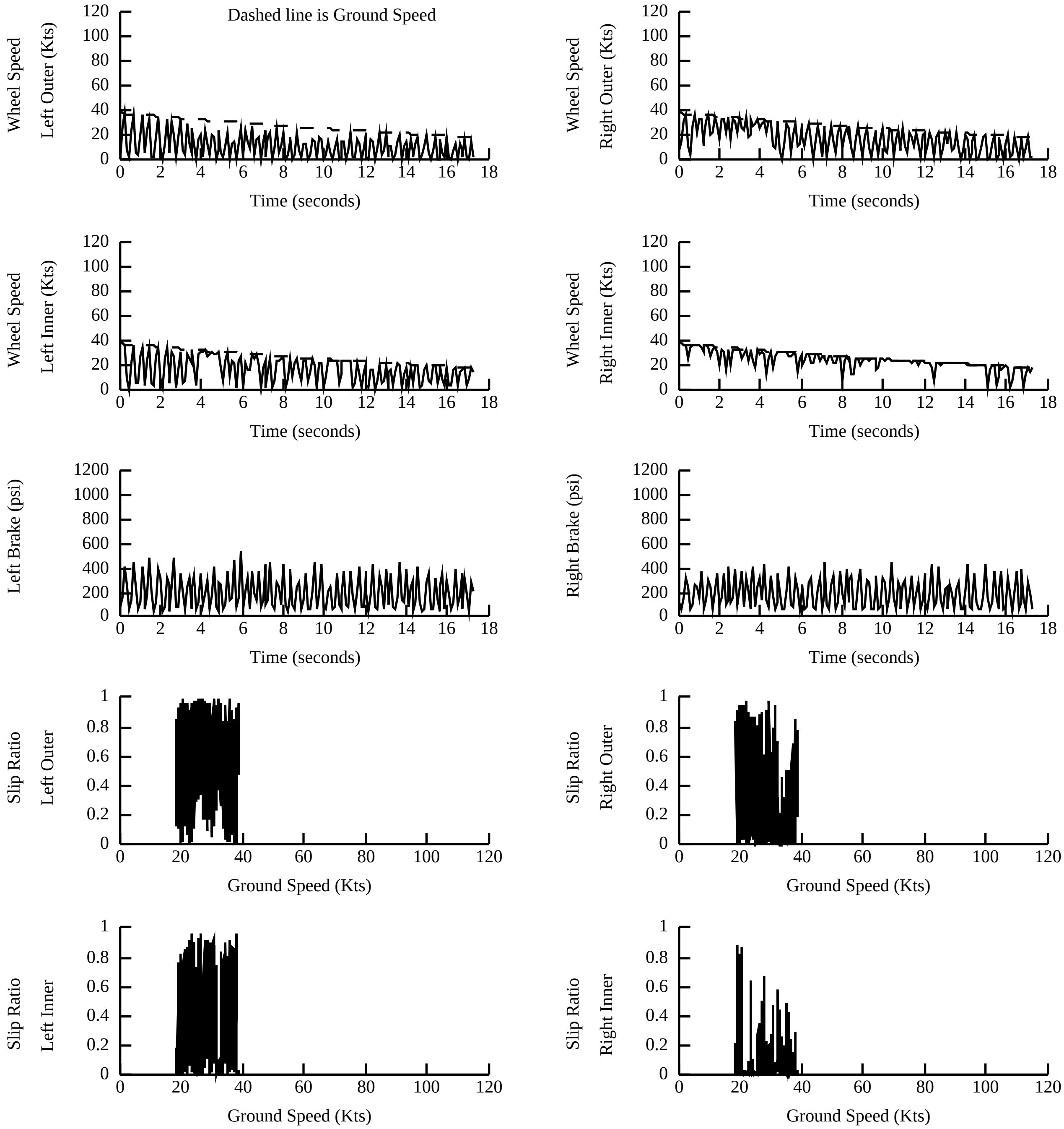


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.13

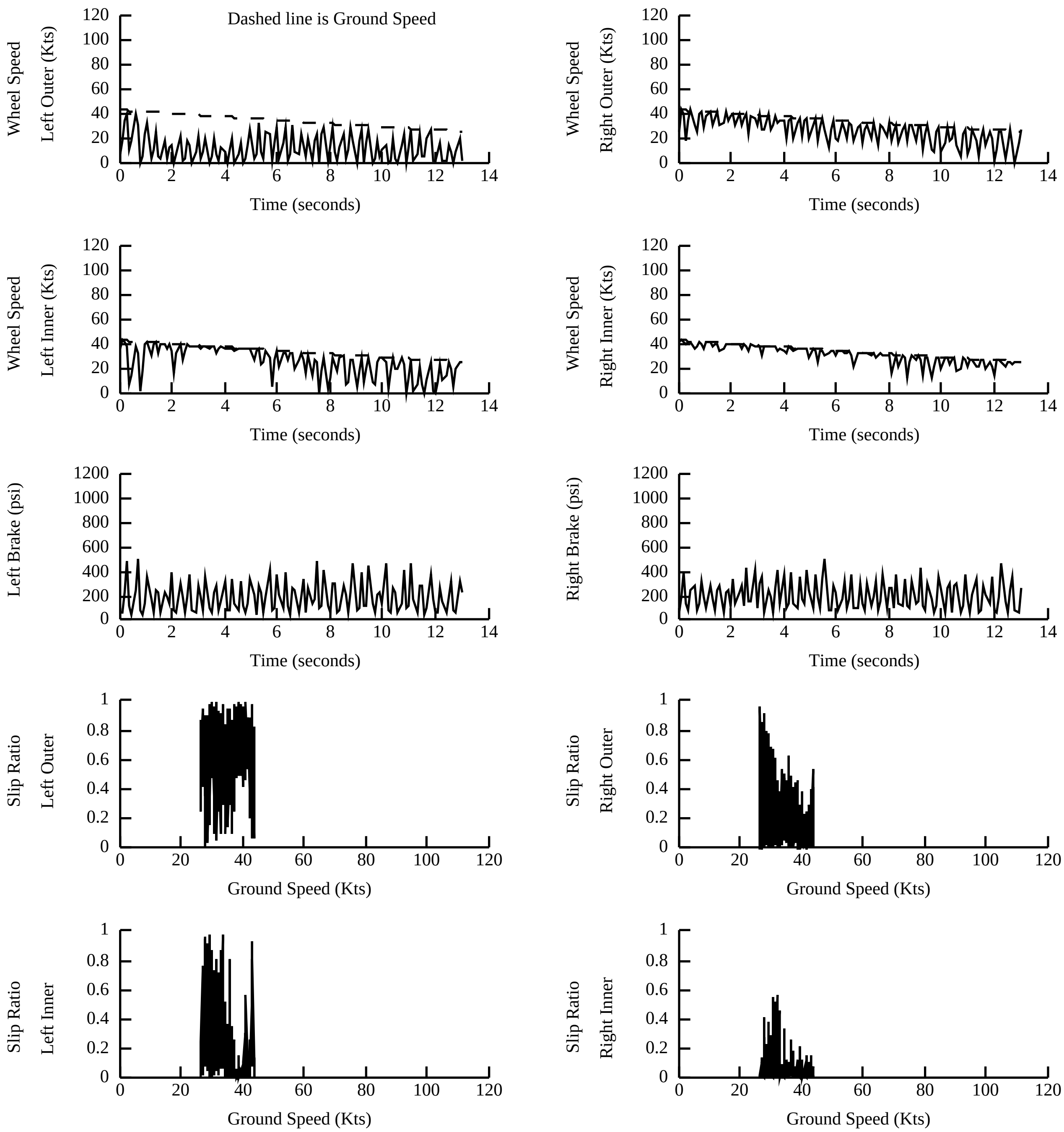


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.12

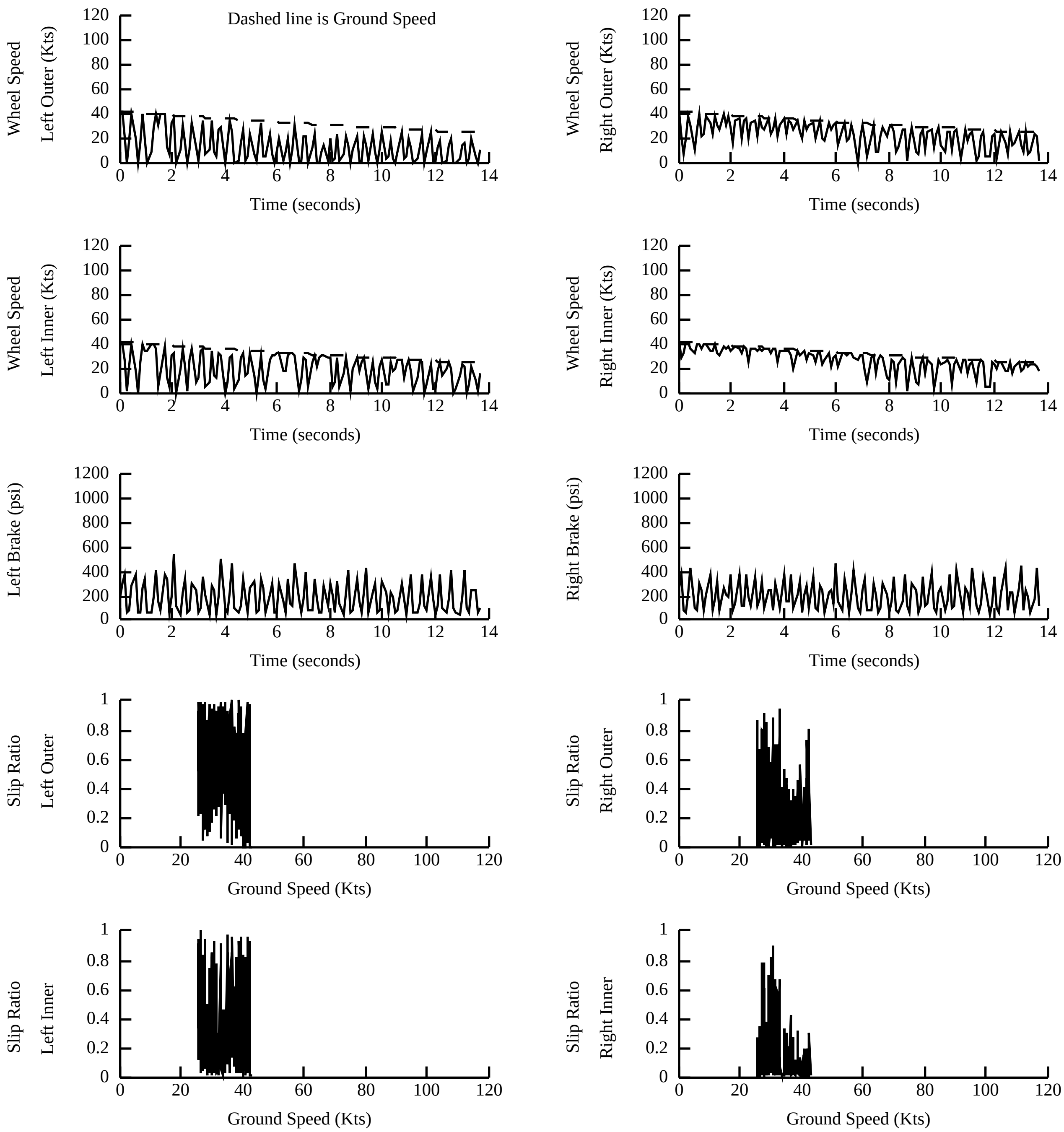


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.12

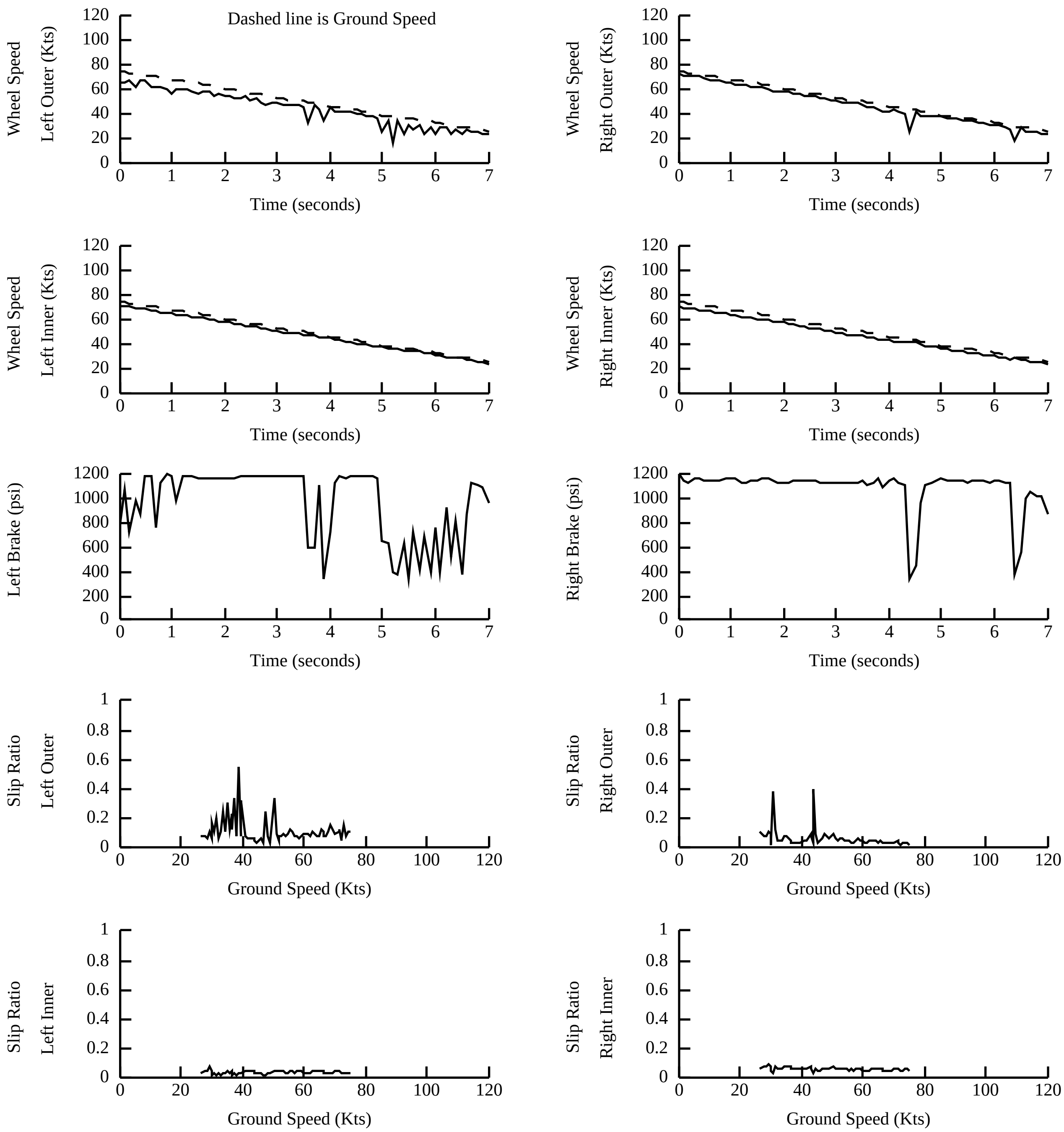


Surface: 100% Bare and Dry, With Occasional Ice Patches

Flight 2000/06, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.73

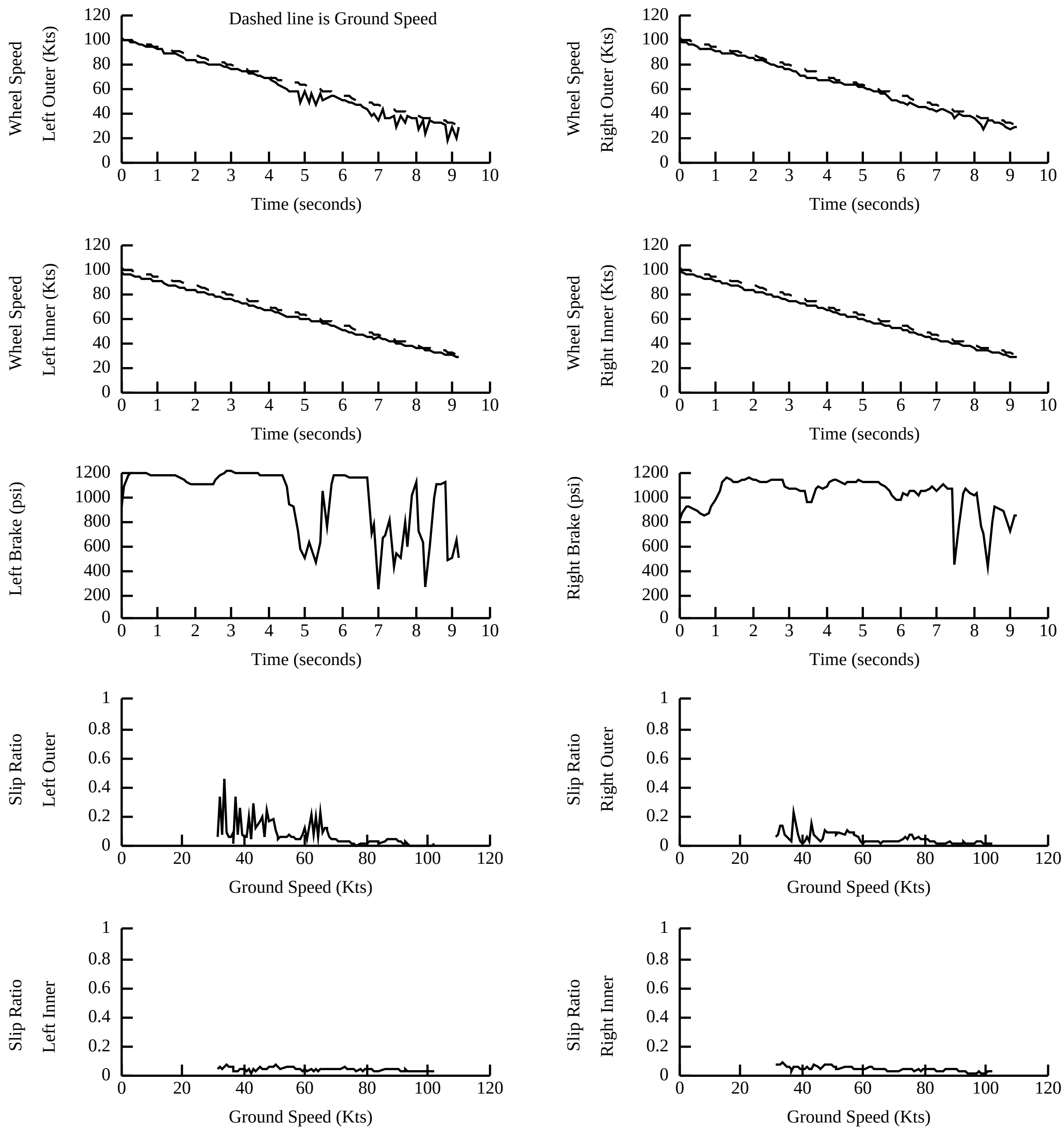


Surface: 100% Bare and Dry, With Occasional Ice Patches

Flight 2000/06, Run Number 2

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.73

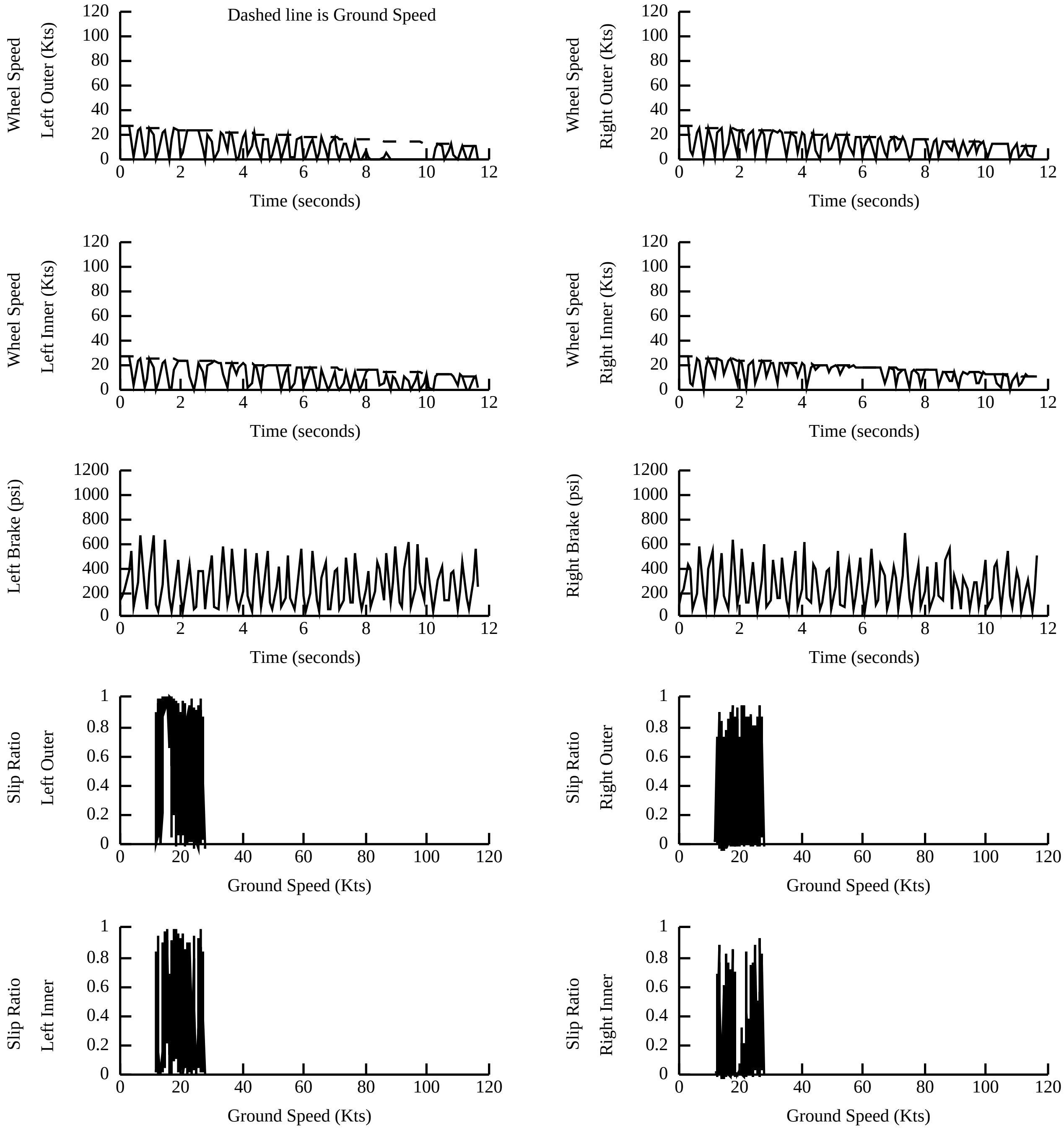


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.10

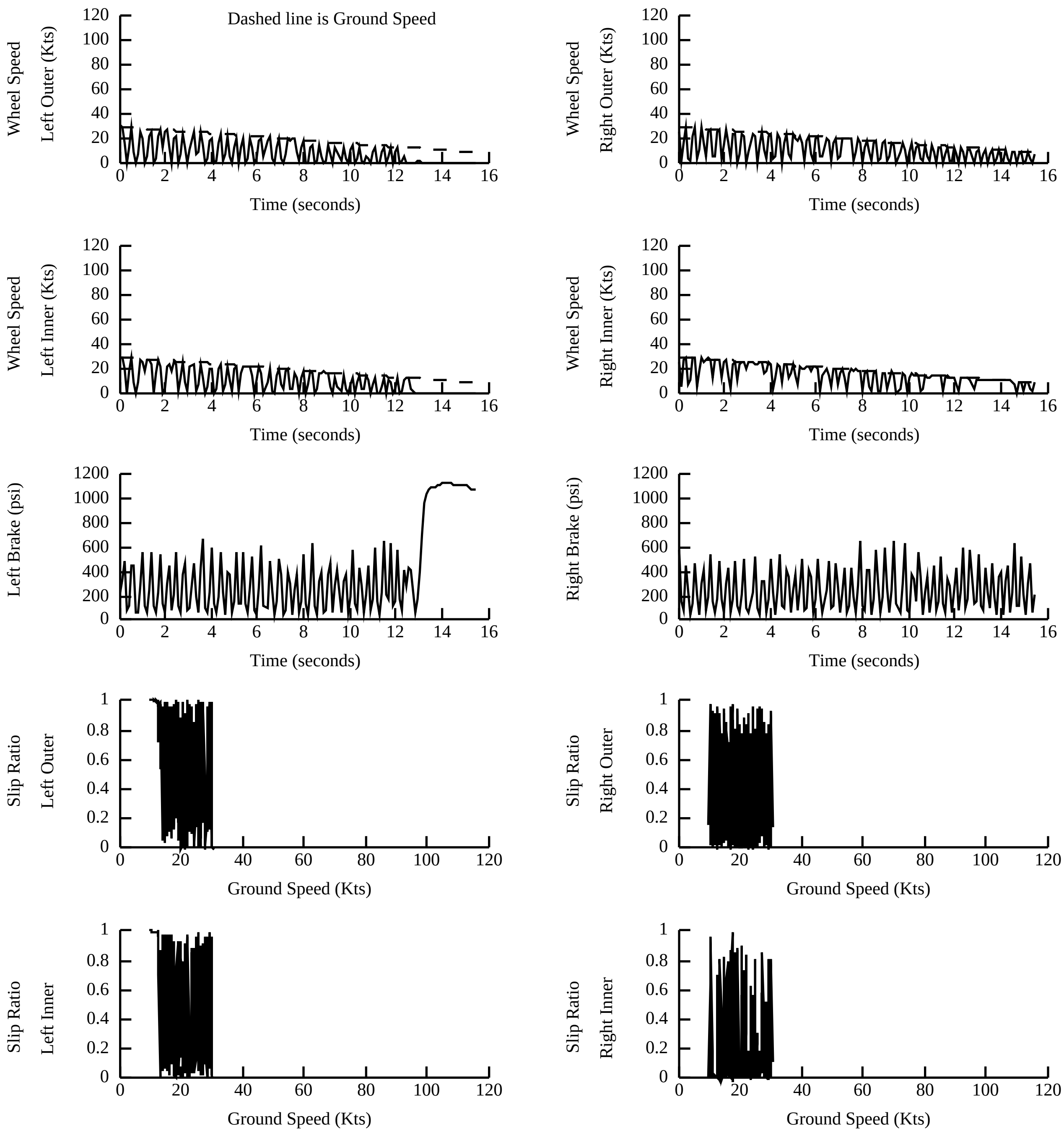


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.10

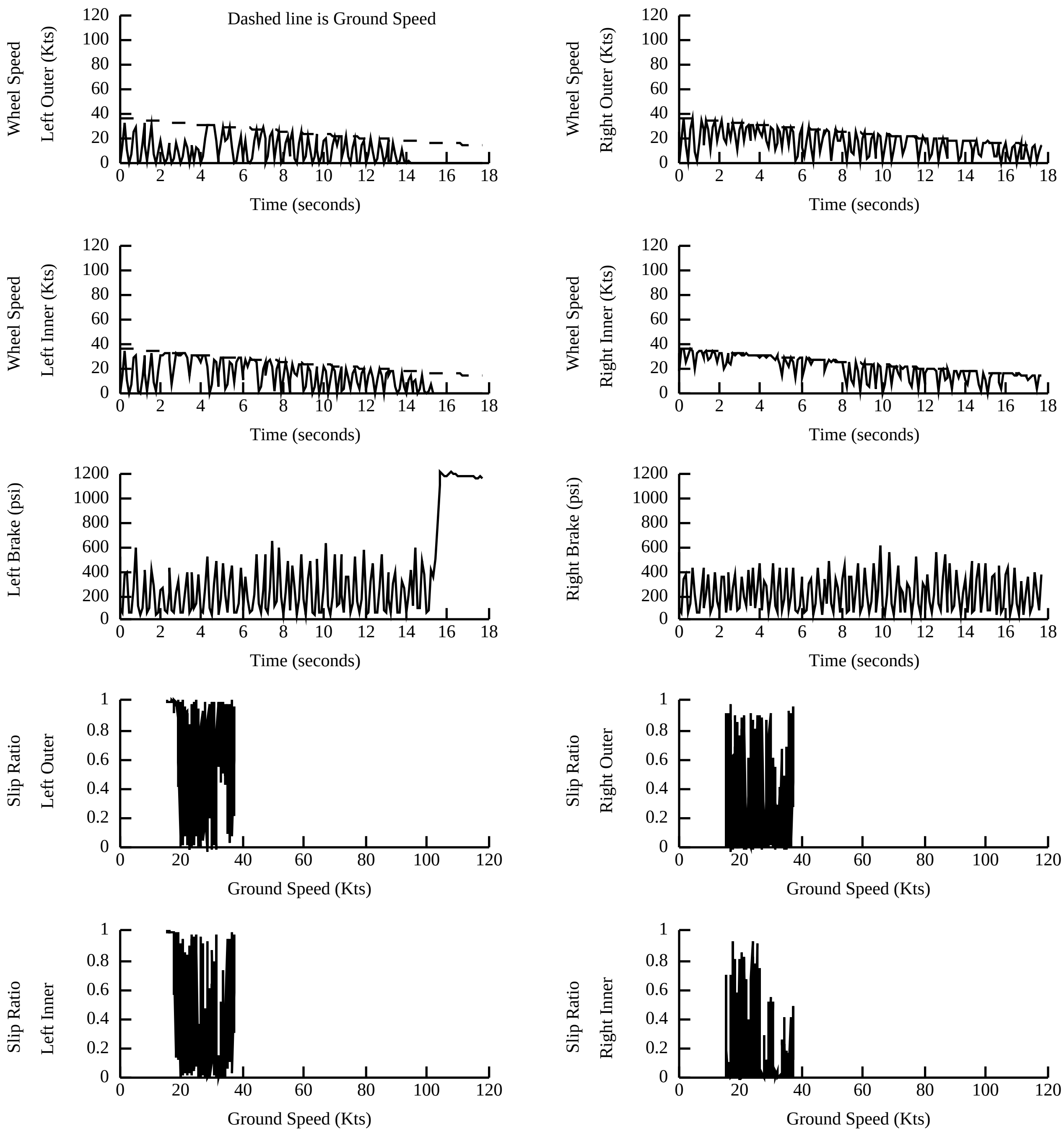


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.11

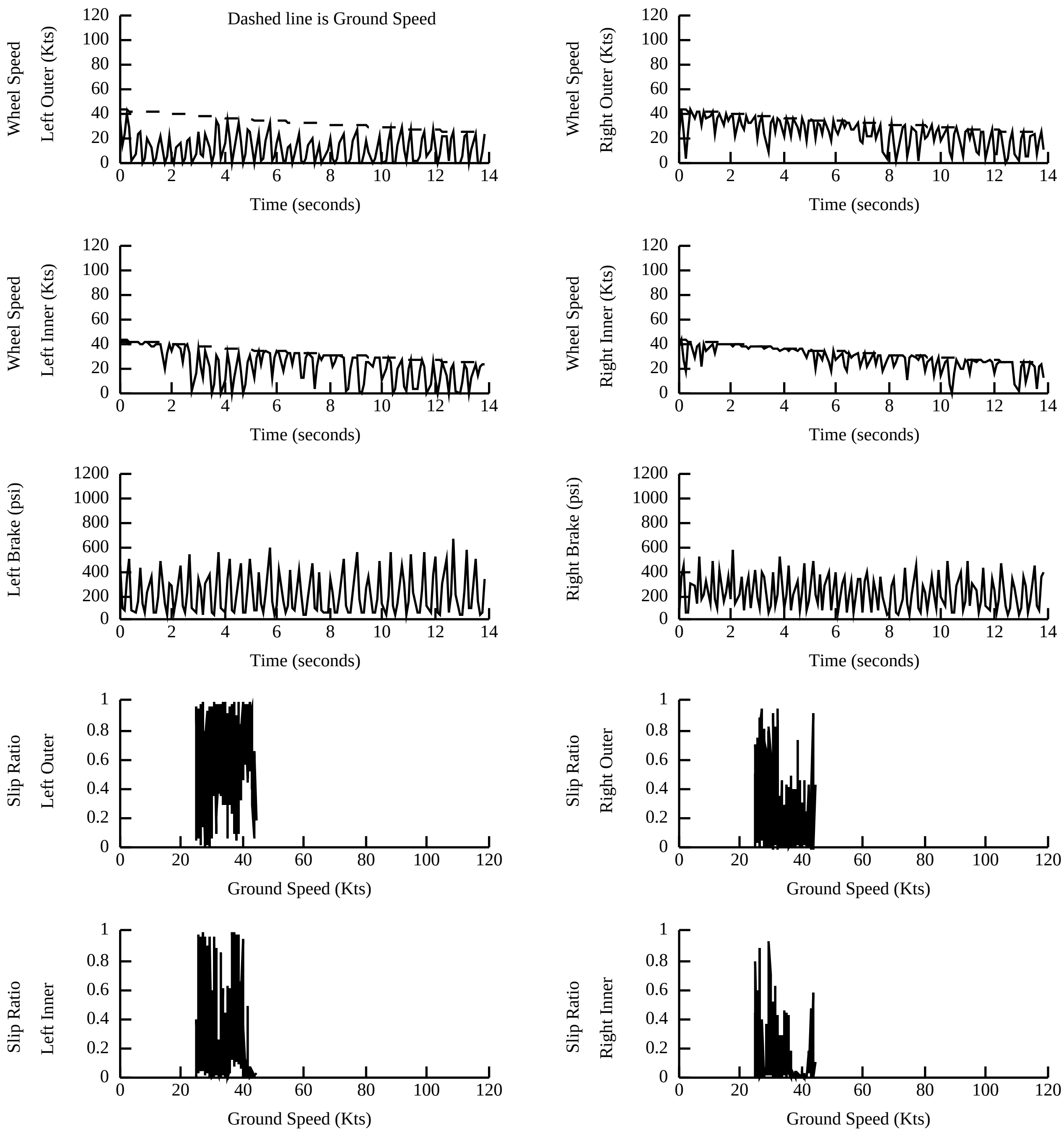


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.11

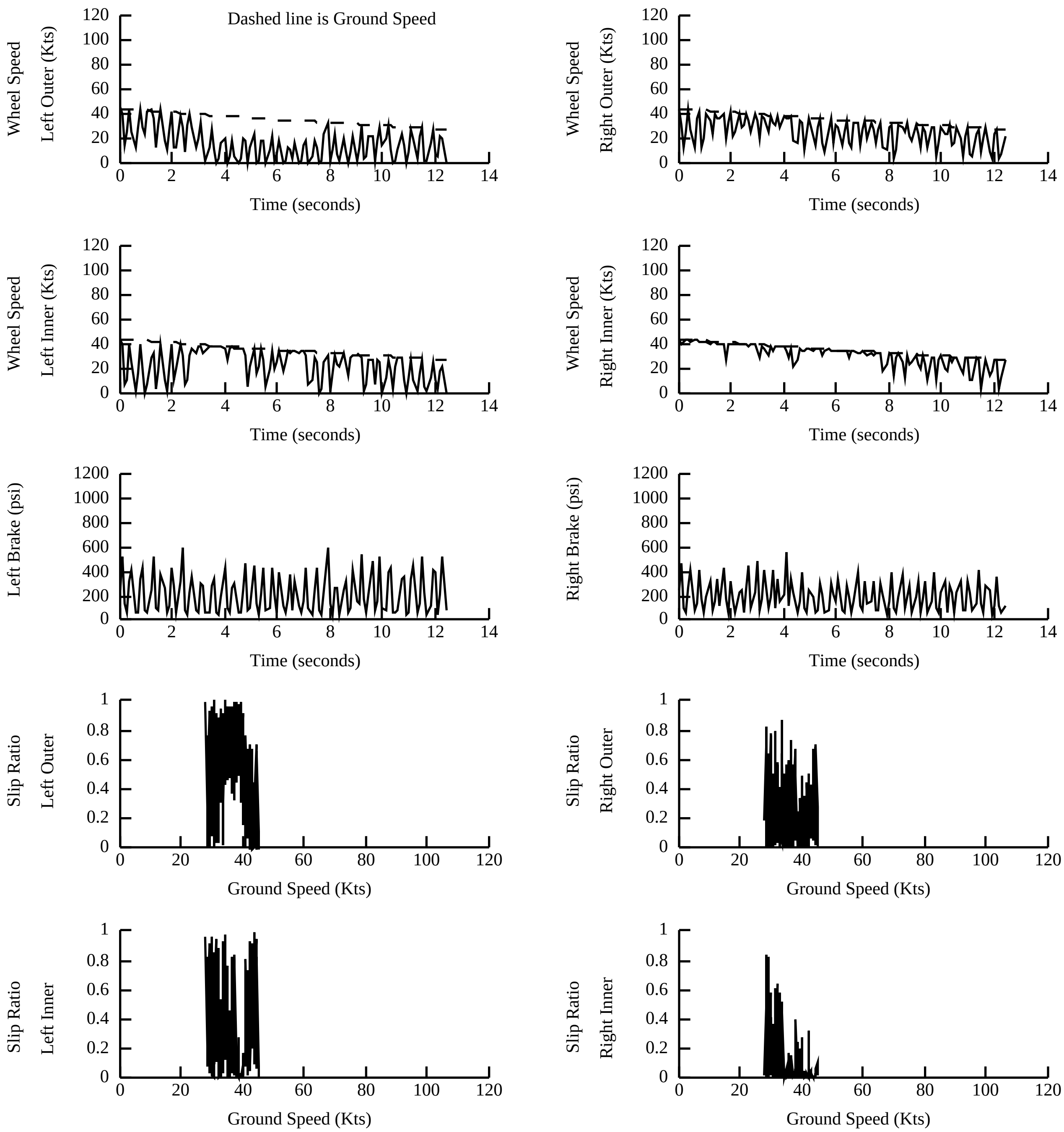


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.09

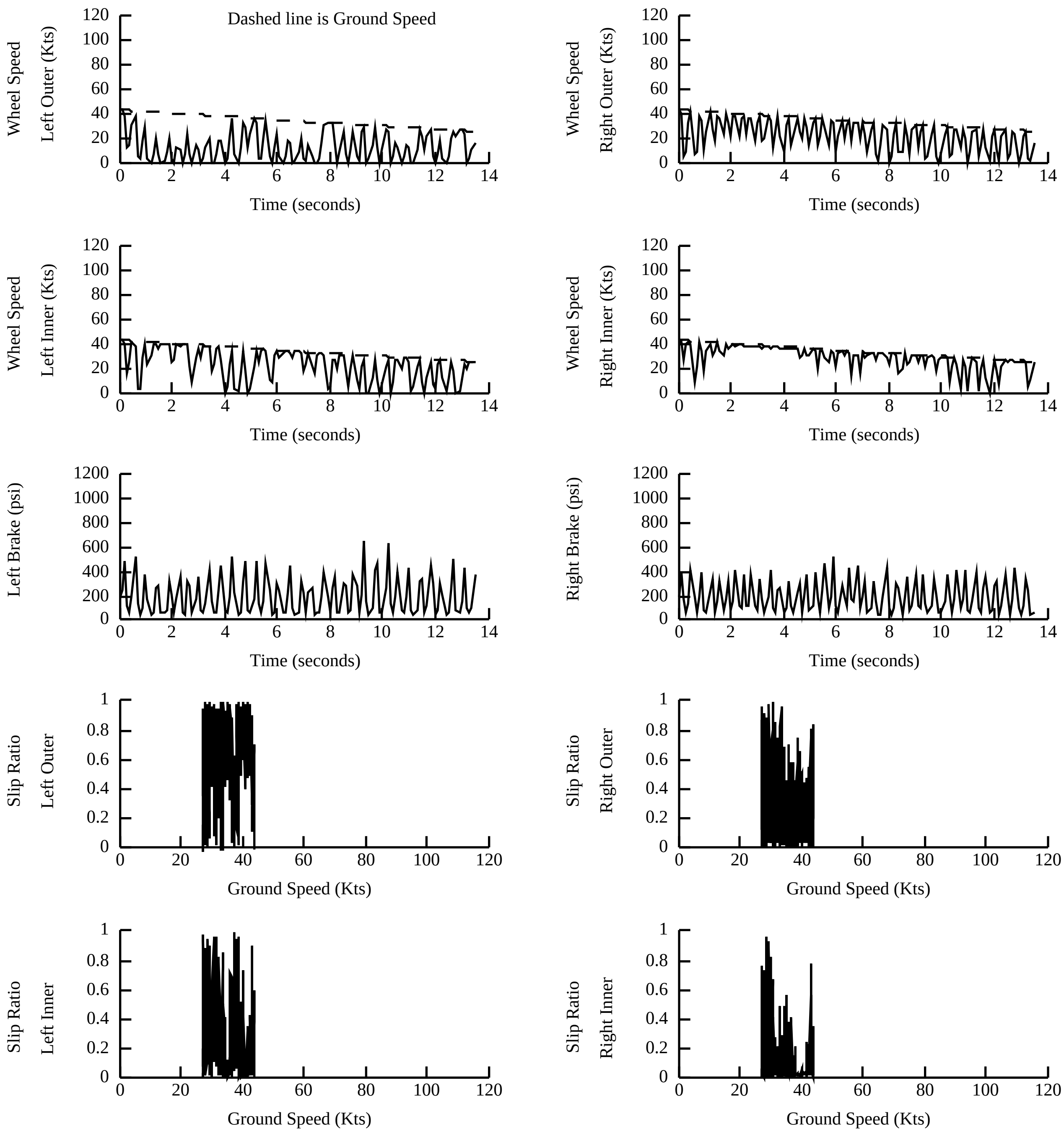


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.09

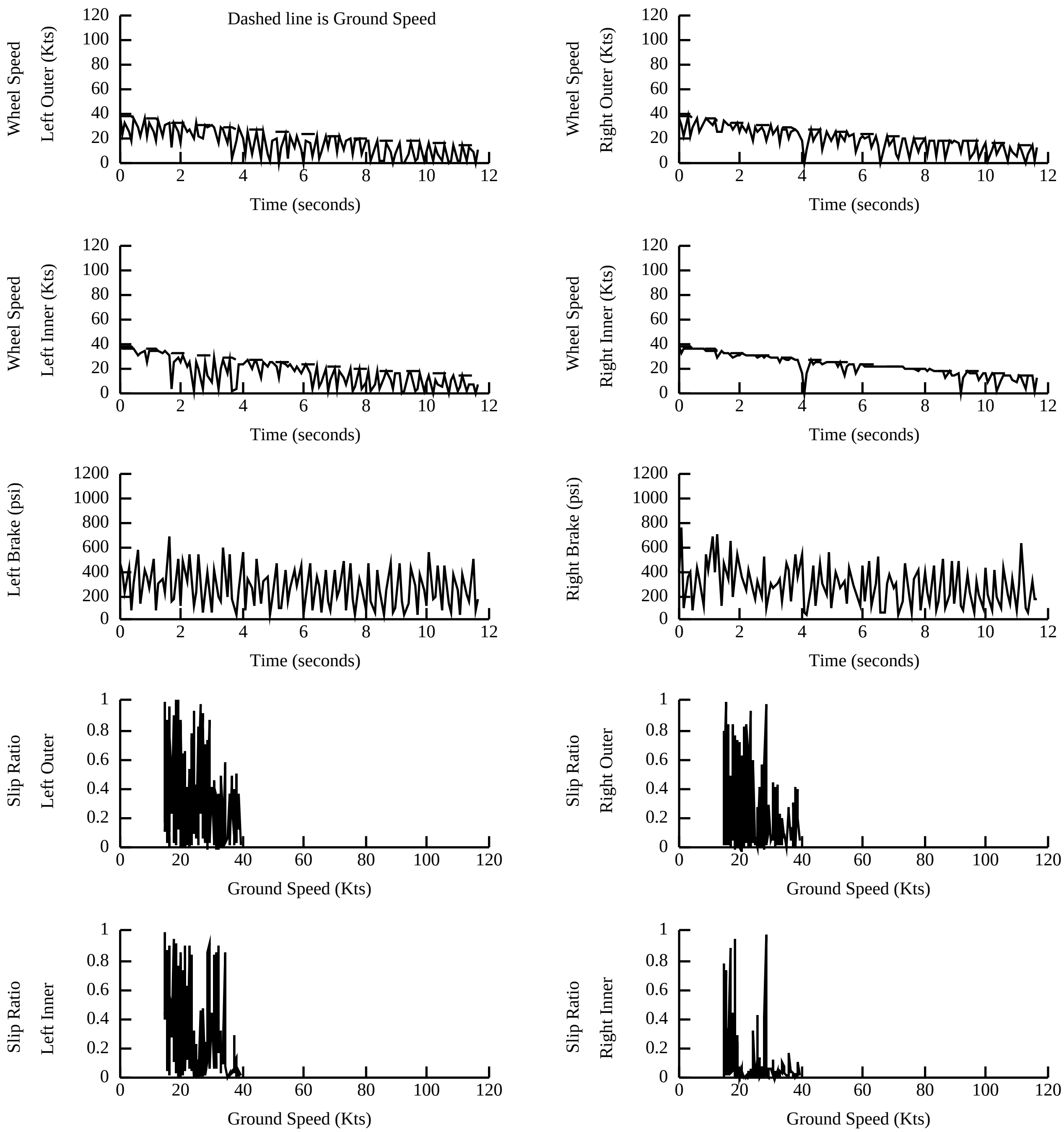


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.20

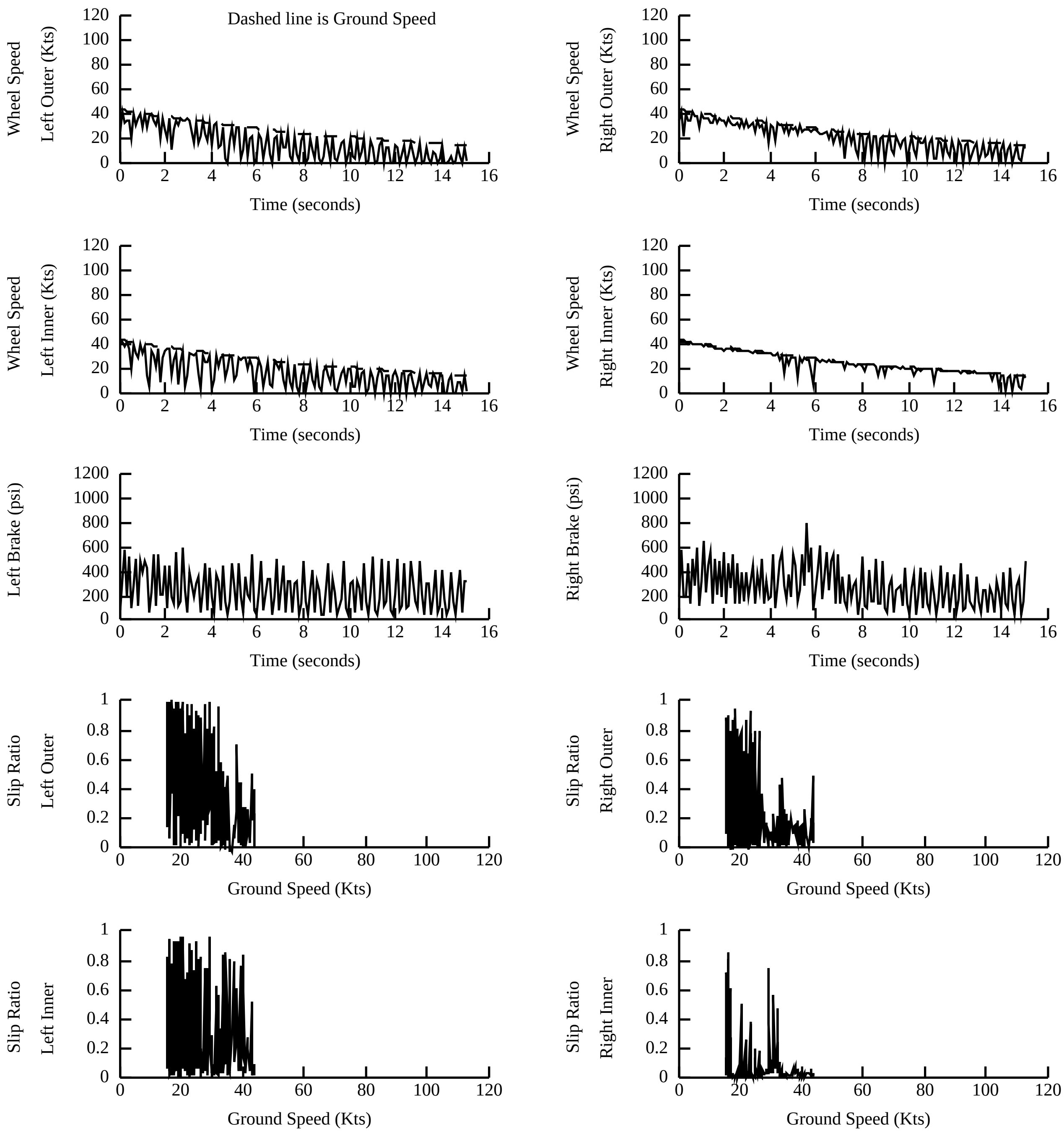


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.20

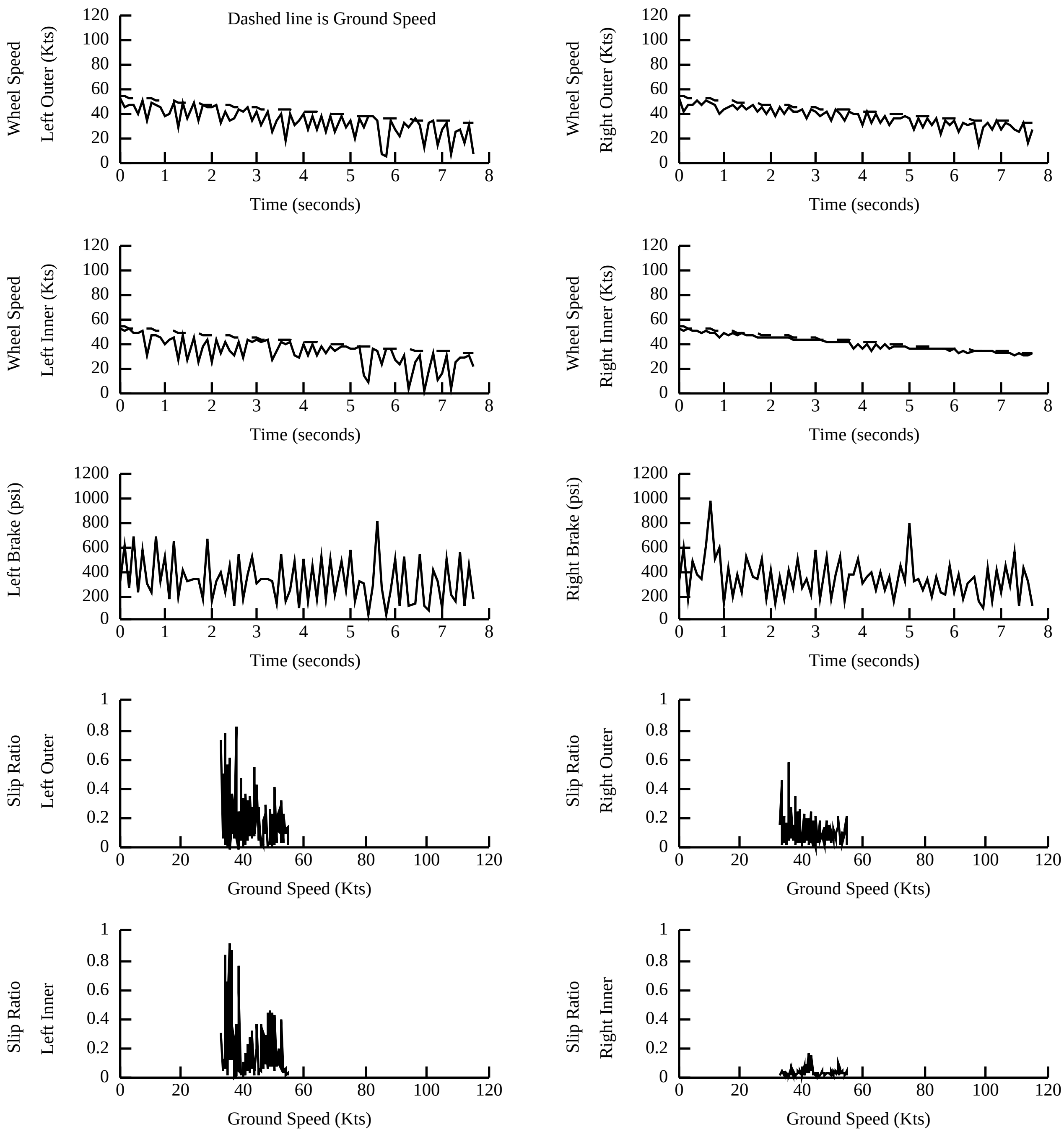


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

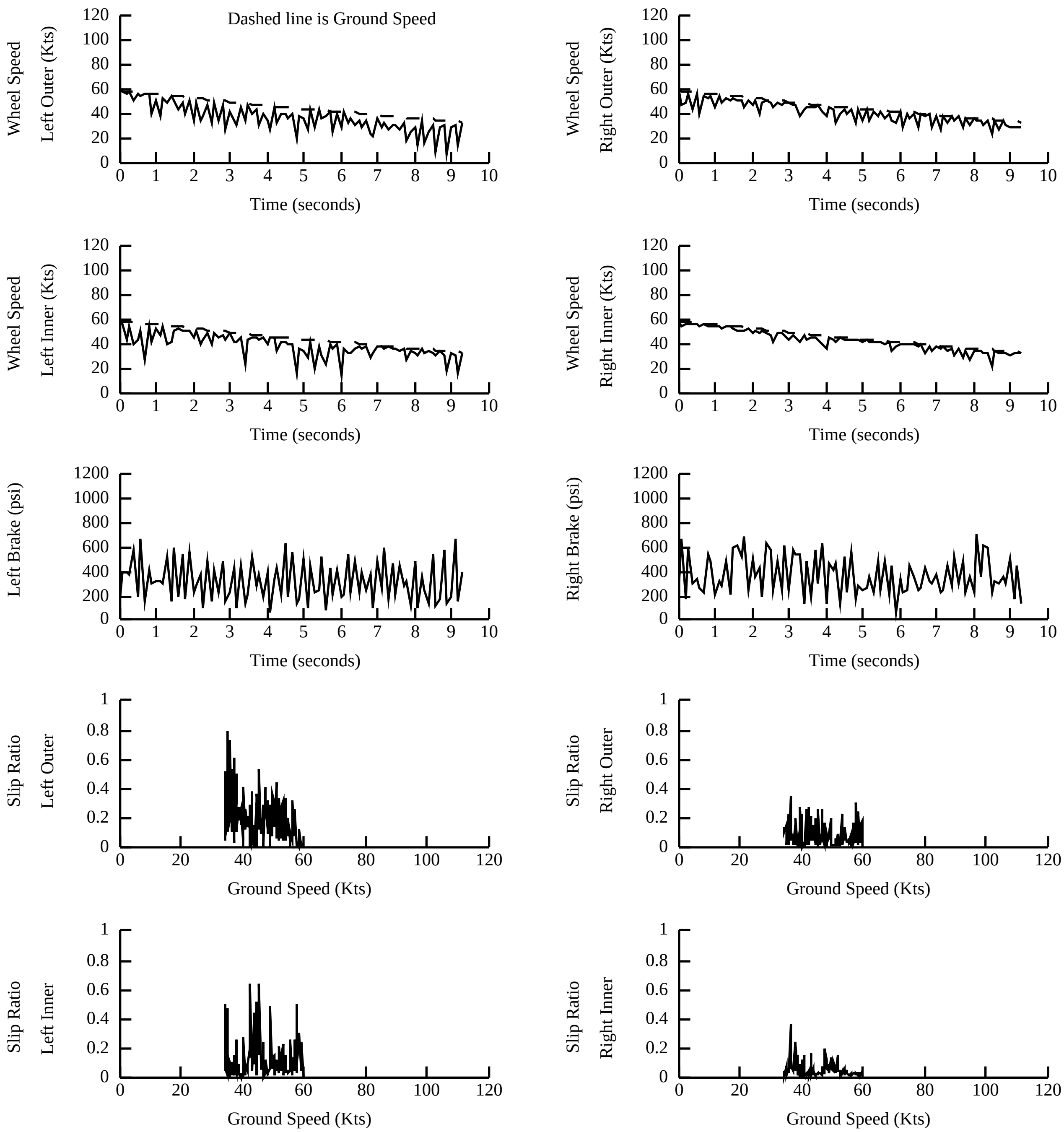


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.22

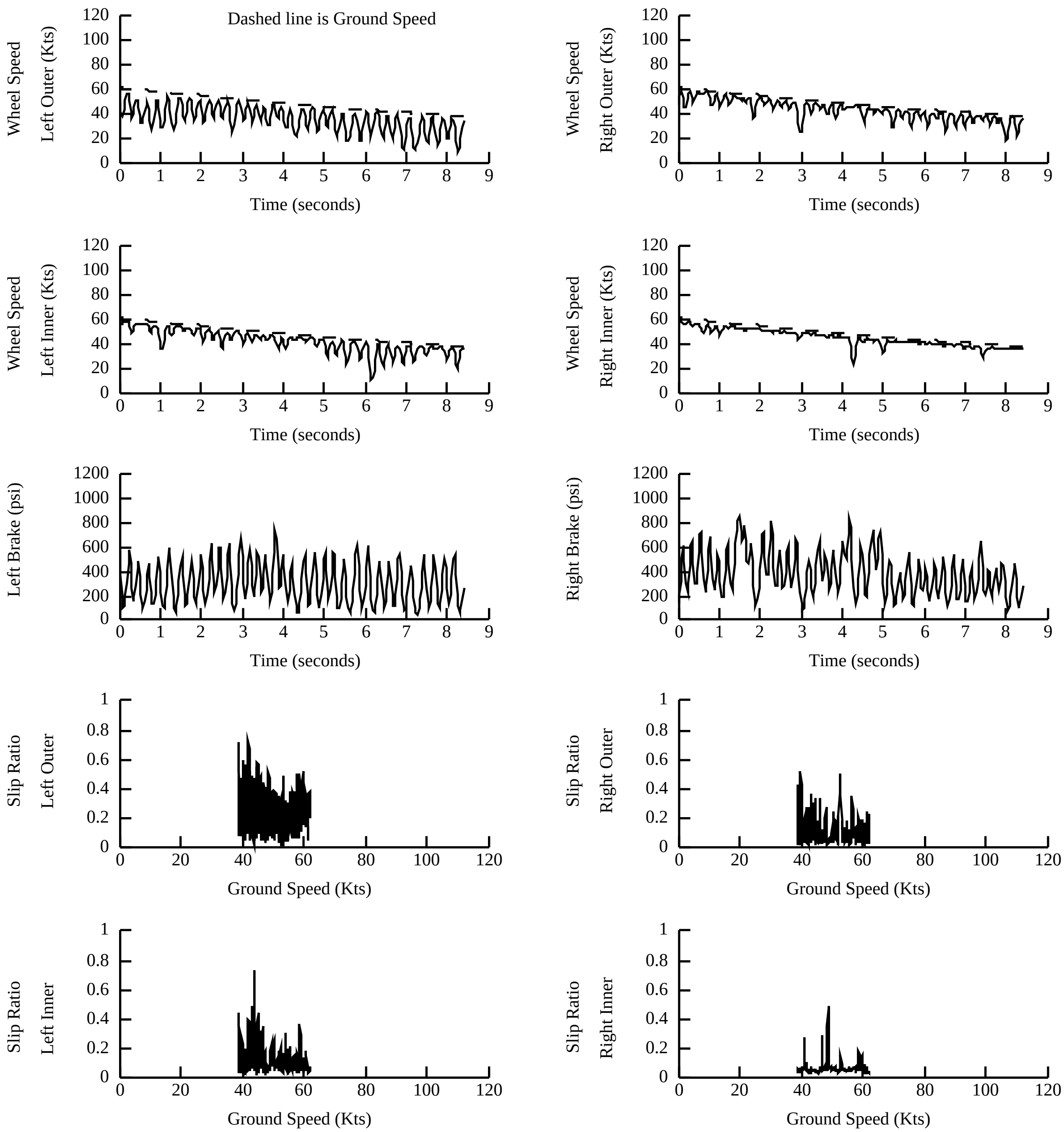


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21

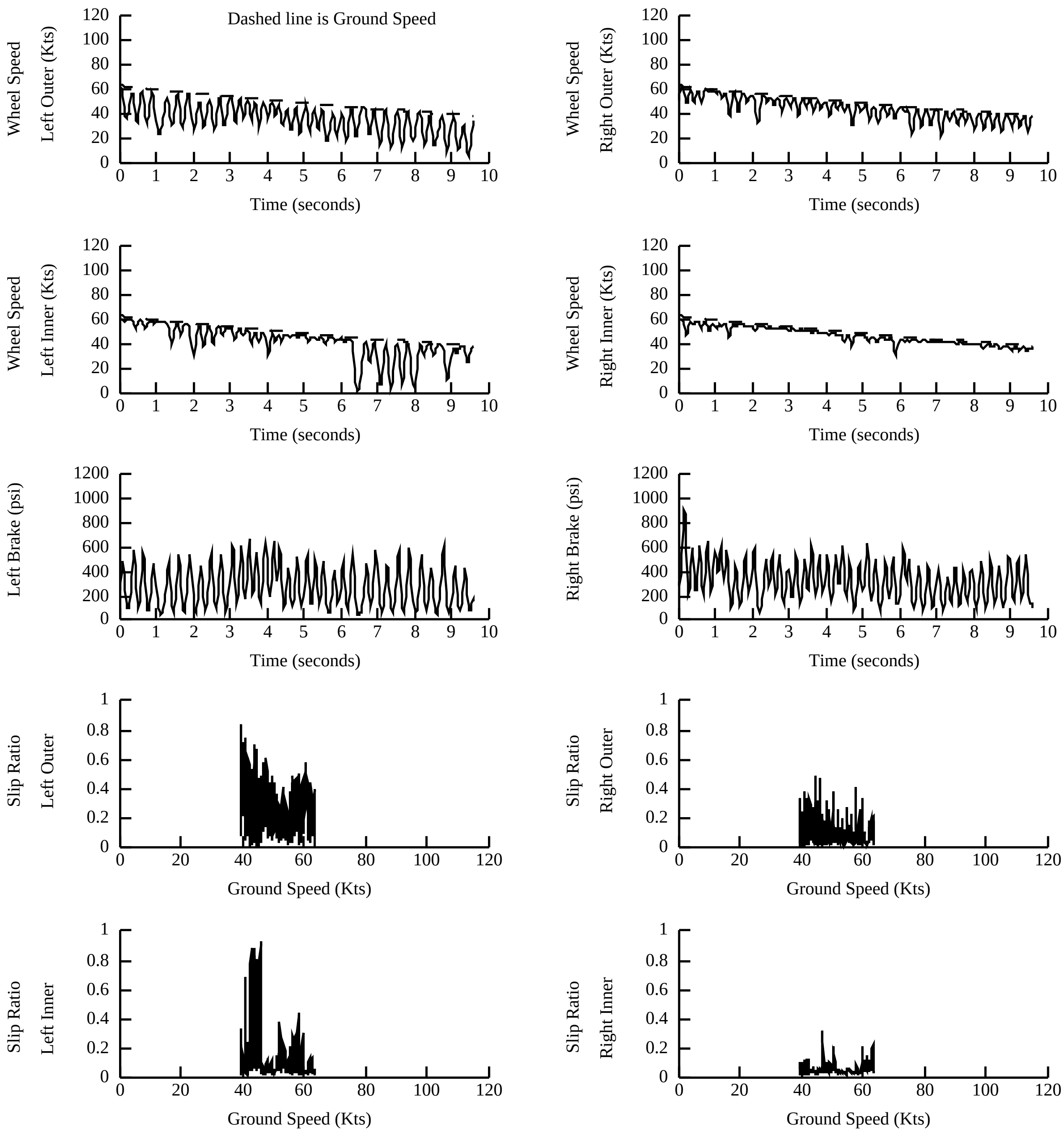


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.21

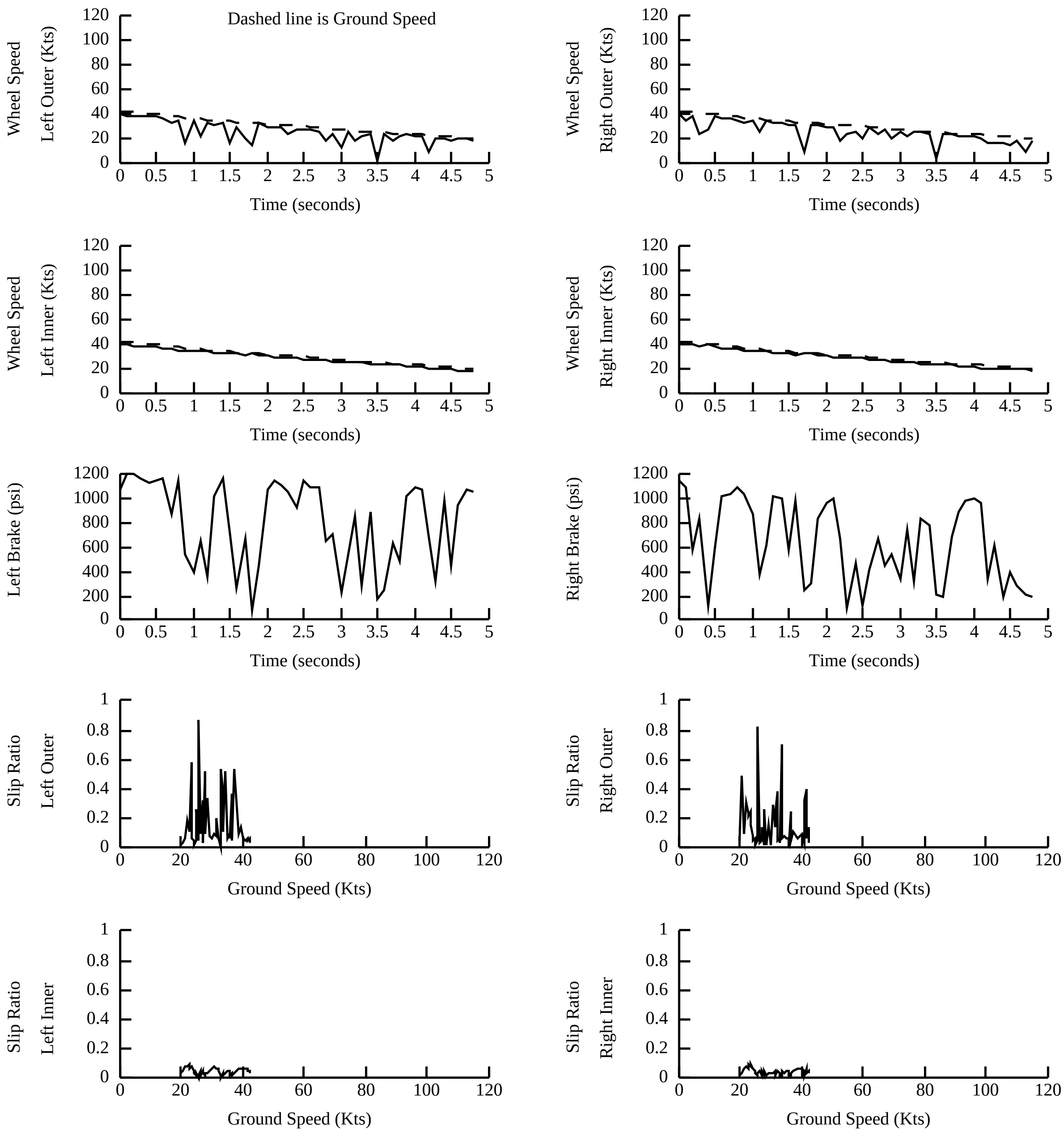


Surface: 70% Bare And Dry, 30% Light Dusting of Snow

Flight 2000/09, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.42

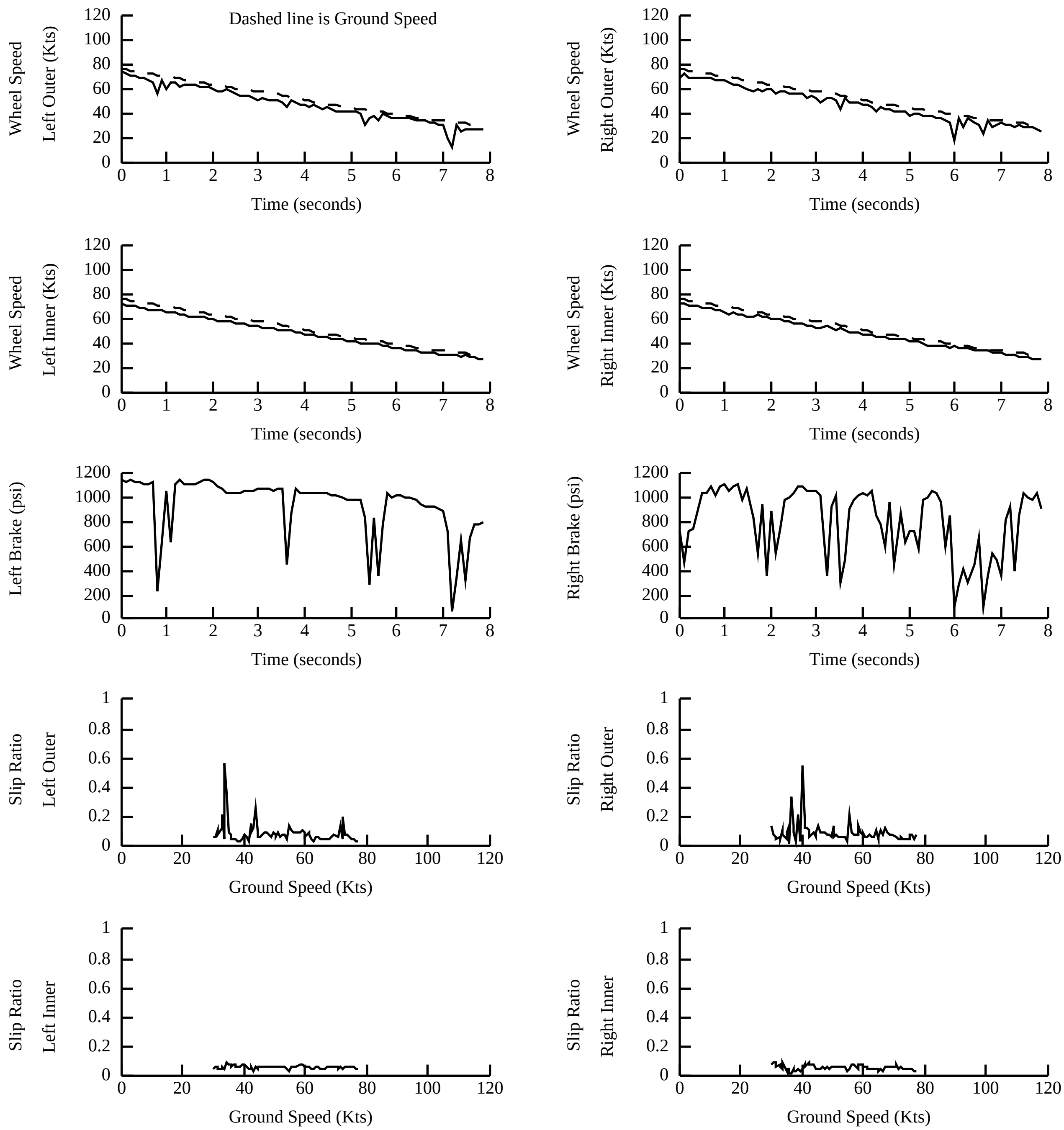


Surface: 70% Bare And Dry, 30% Light Dusting of Snow

Flight 2000/09, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.61

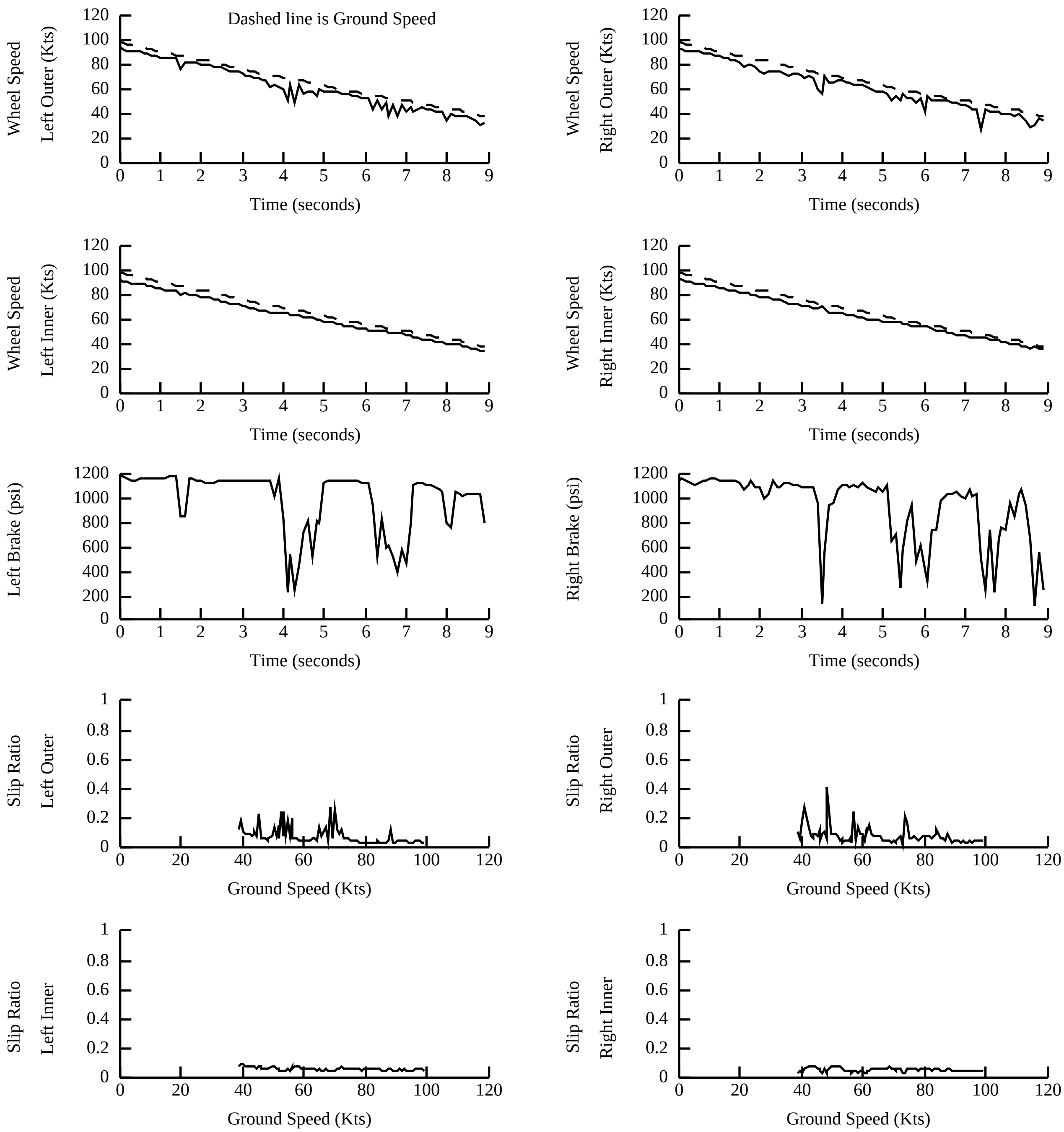


Surface: 70% Bare And Dry, 30% Light Dusting of Snow

Flight 2000/09, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.66

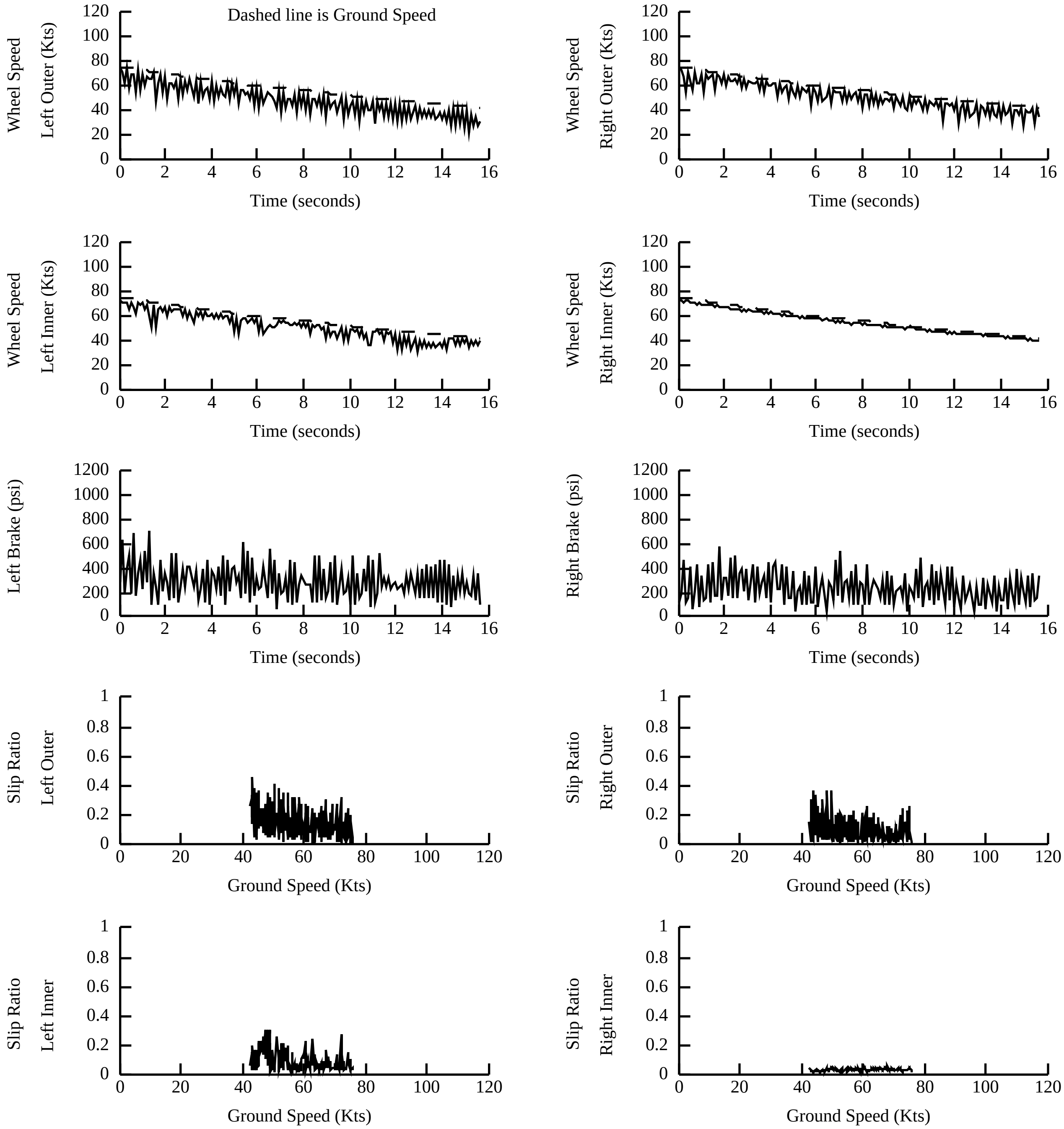


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.27

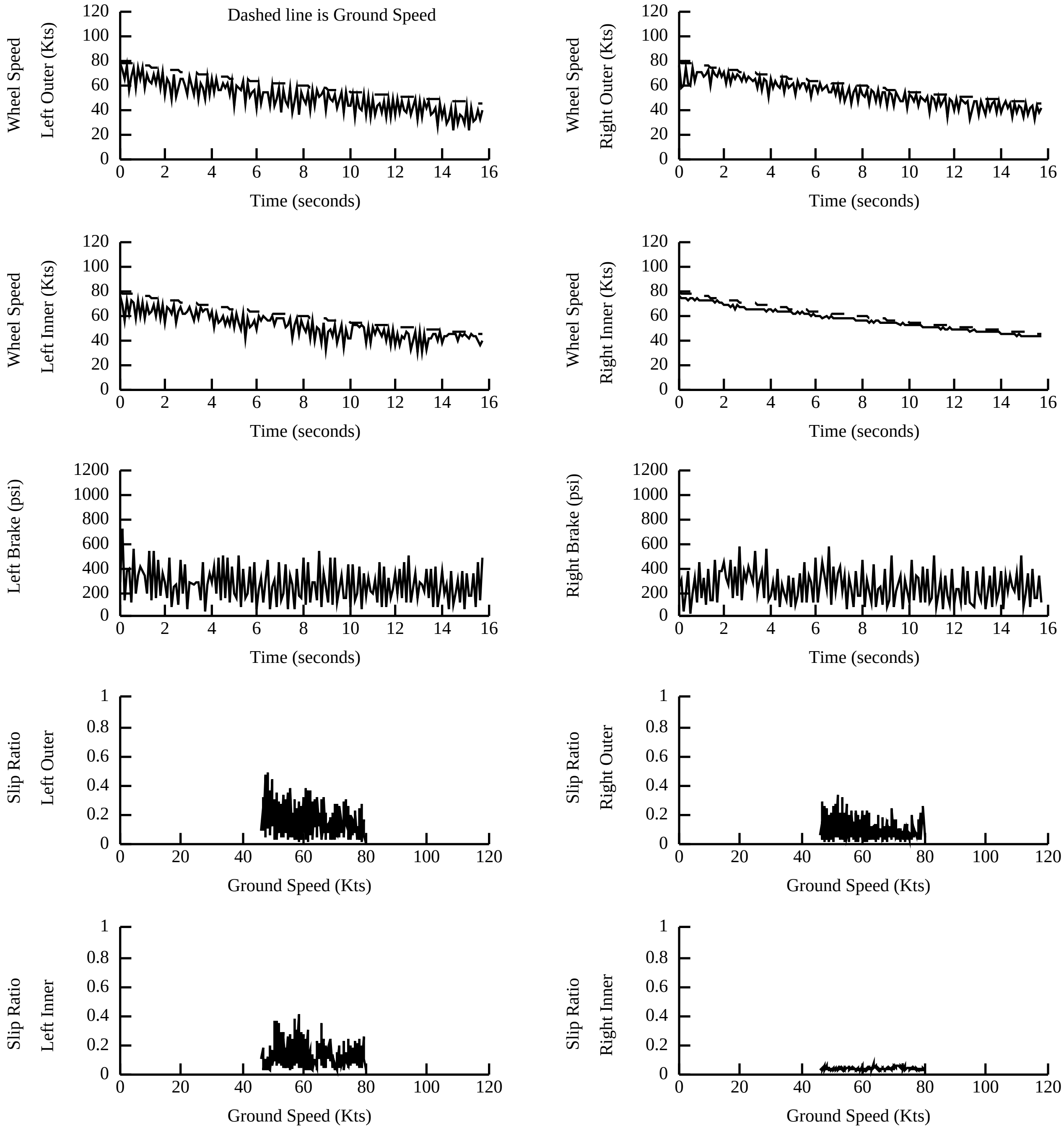


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.27

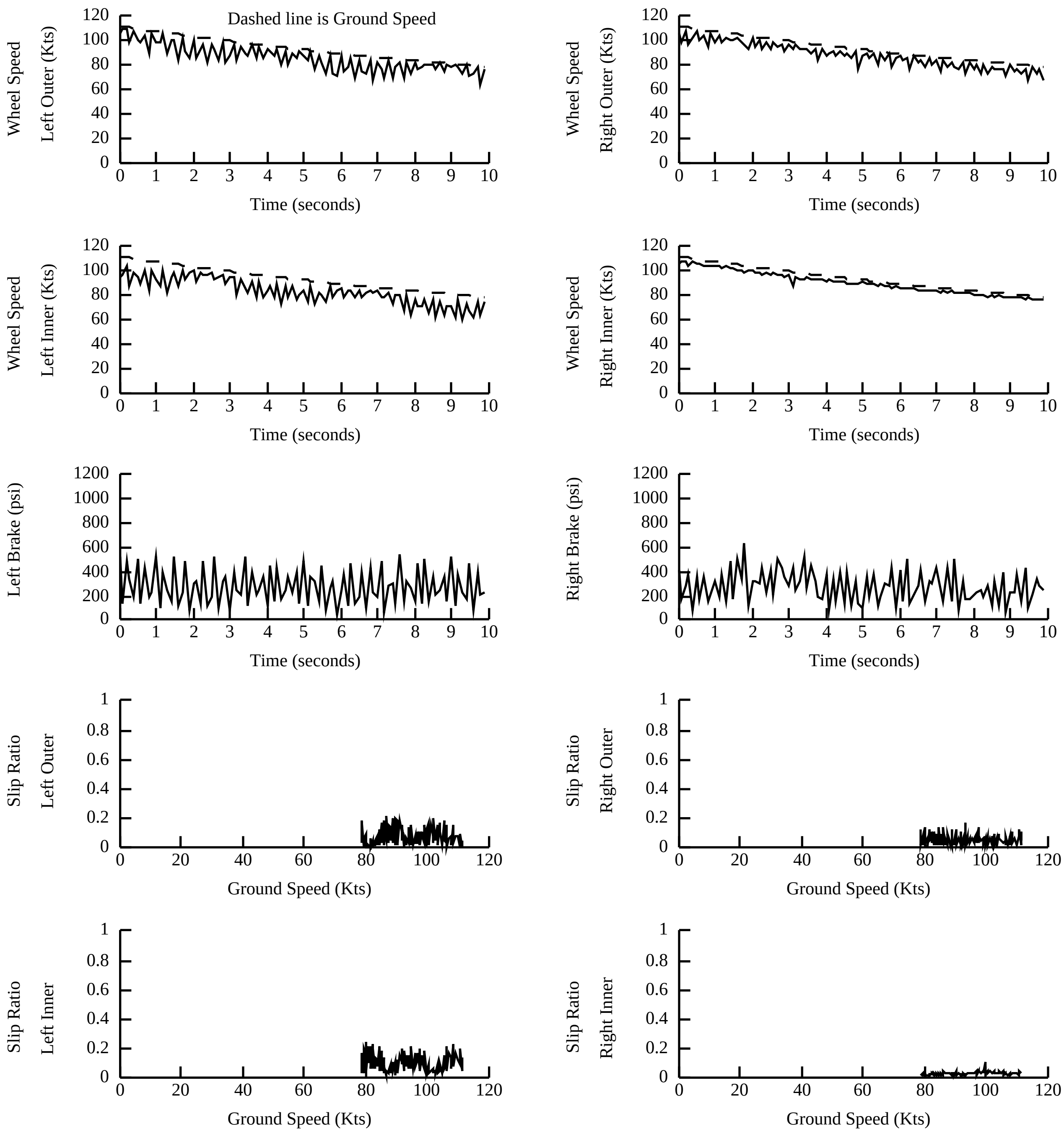


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.26

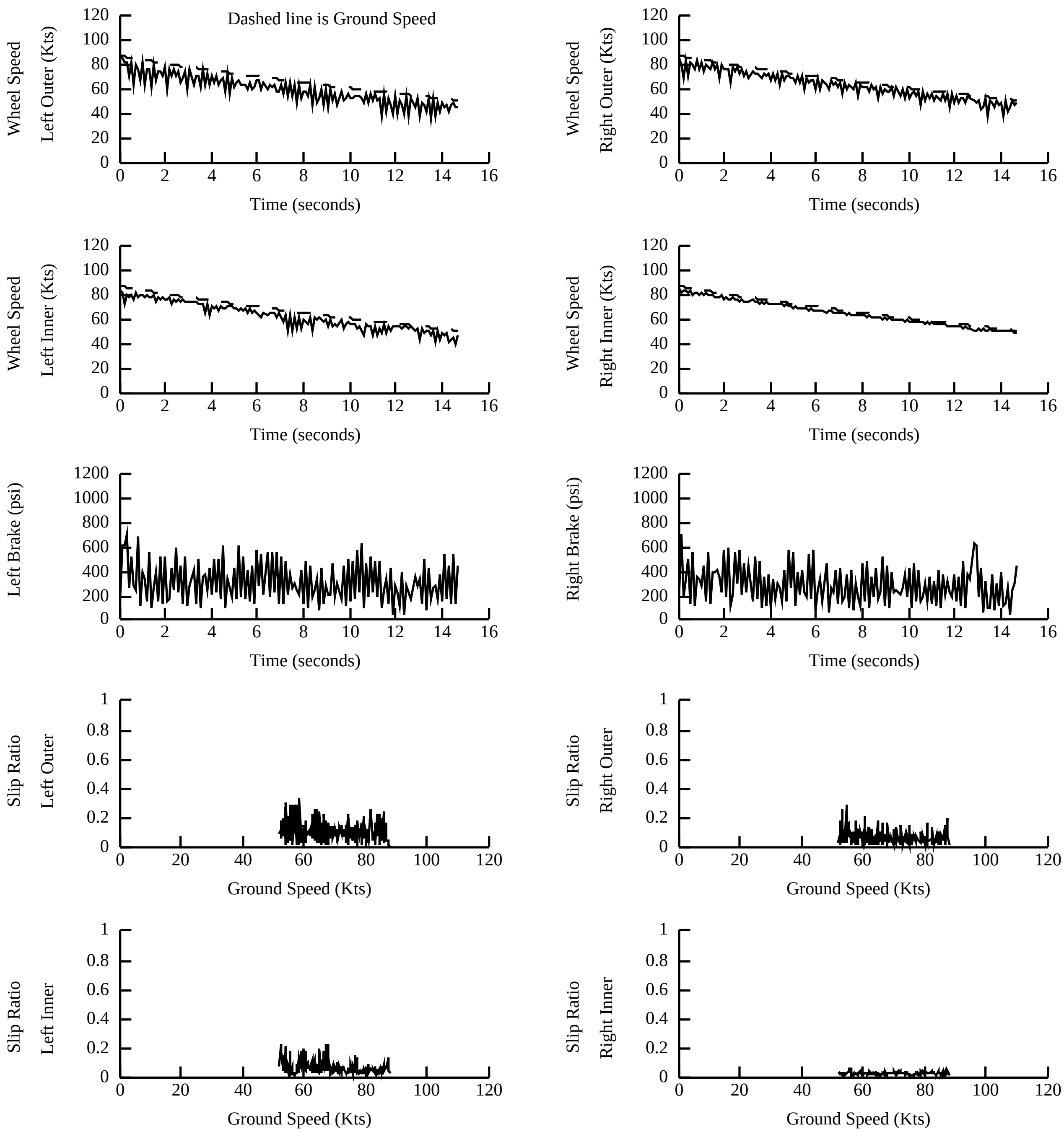


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.26

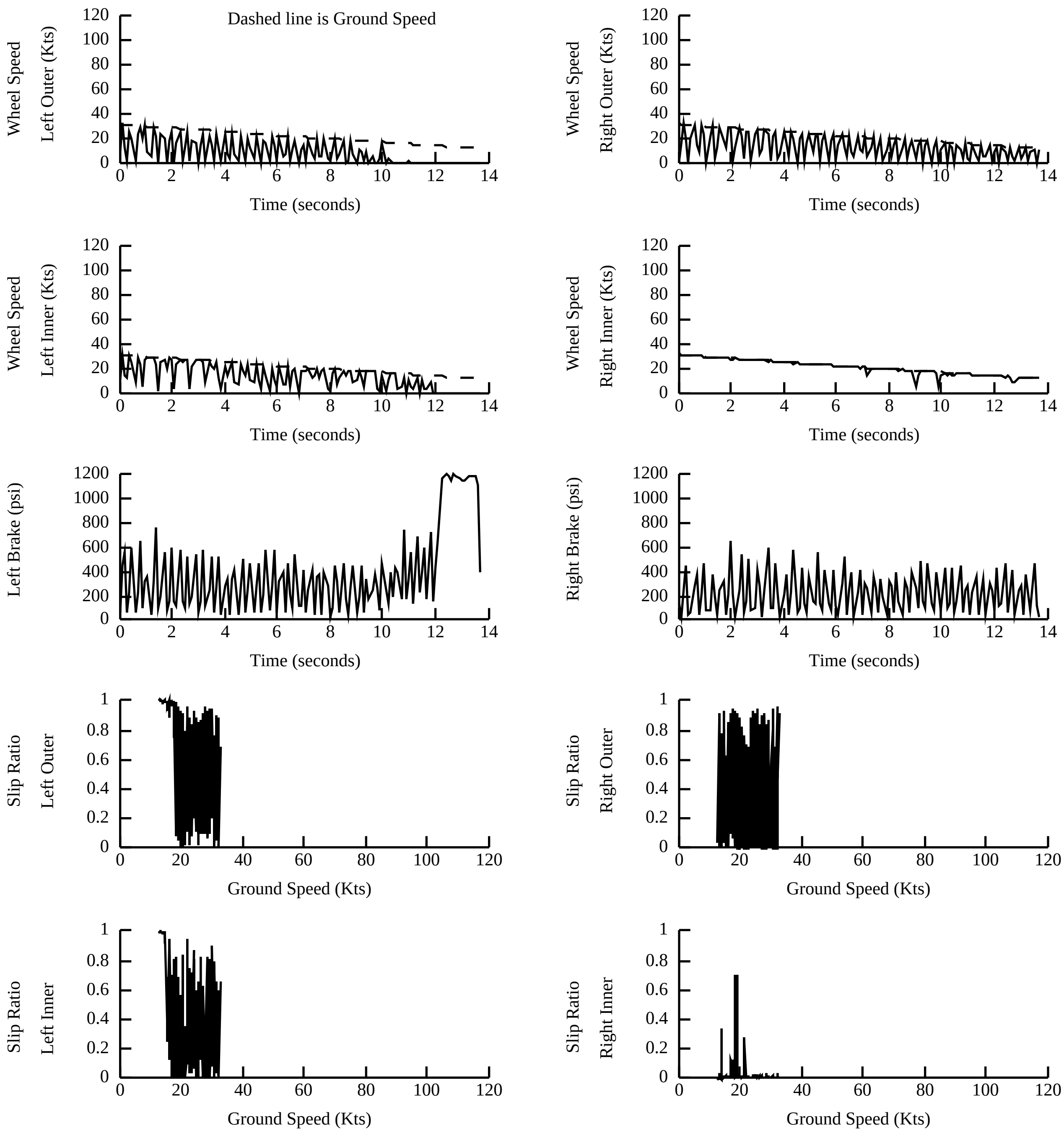


Surface: 100% Longitudinally Scarified Ice

Flight 2000/11, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.19

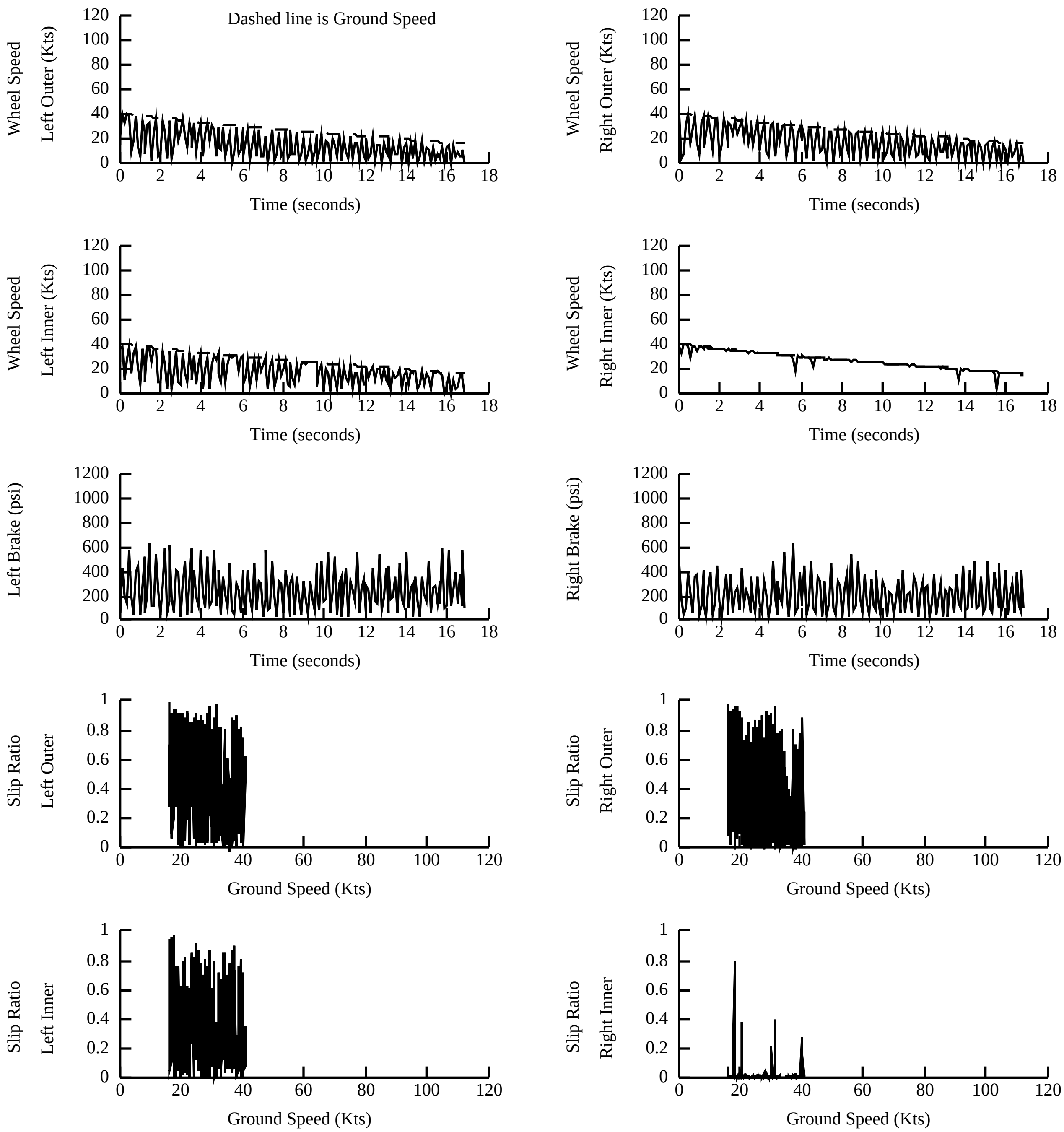


Surface: 100% Longitudinally Scarified Ice

Flight 2000/11, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.19

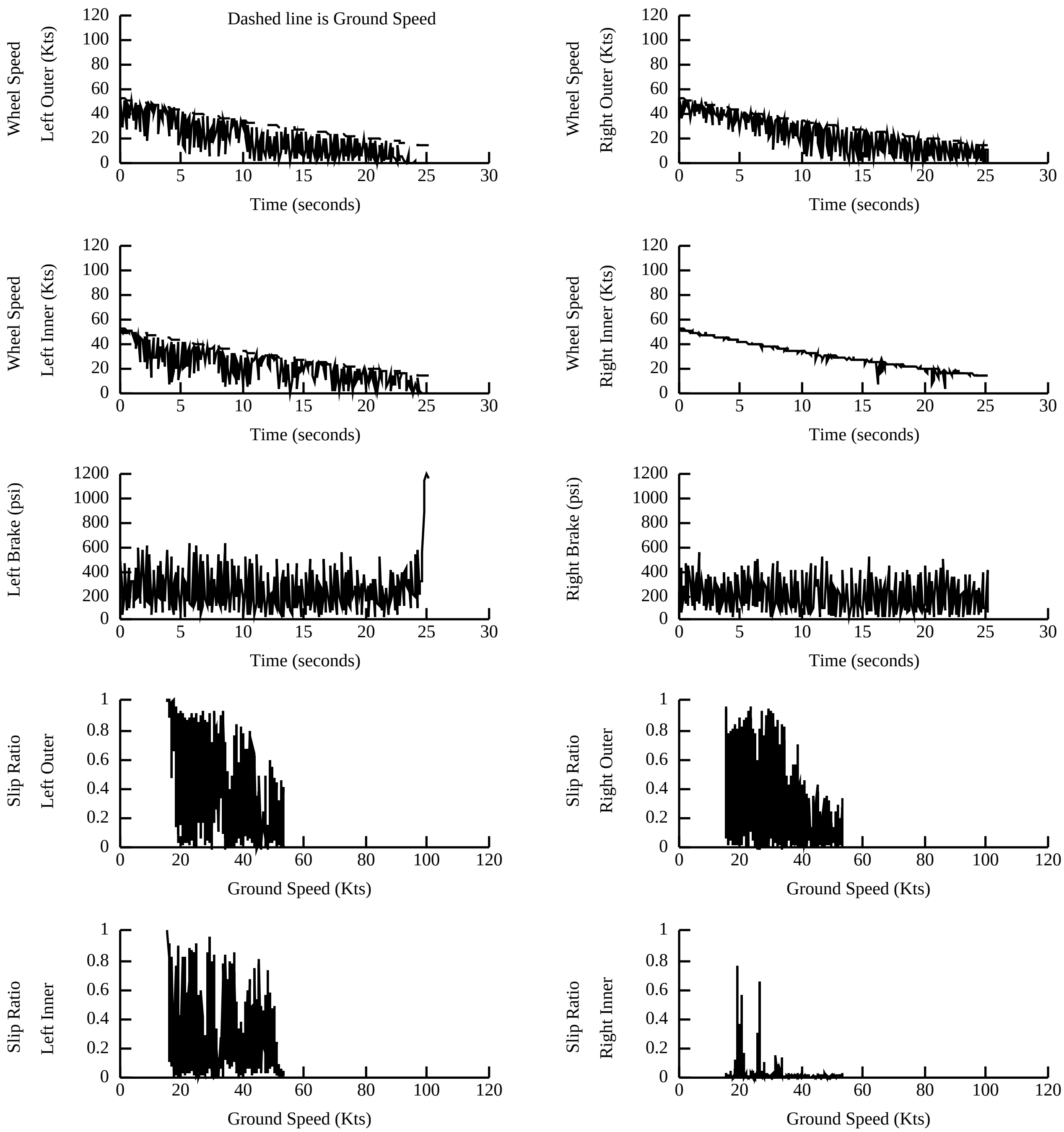


Surface: 100% Longitudinally Scarified Ice

Flight 2000/11, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.21

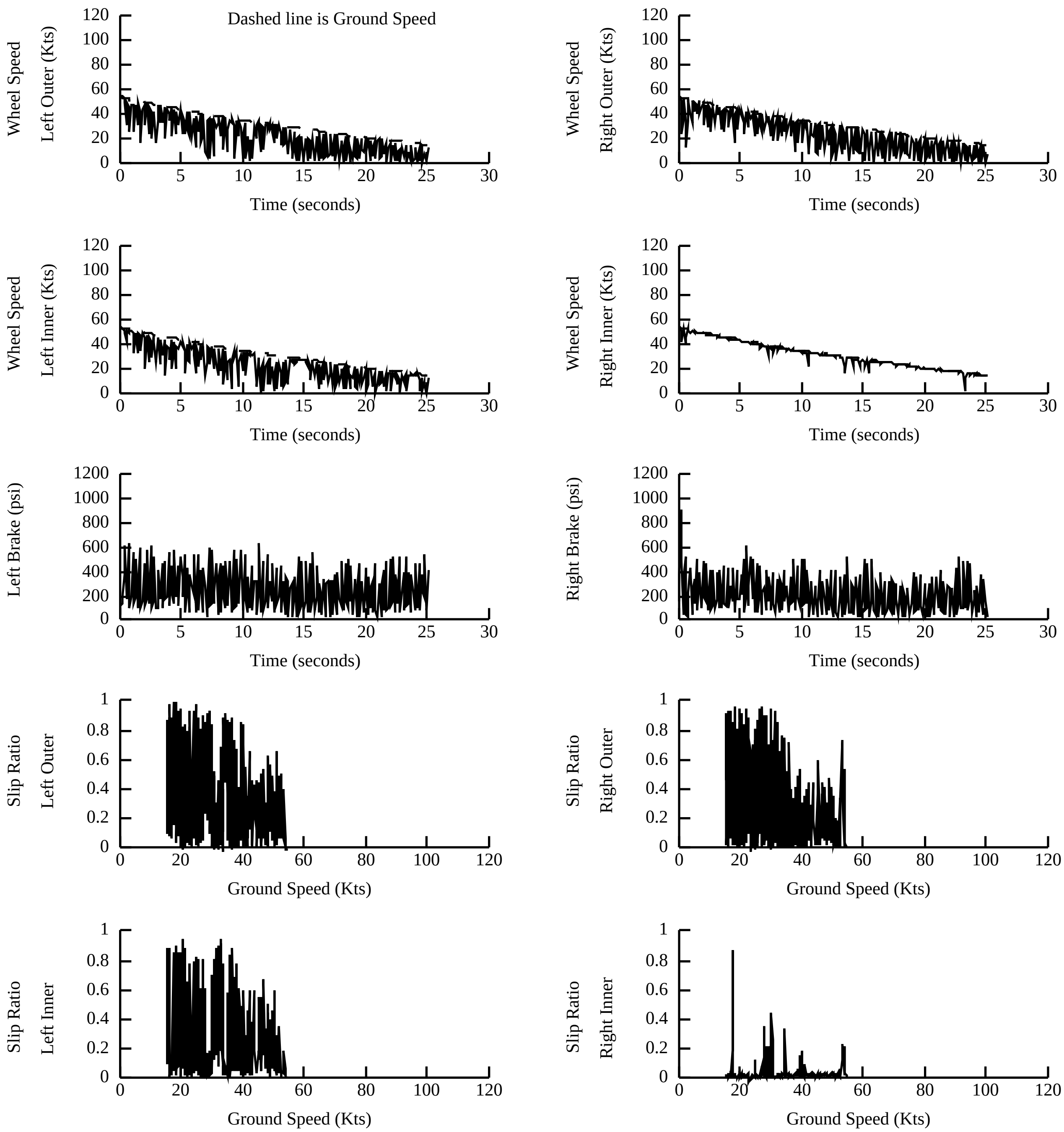


Surface: 100% Longitudinally Scarified Ice

Flight 2000/11, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21

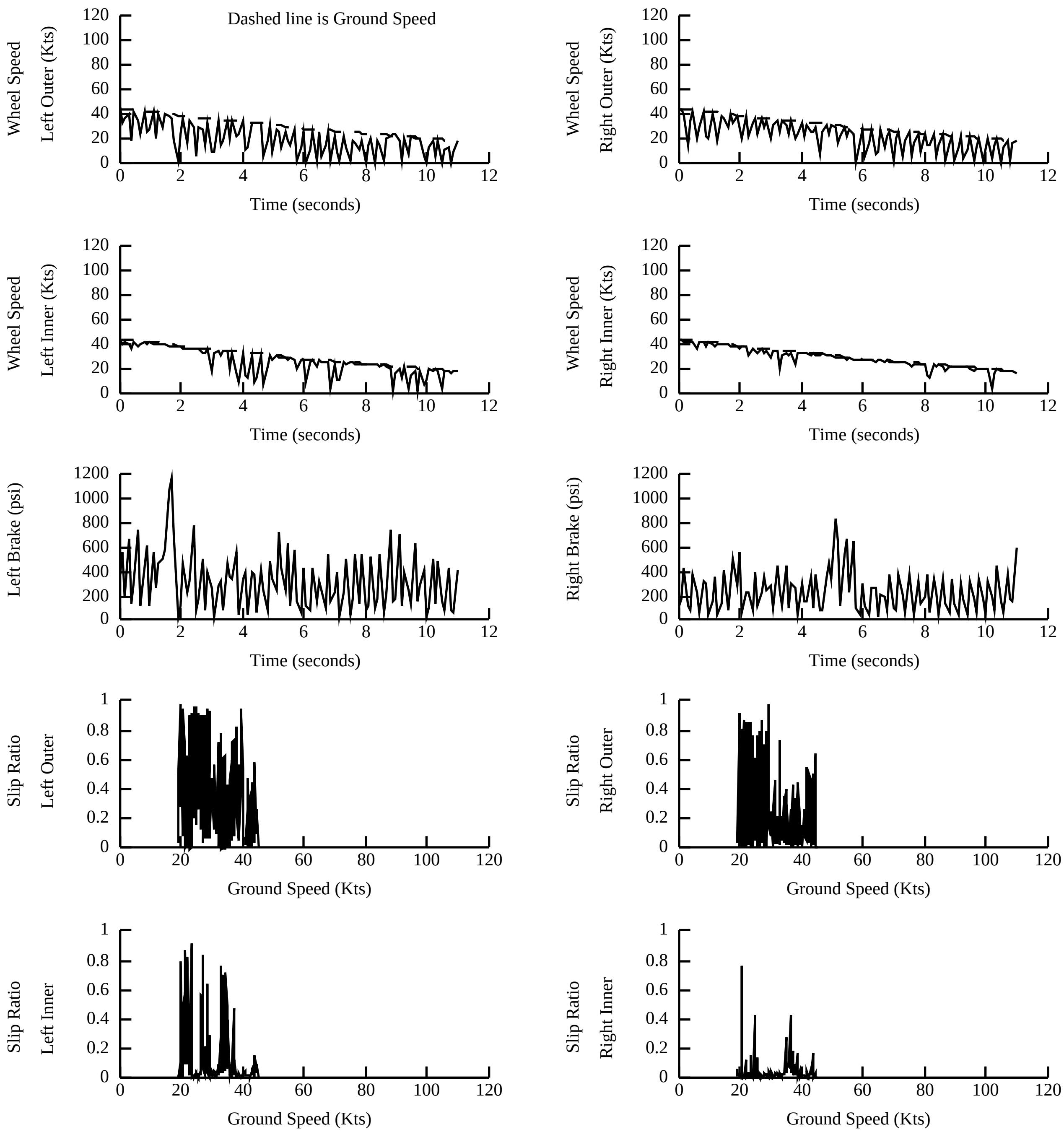


Surface: 90% Sanded Ice, 10% Bare and Dry

Flight 2000/12, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.26

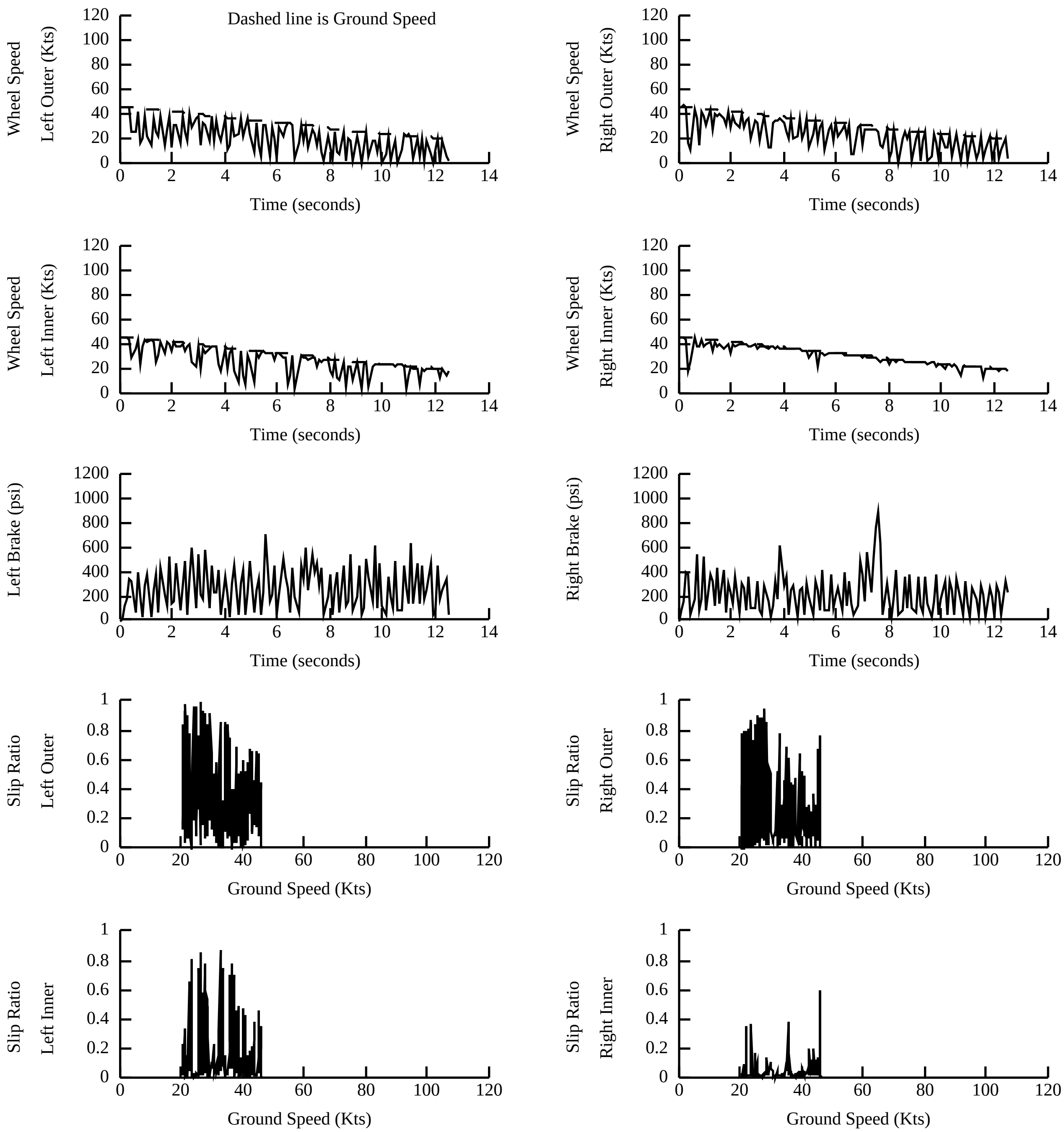


Surface: 90% Sanded Ice, 10% Bare and Dry

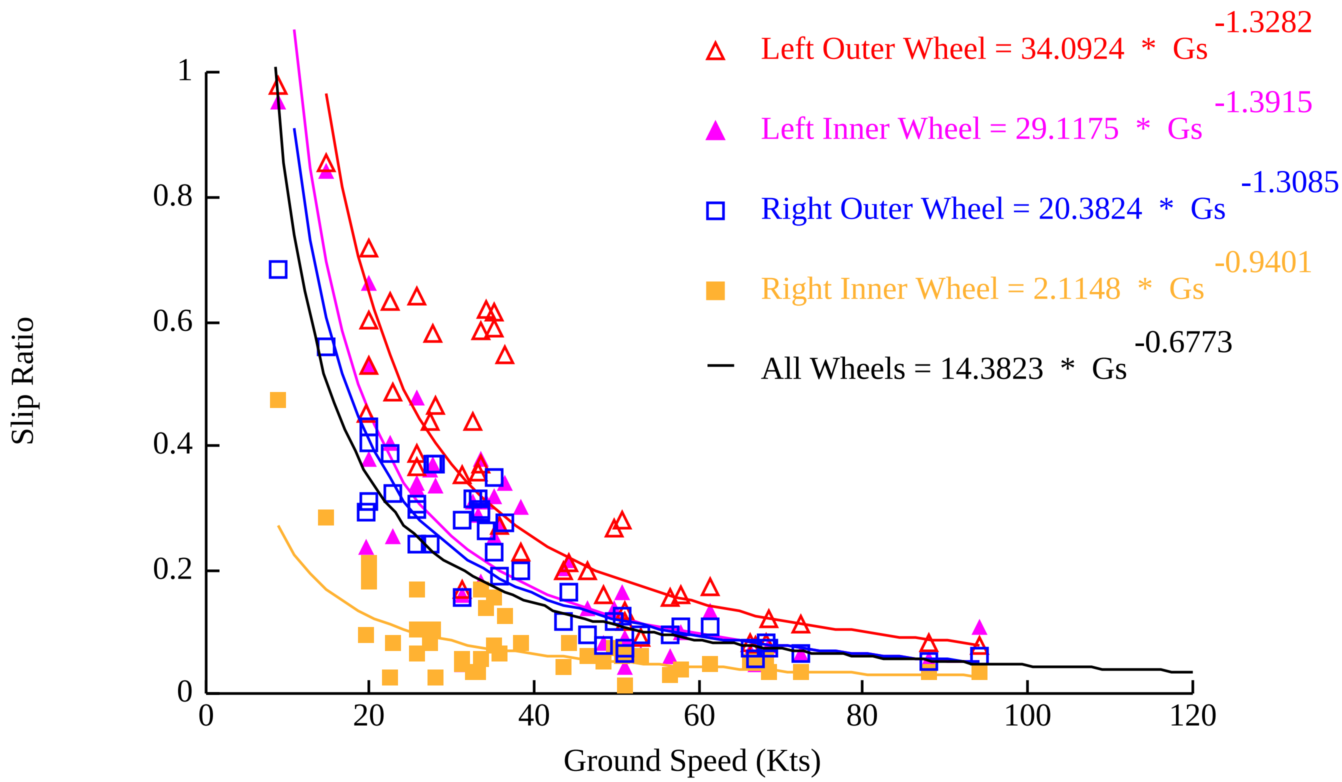
Flight 2000/12, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.26



Slip Ratio versus Ground Speed



APPENDIX D - TEST RUNS FOR AIRCRAFT BRAKING COEFFICIENT ON RUNWAY SURFACES WITH NO OR NEGLIGIBLE CONTAMINATION DRAG

The following table shows the test runs used to determine the aircraft braking coefficient ($_B$) on runway surfaces with no or negligible contamination drag. Pages D3 to D18 show the variation of $_B$ with ground speed for each run. The mean ground speed and mean $_B$ for each run are shown in the table and on Page D19 to D21 for each runway surface condition. Page D22 shows the mean $_B$ plotted against the mean CRFI value for each run, together with the results obtained from the 1996,1997,1998 and 1999 tests and the linear fit obtained from the 1996 and 1997 tests.

FLT	RUN	RWY	TAXI/ RTO/ LAND	CONFIG	WEIGHT (LB)	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN $_B$
2000/02 18/01/00	1 15:52	31TS	RTO	15/OUT/B	22590	0.18	0.36	20	0.112
	2 15:58	31TS	RTO	40/OUT/B	22340	0.18	0.36	23	0.103
	3 16:12	31TS	RTO	40/OUT/B	22090	0.17	0.36	26	0.098
	4 16:23	31TS	RTO	15/OUT/B	21790	0.17	0.36	36	0.109
	5 16:33	31TS	RTO	15/OUT/B	21690	0.16	0.33	39	0.128
	6 16:41	31TS	RTO	40/OUT/B	21440	0.16	0.34	44	0.104
2000/03 18/01/00	1 17:08	08	LAND	40/OUT/B	20590	0.75	0.80	66	0.436
2000/04 19/01/00	1 13:59	26TS	RTO	40/OUT/B	22990	0.28	0.26	51	0.131
	2 14:13	26TS	LAND	40/OUT/B	22490	0.28	0.26	72	0.162
	3 14:20	26TS	RTO	15/OUT/B	22090	0.28	0.26	48	0.159
	4 14:35	26TS	LAND	15/OUT/B	21690	0.31	0.27	88	0.197
	5 14:43	26TS	RTO	40/OUT/B	21340	0.31	0.29	57	0.145
2000/05 20/01/00	1 14:56	31TS	RTO	15/OUT/B	22290	0.13	0.25	9	0.081
	2 15:02	31TS	RTO	40/OUT/B	22140	0.13	0.24	15	0.082
	3 15:32	31TS	RTO	40/OUT/B	21590	0.13	0.23	20	0.084
	4 15:38	31TS	RTO	15/OUT/B	21390	0.13	0.24	28	0.081
	5 15:54	31TS	RTO	15/OUT/B	21190	0.12	0.24	35	0.087
	6 16:01	31TS	RTO	40/OUT/B	20890	0.12	0.25	34	0.080
2000/06 20/01/00	1 16:40	31TS	RTO	40/OUT/B	20390	0.73	0.87	51	0.383
	2 17:02	08	LAND	15/OUT/B	19240	0.73	0.87	67	0.413

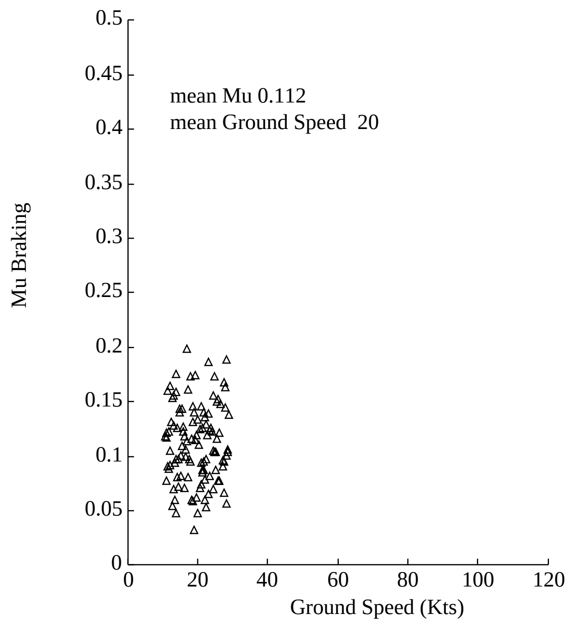
FLT	RUN	RWY	TAXI/ RTO/ LAND	CONFIG	WEIGHT (LB)	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN B
2000/07 21/01/00	1 8:26	31TS	RTO	15/0UT/B	22590	0.10	0.31	20	0.095
	2 8:32	31TS	RTO	40/0UT/B	22390	0.10	0.31	20	0.091
	3 8:43	31TS	RTO	40/0UT/B	22190	0.11	0.31	26	0.084
	4 8:50	31TS	RTO	15/0UT/B	22040	0.11	0.30	34	0.087
	5 9:00	31TS	RTO	15/0UT/B	21790	0.09	0.29	36	0.086
	6 9:08	31TS	RTO	40/0UT/B	21640	0.09	0.28	35	0.077
2000/08 21/01/00	1 13:15	31TS	RTO	15/OUT/B	21090	0.20	0.36	26	0.136
	2 13:21	31TS	RTO	40/OUT/B	20990	0.20	0.36	27	0.123
	3 13:48	31TS	RTO	40/OUT/B	20640	0.22	0.35	44	0.163
	4 13:55	31TS	RTO	15/OUT/B	20340	0.22	0.35	47	0.155
	5 14:10	31TS	RTO	40/OUT/B	20140	0.21	0.36	50	0.151
	6 14:16	31TS	RTO	40/OUT/B	19990	0.21	0.36	51	0.134
2000/09 24/01/00	1 12:12	26TS	RTO	15/OUT/B	22400	0.42	0.64	31	0.292
	2 12:20	26TS	RTO	40/OUT/B	22150	0.61	0.63	53	0.364
	3 12:40	26TS	LAND	40/OUT/B	21400	0.66	0.61	68	0.401
2000/10 25/01/00	3 12:56	26TS	RTO	15/OUT/B	21980	0.27	0.26	58	0.153
	4 1:04	26TS	RTO	40/OUT/B	21630	0.27	0.27	61	0.147
	5 1:33	26TS	LAND	40/OUT/B	20780	0.26	0.30	94	0.174
	6 1:43	26TS	RTO	15/OUT/B	20580	0.26	0.31	69	0.169
2000/11 27/01/00	1 11:24	31	RTO	15/OUT/B	22340	0.19	0.30	23	0.126
	2 11:30	31	RTO	40/OUT/B	22190	0.19	0.30	28	0.125
	3 11:36	31	RTO	40/OUT/B	22040	0.21	0.29	32	0.127
	4 11:44	31	RTO	15/OUT/B	21840	0.21	0.29	33	0.130
2000/12 27/01/00	2 12:51	36	RTO	40/OUT/B	20340	0.26	0.34	31	0.155
	3 12:55	36	RTO	40/OUT/B	20190	0.26	0.34	34	0.140

Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

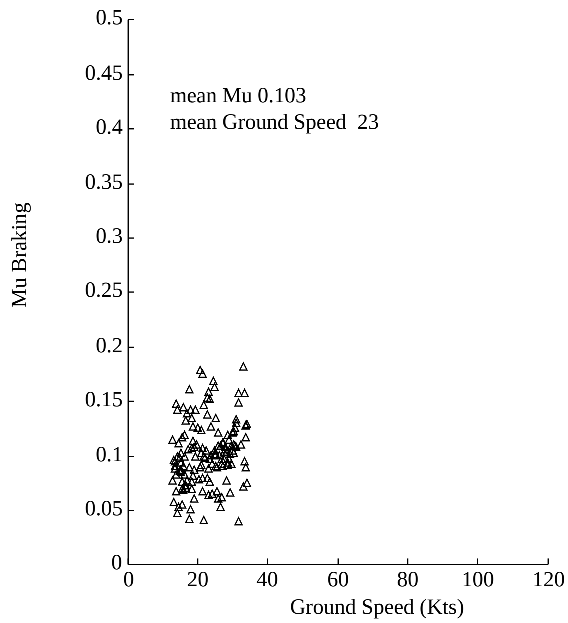
CRFI Average 0.18



Flight 2000/02, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

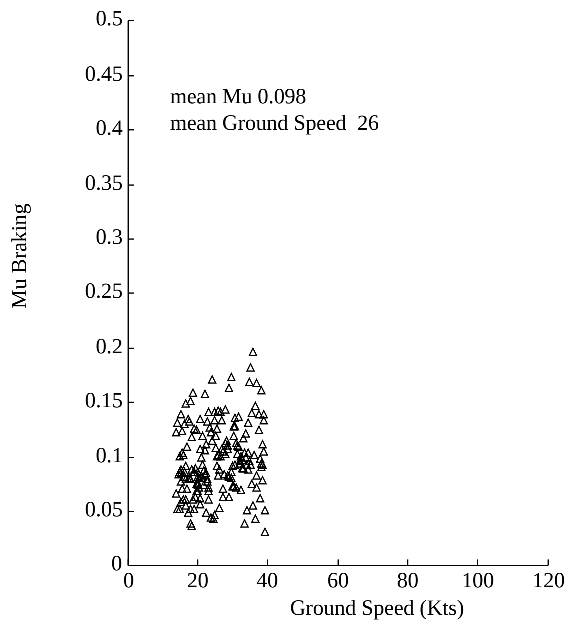
CRFI Average 0.18



Flight 2000/02, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

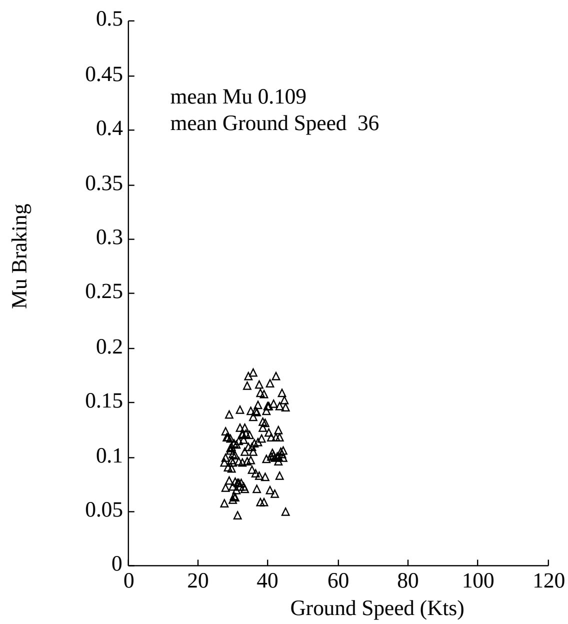
CRFI Average 0.17



Flight 2000/02, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.17

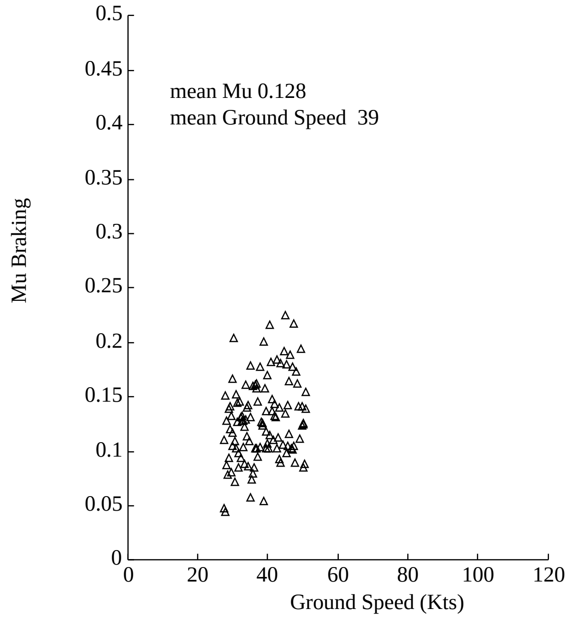


Surface: 60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

Flight 2000/02, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

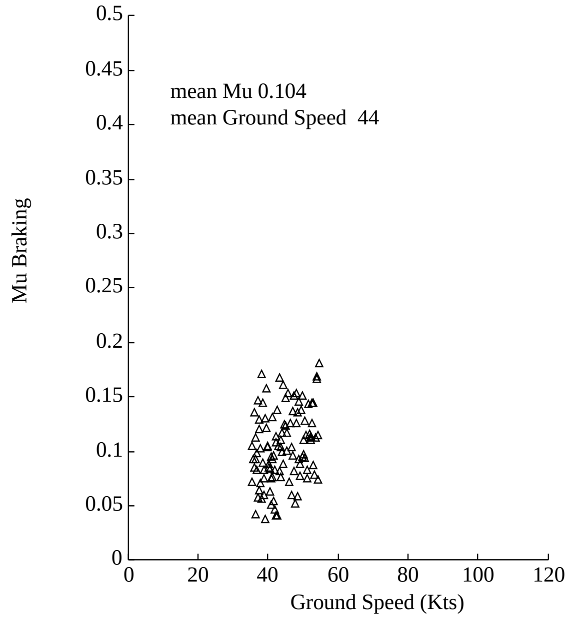
CRFI Average 0.16



Flight 2000/02, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.16

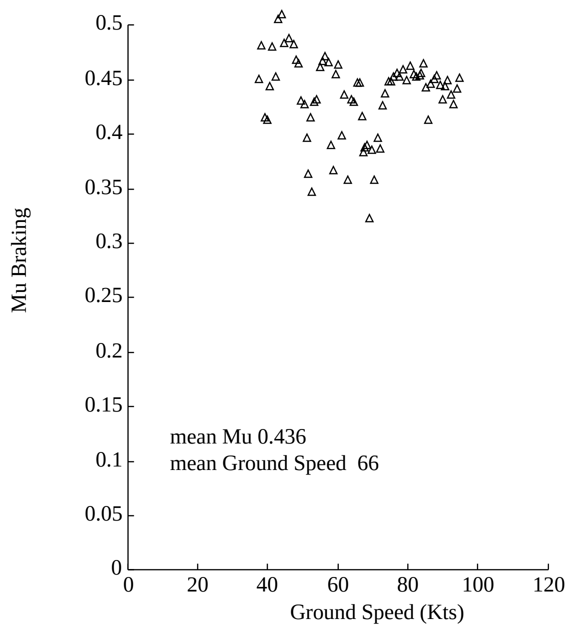


Surface: 100% Bare and Dry, Occasional Ice Patches

Flight 2000/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.75

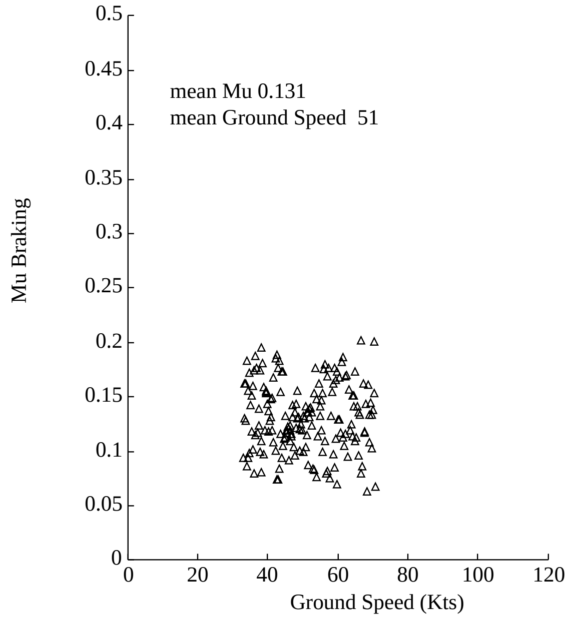


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow
Sg of snow 0.08

Flight 2000/04, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

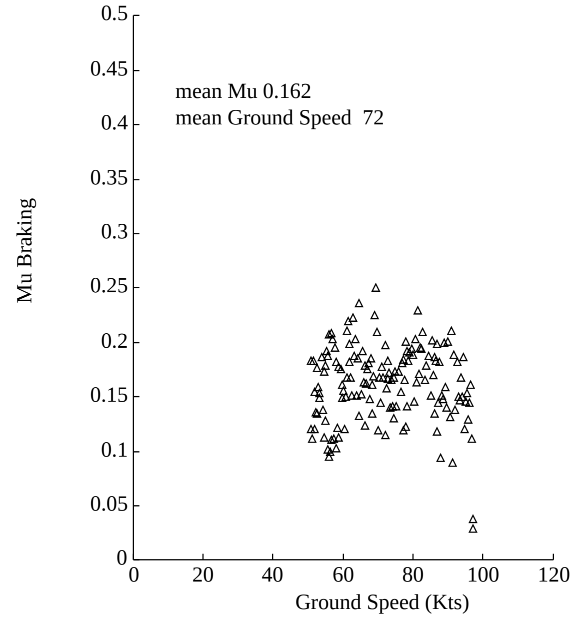
CRFI Average 0.28



Flight 2000/04, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

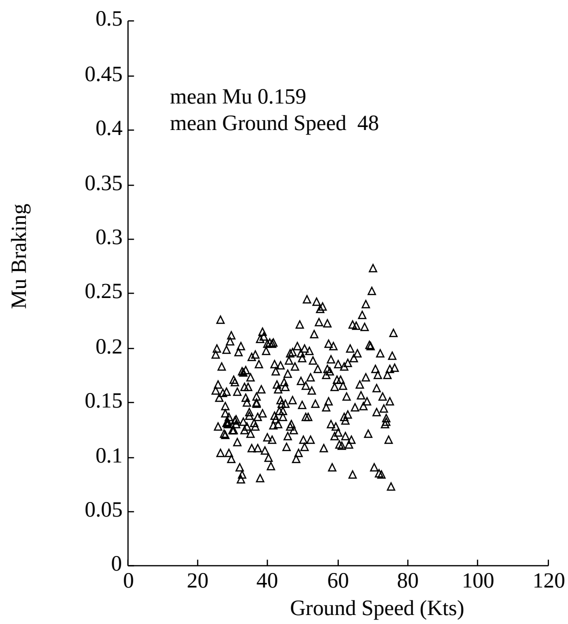
CRFI Average 0.28



Flight 2000/04, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

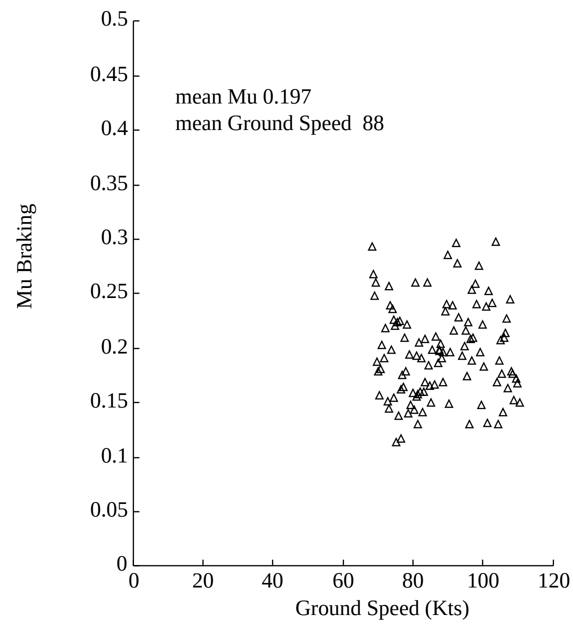
CRFI Average 0.28



Flight 2000/04, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.31

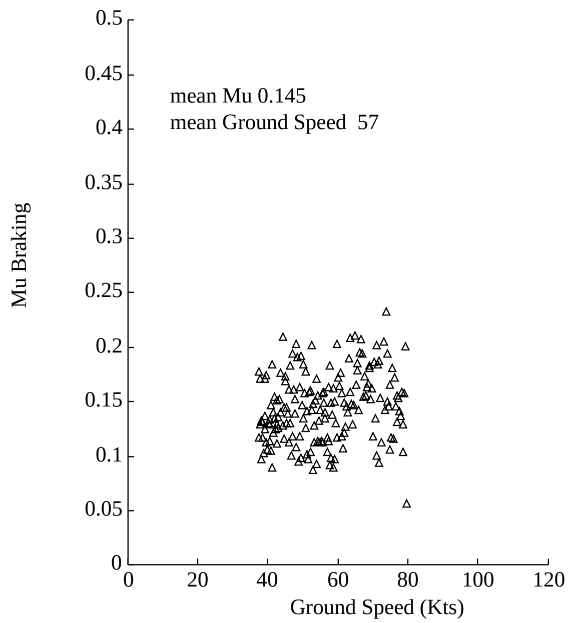


Surface: 100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow
Sg of snow 0.08

Flight 2000/04, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.31

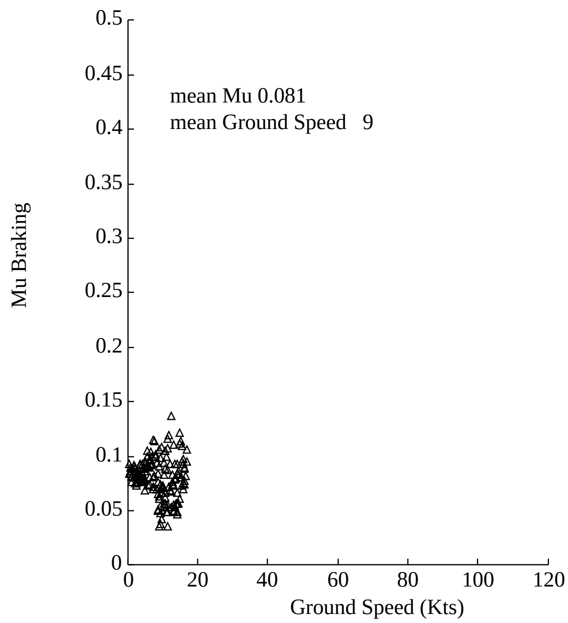


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

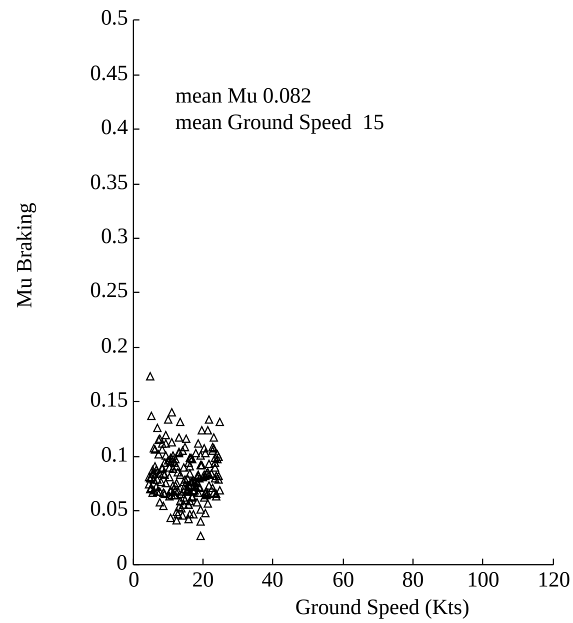
CRFI Average 0.13



Flight 2000/05, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

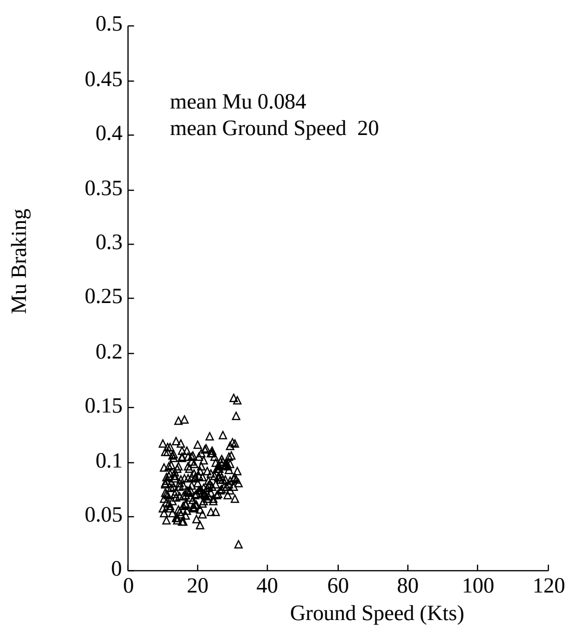
CRFI Average 0.13



Flight 2000/05, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

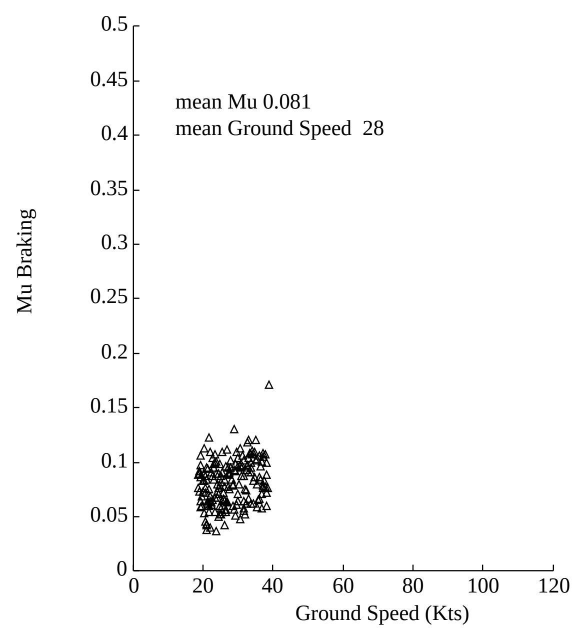
CRFI Average 0.13



Flight 2000/05, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.13

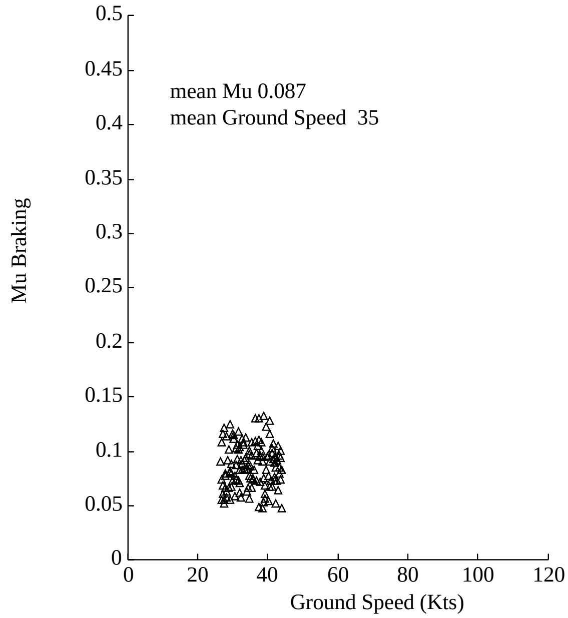


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/05, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

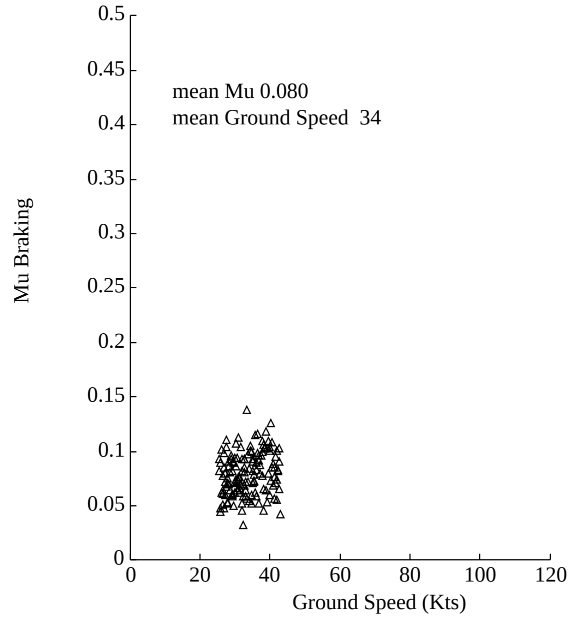
CRFI Average 0.12



Flight 2000/05, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.12

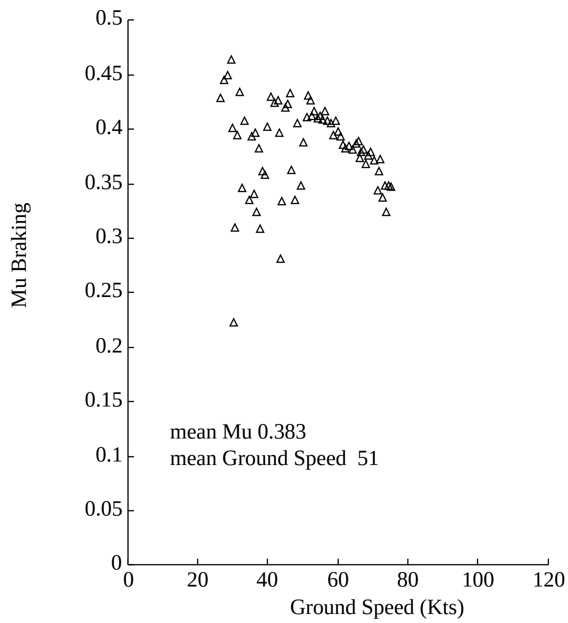


Surface: 100% Bare and Dry, With Occasional Ice Patches

Flight 2000/06, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

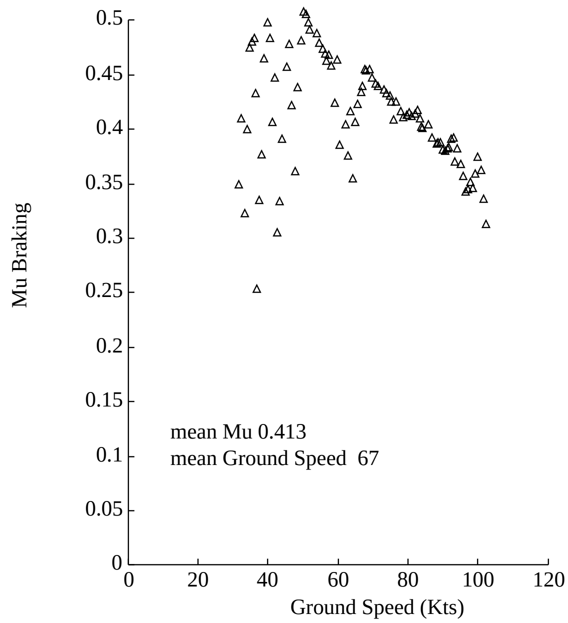
CRFI Average 0.73



Flight 2000/06, Run Number 2

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.73

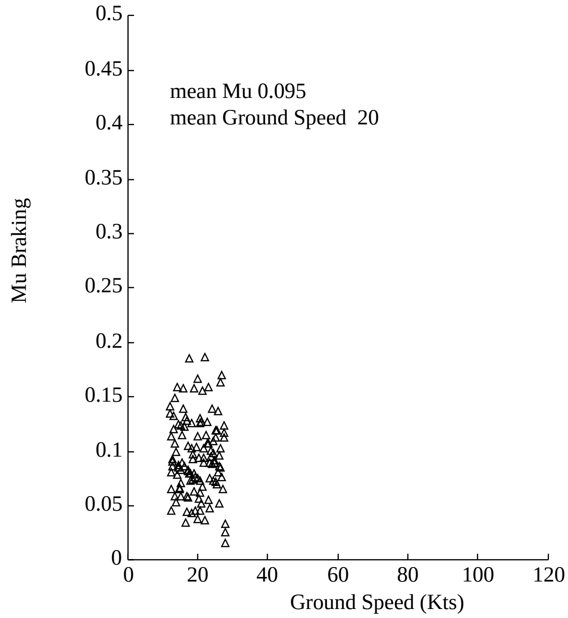


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

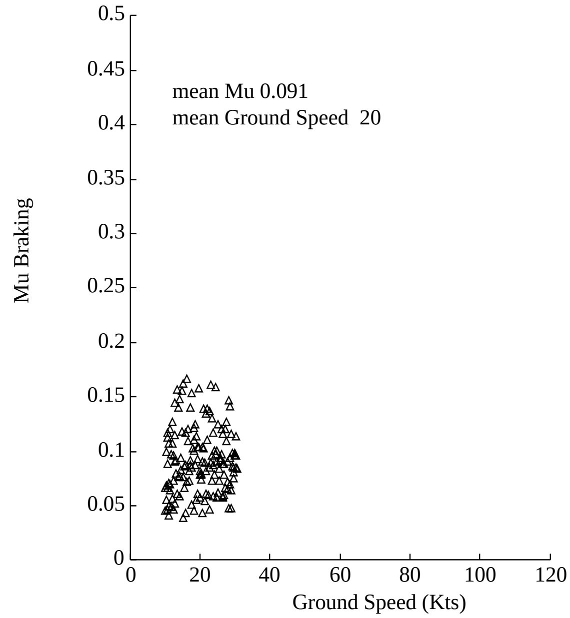
CRFI Average 0.10



Flight 2000/07, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

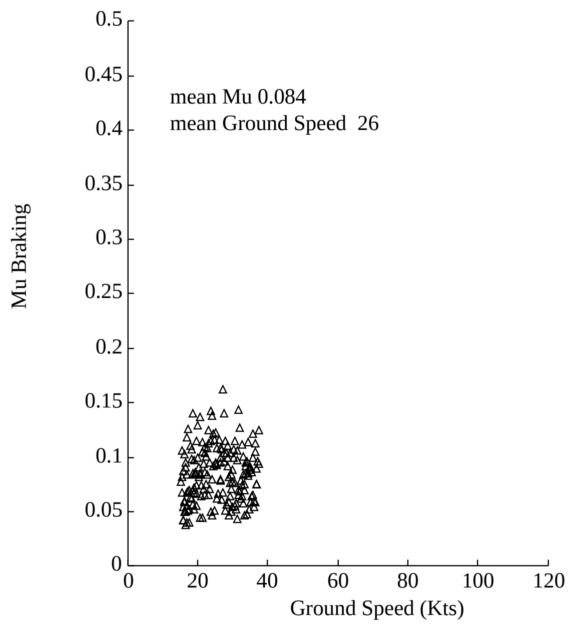
CRFI Average 0.10



Flight 2000/07, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

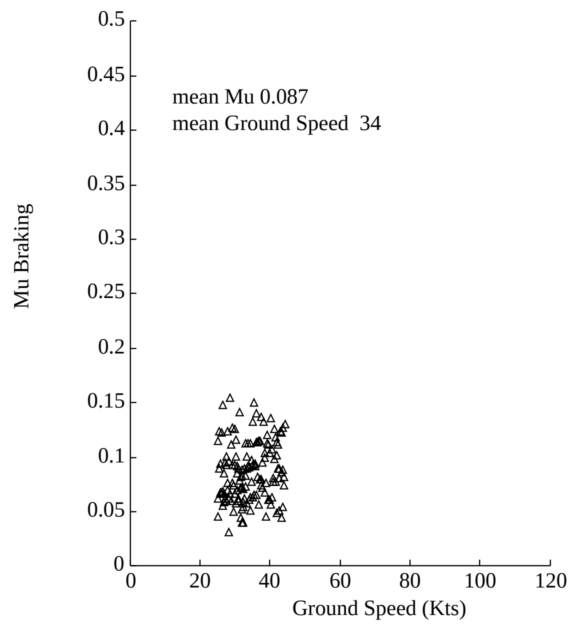
CRFI Average 0.11



Flight 2000/07, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.11

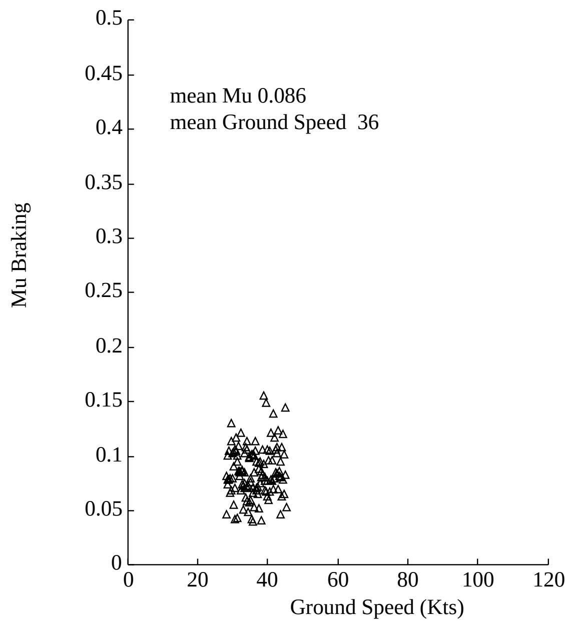


Surface: 100% Ice With Occasional Bare Spots

Flight 2000/07, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

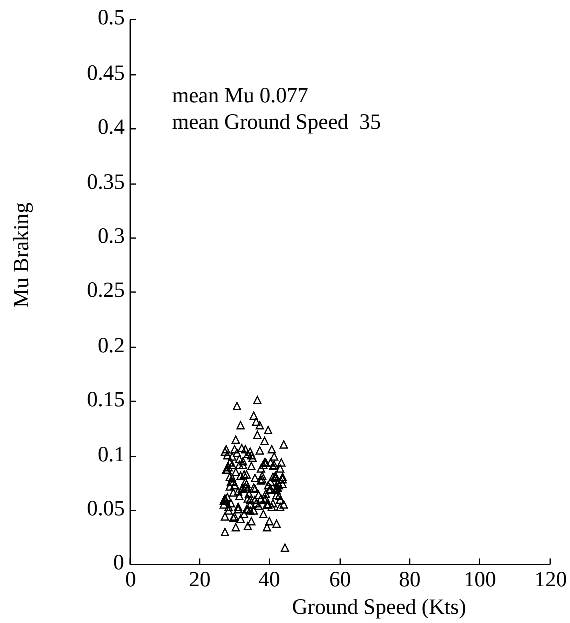
CRFI Average 0.09



Flight 2000/07, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.09

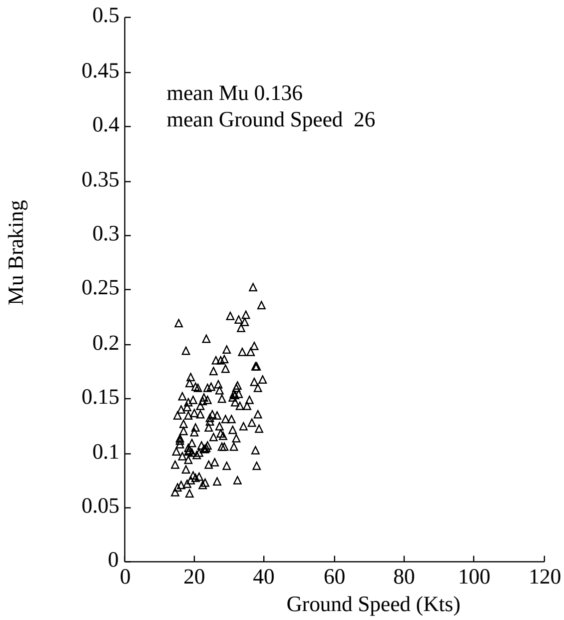


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

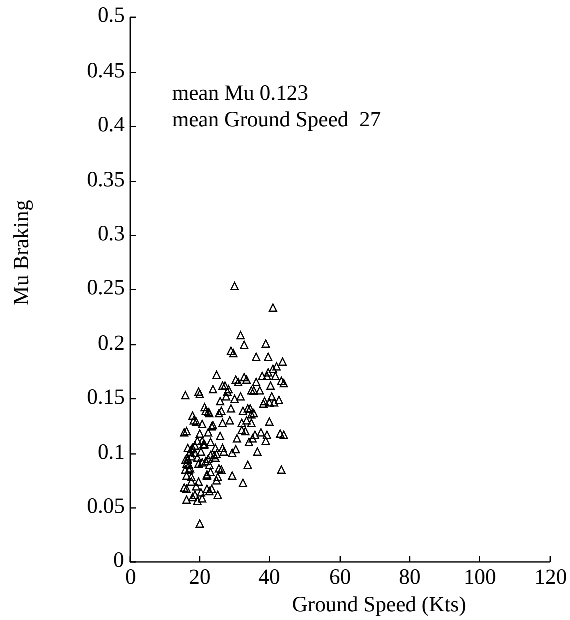
CRFI Average 0.20



Flight 2000/08, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

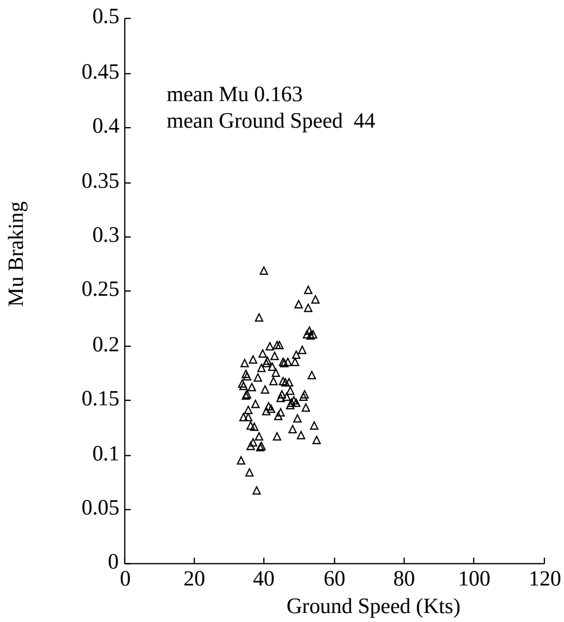
CRFI Average 0.20



Flight 2000/08, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

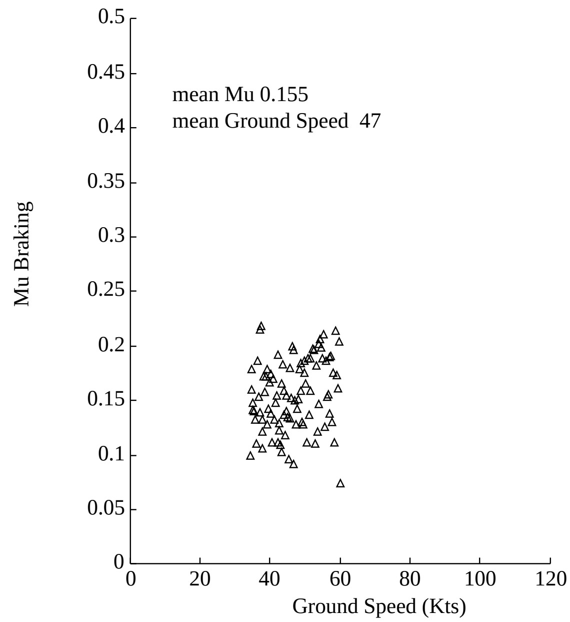
CRFI Average 0.22



Flight 2000/08, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.22

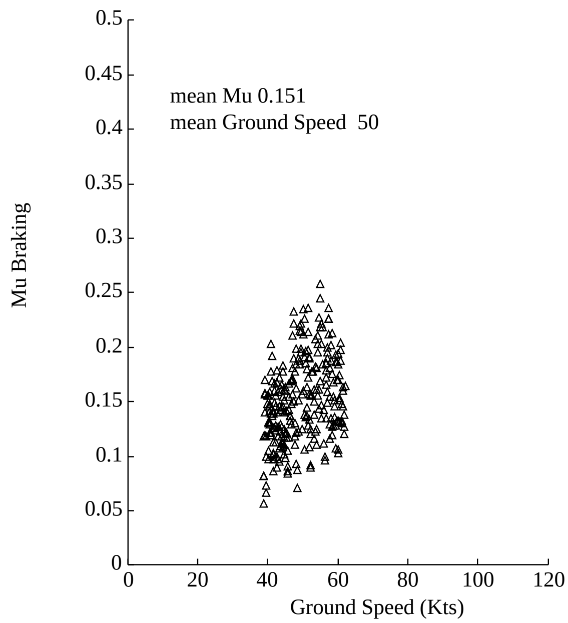


Surface: 100 Ice With Sand Application and Occasional Bare Spots

Flight 2000/08, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

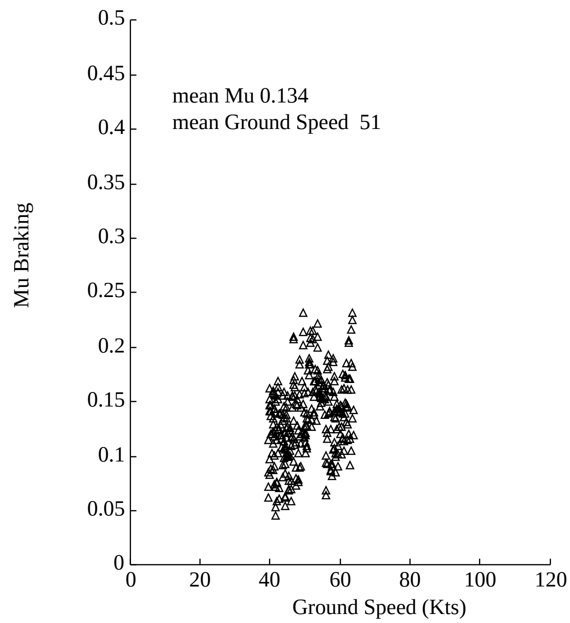
CRFI Average 0.21



Flight 2000/08, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.21

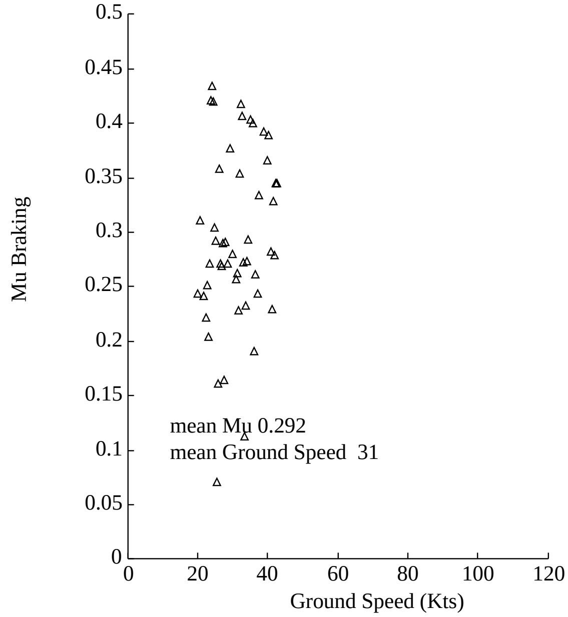


Surface: 70% Bare And Dry, 30% Light Dusting of Snow

Flight 2000/09, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

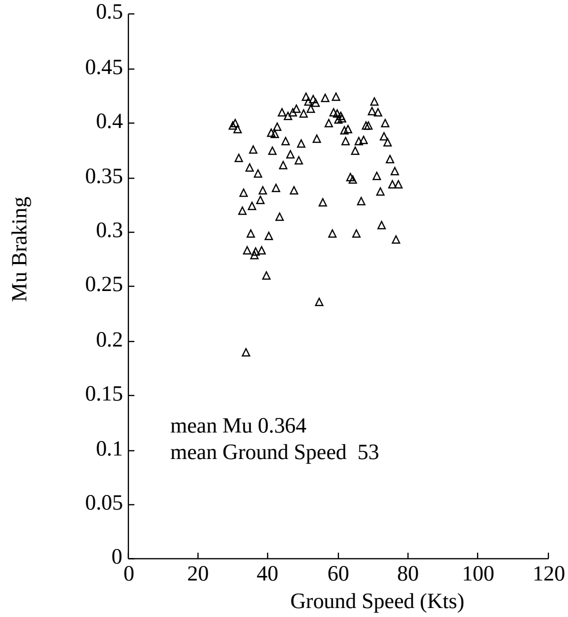
CRFI Average 0.42



Flight 2000/09, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

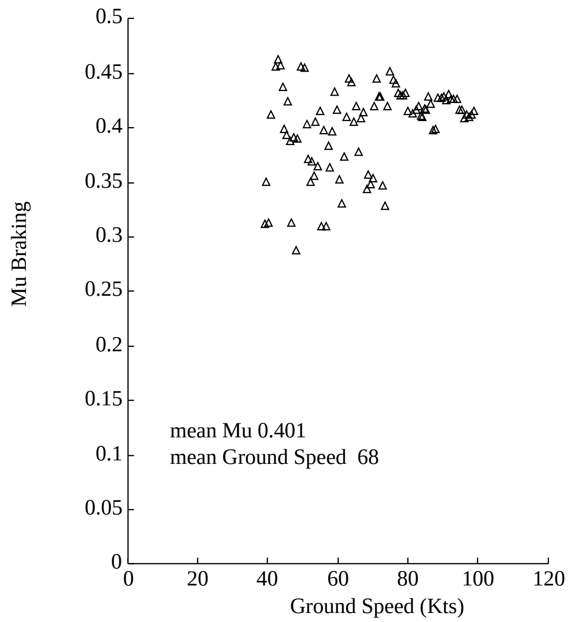
CRFI Average 0.61



Flight 2000/09, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.66

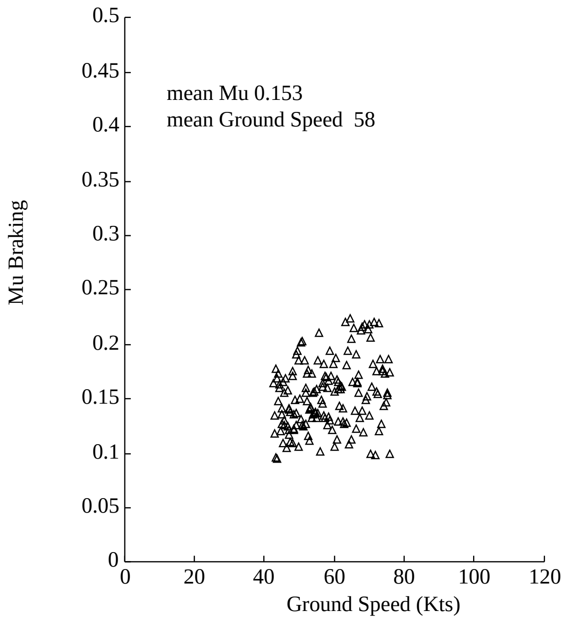


Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

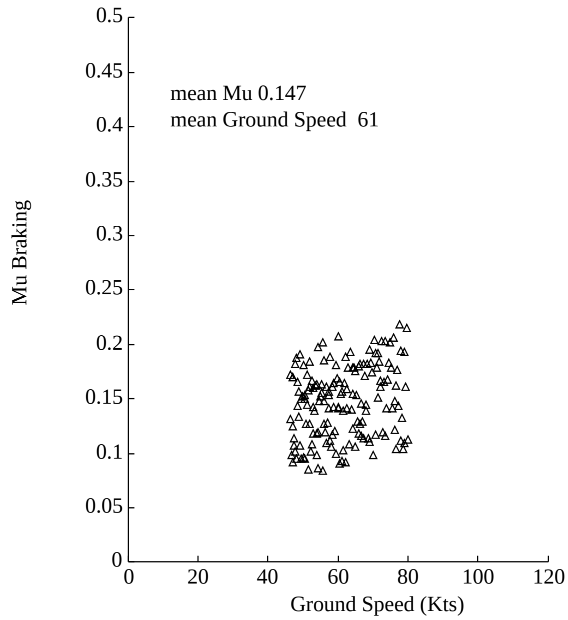
CRFI Average 0.27



Flight 2000/10, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

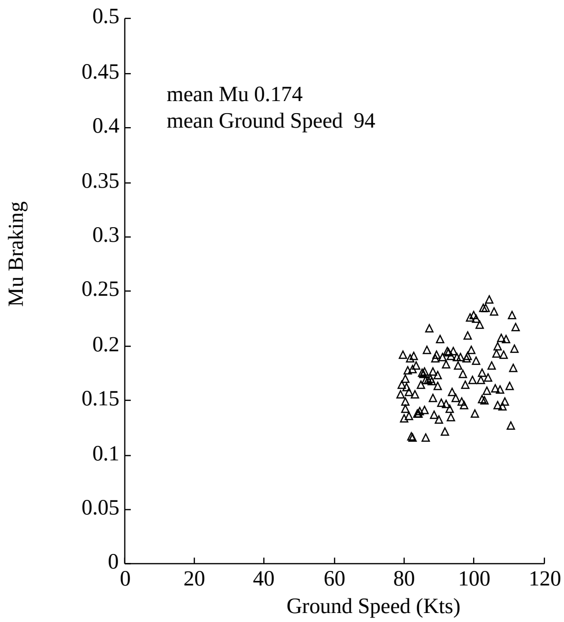
CRFI Average 0.27



Flight 2000/10, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

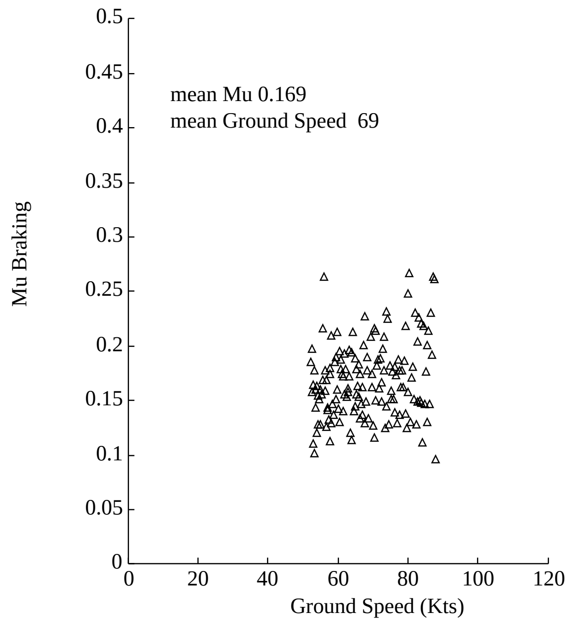
CRFI Average 0.26



Flight 2000/10, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.26

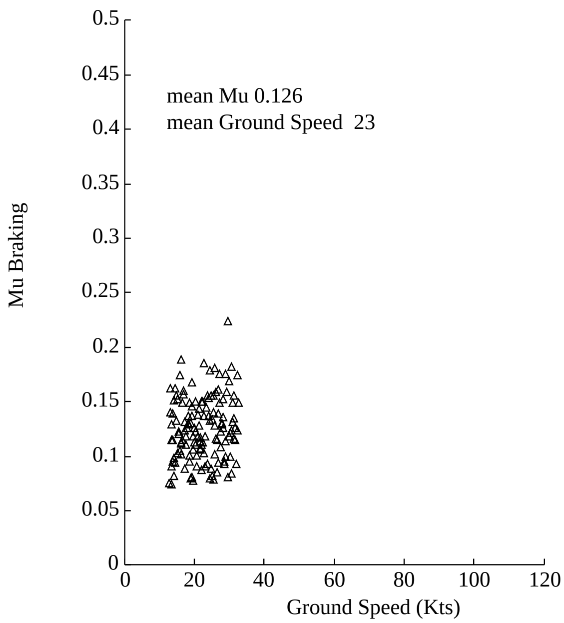


Surface: 100% Longitudinally Scarified Ice

Flight 2000/11, Run Number 1

Configuration: Flaps 15, Air Brakes Out, Max Braking

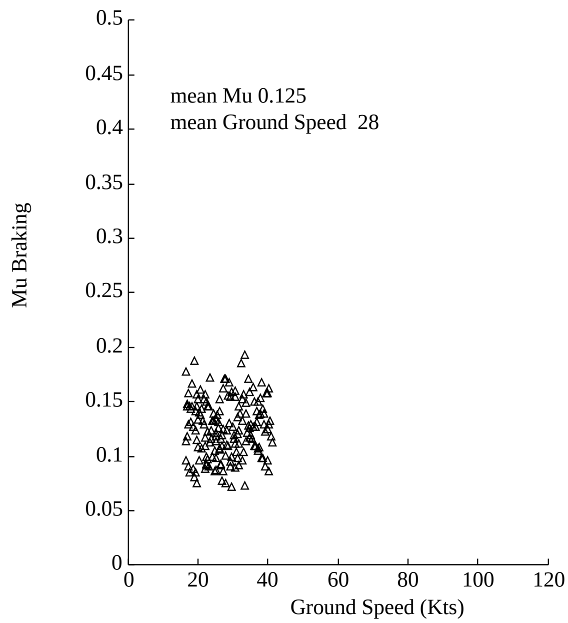
CRFI Average 0.19



Flight 2000/11, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

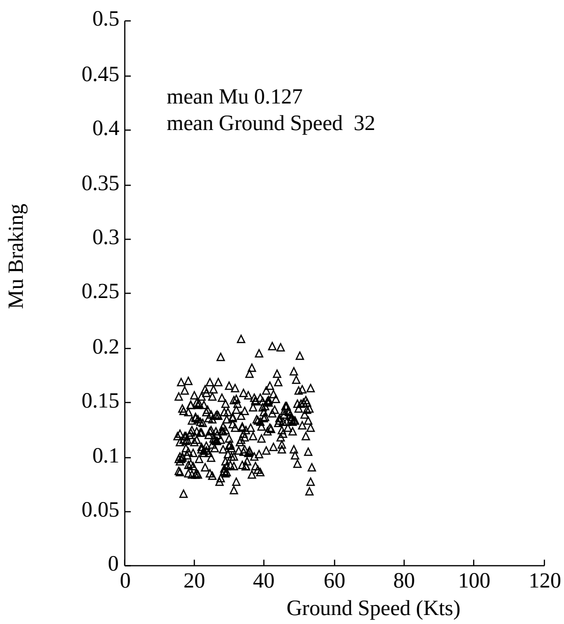
CRFI Average 0.19



Flight 2000/11, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

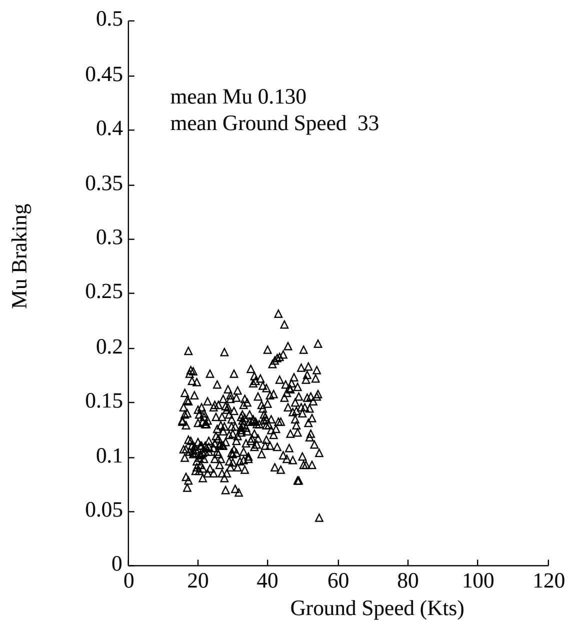
CRFI Average 0.21



Flight 2000/11, Run Number 4

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21

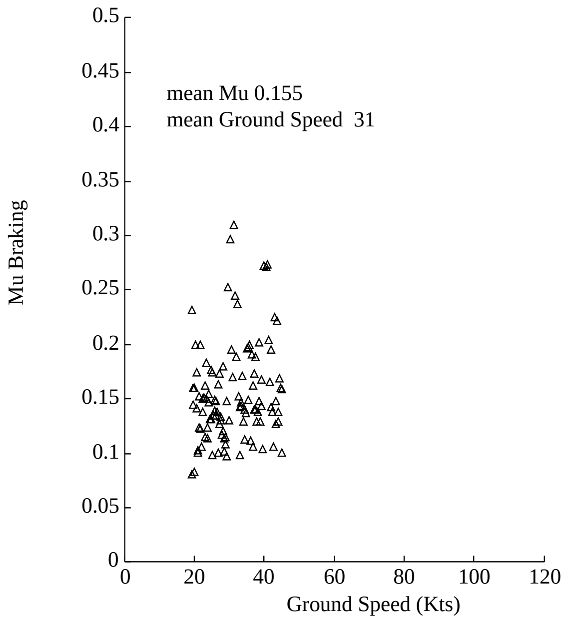


Surface: 90% Sanded Ice, 10% Bare and Dry

Flight 2000/12, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

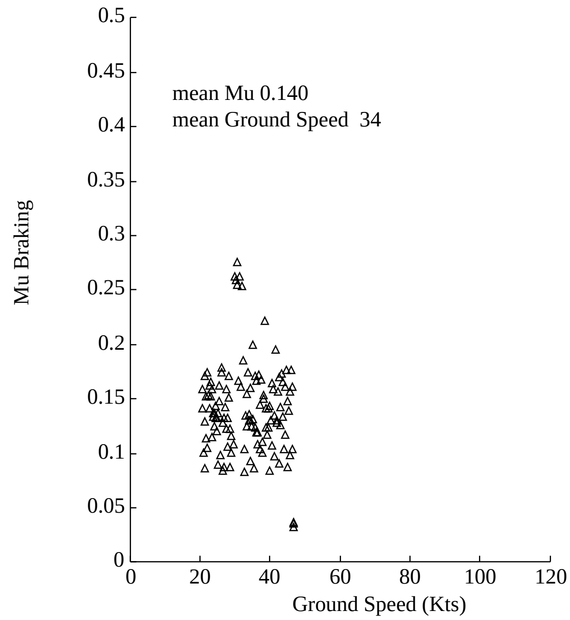
CRFI Average 0.26



Flight 2000/12, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.26

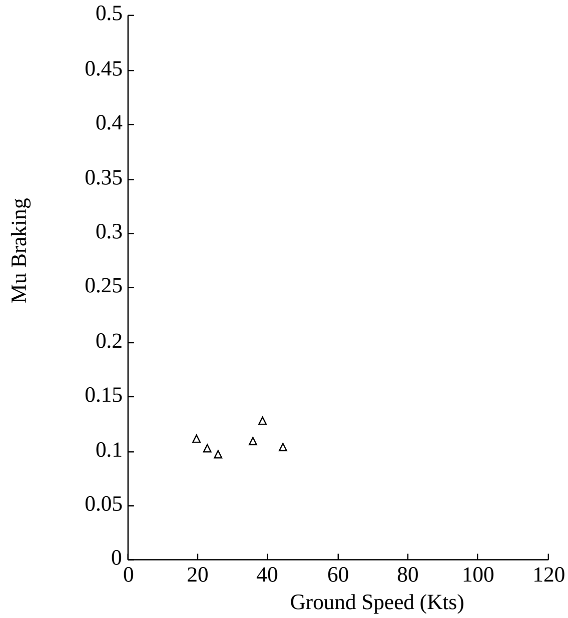


Summary of Aircraft Mu Braking on Surfaces with No or Negligible Contamination Drag

Flight 2000/02, Run Numbers 1 through 6

60% Ice, 40% Compacted Snow Over Ice, Ice Scarified Longitudinally

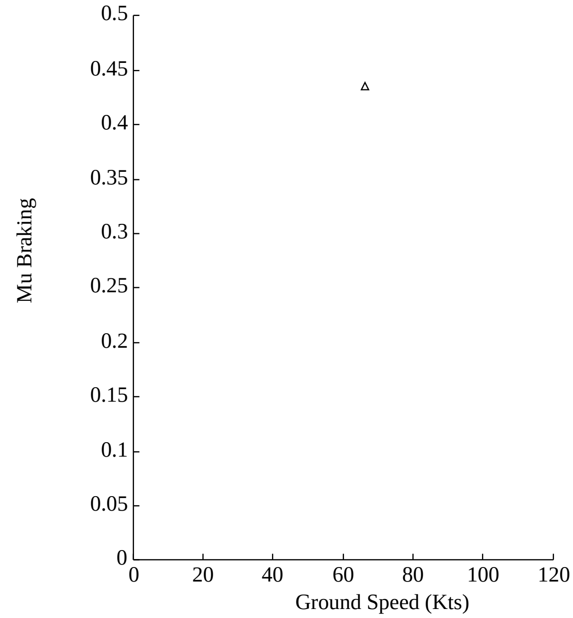
CRFI Average 0.17



Flight 2000/03, Run Number 1

100% Bare and Dry, Occasional Ice Patches

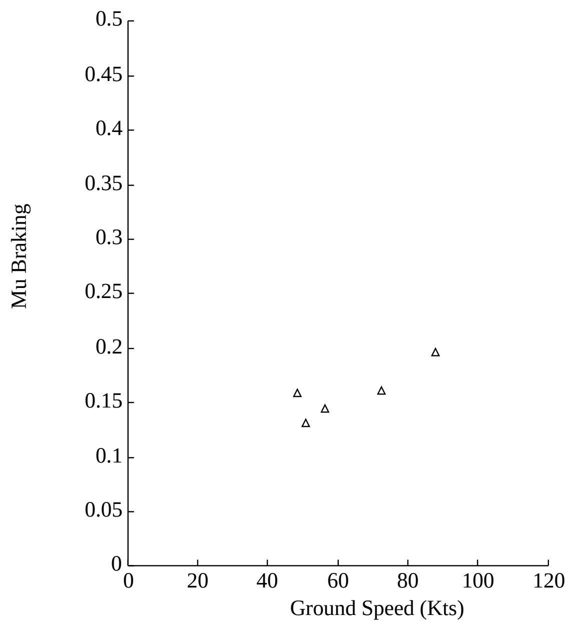
CRFI Average 0.75



Flight 2000/04, Run Numbers 1 through 5

100% 1cm Loose Snow Changing to Loose Snow With Tracks.
20% Bare and Dry, 20% Compressed Snow, 60% Loose Snow

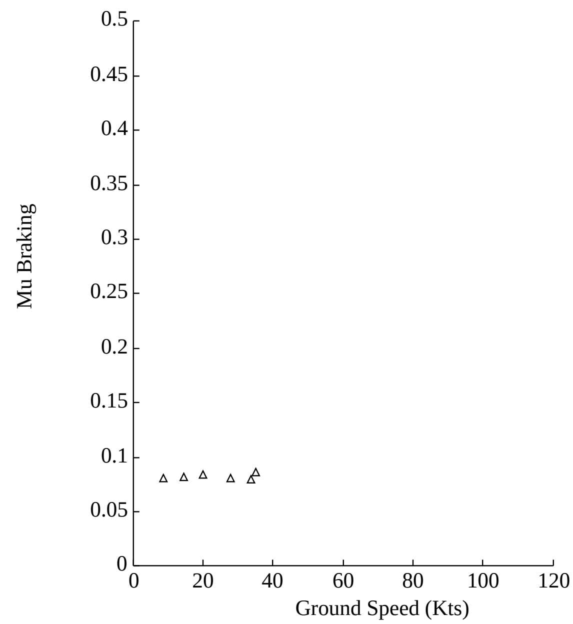
CRFI Average 0.30



Flight 2000/05, Run Numbers 1 through 6

100% Ice With Occasional Bare Spots

CRFI Average 0.13

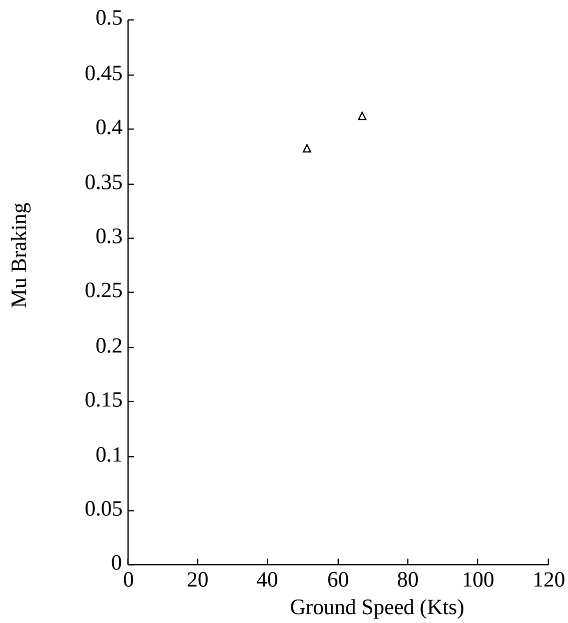


Summary of Aircraft Mu Braking on Surfaces with No or Negligible Contamination Drag

Flight 2000/06, Run Numbers 1 through 2

100% Bare and Dry, With Occasional Ice Patches

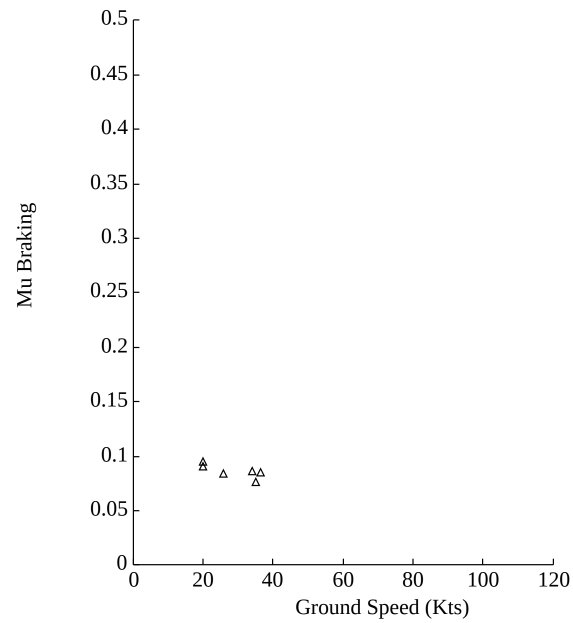
CRFI Average 0.73



Flight 2000/07, Run Numbers 1 through 6

100% Ice With Occasional Bare Spots

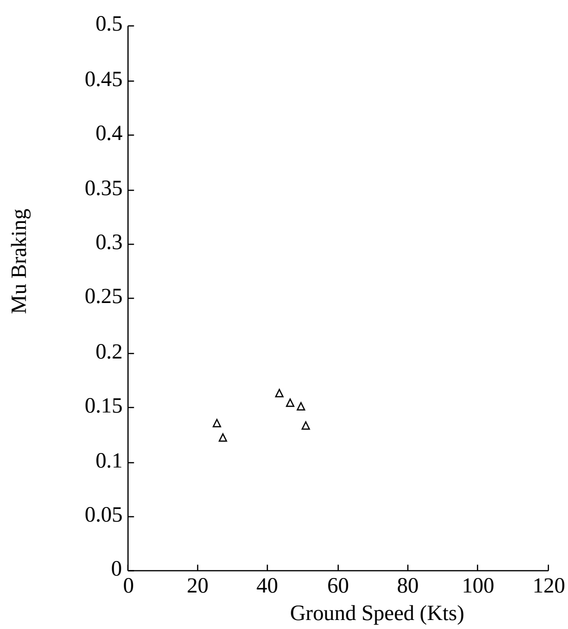
CRFI Average 0.10



Flight 2000/08, Run Numbers 1 through 6

100 Ice With Sand Application and Occasional Bare Spots

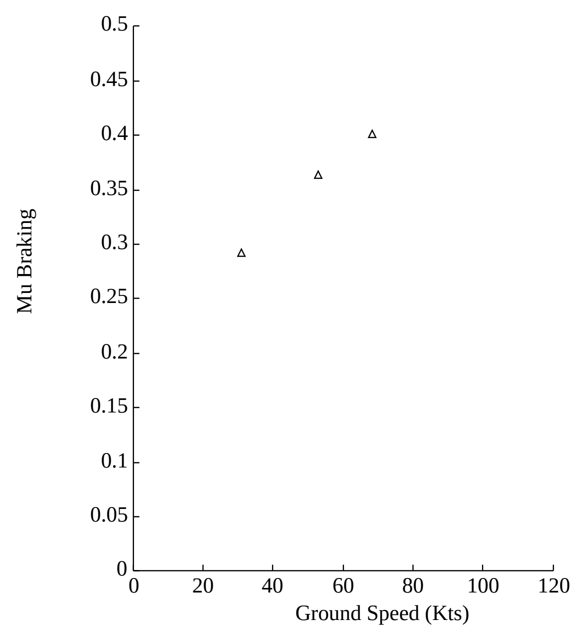
CRFI Average 0.21



Flight 2000/09, Run Numbers 1 through 3

70% Bare And Dry, 30% Light Dusting of Snow

CRFI Average 0.64

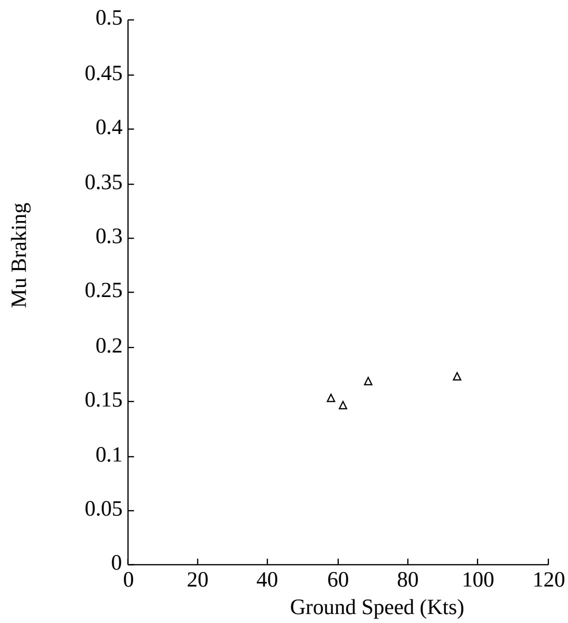


Summary of Aircraft Mu Braking on Surfaces with No or Negligible Contamination Drag

Flight 2000/10, Run Numbers 3 through 6

100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

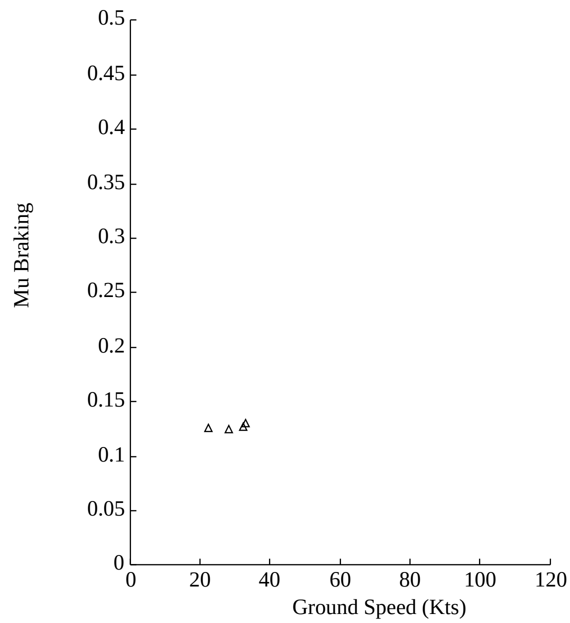
CRFI Average 0.27



Flight 2000/11, Run Numbers 1 through 4

100% Longitudinally Scarified Ice

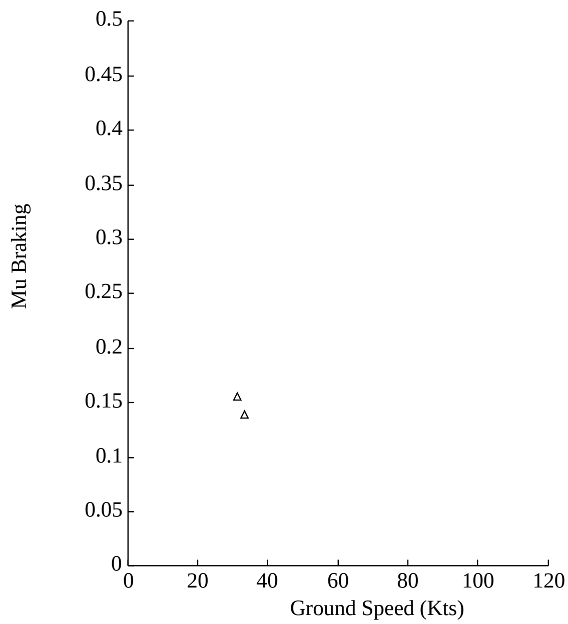
CRFI Average 0.20



Flight 2000/12, Run Numbers 2 through 3

90% Sanded Ice, 10% Bare and Dry

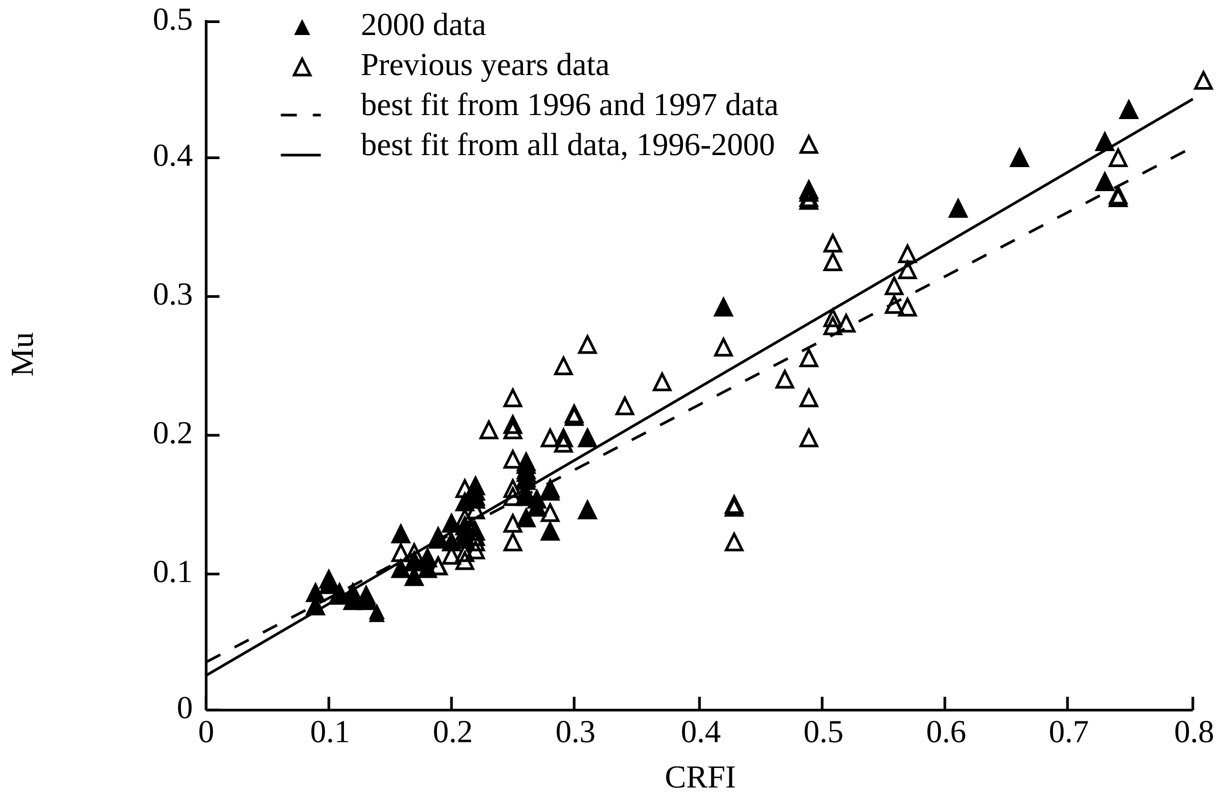
CRFI Average 0.26



Mean Mu Braking versus CRFI

Surfaces with No or Negligible Contamination Drag

Mu Braking = 0.0354 + 0.4658 * CRFI (1996 & 1997)
Mu Braking = 0.0261 + 0.5224 * CRFI (all years)



APPENDIX E - TEST RUNS FOR CONTAMINATION DRAG

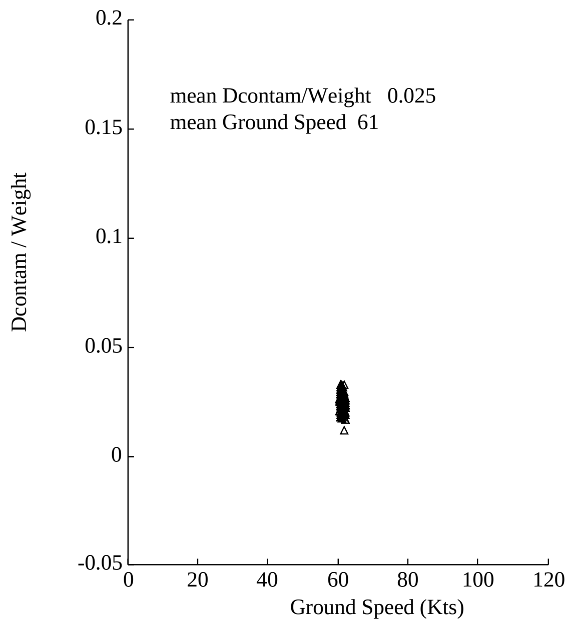
The following table shows the test runs used to determine the contamination drag. Page E2 shows the variation of D_{CONTAM}/W with ground speed for each run. The mean ground speed and mean D_{CONTAM}/W for each run is shown in the table and on Page E3.

FLT	RUN	RWY	TAXI/ RTO/ LAND	CONFIG	WEIGHT (LB)	MEAN DEPTH (INCH)	MEAN SG	MEAN SPEED (KTGS)	MEAN D_{CONTAM} /W	MEAN D_{CONTAM} (LB)
2000/10 25/01/00	1 12:32	26TS	TAXI	15/IN/NO	22480	0.75	0.042	61	0.025	562
	2 12:43	26TS	TAXI	15/IN/NO	22230	0.75	0.042	50	0.026	578

Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow
Sg of snow 0.042

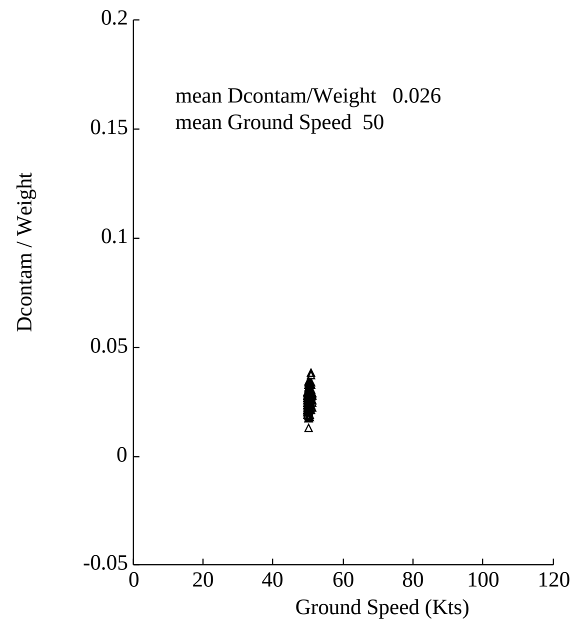
Flight 2000/10, Run Number 1

Configuration: Flaps 15, Air Brakes In, No Braking



Flight 2000/10, Run Number 2

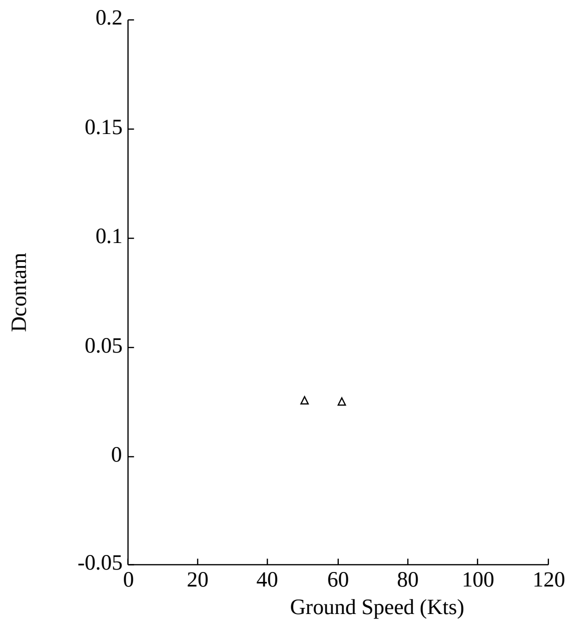
Configuration: Flaps 15, Air Brakes In, No Braking



Summary of Aircraft Contamination Drag

Flight 2000/10, Run Numbers 1 and 2

100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow



APPENDIX F - TEST RUNS FOR AIRCRAFT BRAKING COEFFICIENT ON RUNWAY SURFACES WITH CONTAMINATION DRAG

The following table shows the test runs used to determine the aircraft braking coefficient ($_B$) on runway surfaces with contamination drag. Page F2 shows the variation of $_B$ with ground speed for each run. The mean ground speed and mean $_B$ for each run are shown in the table and on page F3. Page F4 shows the mean $_B$ plotted against the mean CRFI value for each run. Page F5 shows the same relationship of $_B$ versus CRFI on runway surfaces with no or negligible contamination drag, with data obtained form test years 1996 through 2000 tests.

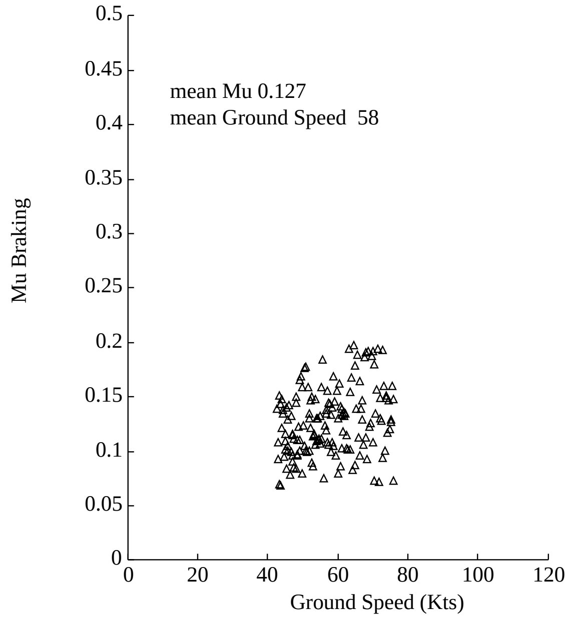
FLT	RUN	RWY	TAXI/ RTO/ LAND	CONFIG	WEIGHT (LB)	MEAN D_{CONTAM}/ W	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN $_B$
2000/10 25/01/00	3 12:56	26	RTO	15/OUT/B	21980	0.026	0.27	0.26	58	0.127
	4 13:04	26	RTO	40/OUT/B	21630	0.026	0.27	0.27	61	0.120
	5 13:05	26	LAND	40/OUT/B	20780	0.026	0.27	0.30	94	0.142
	5 13:06	26	RTO	15/OUT/B	20580	0.026	0.27	0.31	69	0.142

Surface: 100% 3/4" Loose Snow Changing to 60% Packed Snow, 40% 3/4" Loose Snow

Flight 2000/10, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

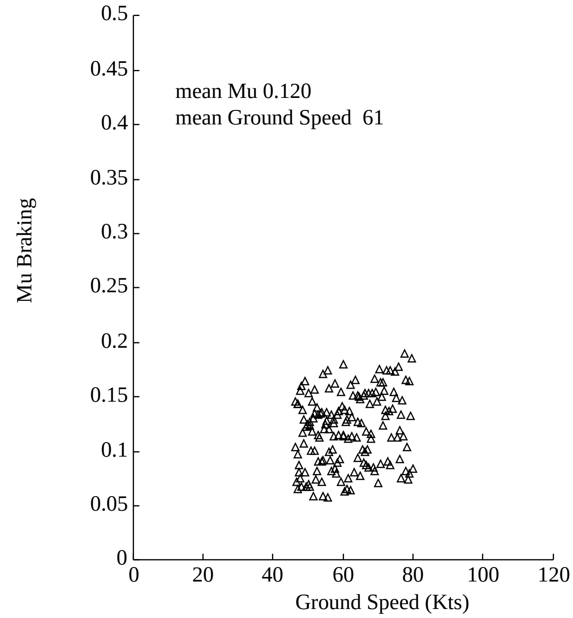
CRFI Average 0.27



Flight 2000/10, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

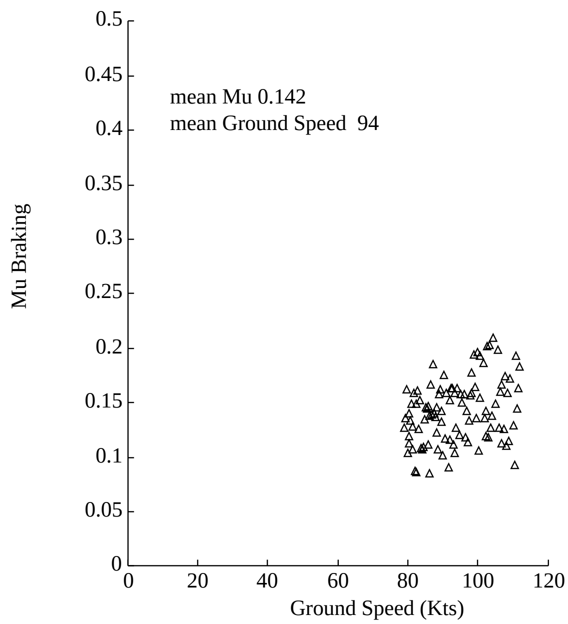
CRFI Average 0.27



Flight 2000/10, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

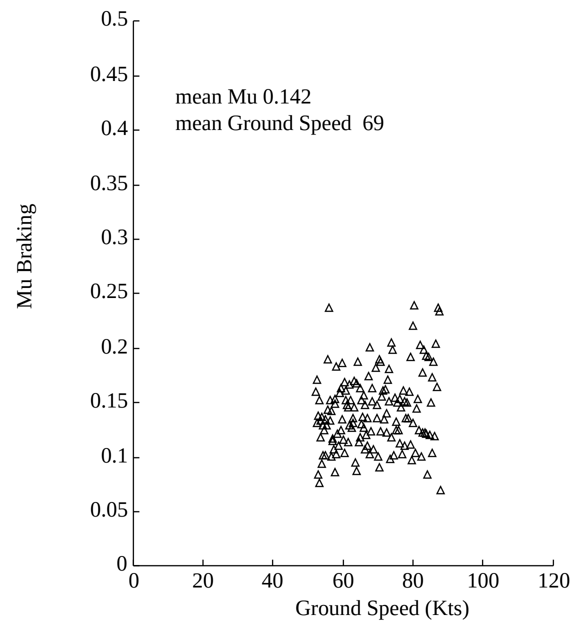
CRFI Average 0.26



Flight 2000/10, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

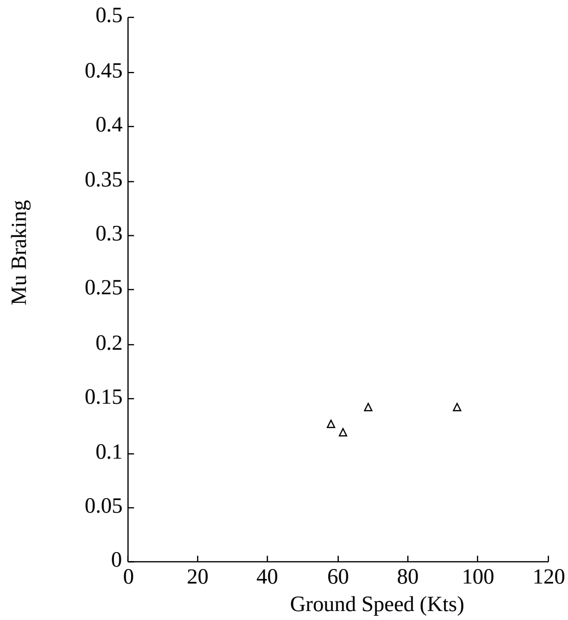
CRFI Average 0.26



Summary of Aircraft Mu Braking on Surfaces with Appreciable Contamination Drag

Flight 2000/10, Run Numbers 3 through 6

100% 3/4" Loose Snow Changing to 60% Packed Snow,
40% 3/4" Loose Snow



Mean Mu Braking versus CRFI

Surfaces with Contamination Drag

Mu Braking = 0.0354 + 0.4658 * CRFI