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## Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1998/1999

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16. Abstract

The performance of the NRC Falcon 20 research aircraft was tested on winter contaminated runway surfaces at the North Bay airport from January to March 1999. This was the fourth year of a five-year collaborative test program among Transport Canada, NASA, NRC, and the FAA.

The aircraft braking performance during full anti-skid braking runs on snow-covered runway surfaces agreed, in general, 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 0.12. The aircraft landing data obtained over the entire four-year test period, including that from additional braking runs, was used to update the aircraft performance model for landings on contaminated runways.

Recommendations were made to update the CRFI table of recommended landing distances currently published in the Transport Canada Aeronautical Information Publication (AIP). Based on an analysis of reverse thrust data for other aircraft types, a recommendation was made to include an additional CRFI table, incorporating the effects of reverse thrust, in the AIP. No data was obtained for contamination drag, because very little natural snow fell in North Bay during the 1998-1999 winter.

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16. Résumé


Des essais visant à étudier les performances de l'avion de recherche Falcon 20 du CNRC sur des pistes chargées de contaminants ont eu lieu de janvier à mars 1999 à l'aéroport de North Bay. Il s'agissait de la quatrième des cinq années d'un programme conjoint de recherche qui réunit Transports Canada, la NASA, le CNRC et la FAA.

Les essais de freinage sur pistes enneigées mettant en jeu un système antipatinage ont révélé des performances qui concordaient, en gros, avec celles des essais antérieurs. D'autres essais ont été réalisés sur des pistes recouvertes de glace lisse, offrant donc une très faible adhérence, soit une valeur de l'Indice canadien de la glissance des pistes (CRFI pour *Canadian Runway Friction Index*) qui atteignait à peine 0,12. La masse de données issues de quatre ans d'essais d'atterrissage, y compris les résultats des essais de freinage, ont permis de perfectionner le modèle des performances de l'avion, celui-ci intégrant désormais des atterrissages sur pistes chargées de contaminants.

Les chercheurs ont recommandé de mettre à jour les tables CRFI figurant dans la Publication d'information aéronautique (AIP) de Transports Canada, laquelle établit des distances d'atterrissage recommandées. C'est que, d'après une analyse des données d'inversion de poussée obtenues pour d'autres types d'avions, il y aurait lieu d'ajouter à l'AIP une table CRFI qui tiendrait compte de ce facteur. Aucune donnée n'a été obtenue sur la traînée due à la contamination, en raison des très faibles chutes de neige à North Bay, au cours de l'hiver 1998-1999.


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## GLOSSARY OF TERMS

| | |
|---|---|
| $ACC_{AV}$ | Average Acceleration During Braking (for Predicted LD) |
| $ACCR_{AV}$ | Average Acceleration During Braking (for Recommended LD) |
| AFM | Aircraft Flight Manual |
| AIP | Aeronautical Information Publication |
| ATIS | Automatic Terminal Information System |
| BDR | Braking Distance Ratio |
| $C_D$ | Aircraft Coefficient of Drag |
| $C_L$ | Aircraft Coefficient of Lift |
| CPU | Computer Processor Unit |
| CRFI | Canadian Runway Friction Index |
| D | Aerodynamic Drag |
| DAS | Data Acquisition System |
| DAT | Digital Audio Tape |
| DC | Direct Current |
| $D_{CONTAM}$ | Contamination Drag |
| DEC | Digital Equipment Corporation |
| DGPS | Differential Global Positioning System |
| D1 | Air Distance from 50 feet to Touchdown |
| D2 | Delay Distance from Touchdown to Brake Application |
| D3 | Braking Distance to a Complete Stop |
| 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 |
| ISA | International Standard Atmosphere |
| JAA | Joint Aviation Authority |
| JBI | James Brake Index |
| KEAS | Knots Equivalent Airspeed |
| KTGS | Knots True Groundspeed |
| L | Aerodynamic Lift |
| lbf | Pounds of force |
| LD | Landing Distance |
| LSI | Large Scale Integration |
| MOU | Memorandum of Understanding |

| | |
|---|---|
| Mu | Coefficient of friction |
| NASA | National Aeronautics and Space Administration |
| NOTAM | Notice to Airmen |
| PA | Pressure Altitude |
| RTO | Rejected Takeoff |
| SD | Standard Deviation |
| SDR | Stopping Distance Ratio |
| SG | Specific Gravity |
| t | Time |
| T | Aircraft Thrust |
| TS | Test Section |
| TW | Tailwind |
| V | Aircraft velocity along the runway (groundspeed) |
| $V_{EAS}$ | Equivalent Airspeed |
| $V_{EFB}$ | Equivalent Airspeed at Application of Full Brakes |
| $V_{E50}$ | Equivalent Airspeed at 50 feet Above the Runway Surface |
| VFR | Visual Flight Rules |
| $V_{GFB}$ | Groundspeed at Application of Full Brakes |
| $V_{G50}$ | Groundspeed at 50 feet Above the Runway Surface |
| $V_{REF}$ | Aircraft Approach Speed |
| $V_{T50}$ | True Airspeed at 50 feet Above the Runway Surface |
| $V_W$ | Wheel speed |
| W | Aircraft Weight |
| $\varepsilon$ | Runway Slope (positive uphill) |
| $\sigma$ | Atmospheric Density Ratio ( $= \rho/\rho_0$ ) |
| $\mu_B$ | Aircraft Braking Coefficient ( = Braking Force/(W-L)) |
| $\mu_R$ | Rolling Friction Coefficient ( = Rolling Resistance/(W-L)) |
| $\mu_S$ | 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 1998/1999

## 1.0 INTRODUCTION

### 1.1 Background

In December 1995, a project 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 three years of testing were conducted at the North Bay airport, Ontario, Canada during the winters of 1995/1996 through 1997/1998, and were successful in providing comparative data for four different types of aircraft (the NRC Falcon 20, the NASA B737, the FAA B727 and the deHavilland Dash 8) and several ground friction measuring vehicles. References 1 through 6 cover the test results for these aircraft.

This report describes the results of the Falcon 20 aircraft flight testing carried out during the fourth winter of testing, and the influence of the additional data on currently established performance models. The tests were conducted by the NRC Institute for Aerospace Research (IAR) in collaboration with the Transport Canada Civil Aviation Aircraft Certification Branch during the months of January through March 1998.

### 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 standardise their outputs into an International Runway Friction Index (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.

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

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

Descriptions of the test equipment, test procedures and analysis methods are included in References 2, 3 and 7 for previous NRC Falcon 20 tests. To permit this report to “stand alone,” these items will be summarised briefly prior to the discussion of the test results.

## 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.

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 1996 and 1997 test periods (References 1 through 3). Data from the 1998 test period (Reference 7), combined with additional data obtained from Falcon 20 and other aircraft tests, covered in this report, will be used to refine aircraft performance data used to produce the CRFI Table. In this report, two new CRFI Tables of Recommended Landing Distances, one with and one without the use of reverse thrust, will be proposed for incorporation into the AIP.

### 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 stabilizer. 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 $7.27 \times 10^6$ ft-lbf per brake.

The anti-skid system on the Falcon 20 is manufactured by Goodyear (now Aircraft Braking Systems Corporation), and 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 preset 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. inners and outers) controlled by separate channels. The Falcon 20 anti-skid system is analogue and was developed in the 1960's. It is considered a "Mark 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, and was also used to provide the precise real-time aircraft guidance required to fly consistent precision approaches to landing. This system is more fully described in Reference 1.

An equipment rack and project operator's station were 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 audio tape (DAT) using the onboard data recording system. This was supplemented by manual recording of some parameters such as type of test, configuration, fuel, reported wind direction/speed and pilot qualitative comment.

## 3.0 TEST PROCEDURES

### 3.1 Test Site Description

The North Bay airport has three runways, two of which were suitable for Falcon 20 operations, with Runway 18/36 being too short. 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 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.

Because of the incident involving the ingestion of snow into the Falcon 20 engines during the 1997/98 test period (Reference 3), and the fact that manipulated snow had an unnaturally high density, the process of moving various quantities of snow into the test section via blower or grader from the edges of the runway, and grooming the snow in place with ground equipment was discontinued. Instead, only natural snow was used for testing, and once the desired depth of snow had accumulated, the test section was formed by removing the snow from both runway edges and a certain distance from each end. 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 Runways 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 1997/98 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 anti-skid braking runs were done to determine the braking coefficient. During these runs, brake pressure cycling could be felt with maximum brake pedal force applied by the pilot (with illumination of cockpit lights), indicating correct operation of the anti-skid system. 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); and
c. landing configuration (flaps 40°, airbrakes out).

In general, the sequence of events for each contaminated surface included the preparation and documentation of the surface to the satisfaction of the various test teams, ground vehicle runs to determine surface friction prior to the aircraft runs, aircraft test runs for contamination drag (if applicable), aircraft test runs for braking coefficient, and ground vehicle runs to record surface friction following the aircraft runs. The following test plans were used for the Falcon 20 test points:

> YYBFJF99/01: 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;
>
> YYBFJF99/02: Contamination Drag Determination. This plan consisted of accelerate/ coast and landing/coast runs through the test section in the continued takeoff configuration;
>
> YYBFJF99/03: 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
>
> YYBFJF99/04: 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 3, namely:

a. Maximum equivalent water depth (EWD, defined as depth multiplied by specific gravity) 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 coordinator 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; and

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

The test section conditions recorded included a qualitative description, depths 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 coordinator 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:

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

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

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 |
| $\mu$ | : | Friction Coefficient |
| $\varepsilon$ | : | Runway Slope (+ve uphill) |
| $V$ | : | Velocity Along Runway |
| $g$ | : | Gravitational Constant |

b. For small $\varepsilon$ : cos $\varepsilon$ ~ 1, sin $\varepsilon$ ~ $\varepsilon$, and the general equation for acceleration, in “g” units, becomes:

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

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:

$$\mu_R = (\frac{T}{W} - \frac{D}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \quad (2)$$

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:

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

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:

$$\frac{D_{CONTAM}}{W} = \frac{T}{W} - \frac{D}{W} - \varepsilon - \mu_R(1 - \frac{L}{W}) - \frac{1}{g}\frac{dV}{dt} \quad (4)$$

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 surface with appreciable contamination drag becomes:

$$\mu_B = (\frac{T}{W} - \frac{D}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \quad (5)$$

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:

$$L = \frac{1}{2}\rho_o V_{EAS}{}^2 S C_L$$
$$D = \frac{1}{2}\rho_o V_{EAS}{}^2 S C_D \quad (6)$$
$$T = 600 - 4.62 V_{EAS} \quad (lbf)$$

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

$\rho_o = 0.002377 slug/ft^3$

$V_{EAS}$ = 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 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 ($\mu_S$) is determined from the equation:

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

where V is the aircraft groundspeed and $V_W$ is the wheel speed.

## 4.0 TEST RESULTS AND DISCUSSION

### 4.1 Summary of Test Runs

During the winter of 1998/1999, a total of seven different contaminated runway surfaces were tested during six separate test sessions in North Bay. An additional two sessions were conducted on bare and dry runway surfaces to evaluate rolling friction coefficients and maximum performance landings to a full stop. A total of four deployments to North Bay were flown over the course of the winter, three for testing and one for equipment dismantling.

#### 4.1.1 Test Section Description

Test section surface conditions evaluated during the period included naturally occurring patchy snow and slush conditions, with a variable distribution of contamination, and man-made ice surfaces with various levels of roughness and applications of sand. Lower CRFI values were achieved this year than in previous years, with a minimum CRFI = 0.12 tested on a smooth ice surface with no sand. Photographs of the test sections tested are shown in Appendix G. This year, an attempt was made to record the surface conditions and CRFI between each test run, rather than just before and after each test session as in previous years. This procedure took additional time, but provided a better comparison of aircraft performance data and runway surface friction by minimising 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 46 test runs were recorded during the eight test sessions. These included 7 runs for rolling friction, 5 runs for combined contamination drag/braking coefficient, and 34 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 eight test sessions (flights 99/03, 99/04, and 99/06 through 99/08), poor weather and/or aircraft serviceability was a factor in preventing the aircraft from taking off and flying VFR DGPS approaches to the test section. As a result, only low and mid-speed data were obtained for four of these five test sessions using accelerate/stop (or coast) runs on Runway 31. High speed data were obtained for flight 99/03 on Runway 08. The inability to cool the brakes in the air also limited the number of ground runs which could be performed, due to the accumulation of brake energy used during the runs.

Each figure in Appendix A (pages A4 through A18) is annotated with the runway surface description and the aircraft configuration, together with time histories of groundspeed (from DGPS), acceleration (from accelerometer data for all runs except the coasting runs on flights 99/01 and 99/02 where the derivative of DGPS groundspeed 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, except for flight 99/03, page A7. On this flight, combined braking friction coefficient and contamination drag runs were conducted on Runway 08. Because the contamination (50% to 70% loose snow drifts) extended the full length of Runway 08, a sufficient length of time was used for each of the braking and coasting events to produce a useful period of steady state data without transitions between braking and coasting. This was a problem for the combined runs on the Runway 31 test section last year, and the recommendation that future combined runs be conducted on longer test sections still holds.

### 4.1.2 Aircraft Braking on a Bare and Dry Surface

As in previous years test results, the operation of the Falcon 20 anti-skid braking system can be verified from the modulation of the left and right brake pressures during full braking runs on the different surfaces. A typical run on a bare and dry surface, CRFI = 0.81, is shown on page A5, flight 99/01, run 6. Both left and right brake pressures are mostly at the torque limit of 1200 lbf/in$^2$ (full brake pressure), with occasional transient skids due to small ice patches or painted runway markings. This run was done to compare the actual landing distance for a performance landing to full stop with that predicted by the Aircraft Flight Manual (AFM). Figure 1 shows the time histories of selected aircraft parameters for this run. The chart on the left shows the decrease in aircraft groundspeed with time, the aircraft touchdown point (activated by a weight on wheels switch), and the variations of vertical and horizontal accelerations in “g” units. The chart on the right shows the DGPS derived x, y, and z positions in feet, with the glide path intercept point (GPIP) at the runway centerline as the zero position reference point.

The landing “event” in Figure 1 starts at 50 feet above the runway (at a data elapsed time of 117 seconds) and ends with a full stop (at 138 seconds). The difference between the maximum and minimum points on the x position chart is the total landing distance, calculated to be 2547 feet.

The AFM landing distance, in comparison, is 2340 feet for an aircraft gross weight of 19,250 lbs and zero wind, or about 200 feet less than was actually achieved. This confirms the difficulty in achieving the AFM predicted landing distances, even using maximum performance landing techniques, as discussed in Reference 7 in the section on CRFI Table verification.

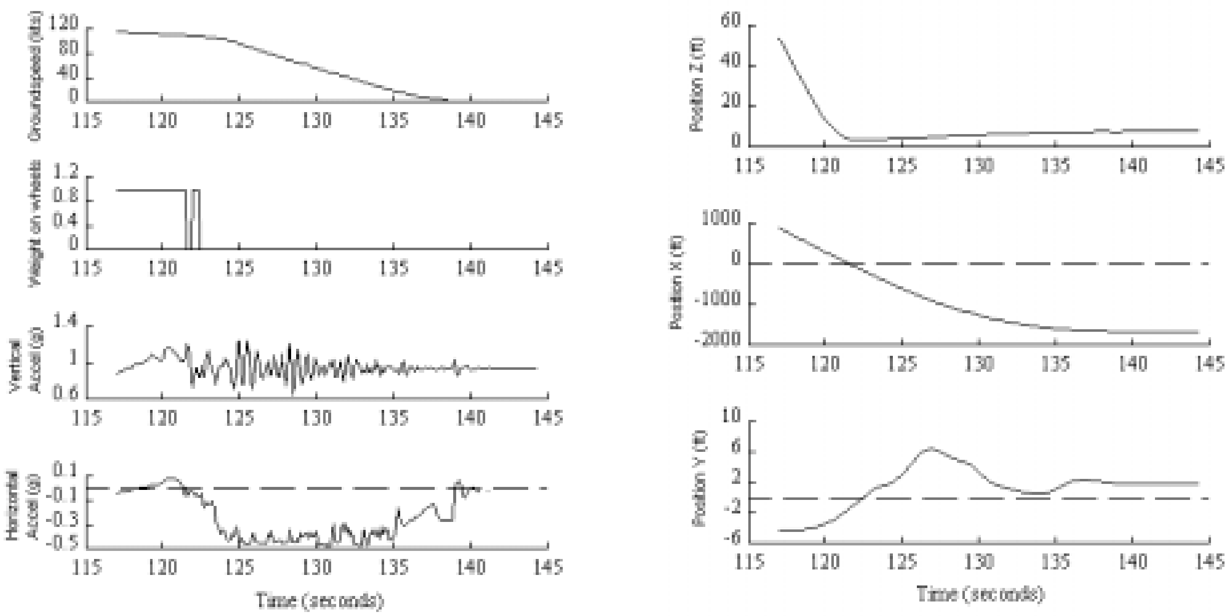


Figure 1
Falcon 20 Performance Landing on a Bare and Dry Runway, CRFI = 0.81

### 4.1.3 Aircraft Braking on a Surface with Variable Friction

Typical maximum braking runs on a surface with moderate, but variable, friction characteristics are shown on page A7, Flight 99/03, on a surface with 50% to 70% loose snow drifts, with average CRFI's between 0.33 and 0.38. Left and right brake pressures are being modulated by the anti-skid system at mid-range, but because the left and right brake systems operate independently due to separate anti-skid control described in Section 2.2, significant lateral excursions can occur on a variable surface condition.

Figure 2 shows an example of the heading oscillations which can result from asymmetric braking friction. The left brake pressure increases rapidly to 1200 psi, presumably on a dry patch, at the 57 second elapsed data time, while the right brake pressure remains modulated at about 400 psi. This results in a heading excursion of about 8 degrees to the left, with a reversal of about 10 degrees back to the right a second later when the brake pressure differentials change rapidly again. Although the lateral acceleration (-0.25 g) and yaw rate changes (-10 degrees per second) are significant, the runway centreline deviation varies only a few feet during the event, and the horizontal acceleration is not overly affected. In fact the aircraft deceleration can be seen to increase slightly at the 57 second mark as a result of the increased left brake pressure. This was a test case however, where the pilot maintained full brake application to obtain the test point, and worked to maintain aircraft heading with nosewheel steering. In an operational scenario, the pilot would more likely release the brakes momentarily on recognition of such a heading excursion, with a consequent increase in landing distance.

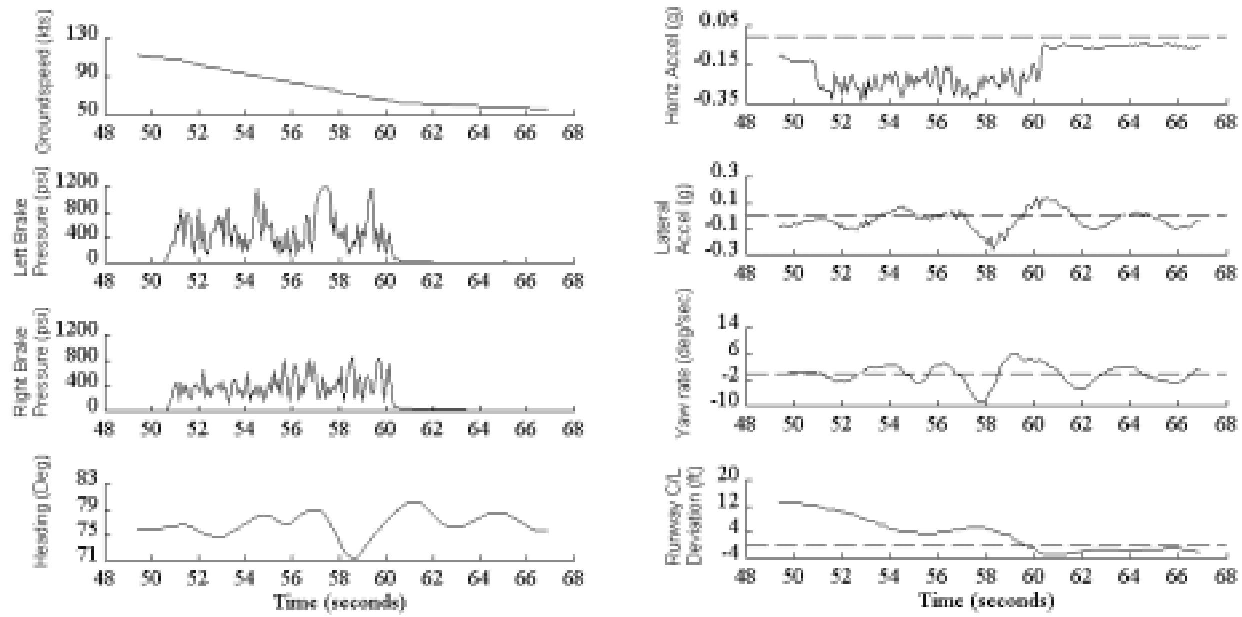


Figure 2
Falcon 20 Lateral Excursions on a Variable Surface Condition, CRFI = 0.38

#### 4.1.4 Aircraft Braking on a Surface Covered with Ice

Maximum braking runs on smooth ice surfaces, with very low values of CRFI, are shown in Appendix A for Flights 99/06 and 99/07, pages A13 through A16. Left and right brake pressures are being modulated by the anti-skid system at very low values, averaging no more than 100 to 200 psi for most runs. On one of these runs, Flight 99/07 Run 1, directional control of the aircraft was lost momentarily due to the loss in cornering friction between the tires and the surface. This occurred on a test section which was 100% ice covered, no application of sand, with CRFI between 0.12 and 0.16, averaging 0.14. The wind may have been a factor, with an 8 knot tailwind component and a 3 knot crosswind component from the right.

Figure 3 shows the modulations in left and right brake pressures for Flight 99/07 Run 1, and the associated wheel speeds, while the brakes were applied for a period of about 1.5 seconds at a groundspeed of about 35 knots. As soon as the brakes were applied, the aircraft heading began to drift to the left, and could not be controlled with either nosewheel steering, due to lack of cornering friction on the nosewheel, or rudder, due to lack of airspeed for aerodynamic effectiveness. The aircraft heading got to a full 10 degrees off runway heading during the 2 seconds prior to brake release, and the aircraft departed the test section to the left, onto the edge of the runway which is purposely kept bare and dry in the event of such an occurrence. On the bare and dry surface, nosewheel traction became effective and the aircraft was easily straightened with nosewheel steering.

The time histories of the four wheel speeds in Figure 3 show the wheel speeds to be cycling between the aircraft groundspeed and essentially zero speed, or between zero and 100% slip ratio. The resulting high mean slip ratios resulted in very low cornering friction, with poor directional control, especially with any amount of crosswind. This occurrence justified the procedure of maintaining about 40 feet of cleared pavement on the edge of the runway in the event of aircraft lateral departure from the test section. The contribution of the few knots of crosswind to the loss of lateral control is unknown, but it is evident that the lack of cornering friction could have caused the problem even without a crosswind. Therefore, this occurrence strengthened the notion that any amount of reported crosswind (5 knots or more) is unacceptable for operations on icy runways with CRFI's below about 0.20.

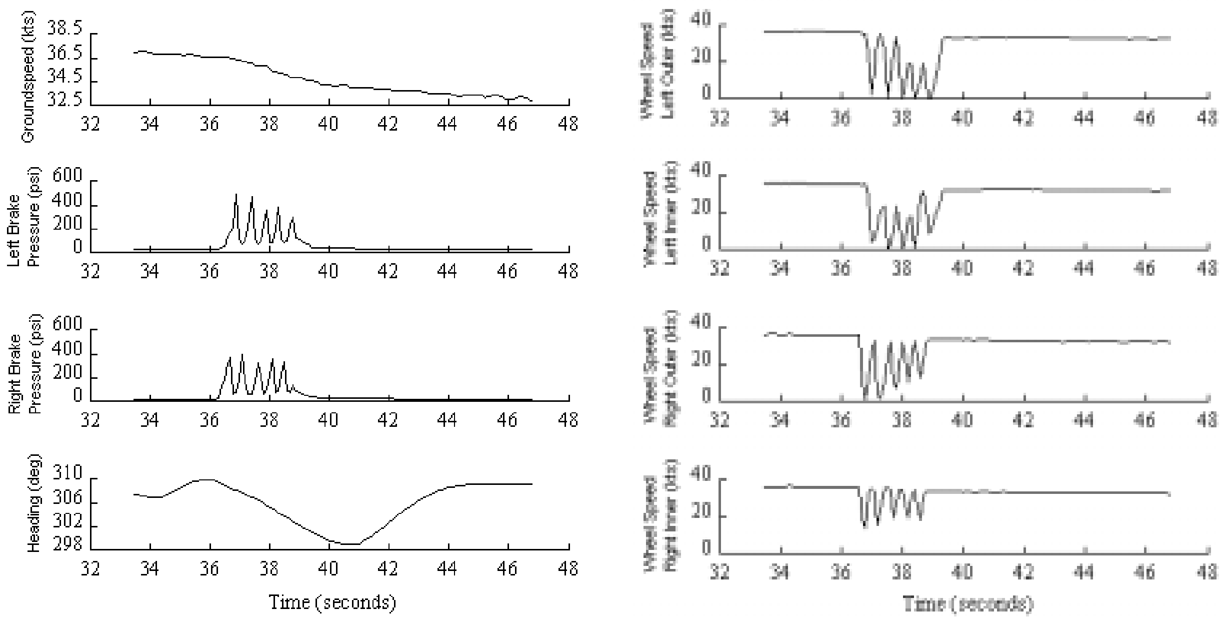


Figure 3
Falcon 20 Directional Control Loss on Smooth Ice

## 4.2 Verification of Rolling Friction Coefficient and Idle Thrust

Four taxi runs and three landing/coast runs were performed on surfaces with negligible contamination drag on flights 99/01 and 99/02 to confirm the aircraft rolling friction coefficient ($\mu_R$) and the idle thrust. Appendix B summarises these seven test runs in the table on page B1. Individual runs are shown on pages B2 and B3, with each data point ($\mu_R$) calculated using equation (2) in section 3.3 paragraph c, and plotted against groundspeed. For each run, the mean $\mu_R$ and mean groundspeed were calculated, with these values tabulated on page B1. A plot of the mean $\mu_R$ versus mean groundspeed for all five runs is shown on page B4. Data from the 1996 through 1998 test periods is also included on this plot.

A good correlation can be seen in the data on page B4 between the 1999 data points and the data points obtained during previous tests. This verifies the relationship (originally derived in Reference 3) between $\mu_R$ and aircraft groundspeed to be:

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

In addition to verifying the equation for $\mu_R$ above, the taxi runs also confirmed the equation for idle thrust, shown in section 3.3, and the landing/coast runs 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 groundspeed and runway surface condition. Appendix C summarises the braking test runs for which the anti-skid slip ratio ($\mu_S$) was determined, and lists the mean slip ratios for each main wheel in the table on pages C1 and C2. Pages C3 through C39 show the time histories of several parameters, with one braking run per page. The parameters plotted for each run are the aircraft groundspeed, 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.

Flight 99/01 runs 6 and 7 were full anti-skid braking runs on a runway surface which was bare and dry with a CRFI of 0.81. The time history data for run 6 is shown on page C3. Unfortunately the data acquisition system failed during run 7, probably due to the high levels of deceleration and aircraft vibration/buffet, and data was not available for this run. On the wheel speed plots for run 6, the difference between the wheel speed (solid line) and aircraft groundspeed (dashed line) indicates a fairly constant slip ratio has been established on the bare and dry surface at the braking torque limit of 1200 psi. The mean slip ratio varies for each wheel, from a low of 5% for the right outer wheel to a high of 12% for the right inner wheel. The mean slip ratios for the left outer and inner wheels are 9% and 7% respectively, indicating that the average slip ratios may be comparable between left and right wheel systems. Minor impending skids were induced by small ice patches or painted runway markings, and are indicated by two or three small spikes in the data for each wheel. Slip ratios increased slightly with decreasing groundspeed, similar to the trends observed for previous tests (Reference 7).

Flight 99/03 runs 1 to 5 (pages C4 to C8) were full anti-skid braking runs on a runway surface 50% bare and dry with 50% loose snow drifts of about one inch depth, changing (over the test period) to 30% bare and dry with 70% loose snow drifts, average CRFI = 0.33. For all five runs, the wheel speeds and slip ratios change rapidly back and forth between the dry pavement and the snow covered surface, never finding a consistent surface condition for long enough to establish a constant slip ratio. The result is a rapid cycling of the anti-skid system with low average slip ratios, from about 3% at the higher speeds to about 5% at the lower speeds. Run 5 on page C8 is a maximum braking effort from 120 knots down to 30 knots, and shows the trend of slightly increasing slip ratio with decreasing groundspeed, at least for the left outer and right inner wheels, which appear to be the dominant wheels for each pair.

Flight 99/04 runs 1 to 6 (pages C9 to C13) were full anti-skid braking runs on a runway surface 25% bare and dry with 75% loose/compacted snow of ¼ inch depth, average CRFI's between

0.29 and 0.34. In general, the performance of the anti-skid system and the slip ratio data are similar to the loose snow results noted above, except that the mean slip ratios are higher, possibly due to the ability of the anti-skid system to adapt to the more consistent surface condition. No data was obtained for run 4 due to failure of the data acquisition system, and runs 5 and 6 were maximum braking efforts from about 90 knots down to 20 knots on the north end of runway 31. Again, the slip ratio data show a trend of increasing slip ratio with decreasing groundspeed

Flight 99/05 runs 1 to 7 (pages C14 to C20) were carried out an a surface which was 100% covered with thin ice with some roughness from the pavement texture, with average CRFI's from 0.23 to 0.29. The time histories of the wheel speeds for these runs show frequent spikes, but in general the anti-skid system is able to establish a consistent slip ratio of about 8-10% to enable some degree of braking. There are some exceptions, where the wheel speeds cycle rapidly between zero and the actual groundspeed, such as the left outer wheel on run 1, page C14. This will become more common for the smooth ice surfaces to be discussed in subsequent paragraphs.

Figure 4 plots the average slip ratio for each wheel pair (left and right), calculated from the individual wheel slip ratios listed for flights 99/04 and 99/05 on page C1, plotted against the groundspeed. The slip ratios are similar in value for each flight, being below about 8% above 60 knots, and increasing with decreasing groundspeed to about 30% at 25-30 knots. The fact that the CRFI values are similar for both flights may have a bearing on the similar values of slip ratios. It is also evident that the left wheel pair operates at a higher slip ratio than the right wheel pair.

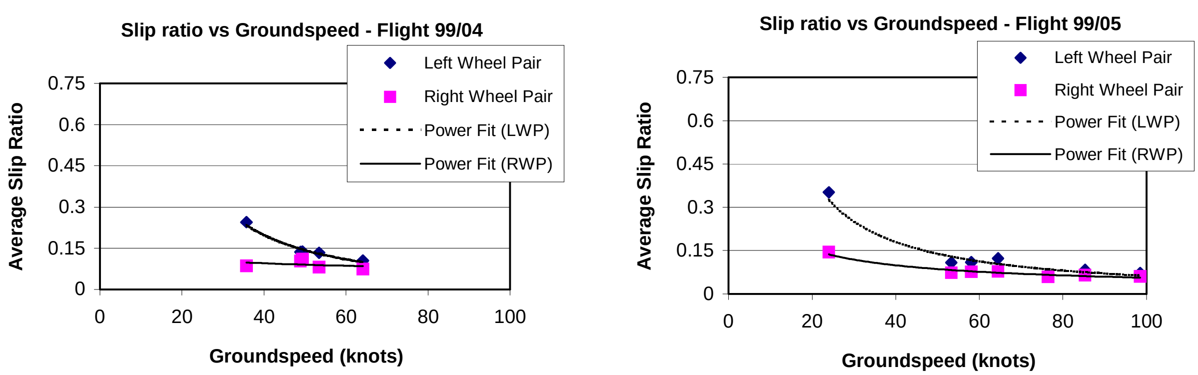


Figure 4
Falcon 20 Wheel Slip Ratios versus Groundspeed – Flights 99/04 and 99/05

Flight 99/06 runs 1 to 6 (pages C21 to C26) and flight 99/07 runs 1 to 8 (pages C27 to C34) were both carried out on a runway surface 100% covered with smooth ice, which was sanded for all runs except flight 99/07 runs 1 and 2. Flight 99/07 run 1 was the incident where the aircraft directional control was lost due to poor cornering friction, described in section 4.1 above. The average CRFI values were very low for all these runs, ranging from a low of 0.16 to a high of 0.22. Many of these 14 runs were characterised by frequent skids, indicated by rapid changes in the wheel speeds between zero and 100% slip ratio, especially at the lower speeds. The charts on page C21 for Flight 99/06 run 1, for example, show three of the four wheel speeds cycling between zero and 100% slip ratio, with calculated mean values of about 0.3 to 0.5 at a mean groundspeed of 28 knots. At the higher speeds, such as flight 99/06 run 5 on page C25, the anti-skid system is able to maintain more consistent slip ratios between 0.08 and 0.19.

Figure 5 plots the average slip ratios for each wheel pair (left and right), for flights 99/06 and 99/07 against the groundspeed. As in Figure 4, the trend of increasing slip ratios with decreasing groundspeed can clearly be seen. The left wheel pair consistently operates at a higher average slip ratio than the right wheel pair, indicating a stronger cycling tendency than the right wheel pair. The average slip ratios shown in Figure 5 are similar in value for each flight, being on surfaces with essentially the same CRFI values (0.16 to 0.22), but are somewhat higher than the average slip ratios shown in Figure 4 for surfaces with higher CRFI values (0.23 to 0.34). It is possible that the anti-skid system is adapting to the surface condition by increasing the slip ratio as the surface friction drops, and it is also possible that the higher average slip ratios are simply due to the higher magnitude of wheel speed cycling on the ice covered surfaces.

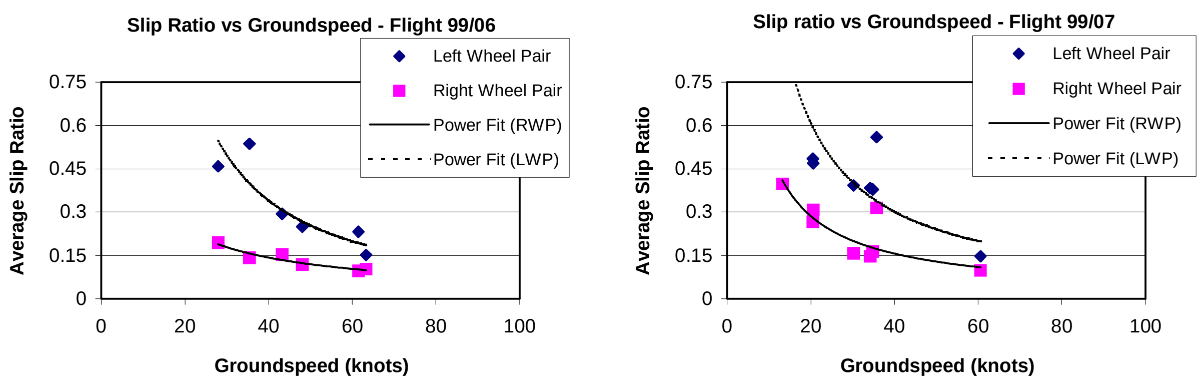


Figure 5
Falcon 20 Wheel Slip Ratios versus Groundspeed – Flights 99/06 and 99/07

The data so far obtained shows a tendency for the mean slip ratios to increase with decreasing groundspeed, and for the Falcon 20 left wheel pair to exhibit a higher mean slip ratio than the right wheel pair. The limited data shows a slight increase in the mean slip ratios with decreased runway friction, but this may also be a function of the increased cycling of the anti-skid system. These data should be interpreted with some caution due to the difficulties of accurately calibrating wheel speeds. However, the significance of these results and comparison with results from other types of anti-skid systems on dry, wet and contaminated runway surfaces is worthy of further study.

## 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 ($\mu_B$) on runway surfaces with no or negligible contamination drag. Six such surfaces were tested during the 1998/99 test period as follows:

a. Flight 99/01, 100% bare and dry, CRFI from 0.79 to 0.84 with an average of 0.81,
b. Flight 99/04, 25% bare and dry, 20% compacted snow, 55% loose snow with an average depth of 0.25 inches, average CRFI's from 0.29 to 0.34,
c. Flight 99/05, 100% thin ice with some roughness from pavement texture, average CRFI's from 0.23 to 0.29,
d. Flight 99/06, 100% ice covered with one application of sand and a thin layer (0.1 inch) of loose snow, average CRFI's from 0.16 to 0.20,
e. Flight 99/07, 100% ice covered with no sand for the first two runs, sanded for the remaining runs, average CRFI's of 0.14 for the first two runs and from 0.17 to 0.22 for the remaining runs,
f. Flight 99/08, 30% slush, 50% wet snow, 20% bare and wet for the first run, 80% wet snow and 20% slush for the remaining runs, average CRFI's of 0.25 for the first run and 0.21 to 0.22 for the remaining runs.

For most of the contaminated surface conditions, especially the prepared ice covered surfaces, the average CRFI values recorded between each run (shown on page D1) turned out to be fairly consistent. Individual CRFI measurements on some surfaces varied by up to ±30% of the mean value for both naturally occurring surface conditions as well as the prepared ice surfaces. For example, on Flight 99/04 run 6, the table on page D1 shows the lowest individual CRFI measurement of 0.24 being almost 30% below the mean value of 0.34. This high variance can be attributed to the surface condition of 25% bare and dry, 20% compacted snow and 55% loose snow. Although the actual values of the individual CRFI measurements are closer together for the ice covered surfaces, a high percentage of variance can occur because of the lower numbers. On Flight 99/07 run 7 for example, the lowest individual CRFI measurement of 0.16 is almost 25% below the mean value of 0.21, even though the difference between the two is only 0.05.

The two examples used above are extreme cases selected from pages D1 and D2, but an examination of the other CRFI readings shows that a variation of 10 to 20% can usually be expected. In determining the recommended aircraft landing distance as a function of the CRFI, a 20% decrease in the reported CRFI value is used as a safety factor due to variable surface conditions or a change in the surface friction over a period of time. The above data supports the use of this safety factor.

Appendix D, pages D3 through D13, shows individual braking runs, with each data point ($\mu_B$) calculated using equation (3) in section 3.3 paragraph d, and plotted against groundspeed. For each speed band over which full anti-skid braking was maintained, there was little variation of $\mu_B$ with groundspeed as observed in previous test results. For each run, the mean $\mu_B$ and mean groundspeed were calculated as shown on each plot, tabulated on page D1, and plotted on pages D14 and D15 for each of the test surfaces with no or negligible contamination drag.

The plots on pages D14 and D15 show that there is no consistent variation of $\mu_B$ with groundspeed except for the data on Flight 99/05, Runs 1 through 7, which shows a linear trend of decreasing $\mu_B$ with decreasing groundspeed. This occurred on a surface covered with 100% thin ice with some roughness from pavement texture, average CRFI = 0.28. Comparative data from previous testing shows a similar trend for only one surface condition tested, which was 100%

compacted snow with ice patches, average CRFI = 0.25, on flight 98/08 (reference 7). These two surfaces are similar, but this limited data does not support any conclusions on how much influence the physical characteristics of the contamination has on the variation of $\mu_B$ with aircraft groundspeed. Since no clear trend is shown one way or the other, the process of calculating a mean $\mu_B$, independent of groundspeed, for comparison with CRFI is considered to remain valid.

The plots of mean $\mu_B$ versus mean groundspeed for Flight 99/07 on page D15 show $\mu_B \approx 0.07$ for runs 1 and 2, and $\mu_B > 0.10$ for the remaining runs 3 through 8. This is consistent, since the first two runs are on an unsanded ice covered surface, and the remaining points are on a sanded surface. Consistent and repeatable data were obtained for both the aircraft $\mu_B$ points and the measured CRFI values on this surface condition, giving confidence that an increase in aircraft braking coefficient of about 0.05 can be obtained through an application of sand on smooth ice. For this test point, a triple application was sand was actually required, primarily because the wind helped to blow the sand off to the side of the test section.

The last plot of mean $\mu_B$ versus mean groundspeed on page D15 is for Flight 99/08, conducted on a surface which was a combination of wet snow, slush and bare and wet. The first run was done on the whole length of the test section with the variable surface and higher average CRFI (0.25) due to the bare and wet portion. The remaining runs were done on a “patch” of the test section 100% covered with wet snow and slush (CRFI = 0.22). The highest $\mu_B$ point of 0.18 is for the first run, and the other $\mu_B$ points (0.15 to 0.16) are on the remaining runs.

The surface condition of wet snow and slush on Flight 99/08 was very similar, qualitatively, to the only other surface tested previously with some wet snow or slush content, and this was on Flight 98/10, reference 3. Both surfaces were tested in the early March timeframe at an air temperature of close to 0ºC, both were patchy and in the melting stage, and both had aircraft $\mu_B$ results of 0.14 to 0.16. The big difference between the two surfaces was the measured CRFI, which was 0.43 for Flight 98/10, putting the points well below the linear fit between $\mu_B$ and CRFI, and 0.22 for Flight 99/08, putting the points directly on the linear fit line. Reference 3 states that the “reason for the poor braking performance is unknown,” but it is now suspected that the braking performance was as expected on wet snow or slush, and that the CRFI of 0.43 was measured in error, possibly on the bare and wet portion of the test section. Again, this substantiates the need for safety factors to account for variations in both aircraft performance and runway condition reporting.

The plot on page D16 shows the mean $\mu_B$ plotted against the mean CRFI for each of the runs contained in Appendix D (1999 data), together with the data obtained from previous years (1996 through 1998) and the linear fit for the 1996 and 1997 tests, currently used as a basis for the CRFI tables of recommended landing distance. The 1999 data adds a full braking point on a bare and dry surface at the upper right side of the chart, and adds several braking points at the lower CRFI levels down to 0.14 at the lower left side. The 1999 data falls close to the linear fit, except for the points on the unsanded smooth ice, CRFI = 0.14, $\mu_B = 0.07$. This will be discussed further in section 5.1, which will address the influence of the 1999 Falcon 20 data on the CRFI tables of recommended landing distance published in the AIP.

### 4.5 Contamination Drag

Appendix E summarises the test runs to determine the contamination drag for only one surface condition which occurred naturally during the 1999 test period. This was about 40% bare and dry with 60% loose snow drifts of 1.2 inch average depth, on Flight 99/03. Pages E2 and E3 show the variation of the drag parameter $D_{CONTAM}/W$ (calculated using equation (4) in section 3.3 paragraph e) with ground speed for each individual run, where $D_{CONTAM}$ is the contamination drag and W is the aircraft weight.

For each run an average $D_{CONTAM}/W$ and average ground speed have been calculated. These values are shown in the table on page E1, and are plotted on page E4. It is obvious from the table and from the plots that there is essentially zero contamination drag for the surface tested. No additional data from the current Falcon 20 test period is available to add to the existing database. Reference 7 covers the previous test results for contamination drag.

### 4.6 Aircraft Braking Coefficient on Runway Surfaces with Appreciable Contamination Drag

Appendix F summarises the test runs to determine the aircraft braking coefficient ($\mu_B$) on runway surfaces with appreciable contamination drag.  Only one such surface was tested during the 1998/1999 test period, and this was on Flight 99/03, where the contamination drag actually turned out to be essentially zero, as described above.

Pages F2 and F3 show individual braking runs, with each data point ($\mu_B$) calculated using equation (5) in section 3.3 paragraph f, and plotted against groundspeed. The value of the contamination drag parameter $D_{CONTAM}/W$ was set to zero in equation (5) for all braking runs, rather than using the individual values of this parameter obtained for each run (listed in Appendix E). The five plots of $\mu_B$ versus groundspeed show a considerable amount of variance from the mean value. Although some of this is scatter, the primary reason is the large variations in aircraft deceleration caused by the action of the anti-skid system on the variable surface condition. Because $\mu_B$ is calculated directly from the recorded deceleration (Appendix A, pages A7 and A8) without smoothing or averaging, the changes in deceleration are transferred directly to the calculated values of $\mu_B$.

The plots on page F2 show little variation of $\mu_B$ with groundspeed for the first four runs on Flight 99/03, but the plot for run 5 on page F3 shows a trend of decreasing $\mu_B$ with decreasing groundspeed over the wide speed band, from 120 knots down to 30 knots, over which full anti-skid braking was maintained. This is consistent with the trend observed for some of the previous tests on surfaces both with and without appreciable contamination drag. The plot of the mean $\mu_B$'s versus mean groundspeeds on page F4 shows the same trend, but this could also be due to the increasing value of CRFI as the runs progressed from low to high speed. The plot of the mean $\mu_B$'s versus CRFI on page F5 shows good agreement with the linear fit for the 1996 and 1997 tests, currently used as a basis for the CRFI tables of recommended landing distance.

CRFI measurements were not taken between runs on Flight 99/03, due to occasional inbound traffic on runway 08, which restricted the aircraft only to perform tests between aircraft arrivals, but restricted the ERD vehicle from entering the runway at all, except for before the start of aircraft tests and well after the termination of tests. As a result, the CRFI's for each run were interpolated with respect to time, rather than directly measured. This was a disadvantage of using the operational runway for testing.

## 5.0 CRFI TABLE UPDATE

In Reference 7, Falcon 20 full anti-skid braking data was used to derive a deceleration model which, in turn, was used to generate the stopping distances used for the CRFI tables of recommended landing distance on contaminated runway surfaces. The deceleration model was based on the linear fit between $\mu_B$ and CRFI obtained from data collected over a three year period. In this report, the effect of the 1998/1999 $\mu_B$ data on the deceleration model will be discussed, and additional data on air distance and delay distance will be used to update the CRFI tables. In addition, the effect of reverse thrust or propeller discing on stopping distance will be examined, and a separate CRFI table will be developed for this case.

### 5.1 Falcon 20 Mu Braking versus CRFI

Figure 6 shows $\mu_B$ versus CRFI data for the Falcon 20 in the landing configuration on runway surfaces with a uniform distribution of contamination and minimal contamination drag. The data was obtained for maximum anti-skid braking runs over a four year period from 1996 through 1999 and includes 67 data points on 23 different runway surface conditions. The effect of contamination drag, however minor, is retained in the Mu Braking term in order to compare the aircraft deceleration due to friction and drag effects with the deceleration measured by the ERD as a function of the same effects.

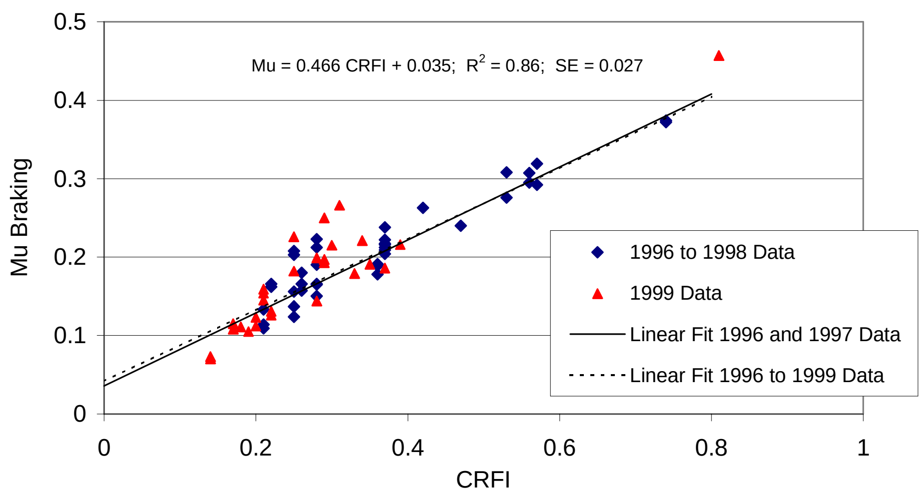


Figure 6
Falcon 20 Mu Braking versus CRFI, Landing Configuration, 1996 through 1999

In Figure 6, the distinction can be seen between the first three years of data obtained for a range of CRFI's between 0.2 and 0.8, and the 1999 data for mostly lower CRFI's between 0.14 and 0.40. The linear fit for the 1996 and 1997 data is shown as a solid line, and the linear fit for all four years of data is shown as a dashed line. The two lines are very close, with the solid line slightly more conservative than the dashed line at the lower CRFI values. Consequently, no changes were made to the Falcon 20 deceleration model as a result of the 1999 $\mu_B$ data.

Figure 7 shows $\mu_B$ versus CRFI data for the Falcon 20 in both landing and RTO configurations, and on all contaminated runway surfaces tested. This represents all the data obtained for the maximum anti-skid braking runs over the four year period from 1996 through 1999, or a total of 126 data points on 35 different runway surface conditions. Again, the effect of contamination drag is retained in the Mu Braking term in order to make a direct comparison between the aircraft and ERD decelerations.

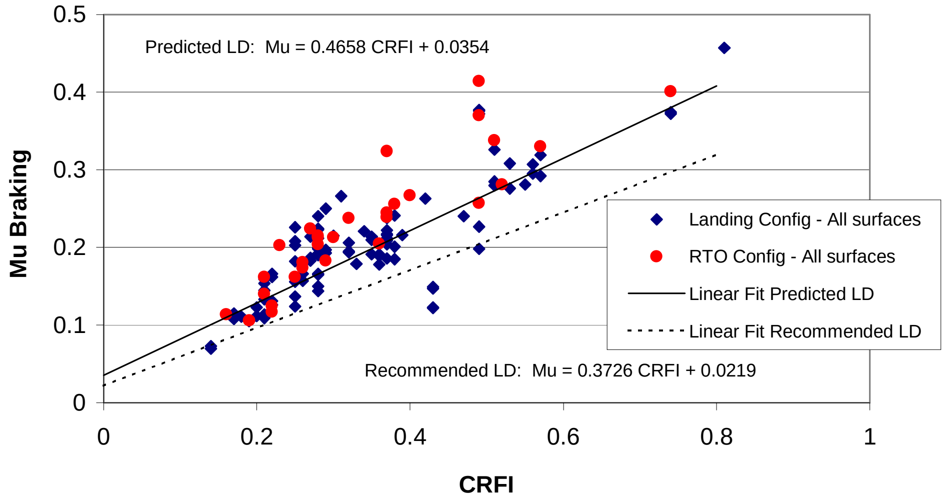


Figure 7
Falcon 20 Mu Braking versus CRFI, All Data 1996 - 1999

The upper solid line in Figure 7 represents the linear fit of $\mu_B$ versus CRFI shown in Figure 6 and described by the equation: $\mu_B = 0.0354 + 0.4658 \times \text{CRFI}$. This relationship is used to determine the predicted landing distance without safety factors as described in Reference 7. The lower dashed line modifies this linear fit by subtracting a value of 0.0135, and lowering the slope by 20% to give the equation: $\mu_B = 0.0219 + 0.8 \times 0.4658 \times \text{CRFI}$. This relationship is used in the calculation of the recommended landing distance, with safety factors. A safety factor of 95% was achieved in Reference 7 with four out of 89 points below the line, and the same safety factor is achieved after the additional year of testing with six out of 126 points below the line (two pairs of overlaid points appear as two points in Figure 7). Therefore, no changes were made to the Reference 7 CRFI table of recommended landing distance based on the aircraft stopping distance, with or without safety factors.

### 5.2 Falcon 20 Air Distance and Delay Distance

The total landing distance (LD) is defined as the distance from a height of 50 feet above the runway threshold to a complete stop. Total landing distance LD = D1+D2+D3, where D1 is the air distance from 50 feet to aircraft touchdown, D2 is the delay distance from touchdown to the application of full braking and D3 is the braking distance (or stopping distance) from the application of full braking to a complete stop. Falcon 20 performance landings were flown to establish a statistical database for distances D1 and D2. The original CRFI tables (Reference 1) and the version 2 CRFI tables (Reference 7) were based on the database for the 1996 test period. The additional data from the 1997 through 1999 test periods were added to the database to update the equations for D1 and D2, resulting in some minor changes to the CRFI tables. The updated equations for the recommended air and delay distances, D1R and D2R, which include safety factors, are as follows:

$$D1R = 1.55 \times (V_{G50} - 80)^{1.35} + 964 + (V_{G50} - 6.52) \times 1.688 \times 1.56 \qquad (ft) \tag{1}$$

$$D2R = (V_{G50} - 6.52 + V_{G50} - 13.44)/2 \times 1.688 \times 2.96 + (V_{G50} - 13.44) \times 1.688 \times 1.86 \quad (ft) \tag{2}$$

These equations provide distances slightly lower than those given by the equivalent equations in Reference 7. The two sigma safety factor for D1R is the distance equivalent of 1.56 seconds and the two sigma safety factor for D2R is the distance equivalent of 1.86 seconds. With a mean delay time of 2.96 seconds shown in equation (2), the total delay distance for example, with no safety factor, is about 600 feet at a groundspeed of 120 knots. With a 95% safety factor, the total delay distance is equal to 4.83 seconds multiplied by the aircraft groundspeed, or about 980 feet.

To complete the equations needed for the recommended landing distances, the recommended braking distance D3R, is computed from the following (unchanged) equations from reference 7:

$$D3R = (V_{GFB} \times 1.688)^2 \div (64.348 \times ACCR_{AV}) \qquad (ft) \tag{3}$$

where the average (recommended) deceleration, $ACCR_{AV}$, is given by:

$$ACCR_{AV} = \left(\frac{600}{W} - 0.0219 - 0.4658 \times 0.8 \times CRFI\right) + \left(\frac{-4.62}{W}\right) \times \frac{V_{EFB}}{\sqrt{2}} + \left(\frac{-0.1874}{W} + \frac{0.2087 \times 0.8 \times CRFI}{W}\right) \times \frac{V_{EFB}^2}{2}$$

Equations (1), (2), and (3) together are used to compute the recommended landing distances in Table 1 of this report, section 5.4.

### 5.3 Reverse Thrust Effect on Braking Distance

One of the acknowledged deficiencies of the current version of the CRFI table of recommended landing distances, which does not include credit for reverse thrust, is that the data may be too conservative for contaminated runways on which turbojet powered aircraft can operate thrust reverser systems, or on which turbopropeller powered aircraft can operate propeller reversing systems. This conservatism could lead to these aircraft needlessly returning to origin or diverting to an alternate airport when there is sufficient runway distance available for a safe landing with the use of reverse thrust. Reference 8 contains an analysis of the effects of reverse thrust on the aircraft stopping distance on low friction runways, and recommends amending the current CRFI Table to account for these effects. In this section, the analysis in reference 8 will be summarized, and a second CRFI Table will be developed to include credit for reverse thrust.

For a turbojet aircraft, no credit is taken for the use of thrust reverse in establishing the Airplane Flight Manual landing distance (AFM LD) on a dry runway. The stopping distance D3 with reverse can therefore be compared directly to the stopping distance D3 without reverse for the purpose of amending the CRFI Table, which uses AFM LD as an entry point. Table 1 shows the effect of reverse thrust on the stopping distance of a representative turbojet aircraft for rejected takeoffs on low friction (contaminated) runways. The data are also considered to be applicable to the stopping distance D3 in a landing. The thrust reverser system used to obtain these data is considered to have low to medium effectiveness in producing reverse thrust.

| **Aircraft Braking Coefficient (MuB)** | **Ratio of MuB to MUB (dry)** | **Decision Speed V1 (KEAS)** | **D3 without reverse (ft)** | **D3 with reverse (ft)** | **Ratio of D3 with reverse to D3 without reverse** |
|---|---|---|---|---|---|
| 0.5 | 1.0 | 132.4 | 1979 | 1852 | 0.94 |
| | | 103.9 | 1268 | 1231 | 0.97 |
| 0.35 | 0.7 | 132.4 | 2670 | 2365 | 0.89 |
| | | 103.9 | 1761 | 1627 | 0.92 |
| 0.25 | 0.5 | 132.4 | 3586 | 2958 | 0.82 |
| | | 103.9 | 2403 | 2080 | 0.87 |
| 0.15 | 0.3 | 132.4 | 5556 | 3988 | 0.72 |
| | | 103.9 | 3843 | 2906 | 0.76 |
| 0.05 | 0.1 | 132.4 | 13639 | 6579 | 0.48 |
| | | 103.9 | 10462 | 5162 | 0.49 |
| | | | | | |

Table 1
Effect of Reverse Thrust on Stopping Distance for a Turbojet Aircraft

In Table 1, the aircraft braking coefficient ratio (MuB ratio) is the ratio of MuB on a contaminated surface to Mub on a dry surface. The stopping distance ratio (D3 ratio) is the ratio of D3 with reverse to D3 without reverse. Data are presented for two different speeds on each surface condition. The D3 ratios in the right hand column of Table 1 show that reverse thrust is not significant on a dry runway, with a D3 ratio of 0.94 to 0.97, but is much more effective when combined with the lower braking coefficients on a contaminated runway. For example, the stopping distance is approximately halved by using reverse thrust on a very slippery surface where MuB = 0.05.

The analysis is slightly different for a turbopropeller aircraft in that most of these aircraft take credit for "discing" in the determination of the AFM LD on a dry runway. Discing is defined as a propeller blade position and propeller speed which produces zero thrust at zero forward airspeed. The discing drag (or reverse thrust) increases rapidly with increasing airspeed and is a significant component in the deceleration of a turbopropeller powered aircraft, even on a dry runway.

Because the dry runway landing distance already includes credit for propeller discing, a D3 ratio similar to that used in the turbojet case cannot be used directly to determine the effect of propeller discing on the CRFI table data. Instead, the "quotient" of D3 ratios will be made, where each D3 ratio is defined as the ratio of the stopping distance on a contaminated runway to the stopping distance on a dry runway. The quotient is formed by dividing the D3 ratio with discing by the D3 ratio without discing. Table 2 contains data representative of a turboprop aircraft, and is similar in layout to Table 1, except that D3 ratios are listed in columns 4 and 5, and the quotients of D3 ratios are listed in the right hand column.

| **Aircraft Braking Coefficient (MuB)** | **Ratio of MuB to MuB (dry)** | **Full Braking Speed (KEAS)** | **D3 Ratio without Discing** | **D3 Ratio with Discing** | **D3 Ratio with Discing / D3 Ratio without Discing** |
|---|---|---|---|---|---|
| 0.620 | 1.0 | 100 | 1.0 | 1.0 | 1.0 |
| 0.593 | 1.0 | 80 | 1.0 | 1.0 | 1.0 |
| 0.434 | 0.7 | 100 | 1.41 | 1.31 | 0.93 |
| 0.415 | 0.7 | 80 | 1.42 | 1.34 | 0.94 |
| 0.310 | 0.5 | 100 | 1.92 | 1.64 | 0.85 |
| 0.296 | 0.5 | 80 | 1.97 | 1.74 | 0.88 |
| 0.214 | 0.3 | 100 | 2.69 | 2.05 | 0.76 |
| 0.178 | 0.3 | 80 | 3.14 | 2.45 | 0.78 |
| 0.071 | 0.1 | 100 | 6.67 | 3.28 | 0.49 |
| 0.059 | 0.1 | 80 | 8.14 | 4.20 | 0.52 |
| | | | | | |

Table 2
Effect of Reverse Thrust on Stopping Distance ratios for a Turboprop Aircraft

A comparison of the above two tables shows the D3 ratios in the right hand column of table 1 to be similar to the quotients of D3 ratios in the right hand column of table 2, for the same corresponding values of MuB ratios. Because of the similarity of data for the two aircraft types, it is possible to derive a generic effect on stopping distances for aircraft with thrust reverser systems or propeller reversing systems. A stopping distance "factor," defined as the generic aircraft D3 ratio with reverse/discing to the D3 ratio without reverse/discing, can be determined as a function of the MuB ratio, as shown in Figure 8.

In Figure 8, the stopping distance ratios, or quotients, are plotted against the MuB ratios for both aircraft types. A second order curve is shown for a generic aircraft, and this curve is chosen on the conservative side at MuB ratios down to about 0.20. The over-conservatism of the curve at a Mub ratio of 0.10 has no effect on the analysis, since this low value of MuB is equivalent to a CRFI of less than 0.05, which is well below the minimum CRFI of 0.18 in the CRFI Tables. The relationship shown on the chart in Figure 8 for the generic aircraft D3 ratio will be used to determine the stopping distance factor.

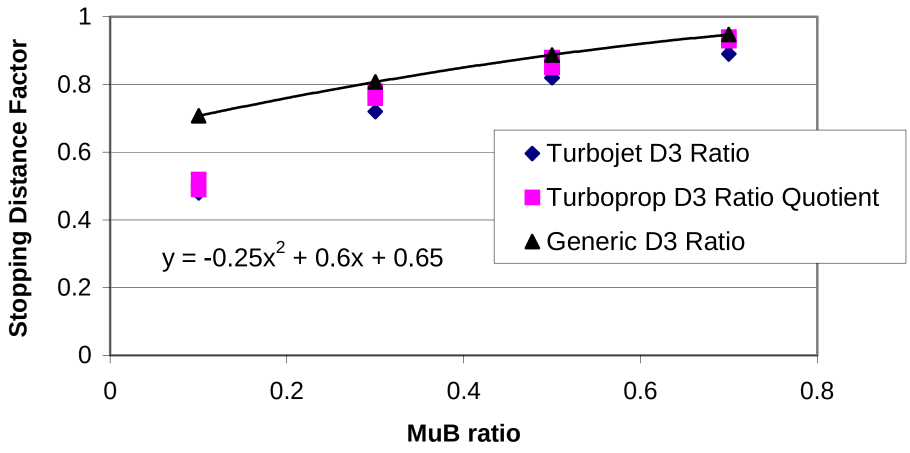


Figure 8
Stopping Distance Ratios versus Mu Braking Ratios

To determine the effect of reverse thrust on the CRFI Table data, the stopping distance factor is applied to the stopping distance without reverse thrust in the current CRFI Table (at the corresponding Mu Braking ratio) to obtain the stopping distance with reverse thrust. The Mu Braking ratio is determined from the value of the CFRI, using the relationship which has been established for the Falcon 20, considered to be generally applicable to other aircraft. The following equations are used for these calculations:

$$\begin{aligned} &MuB = 0.0354 + 0.4658 \times CRFI \\ &MuB\ ratio = MuB / MuB_{DRY}\ , \quad where\ MuB_{DRY} = 0.408\ at\ CRFI = 0.8 \end{aligned} \tag{4}$$

$$\begin{aligned} &SD\ Factor = 0.65 + 0.6 \times MuB\ ratio - 0.25 \times (MuB\ ratio)^2 \\ &D3R\ (reverse) = D3R\ (no\ reverse) \times SD\ Factor \\ &LDR\ (reverse) = D1R + D2R + D3R\ (reverse) \end{aligned} \tag{5}$$

To ensure the CRFI Table of recommended Landing Distance, with reverse thrust, remains conservative, it is assumed that the effectiveness of the thrust reverser system or propeller reversing system will be similar to, or better than, the systems used for this analysis. It is also assumed that thrust reverse on a turbojet aircraft will be reduced to idle reverse at 60 KEAS. For turboprop aircraft full reverse would be available, but no more than discing reverse thrust is assumed.

| *Reported Canadian Runway Friction Index (CRFI)* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landing Distance | 0.60 | 0.55 | 0.50 | 0.45 | 0.40 | 0.35 | 0.30 | 0.27 | 0.25 | 0.22 | 0.20 | 0.18 | Landing Field Length | Landing Field Length |
| Bare and Dry | **Recommended Landing Distances (no Reverse Thrust)** | | | | | | | | | | | | Bare and Dry | Bare and Dry |
| Unfactored | | | | | | | | | | | | | 60% Factor | 70% Factor |
| 1 800 | 3 180 | 3 260 | 3 360 | 3 480 | 3 610 | 3 780 | 3 970 | 4 120 | 4 220 | 4 400 | 4 540 | 4 690 | 3 000 | 2 571 |
| 2 000 | 3 550 | 3 650 | 3 770 | 3 910 | 4 070 | 4 260 | 4 490 | 4 660 | 4 780 | 4 990 | 5 150 | 5 330 | 3 333 | 2 857 |
| 2 200 | 3 800 | 3 910 | 4 050 | 4 200 | 4 380 | 4 590 | 4 850 | 5 030 | 5 170 | 5 410 | 5 580 | 5 780 | 3 667 | 3 143 |
| 2 400 | 4 190 | 4 320 | 4 470 | 4 640 | 4 840 | 5 080 | 5 370 | 5 570 | 5 730 | 5 980 | 6 180 | 6 390 | 4 000 | 3 429 |
| 2 600 | 4 550 | 4 700 | 4 860 | 5 050 | 5 270 | 5 530 | 5 850 | 6 080 | 6 240 | 6 520 | 6 730 | 6 970 | 4 333 | 3 714 |
| 2 800 | 4 830 | 4 980 | 5 160 | 5 360 | 5 600 | 5 880 | 6 220 | 6 460 | 6 630 | 6 930 | 7 150 | 7 400 | 4 667 | 4 000 |
| 3 000 | 5 190 | 5 360 | 5 560 | 5 780 | 6 040 | 6 360 | 6 730 | 7 000 | 7 190 | 7 520 | 7 770 | 8 040 | 5 000 | 4 286 |
| 3 200 | 5 580 | 5 770 | 5 980 | 6 230 | 6 520 | 6 870 | 7 280 | 7 570 | 7 790 | 8 150 | 8 430 | 8 730 | 5 333 | 4 571 |
| 3 400 | 5 880 | 6 090 | 6 320 | 6 590 | 6 900 | 7 270 | 7 720 | 8 030 | 8 260 | 8 650 | 8 950 | 9 270 | 5 667 | 4 857 |
| 3 600 | 6 200 | 6 420 | 6 660 | 6 950 | 7 290 | 7 680 | 8 160 | 8 500 | 8 750 | 9 170 | 9 480 | 9 830 | 6 000 | 5 143 |
| 3 800 | 6 500 | 6 740 | 7 000 | 7 310 | 7 660 | 8 090 | 8 600 | 8 960 | 9 220 | 9 670 | 10 010 | 10 380 | 5 333 | 5 429 |
| 4 000 | 6 710 | 6 960 | 7 230 | 7 550 | 7 920 | 8 360 | 8 890 | 9 270 | 9 540 | 10 010 | 10 360 | 10 750 | 6 667 | 5 714 |

Figure 9
CRFI Table of Recommended Landing Distances (no Reverse Thrust)

## 5.4 New CRFI Tables of Recommended Landing Distance

With the application of the changes described in the two previous sections, the modified CRFI Tables of recommended landing distances are shown in Figures 9 and 10.

It is recommended that the data in Figure 9 be used to update the previous versions of the CRFI Table of recommended landing distances with no reverse thrust (currently entitled “Table 1” in the AIP). It is also recommended that the data in Figure 10 be used to create a new “Table 2” of recommended landing distances for aircraft with operable thrust reversers or operable propeller reverse systems.

| *Reported Canadian Runway Friction Index (CRFI)* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Landing Distance | 0.60 | 0.55 | 0.50 | 0.45 | 0.40 | 0.35 | 0.30 | 0.27 | 0.25 | 0.22 | 0.20 | 0.18 | Landing Field Length | Landing Field Length |
| Bare and Dry | **Recommended Landing Distances (with Reverse Thrust)** | | | | | | | | | | | | Bare and Dry | Bare and Dry |
| Unfactored | | | | | | | | | | | | | 60% Factor | 70% Factor |
| 1 800 | 3 130 | 3 200 | 3 270 | 3 350 | 3 450 | 3 560 | 3 690 | 3 790 | 3 860 | 3 970 | 4 060 | 4 150 | 3 000 | 2 571 |
| 2 000 | 3 500 | 3 580 | 3 660 | 3 760 | 3 870 | 4 000 | 4 160 | 4 270 | 4 350 | 4 480 | 4 580 | 4 700 | 3 333 | 2 857 |
| 2 200 | 3 740 | 3 830 | 3 930 | 4 040 | 4 160 | 4 310 | 4 480 | 4 600 | 4 690 | 4 840 | 4 950 | 5 080 | 3 667 | 3 143 |
| 2 400 | 4 130 | 4 220 | 4 330 | 4 460 | 4 590 | 4 760 | 4 950 | 5 080 | 5 180 | 5 340 | 5 460 | 5 600 | 4 000 | 3 429 |
| 2 600 | 4 480 | 4 590 | 4 710 | 4 840 | 4 990 | 5 170 | 5 380 | 5 520 | 5 630 | 5 810 | 5 940 | 6 080 | 4 333 | 3 714 |
| 2 800 | 4 740 | 4 860 | 4 990 | 5 130 | 5 300 | 5 490 | 5 710 | 5 860 | 5 970 | 6 160 | 6 300 | 6 450 | 4 667 | 4 000 |
| 3 000 | 5 100 | 5 230 | 5 370 | 5 530 | 5 710 | 5 920 | 6 170 | 6 340 | 6 460 | 6 670 | 6 820 | 6 990 | 5 000 | 4 286 |
| 3 200 | 5 480 | 5 620 | 5 780 | 5 960 | 6 160 | 6 390 | 6 660 | 6 840 | 6 980 | 7 210 | 7 380 | 7 560 | 5 333 | 4 571 |
| 3 400 | 5 780 | 5 930 | 6 100 | 6 290 | 6 510 | 6 750 | 7 040 | 7 250 | 7 390 | 7 640 | 7 820 | 8 020 | 5 667 | 4 857 |
| 3 600 | 6 080 | 6 250 | 6 430 | 6 630 | 6 860 | 7 130 | 7 440 | 7 660 | 7 820 | 8 080 | 8 270 | 8 490 | 6 000 | 5 143 |
| 3 800 | 6 380 | 6 560 | 6 750 | 6 970 | 7 210 | 7 500 | 7 830 | 8 060 | 8 230 | 8 510 | 8 720 | 8 940 | 5 333 | 5 429 |
| 4 000 | 6 590 | 6 770 | 6 970 | 7 200 | 7 450 | 7 750 | 8 100 | 8 330 | 8 510 | 8 800 | 9 010 | 9 250 | 6 667 | 5 714 |

Figure 10
CRFI Table of Recommended Landing Distances (with Reverse Thrust)

## 6.0 CONCLUSIONS

During the winter of 1998/1999, a total of seven different contaminated runway surfaces were tested during six separate test sessions in North Bay. The results of the tests provided some new information on aircraft braking performance on runway surfaces with very low CRFI values, such as those covered with smooth ice. The results of 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 process of measuring the runway friction index between each aircraft braking run worked well to minimise the data scatter resulting from the effects of changing surface friction over the duration of the test session;

b. Falcon 20 slip ratio data showed the anti-skid system to be well designed for variable tire to surface friction characteristics on winter contaminated surfaces, with the exception that the magnitude of wheel speed cycling increased rapidly on surfaces covered with smooth ice, CRFI less than about 0.20;

c. Falcon 20 wheel slip ratios tended to increase with decreasing aircraft groundspeed, on various contaminated surfaces, and the left wheel pair had a consistently higher mean slip ratio than the right wheel pair during full anti-skid braking runs;

d. The independent operation of the Falcon 20 left and right anti-skid systems caused lateral heading oscillations of about 10 degrees during full braking runs on a widely varying contaminated runway surface, typical of many operational surfaces;

e. Directional control of the aircraft was lost briefly, due to low cornering friction, on a slow speed braking run on smooth ice, average CRFI = 0.14. The aircraft departed the test section laterally, but was recovered on the edge of the runway which was kept bare and dry in the event of such an occurrence;

f. The Falcon 20 braking coefficients obtained on runway surfaces with a uniform distribution of contamination, and with minimal contamination drag, were consistent with the existing correlation between braking coefficients and the CRFI value;

g. No changes were made to the existing Falcon 20 full braking deceleration model as a result of the additional 1999 data, but the CRFI table of recommended landing distances, with no reverse thrust, was updated to reflect additional air distance and delay distance data for performance landings;

h. A CRFI table of recommended landing distances, with reverse thrust included, was developed by analysing data from other aircraft tests for the effects of reverse thrust on stopping distance;

i. As stated in the references for previous testing, the measurement of aircraft braking performance and contamination drag on winter contaminated runway surfaces is not an exact science. Although attempts are made to minimise it, considerable scatter is evident in the test results due to variation in the parameters involved. The test results contained in this report and the comparison with previous results confirm that care must be taken when using these types of measurements to establish models for certification and operational performance.

## 7.0 RECOMMENDATIONS

### 7.1 Test Procedures

From experience gained during this phase of the test program, the recommendations made in Reference 7 regarding test procedures and limitations should be retained for future testing. The following additional procedures should be implemented on ice covered surfaces:

a. Maximum crosswind should be five (5) knots for braking runs on contaminated test sections with a measured CRFI of 0.20 or less;

b. Since the Falcon 20 rudder effectiveness is marginal below about 80 knots, a build-up technique should be used in evaluating aircraft directional control (cornering friction) during braking on ice covered surfaces at very low speeds (20 to 40 knots) before proceeding to higher speed test points (40 to 80 knots).

## 7.2 Falcon 20 Tests

The following recommendations are made with respect to future Falcon 20 tests:

a. Determine the aircraft braking coefficient and wheel slip ratios on contaminated runway surfaces with lower friction index values;

b. Determine a method of predicting the aircraft braking performance on operationally representative runway surfaces with widely varying friction index values;

c. Determine the contamination drag and the effect of groundspeed on contamination drag on surfaces covered with natural snow. The physical characteristics of the snow should be recorded;

e. Establish the effect of low ambient temperatures on the ERD friction index (CRFI) and aircraft braking coefficient.

## 7.3 Test Result Coordination

With respect to the overall program, the following recommendations are made:

a. The results from the Falcon 20 should be compared to those from the NASA B737 and B757, the FAA B727 and the deHavilland DHC-8; and

c. A correlation should be established between the aircraft braking coefficients and the International Runway Friction Index (IFRI), using existing data as a baseline, and conducting tests on various aircraft types against the IRFI Reference vehicle.

# 8.0 ACKNOWLEDGEMENTS

The authors are indebted to the many people who contributed to the success of this project over the four years of testing so far completed. These include 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 coordination and financial administration, the Transport Canada Airports Branch who coordinated 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


| | | |
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| 8. | 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 A18 show the time histories of ground speed, acceleration, left brake pressure and right brake pressure for each run (up to 4 runs per page). 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) |
|---|---|---|---|---|---|---|---|
| 99/01<br>25/01/99 | 1<br>11:04 | 31 | TAXI | 15/IN/NO | 21050 | 0 | 100% Bare and Dry |
| | 2<br>11:10 | 13 | TAXI | 15/IN/NO | 21000 | 0 | " |
| | 3<br>11:18 | 26 | TAXI | 15/IN/NO | 20900 | 0 | " |
| | 4<br>11:27 | 08 | TAXI | 15/IN/NO | 20850 | 0 | " |
| | 5<br>11:54 | 08 | LAND | 15/IN/NO | 20100 | 0 | " |
| | 6<br>12:15 | 31 | LAND | 40/OUT/B | 19250 | 0 | 100% Bare and Dry<br>Air Temperature -7<br>CRFI from 0.79 to 0.84, Average 0.81 |
| | 7<br>12:38 | 31 | LAND | 15/OUT/B | 18550 | 0 | No data due to instrumentation system failure |
| 99/02<br>26/01/99 | 1<br>11:09 | 26 | LAND | 40/OUT/NO | 21110 | +12 | 100% Bare and Dry |
| | 2<br>11:29 | 26 | LAND | 15/OUT/NO | 20310 | +12 | " |
| 99/03<br>28/01/99 | 1a<br>10:48 | 08 | RTO | 40/OUT/B | 23250 | +9 | 50% Bare and Dry, 50% Loose Snow in Drifts changing to 30% Bare and Dry, 70% Loose Snow in Drifts.<br>Average Depth of Snow in Drifts 1.2 inch<br>Average Specific Gravity 0.12<br>Air Temperature -13, Surface Temperature -11<br>CRFI from 0.30 to 0.36, Average 0.33 |
| | 1b | " | " | 40/OUT/NO | " | " | " |
| | 2a<br>11:01 | 08 | RTO | 40/OUT/B | 22950 | +7 | CRFI Average 0.35 (see Note 3) |
| | 2b | " | " | 40/OUT/NO | " | " | " |
| | 3a<br>11:14 | 08 | RTO | 40/OUT/B | 22700 | +5 | CRFI Average 0.36 (see Note 3) |
| | 3b | " | " | 40/OUT/NO | " | " | " |
| | 4a<br>11:28 | 08 | RTO | 40/OUT/B | 22450 | +7 | CRFI Average 0.38 (see Note 3) |
| | 4b | " | " | 40/OUT/NO | " | " | " |
| | 5a<br>11:42 | 08 | RTO | 15/OUT/B | 21850 | +7 | CRFI from 0.36 to 0.44, Average 0.40<br>" |

| FLT/ DATE | RUN/ TIME | RW | TAXI/ RTO/ LAND | CONFIG (see Note 1) | WEIGHT (LB) | HW (KT) | SURFACE DESCRIPTION (see Note 2) |
|---|---|---|---|---|---|---|---|
| | 5b | " | RTO | 15/OUT/NO | " | " | " |
| 99/04 28/01/99 | 1 14:38 | 31 | RTO | 40/OUT/B | 21450 | -2 | 20% Bare and Dry, 20% Compacted Snow, 60%Loose Snow changing to 30% Bare and Dry, 20% Compacted Snow, 50% Loose Snow. Average Depth of Loose Snow 0.25 inch. Specific Gravity not recorded. Air Temperature -11 CRFI from 0.23 to 0.36, Average 0.29 |
| | 2 14:42 | 31 | RTO | 40/OUT/B | 21350 | -2 | CRFI from 0.26 to 0.38, Average 0.30 |
| | 3 14:49 | 31 | RTO | 40/OUT/B | 21250 | -3 | CRFI from 0.25 to 0.37, Average 0.31 |
| | 4 15:00 | 31 | RTO | 40/OUT/B | 21000 | -2 | No data due to instrumentation system failure |
| | 5 15:15 | 31 | RTO | 15/OUT/B | 20750 | -3 | CRFI from 0.23 to 0.43, Average 0.30 |
| | 6 15:36 | 31 | RTO | 40/OUT/B | 20400 | -3 | CRFI from 0.24 to 0.40, Average 0.34 |
| 99/05 29/01/99 | 1 10:21 | 31TS | RTO | 40/OUT/B | 22760 | 0 | 100% Thin Ice with some Roughness from Pavement Texture Air temperature -12 CRFI from 0.25 to 0.32, Average 0.28 |
| | 2 10:28 | 31TS | RTO | 40/OUT/B | 22560 | 0 | CFRI from 0.28 to 0.30, Average 0.29 |
| | 3 10:34 | 31TS | RTO | 15/OUT/B | 22310 | 0 | CRFI from 0.22 to 0.25, Average 0.23 |
| | 4 10:59 | 31TS | LAND | 40/OUT/B | 21810 | 0 | CRFI from 0.21 to 0.30, Average 0.25 |
| | 5 11:06 | 31TS | RTO | 15/OUT/B | 21410 | 0 | CRFI from 0.25 to 0.27, Average 0.26 |
| | 6 11:29 | 31TS | LAND | 40/OUT/B | 21010 | 0 | CRFI from 0.24 to 0.34, Average 0.29 |
| | 7 11:35 | 31TS | RTO | 40/OUT/B | 20660 | 0 | CRFI from 0.22 to 0.34, Average 0.28 |
| 99/06 29/01/99 | 1 15:34 | 31TS | RTO | 40/OUT/B | 22900 | 0 | 100% Ice with One Application of Sand changing to 100% Ice with One Application of Sand and 0.1 inch Loose Snow Layer. Air Temperature -10 CRFI from 0.15 to 0.22, Average 0.19 |
| | 2 15:40 | 31TS | RTO | 40/OUT/B | 22600 | 0 | CRFI from 0.16 to 0.20, Average 0.18 |
| | 3 15:46 | 31TS | RTO | 40/OUT/B | 22500 | 0 | CRFI from 0.19 to 0.22, Average 0.20 |
| | 4 15:56 | 31TS | RTO | 40/OUT/B | 22350 | -1 | CRFI from 0.14 to 0.19, Average 0.17 |

| FLT/ DATE | RUN/ TIME | RW | TAXI/ RTO/ LAND | CONFIG (see Note 1) | WEIGHT (LB) | HW (KT) | SURFACE DESCRIPTION (see Note 2) |
|---|---|---|---|---|---|---|---|
| | 5<br>16:06 | 31TS | RTO | 15/OUT/B | 22150 | -1 | CRFI from 0.13 to 0.20, Average 0.16 |
| | 6<br>16:12 | 31TS | RTO | 15/OUT/B | 21900 | -1 | CRFI from 0.15 to 0.23, Average 0.19 |
| 99/07<br>9/03/99 | 1<br>08:45 | 31TS | RTO | 40/OUT/B | 21490 | -6 | 100% Ice, No sand<br>Air Temperature changing from -7 to -4<br>CRFI from 0.12 to 0.16, Average 0.14 |
| | 2<br>08:54 | 31TS | RTO | 40/OUT/B | 21390 | -6 | 100% Ice, No sand<br>CRFI from 0.12 to 0.16, Average 0.14 |
| | 3<br>09:35 | 31TS | RTO | 40/OUT/B | 20490 | -10 | 100% Ice, sanded<br>CRFI from 0.16 to 0.17, Average 0.17 |
| | 4<br>09:47 | 31TS | RTO | 40/OUT/B | 20340 | -8 | 100% Ice, sanded<br>CRFI from 0.17 to 0.28, Average 0.22 |
| | 5<br>10:02 | 31TS | RTO | 40/OUT/B | 20010 | -8 | 100% Ice, sanded<br>CRFI from 0.17 to 0.31, Average 0.22 |
| | 6<br>10:19 | 31TS | RTO | 40/OUT/B | 19490 | -8 | 100% Ice, sanded<br>CRFI from 0.17 to 0.31, Average 0.22 |
| | 7<br>10:46 | 31TS | RTO | 15/OUT/B | 18740 | -8 | 100% Ice, sanded<br>CRFI from 0.16 to 0.26, Average 0.21 |
| | 8<br>11:00 | 31TS | RTO | 15/OUT/B | 18540 | -8 | 100% Ice, sanded<br>CRFI from 0.17 to 0.30, Average 0.22 |
| 99/08<br>23/03/99 | 1<br>16:24 | 31TS | RTO | 40/OUT/B | 22040 | 4 | 30% slush , 50% wet snow, 20% bare and wet.<br>Depth of snow and slush 0.25 to 0.5 inch<br>Air Temperature -2<br>CRFI from 0.20 to 0.29, Average 0.25 |
| | 2<br>16:30 | 31TS (see Note 4) | RTO | 40/OUT/B | 21840 | 4 | 80% moist snow, 20% slush (see Note 4)<br>Depth of snow and slush 0.25 to 0.5 inch<br>Snow patch used for braking runs<br>CRFI from 0.20 to 0.25, Average 0.22 |
| | 3<br>16:39 | 31TS (see Note 4) | RTO | 40/OUT/B | 21640 | 5 | 80% moist snow, 20% slush (see Note 4)<br>Snow patch used for braking runs<br>CRFI from 0.20 to 0.25, Average 0.22 |
| | 4<br>16:46 | 31TS (see Note 4) | RTO | 40/OUT/B | 21540 | 5 | 80% moist snow, 20% slush (see Note 4)<br>Snow patch used for braking runs<br>CRFI from 0.20 to 0.25, Average 0.22 |
| | 5<br>16:50 | 31TS (see Note 4) | RTO | 15/OUT/B | 21440 | 2 | 80% moist snow, 20% slush (see Note 4)<br>Snow patch used for braking runs<br>CRFI from 0.21 to 0.22, Average 0.21 |

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.

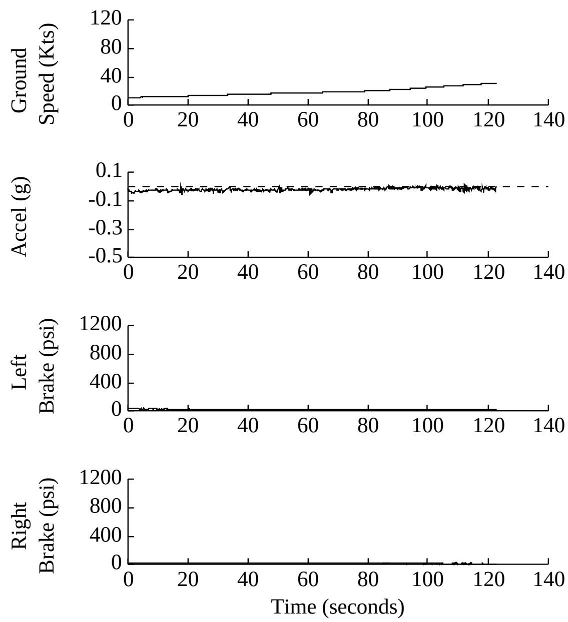
Note 3: CRFI Average obtained by interpolation from before and after aircraft tests

Note 4: Only limited portion of RW 31TS utilized

## Surface: 100% Bare and Dry

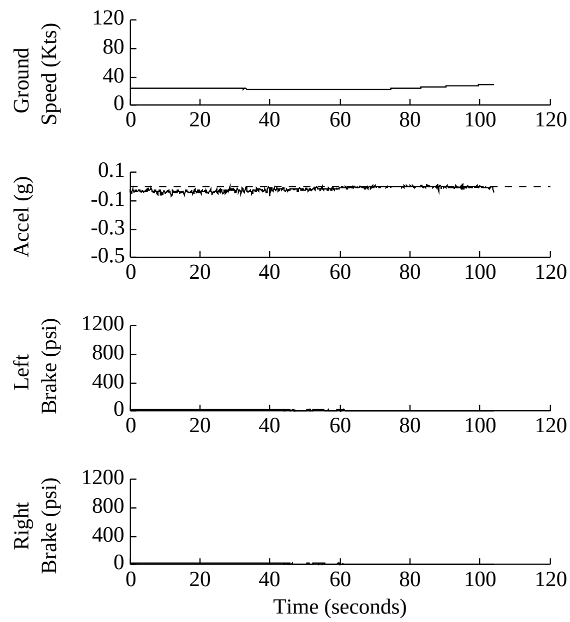
### Flight 99/01, Run Number 1

Configuration: Flaps 15, Air Brakes In, No Braking



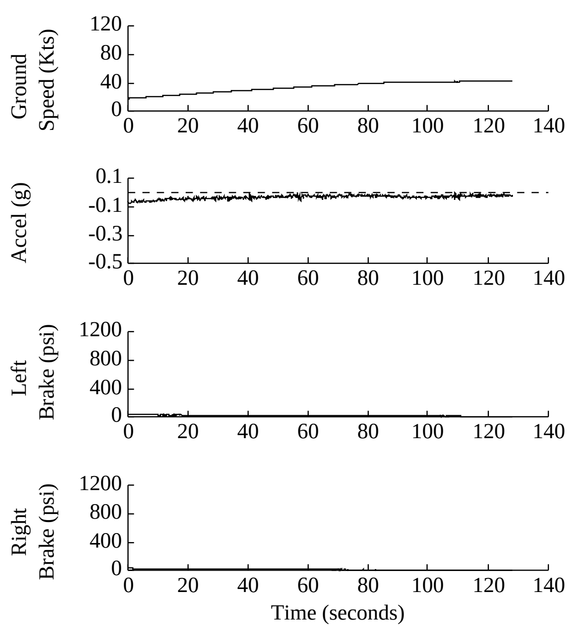

### Flight 99/01, Run Number 2

Configuration: Flaps 15, Air Brakes In, No Braking



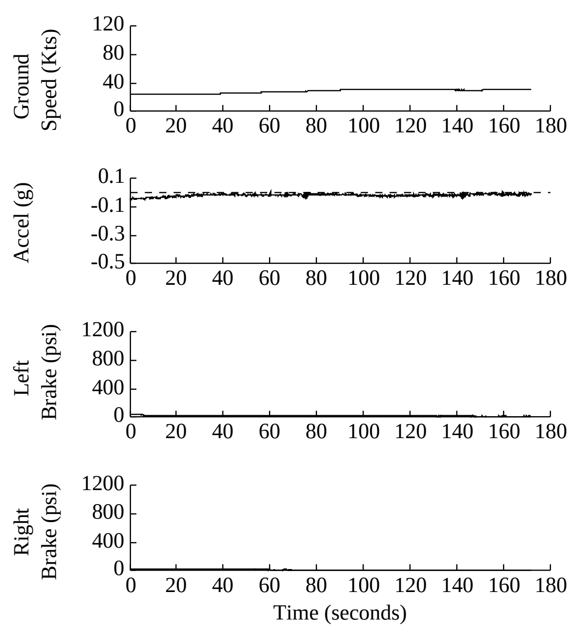

### Flight 99/01, Run Number 3

Configuration: Flaps 15, Air Brakes In, No Braking




### Flight 99/01, Run Number 4

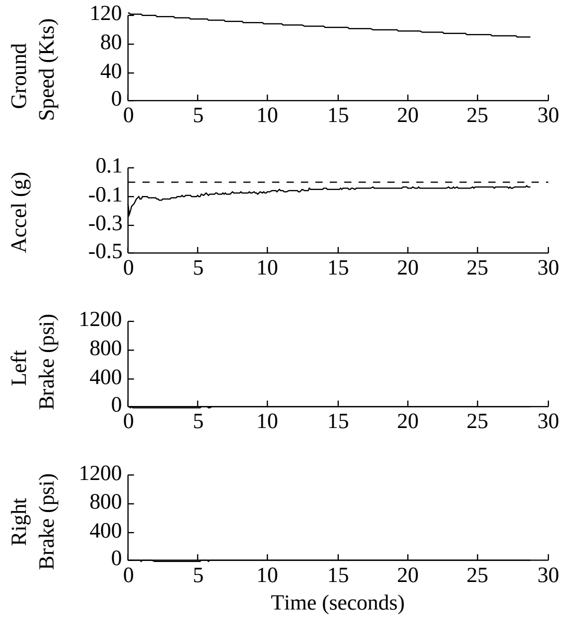
Configuration: Flaps 15, Air Brakes In, No Braking



Surface: 100% Bare and Dry

Flight 99/01, Run Number 5

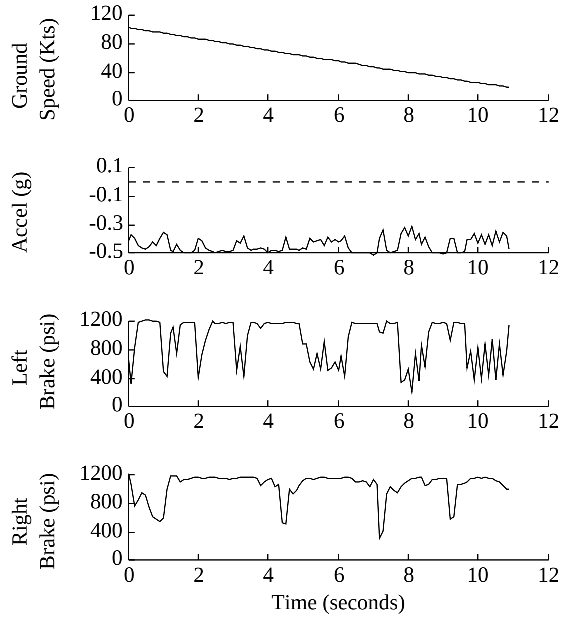
Configuration: Flaps 15, Air Brakes In, No Braking




Flight 99/01, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

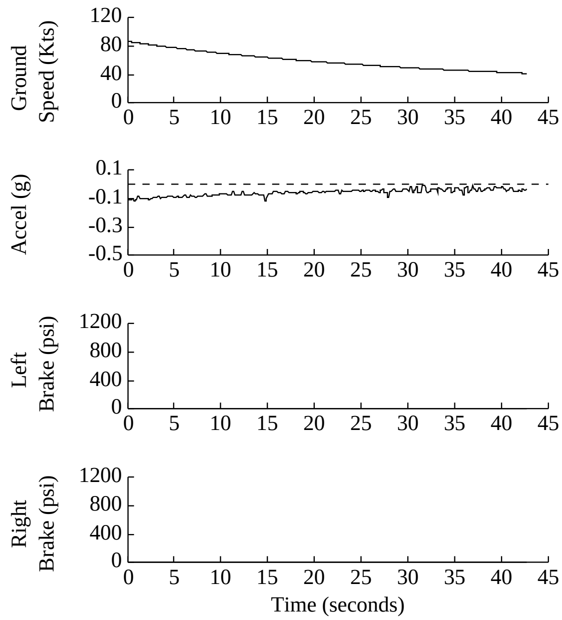
CRFI Average 0.81



Surface: 100% Bare and Dry

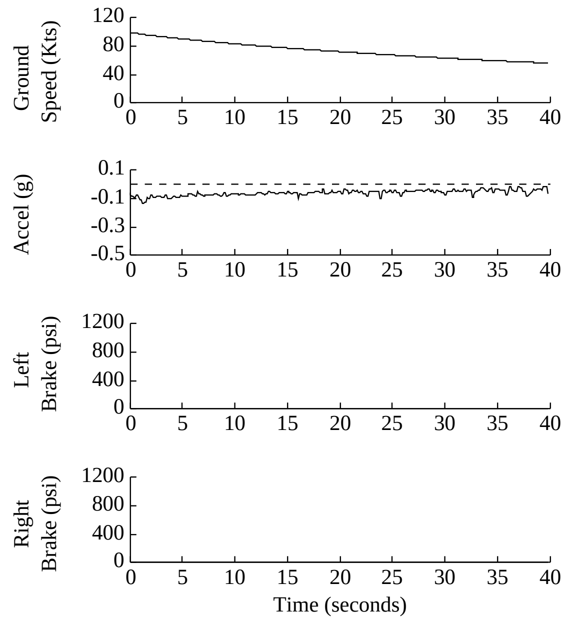
## Flight 99/02, Run Number 1

Configuration: Flaps 40, Air Brakes Out, No Braking




## Flight 99/02, Run Number 2

Configuration: Flaps 15, Air Brakes out, No Braking

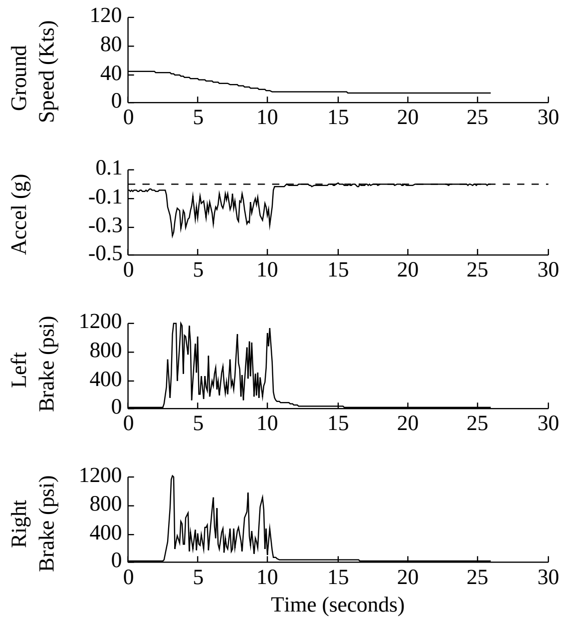


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

### Flight 99/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Split Run

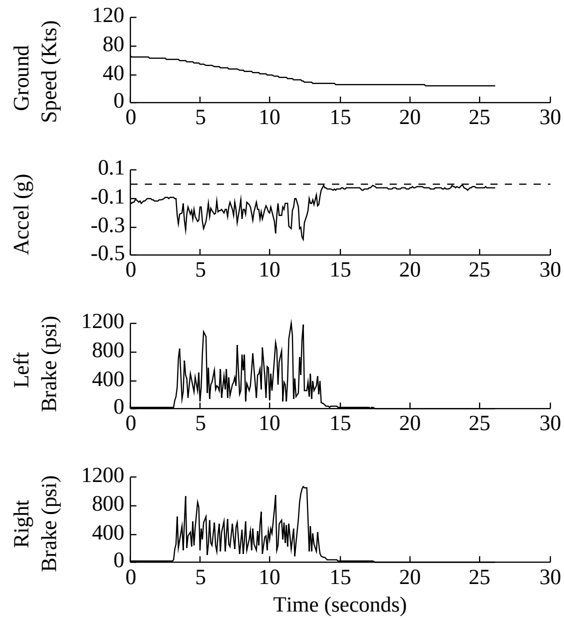
CRFI Average 0.33




### Flight 99/03, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Split Run

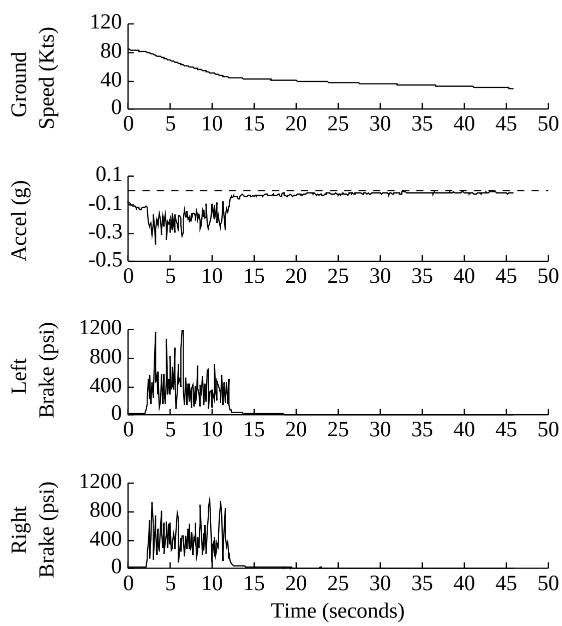
CRFI Average 0.35




### Flight 99/03, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Split Run

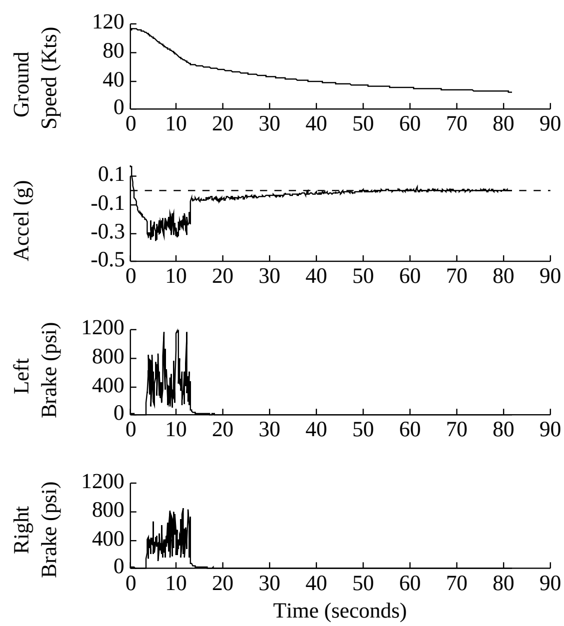
CRFI Average 0.36




### Flight 99/03, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Split Run

CRFI Average 0.38

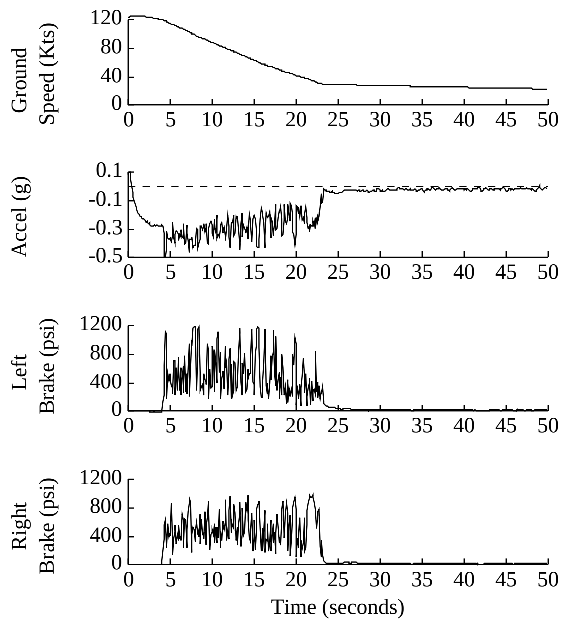


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

Flight 99/03, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Split Run

CRFI Average 0.40

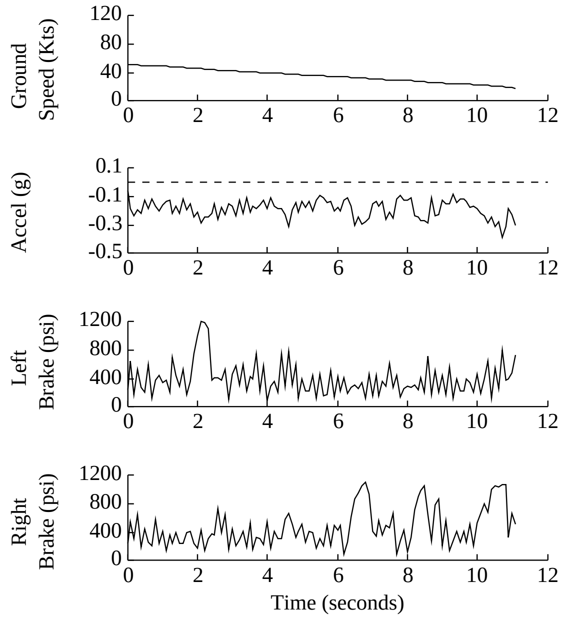


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

## Flight 99/04, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

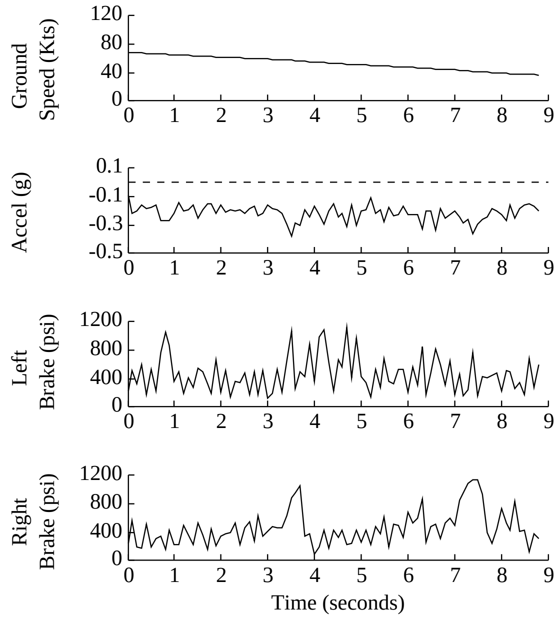
CRFI Average 0.29




## Flight 99/04, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

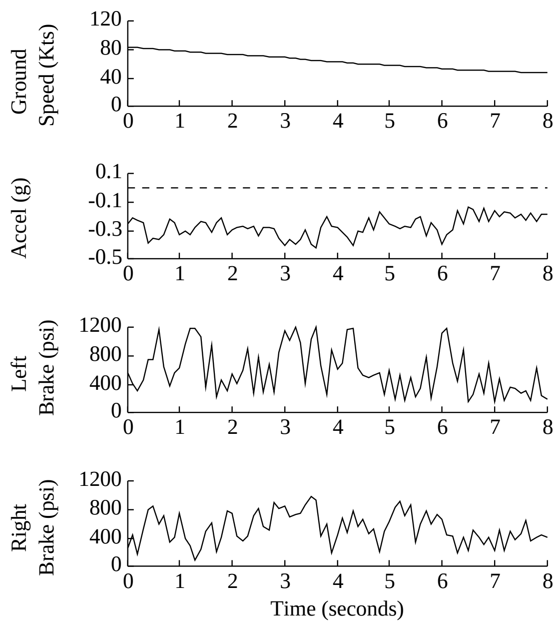
CRFI Average 0.30




## Flight 99/04, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.31

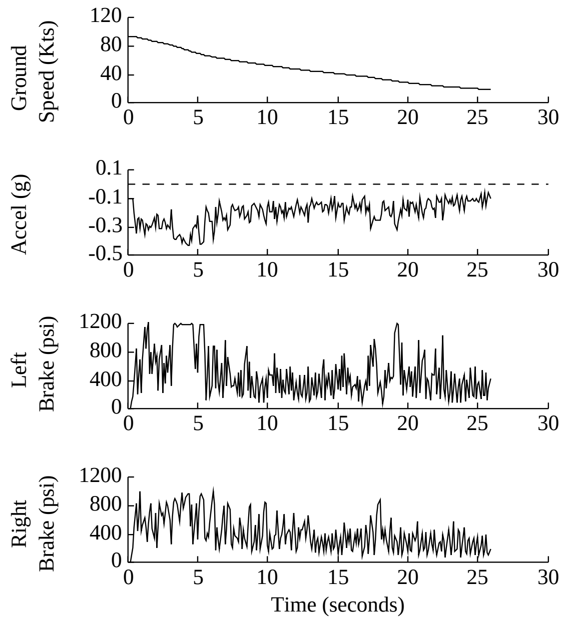


## Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

### Flight 99/04, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

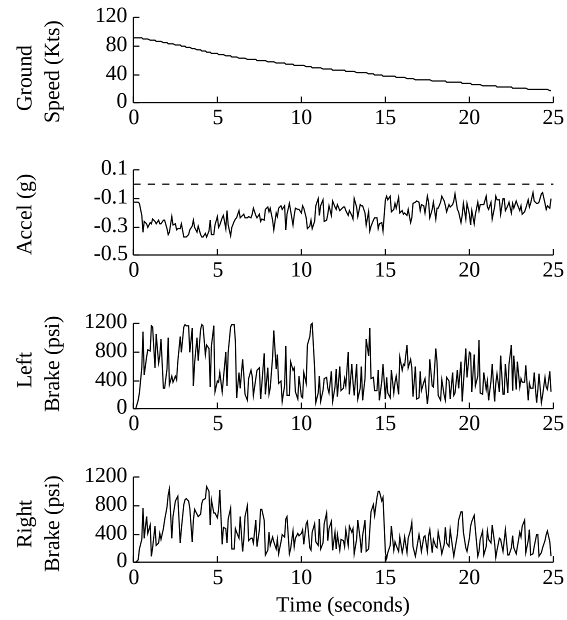
CRFI Average 0.30




### Flight 99/04, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.34

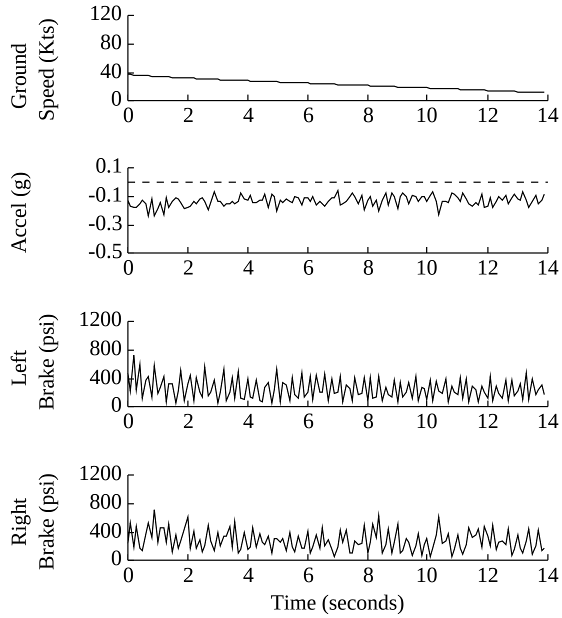


Surface: 100% Thin Ice with some Roughness from Pavement Texture

## Flight 99/05, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

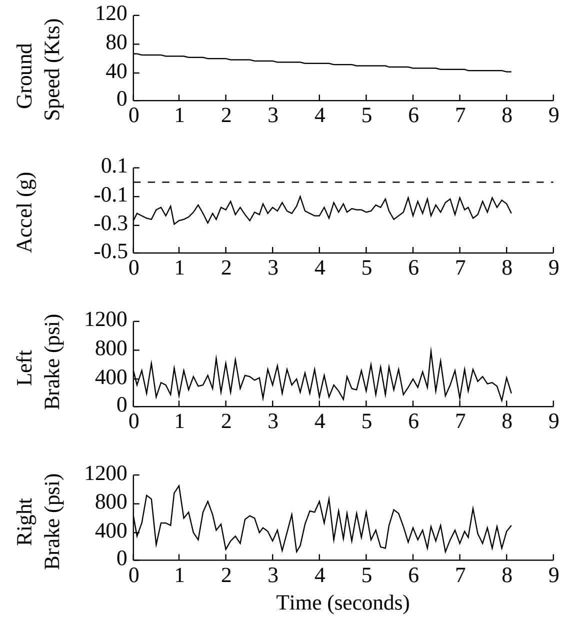
CRFI Average 0.28




## Flight 99/05, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

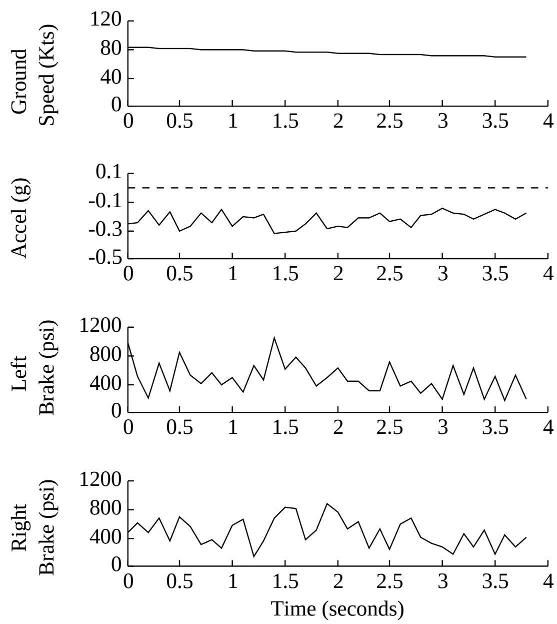
CFRI Average 0.29




## Flight 99/05, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

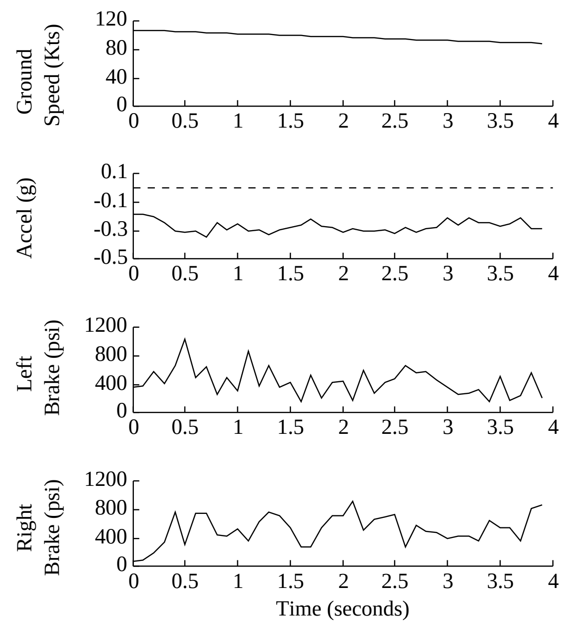
CRFI Average 0.23




## Flight 99/05, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.25

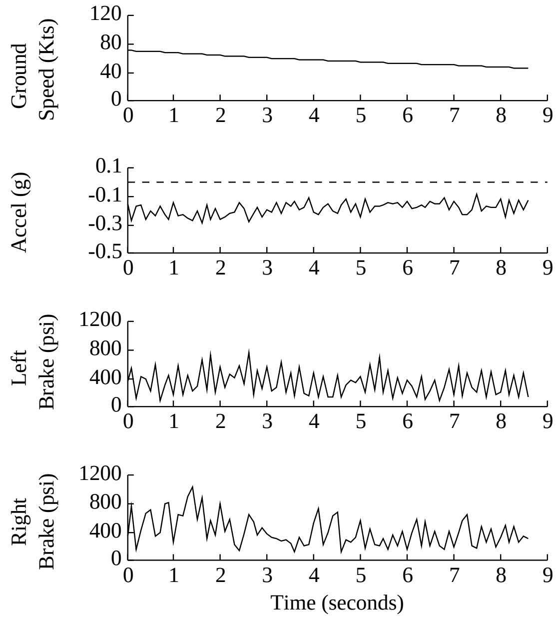


Surface: 100% Thin Ice with some Roughness from Pavement Texture

## Flight 99/05, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

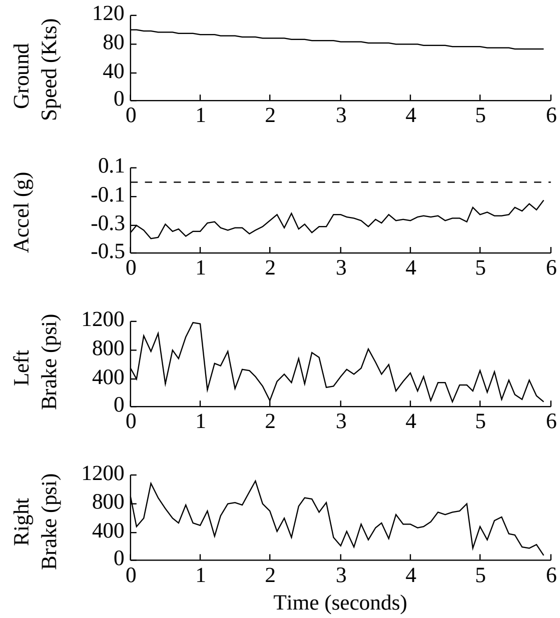
CRFI Average 0.26




## Flight 99/05, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

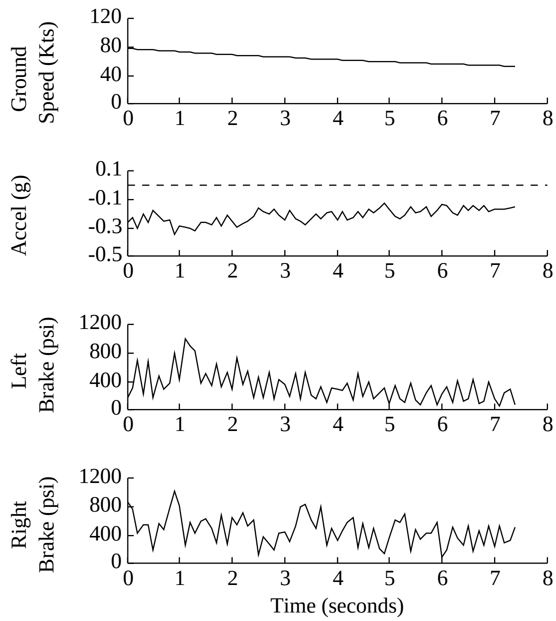
CRFI Average 0.29




## Flight 99/05, Run Number 7

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.28

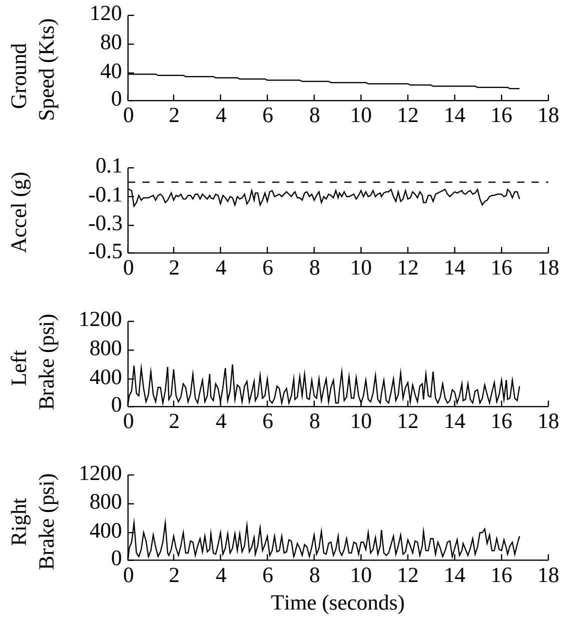


## Surface: 100% Ice with One Application of Sand and Falling Loose Snow

### Flight 99/06, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

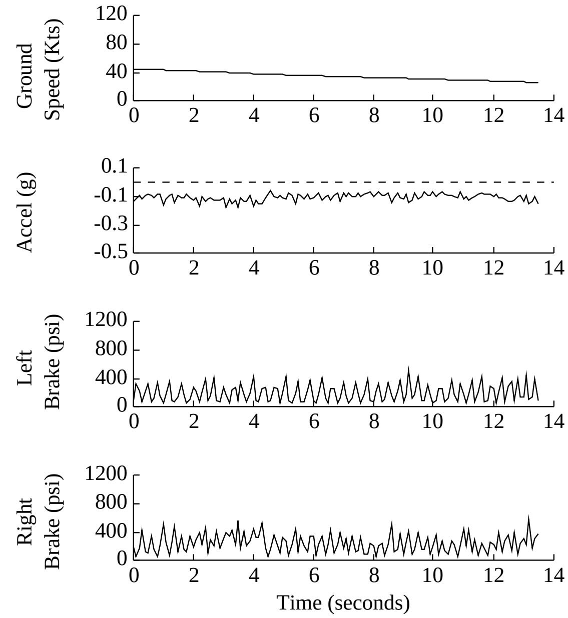
CRFI Average 0.19




### Flight 99/06, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

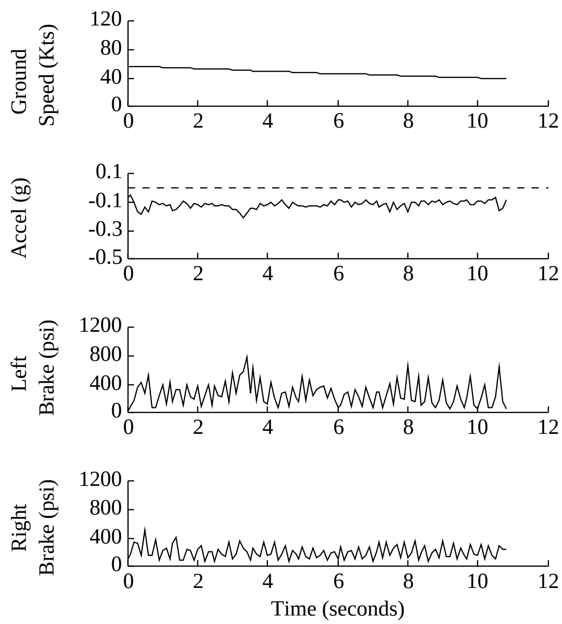
CRFI Average 0.18




### Flight 99/06, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

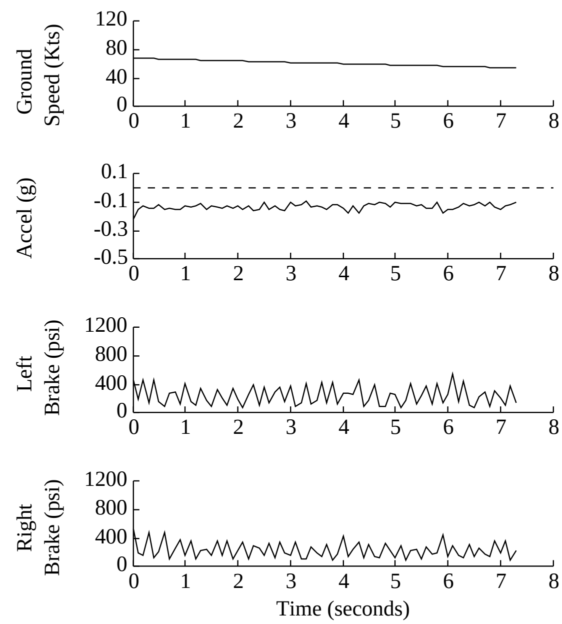
CRFI Average 0.20




### Flight 99/06, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.17

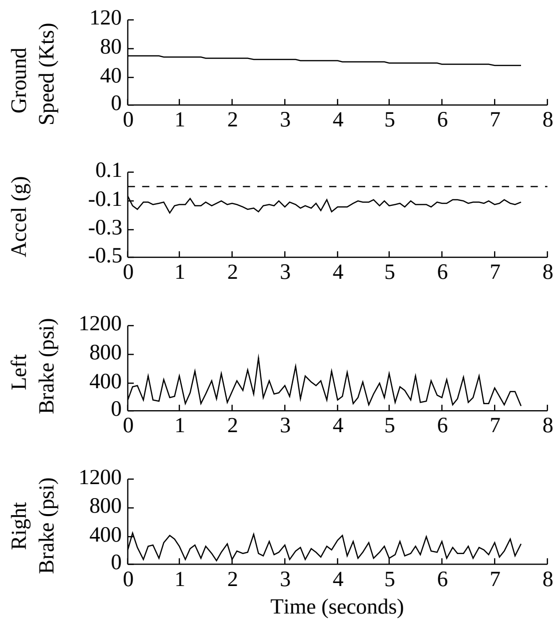


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

## Flight 99/06, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

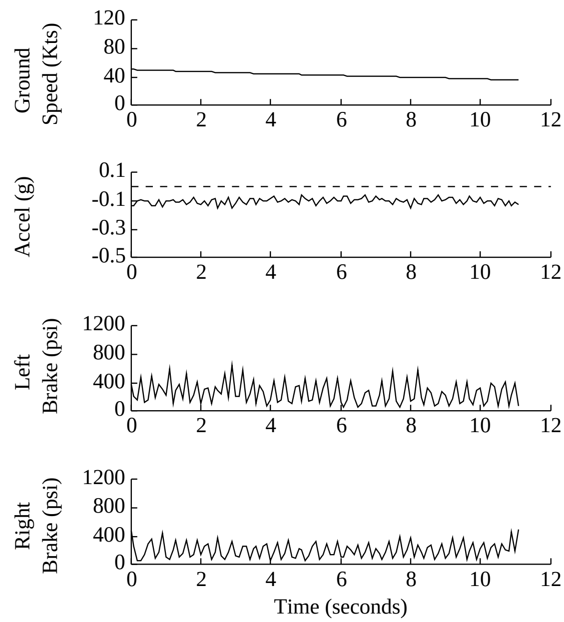
CRFI Average 0.16




## Flight 99/06, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.19

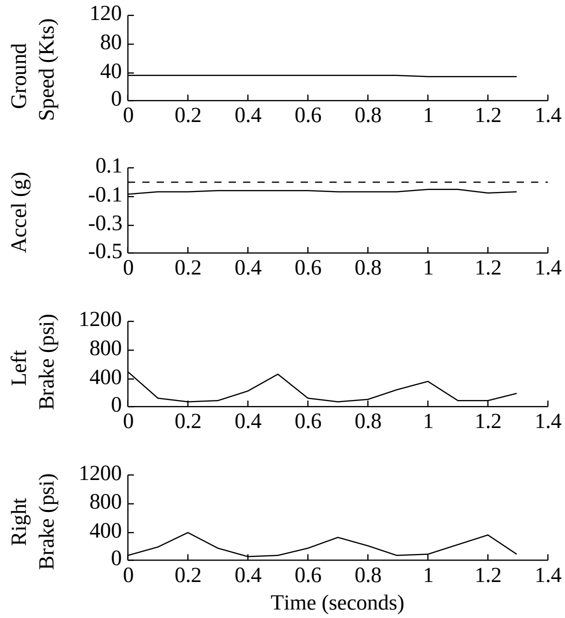


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

## Flight 99/07, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

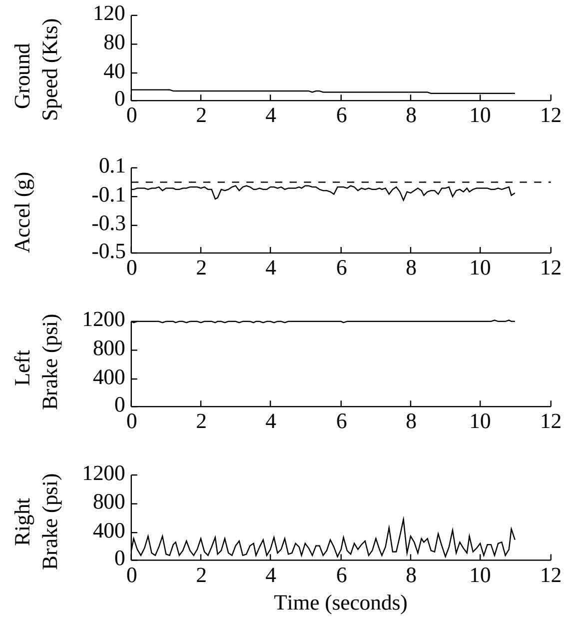
CRFI Average 0.14




## Flight 99/07, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

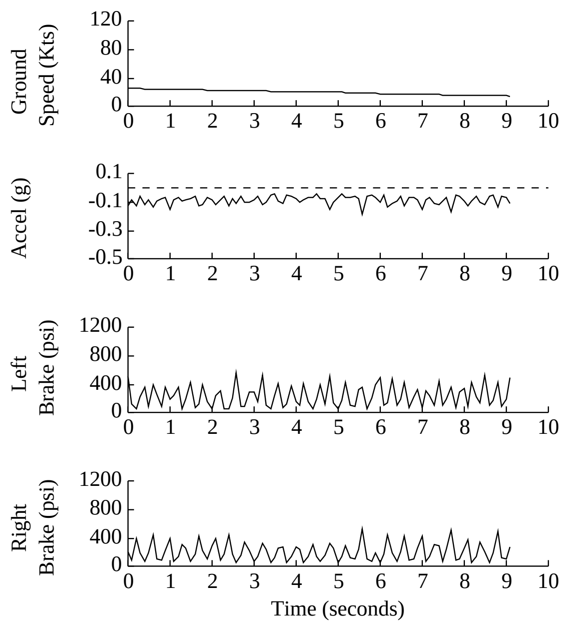
CRFI Average 0.14




## Flight 99/07, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

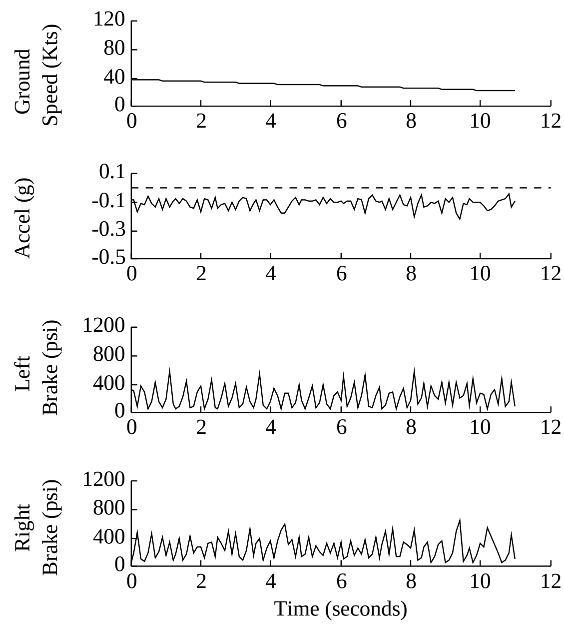
CRFI Average 0.17




## Flight 99/07, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

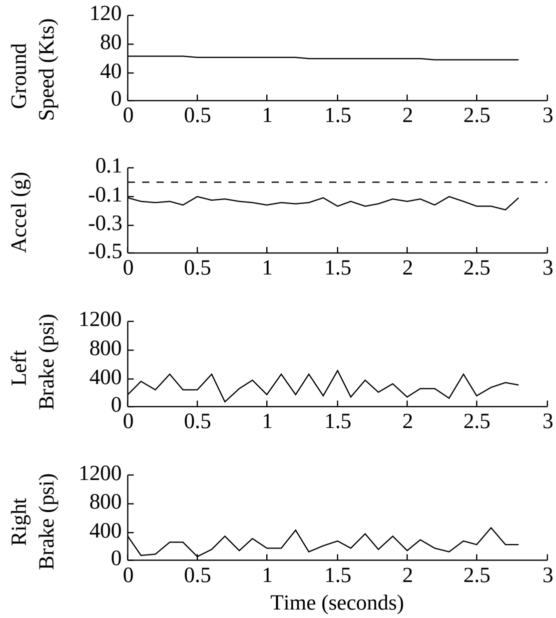


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

## Flight 99/07, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

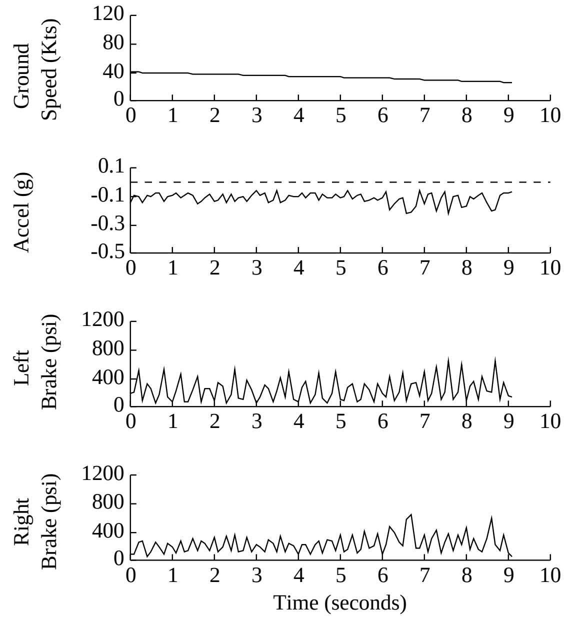
CRFI Average 0.22




## Flight 99/07, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

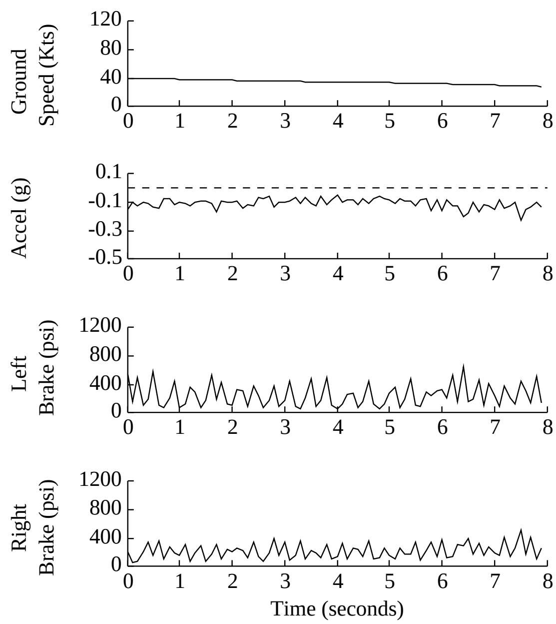
CRFI Average 0.22




## Flight 99/07, Run Number 7

Configuration: Flaps 15, Air Brakes Out, Max Braking

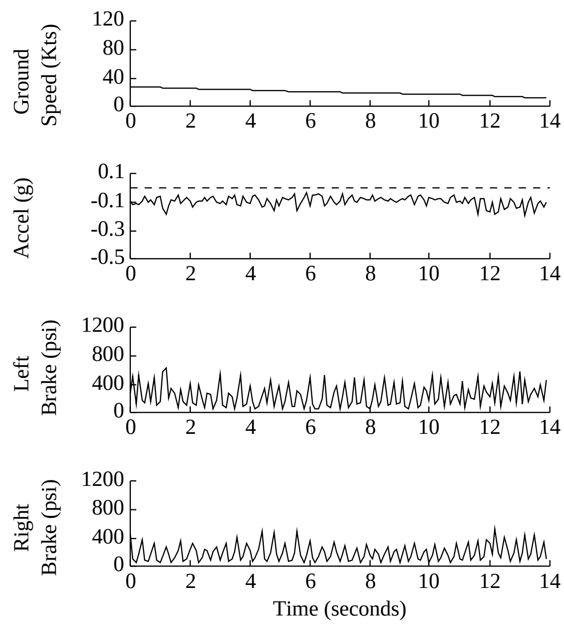
CRFI Average 0.21




## Flight 99/07, Run Number 8

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.22

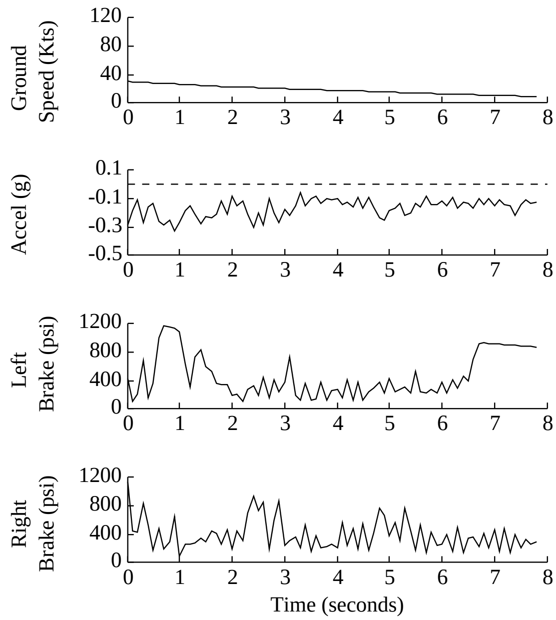


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

## Flight 99/08, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

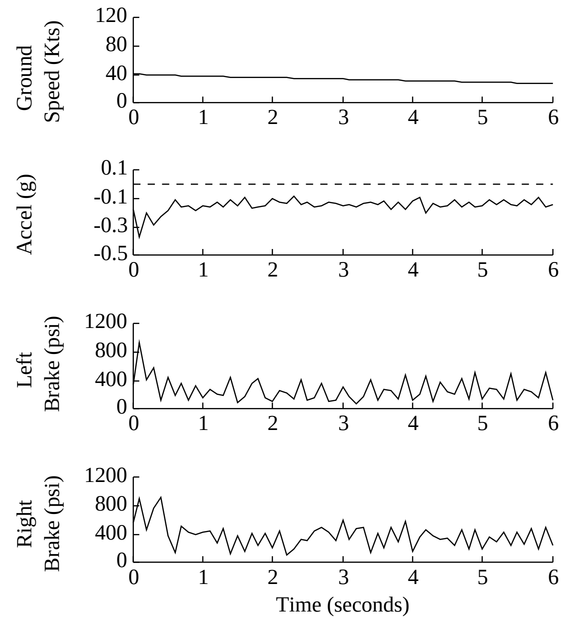
CRFI Average 0.25




## Flight 99/08, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

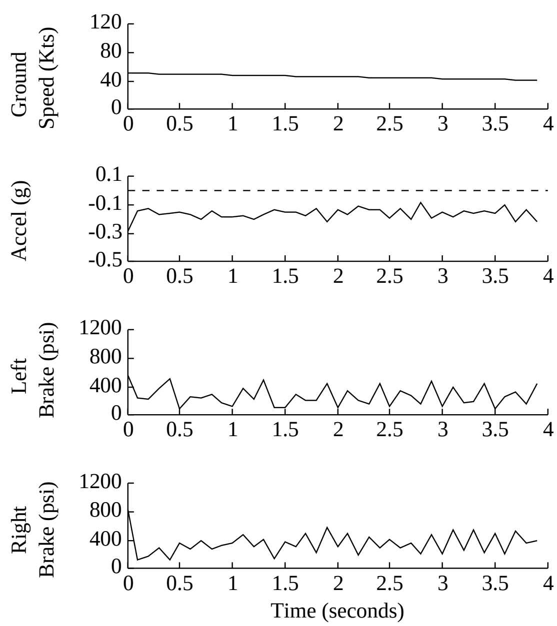
CRFI Average 0.22




## Flight 99/08, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

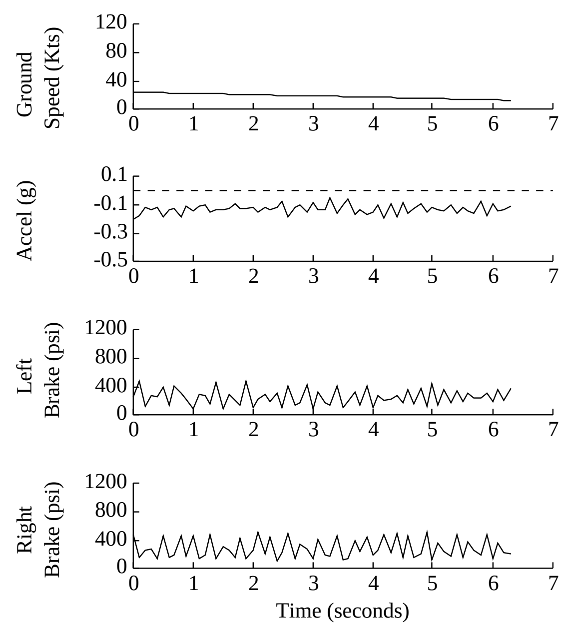
CRFI Average 0.22




## Flight 99/08, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

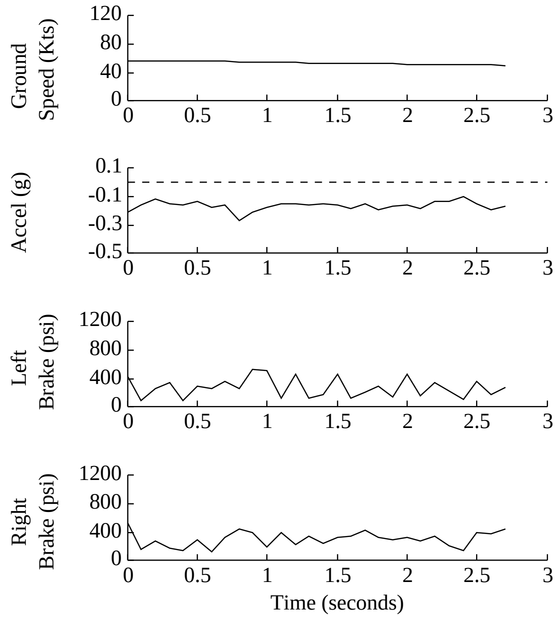


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

## Flight 99/08, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21



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

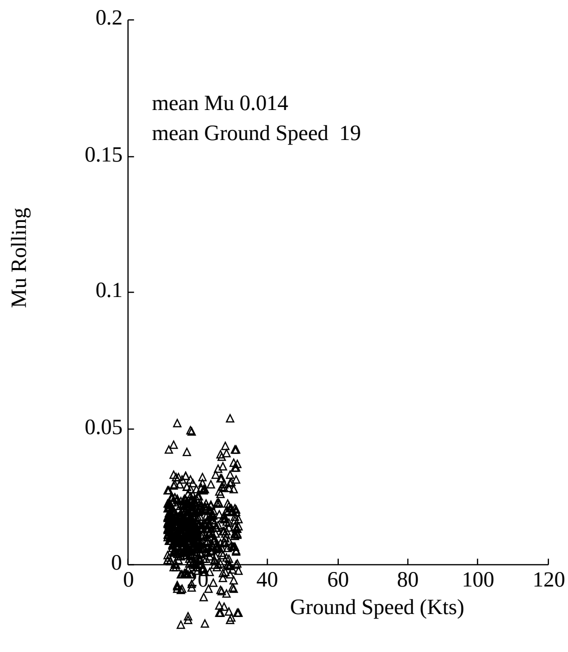
The following table shows the test runs used to verify the aircraft rolling coefficient ($\mu_R$) and idle thrust on runway surfaces with no or negligible contamination drag. Pages B2 to B3 show the variation of $\mu_R$ with ground speed for each run. The mean ground speed and mean $\mu_R$ for each run are shown in the table and on Page B4, together with the results obtained in the 1996, 1997 and 1998 tests.

| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG | WEIGHT (LB) | MEAN SPEED (KTGS) | MEAN $\mu_R$ |
|---|---|---|---|---|---|---|---|
| 99/01 | 1 | 31 | TAXI | 15/IN/NO | 21050 | 19 | 0.014 |
| | 2 | 13 | TAXI | 15/IN/NO | 21000 | 24 | 0.018 |
| | 3 | 26 | TAXI | 15/IN/NO | 20900 | 34 | 0.012 |
| | 4 | 08 | TAXI | 15/IN/NO | 20850 | 29 | 0.011 |
| | 5 | 08 | LAND | 15/IN/NO | 20100 | 105 | 0.024 |
| 99/02 | 1 | 26 | LAND | 40/OUT/NO | 21110 | 60 | 0.026 |
| | 2 | 26 | LAND | 15/OUT/NO | 20310 | 74 | 0.031 |

Surface: 100% Bare and Dry

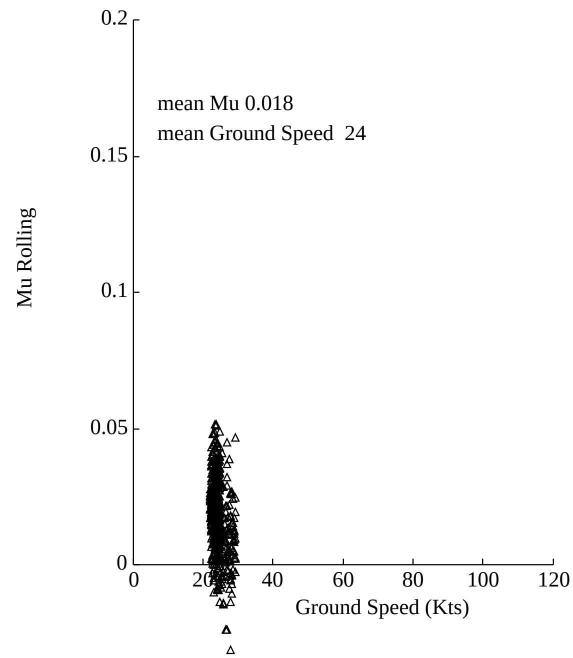
## Flight 99/01, Run Number 1

Configuration: Flaps 15, Air Brakes In, No Braking



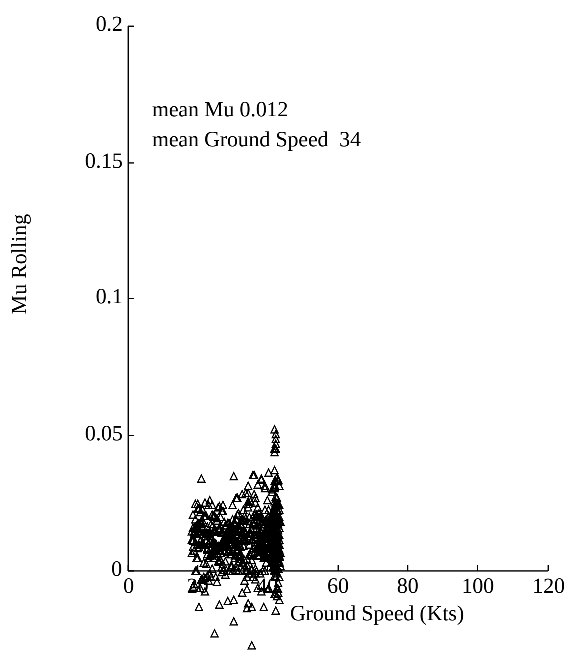

## Flight 99/01, Run Number 2

Configuration: Flaps 15, Air Brakes In, No Braking



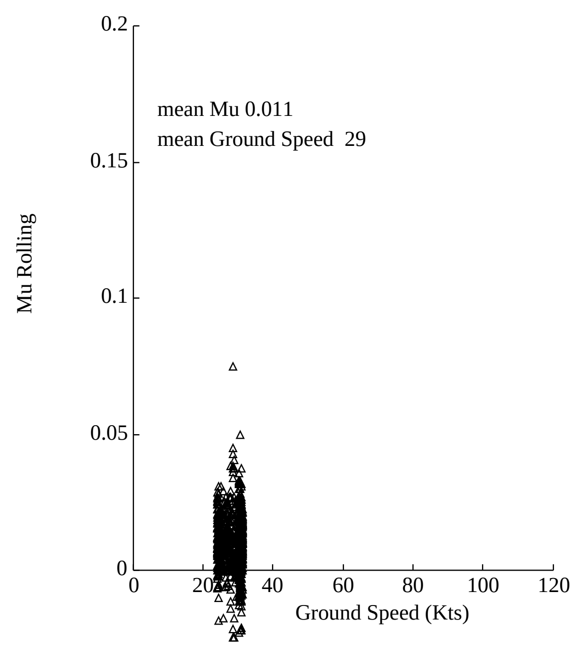

## Flight 99/01, Run Number 3

Configuration: Flaps 15, Air Brakes In, No Braking




## Flight 99/01, Run Number 4

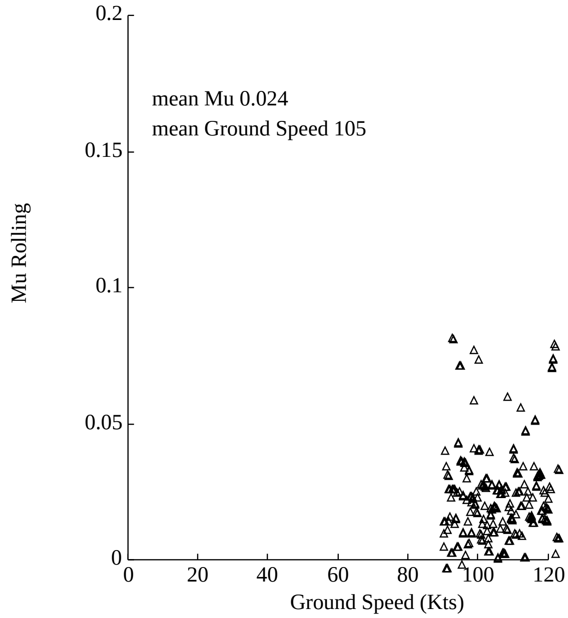
Configuration: Flaps 15, Air Brakes In, No Braking



Surface: 100% Bare and Dry

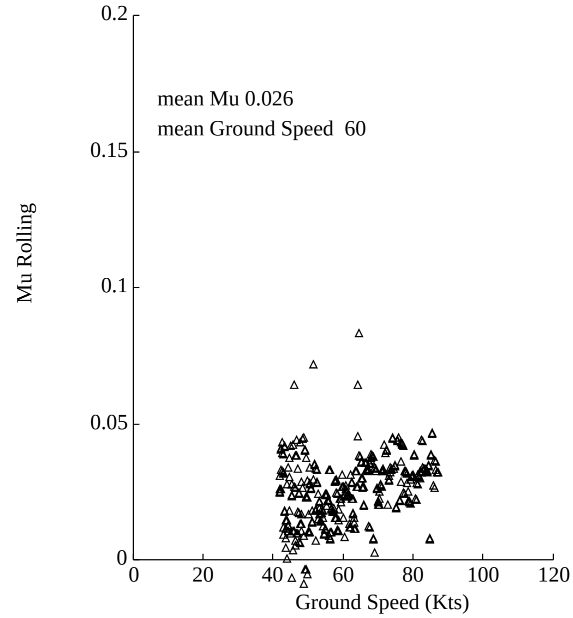
## Flight 99/01, Run Number 5

Configuration: Flaps 15, Air Brakes In, No Braking



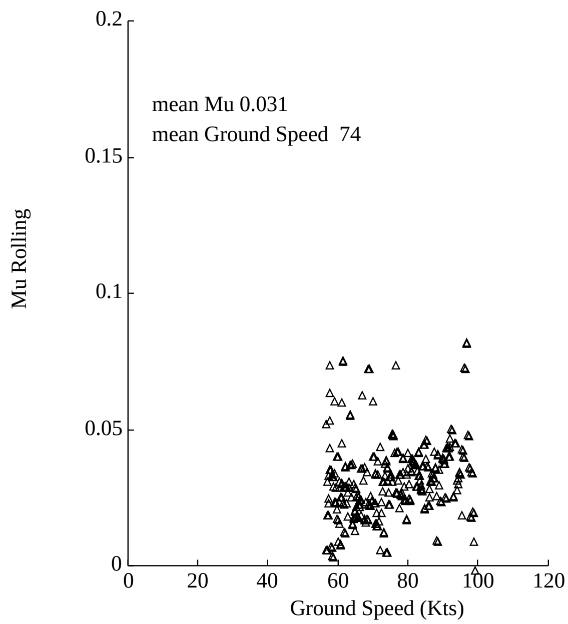

## Flight 99/02, Run Number 1

Configuration: Flaps 40, Air Brakes Out, No Braking




## Flight 99/02, Run Number 2

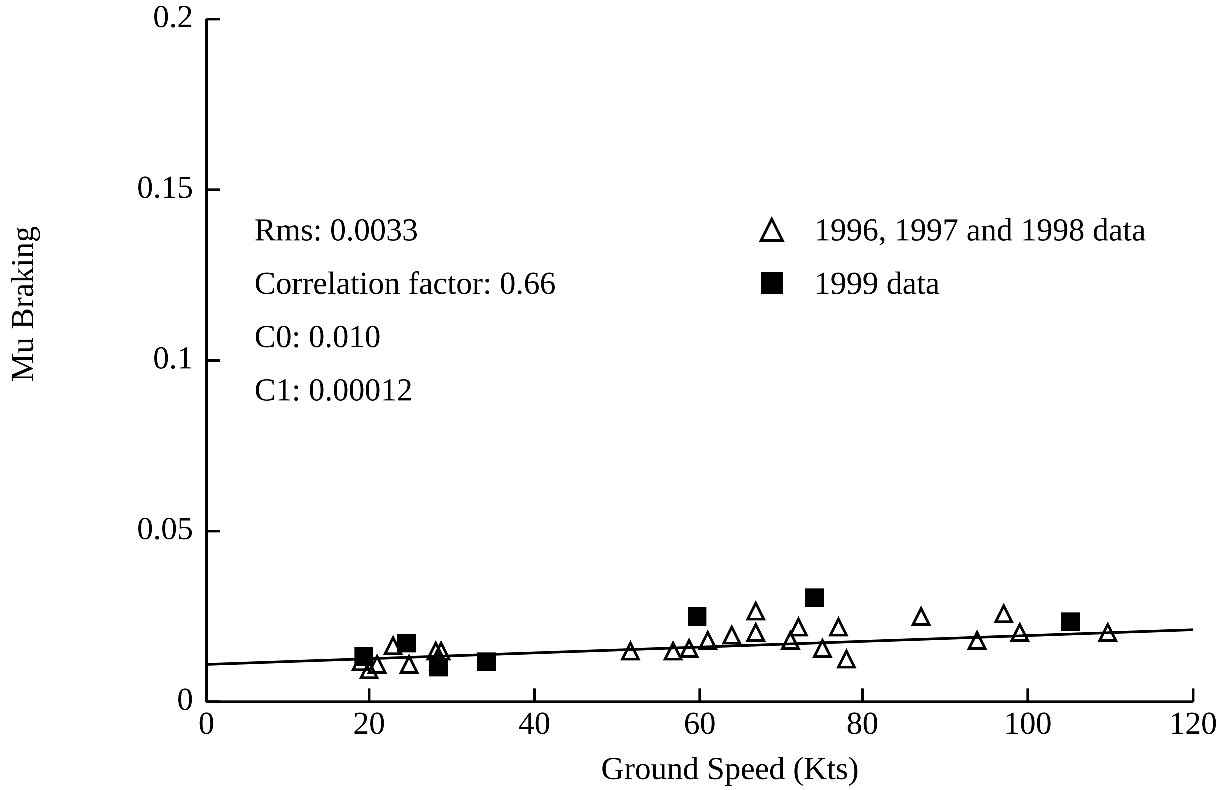
Configuration: Flaps 15, Air Brakes out, No Braking



Surface: No or Negligible Contamination

Flight 99/01 Run Numbers 1 through 5 and Flight 99/02 Runs 1 and 2

Mu Rolling = C0 + C1 * 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 ($\mu_S$). Pages C3 to C39 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 are the variation of left outer and inner, and right outer and inner wheel slip ratios with ground speed. The average run value of ground speed and $\mu_S$ for each wheel are shown in the table and on Page C40.

| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG | WEIGHT (LB) | MEAN SPEED (KTGS) | MEAN SLIP RATIO $\mu_S$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | LO | LI | RO | RI |
| 99/01 | 6 | 31 | LAND | 40/OUT/B | 19250 | 61 | 0.094 | 0.070 | 0.051 | 0.119 |
| | 7 | 31 | LAND | 15/OUT/B | 18550 | No Data | No Data | No Data | No Data | No Data |
| 99/03 | 1a | 08 | RTO | 40/OUT/B | 23250 | 30 | 0.043 | 0.035 | 0.028 | 0.022 |
| | 2a | 08 | RTO | 40/OUT/B | 22950 | 46 | 0.082 | 0.062 | 0.030 | 0.051 |
| | 3a | 08 | RTO | 40/OUT/B | 22700 | 62 | 0.030 | 0.020 | 0.003 | 0.035 |
| | 4a | 08 | RTO | 40/OUT/B | 22450 | 85 | 0.013 | 0.010 | 0.004 | 0.050 |
| | 5a | 08 | RTO | 15/OUT/B | 21850 | 72 | 0.065 | 0.045 | 0.029 | 0.081 |
| 99/04 | 1 | 31 | RTO | 40/OUT/B | 21450 | 36 | 0.248 | 0.241 | 0.088 | 0.084 |
| | 2 | 31 | RTO | 40/OUT/B | 21350 | 53 | 0.148 | 0.119 | 0.089 | 0.073 |
| | 3 | 31 | RTO | 40/OUT/B | 21250 | 64 | 0.117 | 0.091 | 0.074 | 0.075 |
| | 4 | 31 | RTO | 40/OUT/B | 21000 | No Data | No Data | No Data | No Data | No Data |
| | 5 | 31 | RTO | 15/OUT/B | 20750 | 49 | 0.194 | 0.082 | 0.108 | 0.114 |
| | 6 | 31 | RTO | 40/OUT/B | 20400 | 49 | 0.173 | 0.099 | 0.113 | 0.095 |
| 99/05 | 1 | 31TS | RTO | 40/OUT/B | 22760 | 24 | 0.428 | 0.276 | 0.053 | 0.237 |
| | 2 | 31TS | RTO | 40/OUT/B | 22560 | 53 | 0.147 | 0.071 | 0.063 | 0.083 |
| | 3 | 31TS | RTO | 15/OUT/B | 22310 | 76 | 0.093 | 0.043 | 0.037 | 0.082 |
| | 4 | 31TS | LAND | 40/OUT/B | 21810 | 98 | 0.078 | 0.067 | 0.051 | 0.071 |
| | 5 | 31TS | RTO | 15/OUT/B | 21410 | 58 | 0.165 | 0.054 | 0.035 | 0.118 |
| | 6 | 31TS | LAND | 40/OUT/B | 21010 | 85 | 0.096 | 0.071 | 0.049 | 0.082 |
| | 7 | 31TS | RTO | 40/OUT/B | 20660 | 64 | 0.169 | 0.077 | 0.059 | 0.096 |
| 99/06 | 1 | 31TS | RTO | 40/OUT/B | 22900 | 28 | 0.499 | 0.418 | 0.116 | 0.272 |
| | 2 | 31TS | RTO | 40/OUT/B | 22600 | 35 | 0.633 | 0.441 | 0.068 | 0.215 |
| | 3 | 31TS | RTO | 40/OUT/B | 22500 | 48 | 0.307 | 0.193 | 0.087 | 0.150 |

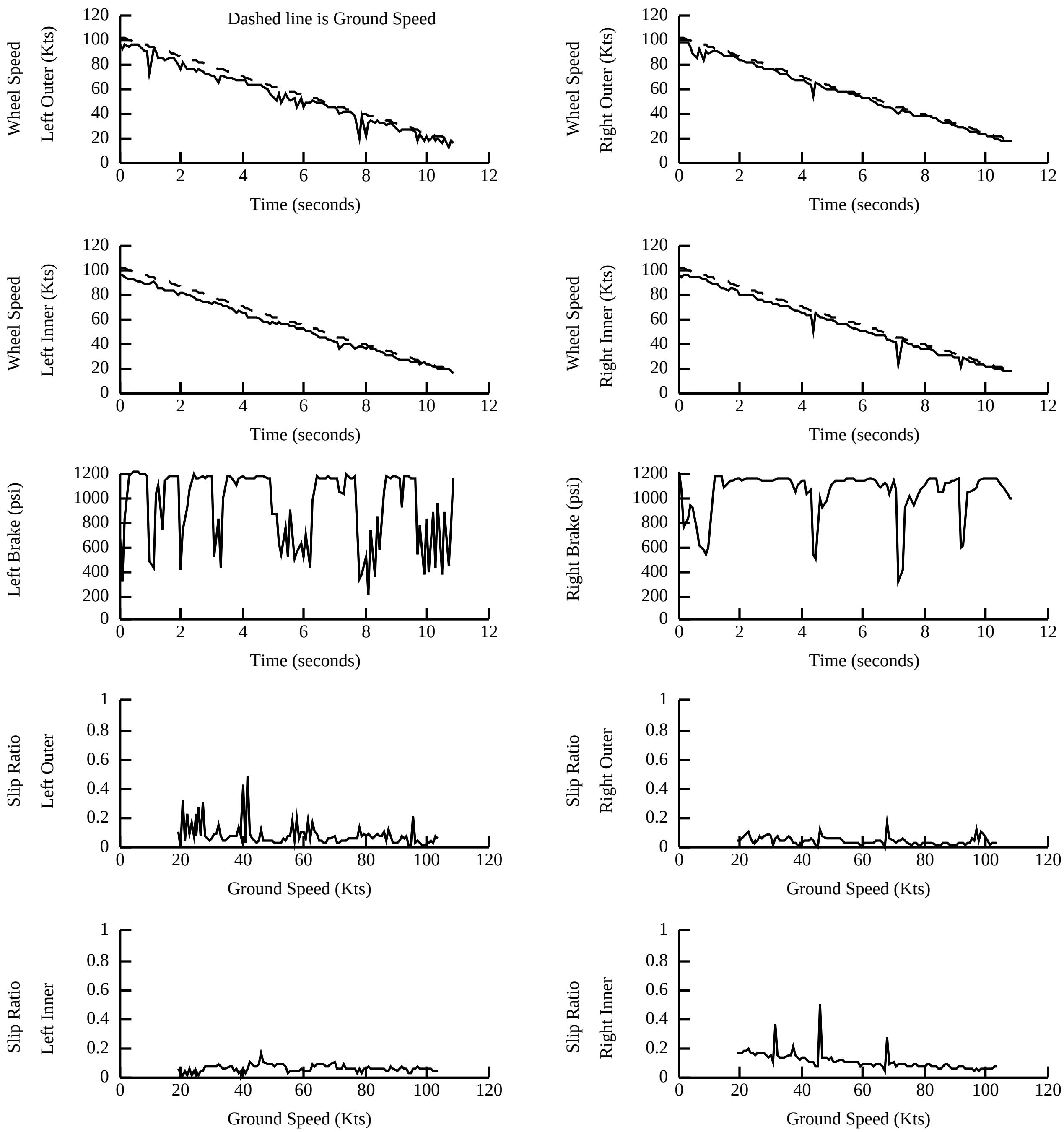
| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG | WEIGHT (LB) | MEAN SPEED (KTGS) | MEAN SLIP RATIO $\mu_S$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4 | 31TS | RTO | 40/OUT/B | 22350 | 61 | 0.321 | 0.144 | 0.083 | 0.110 |
| | 5 | 31TS | RTO | 15/OUT/B | 22150 | 63 | 0.196 | 0.107 | 0.076 | 0.129 |
| | 6 | 31TS | RTO | 15/OUT/B | 21900 | 43 | 0.359 | 0.229 | 0.100 | 0.206 |
| 99/07 | 1 | 31TS | RTO | 40/OUT/B | 21490 | 36 | 0.465 | 0.654 | 0.474 | 0.155 |
| | 2 | 31TS | RTO | 40/OUT/B | 21390 | 13 | 0.999 | 0.998 | 0.400 | 0.396 |
| | 3 | 31TS | RTO | 40/OUT/B | 20490 | 21 | 0.436 | 0.535 | 0.367 | 0.164 |
| | 4 | 31TS | RTO | 40/OUT/B | 20340 | 30 | 0.415 | 0.369 | 0.209 | 0.106 |
| | 5 | 31TS | RTO | 40/OUT/B | 20010 | 61 | 0.180 | 0.113 | 0.127 | 0.069 |
| | 6 | 31TS | RTO | 40/OUT/B | 19490 | 34 | 0.348 | 0.419 | 0.179 | 0.115 |
| | 7 | 31TS | RTO | 15/OUT/B | 18740 | 35 | 0.287 | 0.469 | 0.156 | 0.171 |
| | 8 | 31TS | RTO | 15/OUT/B | 18540 | 21 | 0.456 | 0.483 | 0.338 | 0.277 |
| 99/08 | 1 | 31TS | RTO | 40/OUT/B | 22040 | 19 | 0.517 | 0.387 | 0.208 | 0.190 |
| | 2 | 31TS | RTO | 40/OUT/B | 21840 | 34 | 0.398 | 0.175 | 0.120 | 0.089 |
| | 3 | 31TS | RTO | 40/OUT/B | 21640 | 46 | 0.297 | 0.138 | 0.092 | 0.098 |
| | 4 | 31TS | RTO | 40/OUT/B | 21540 | 19 | 0.484 | 0.314 | 0.214 | 0.164 |
| | 5 | 31TS | RTO | 15/OUT/B | 21440 | 54 | 0.235 | 0.186 | 0.092 | 0.101 |

Surface: 100% Bare and Dry

Flight 99/01, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.81

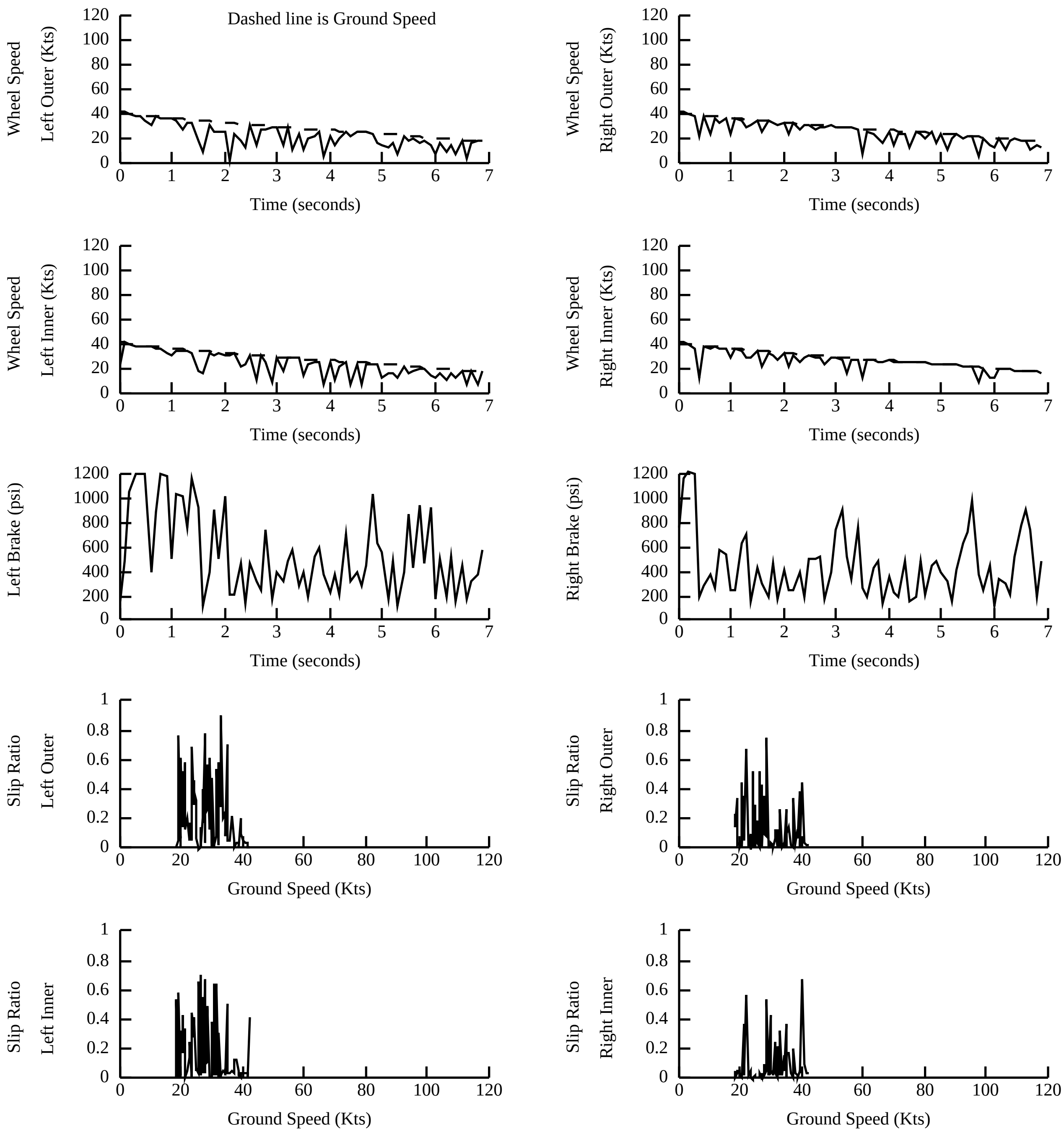


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

Flight 99/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.33

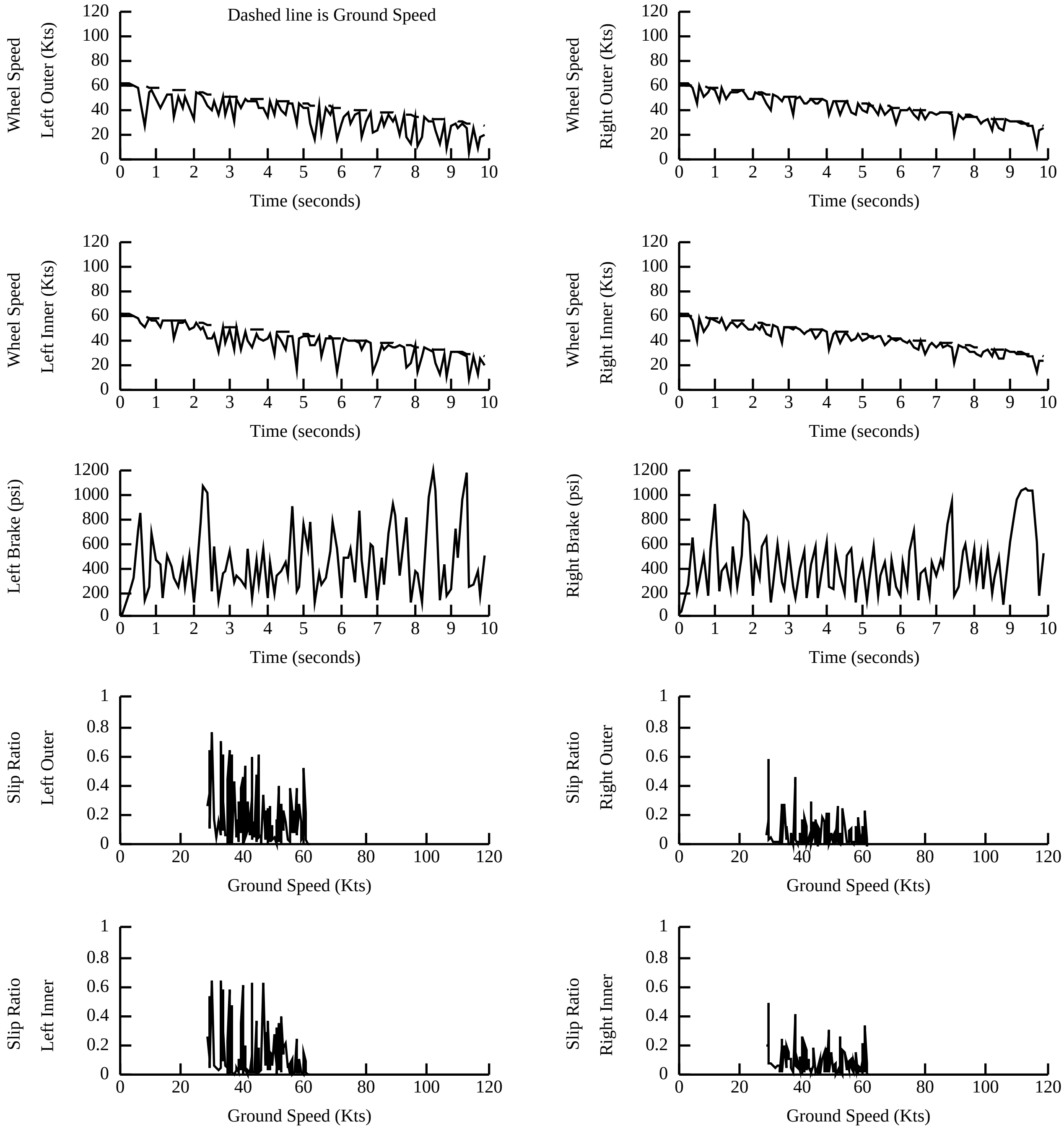


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

Flight 99/03, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.35

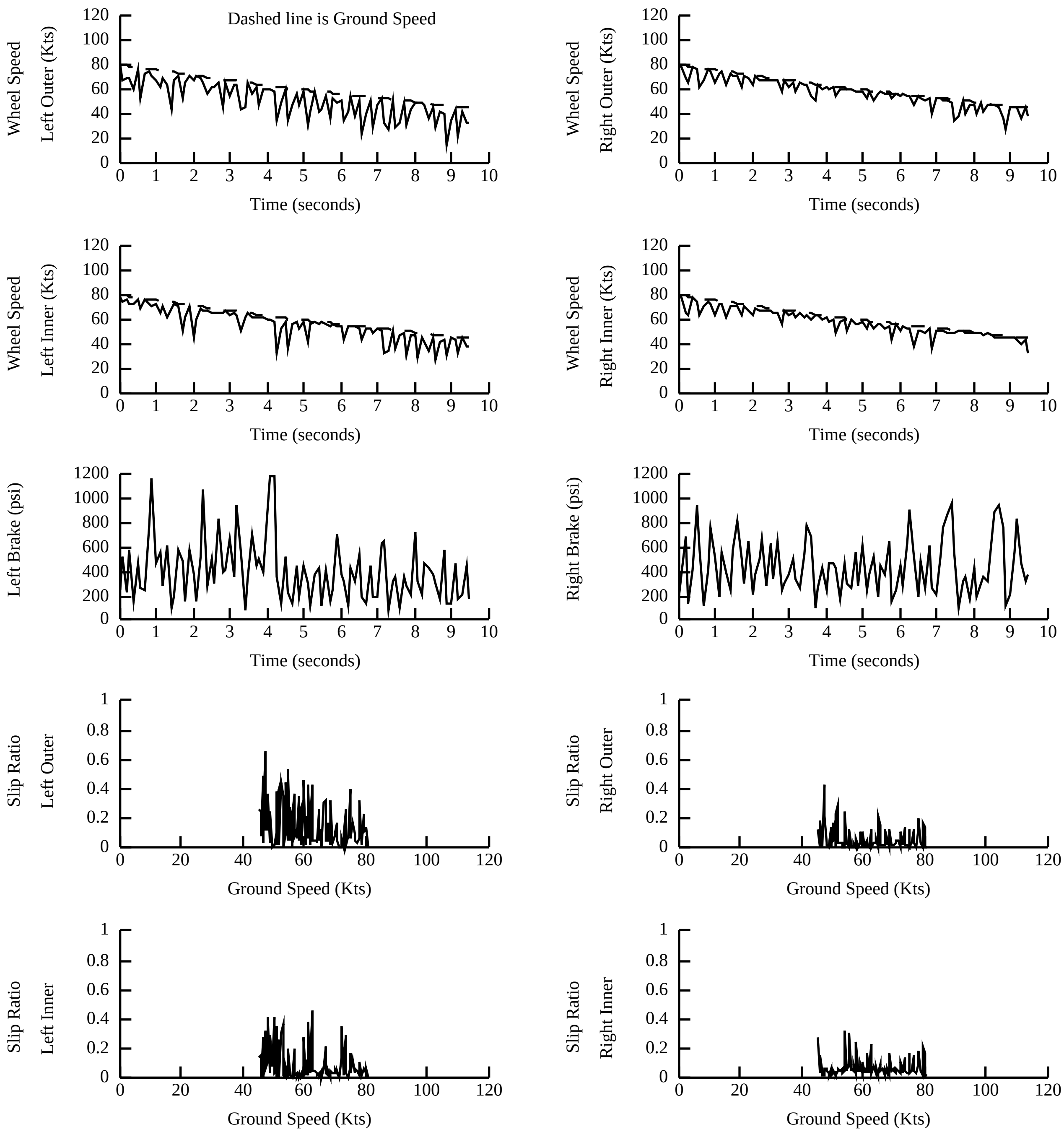


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

Flight 99/03, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.36

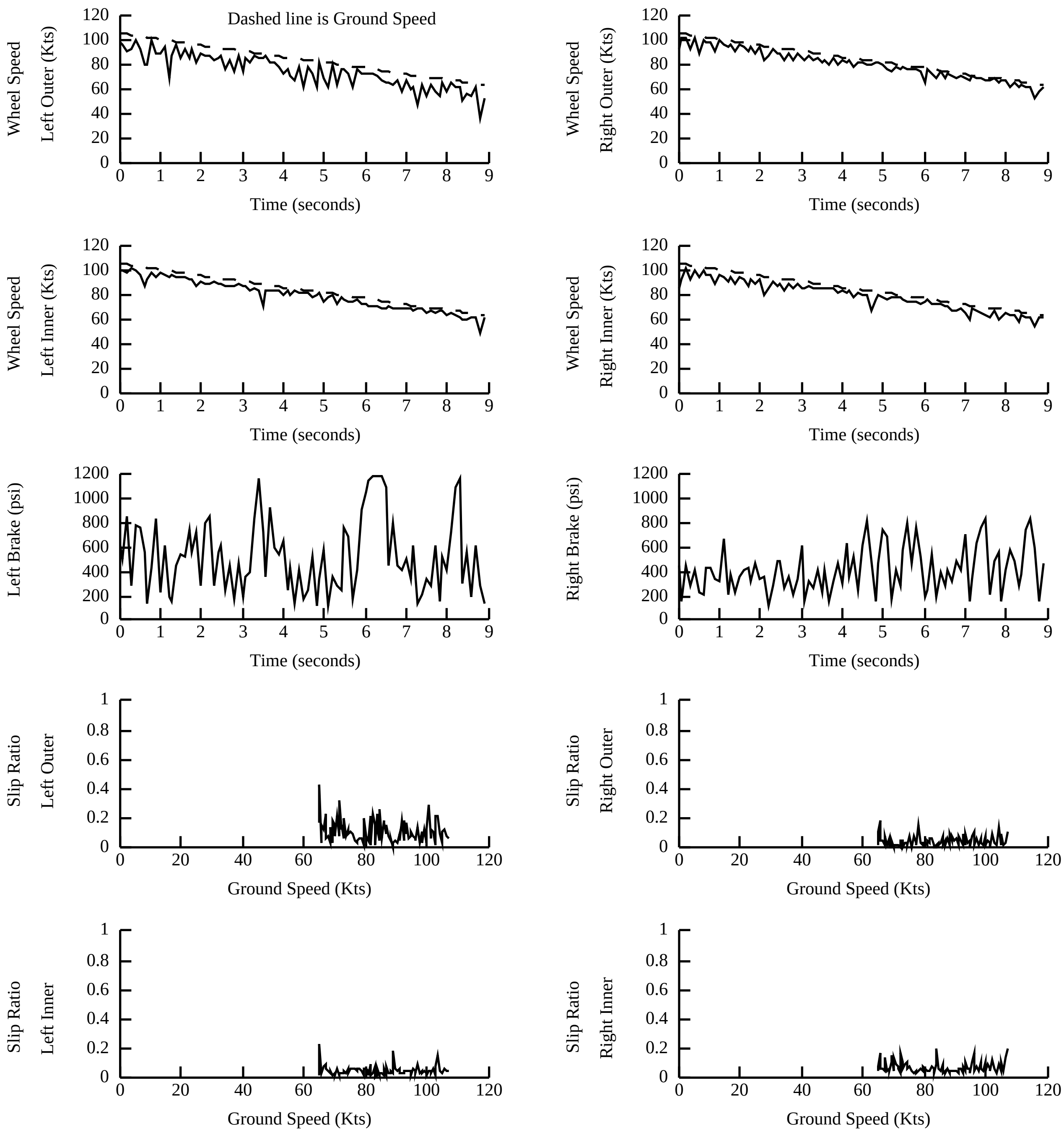


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

Flight 99/03, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.38

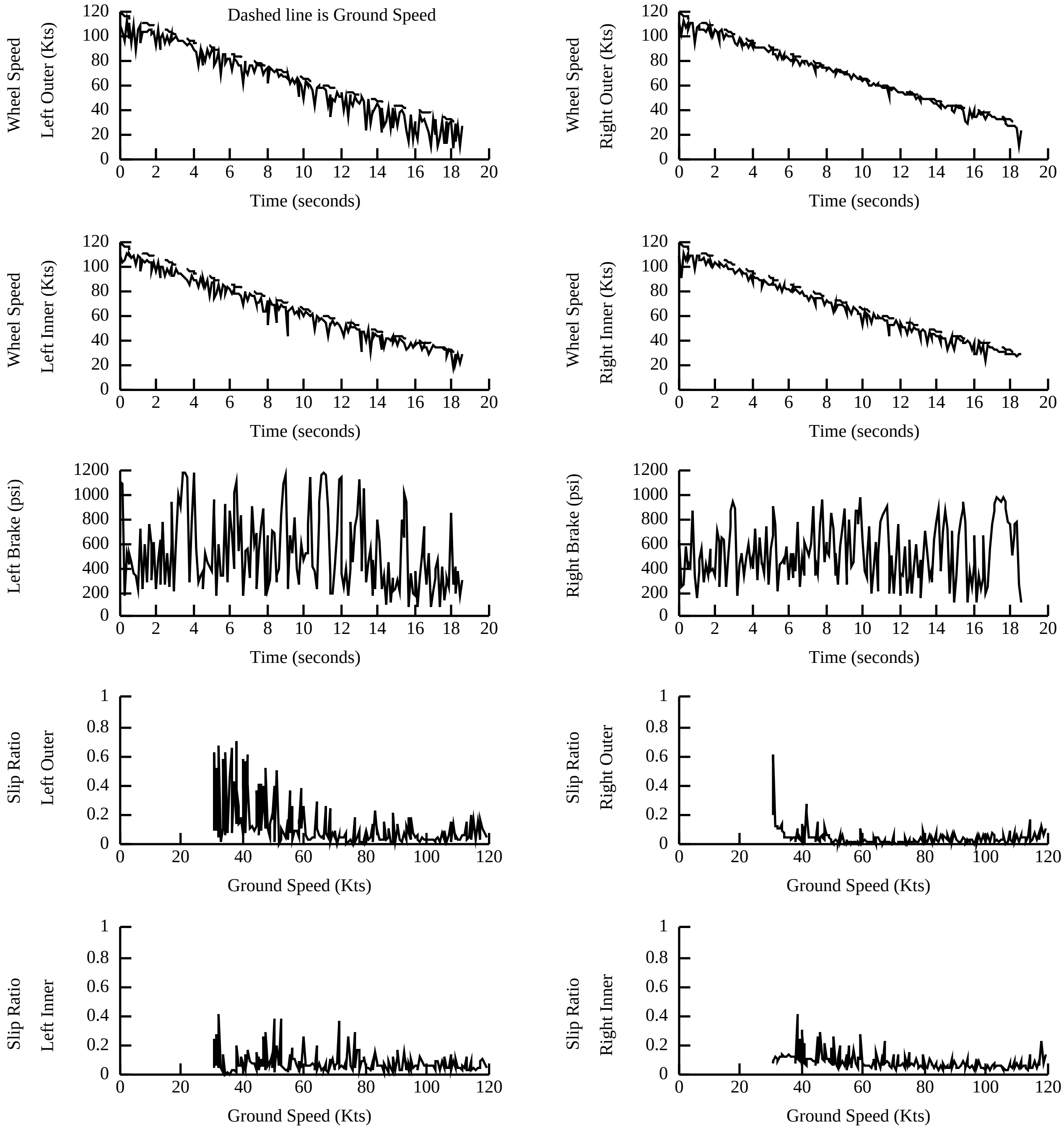


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts

Flight 99/03, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.40

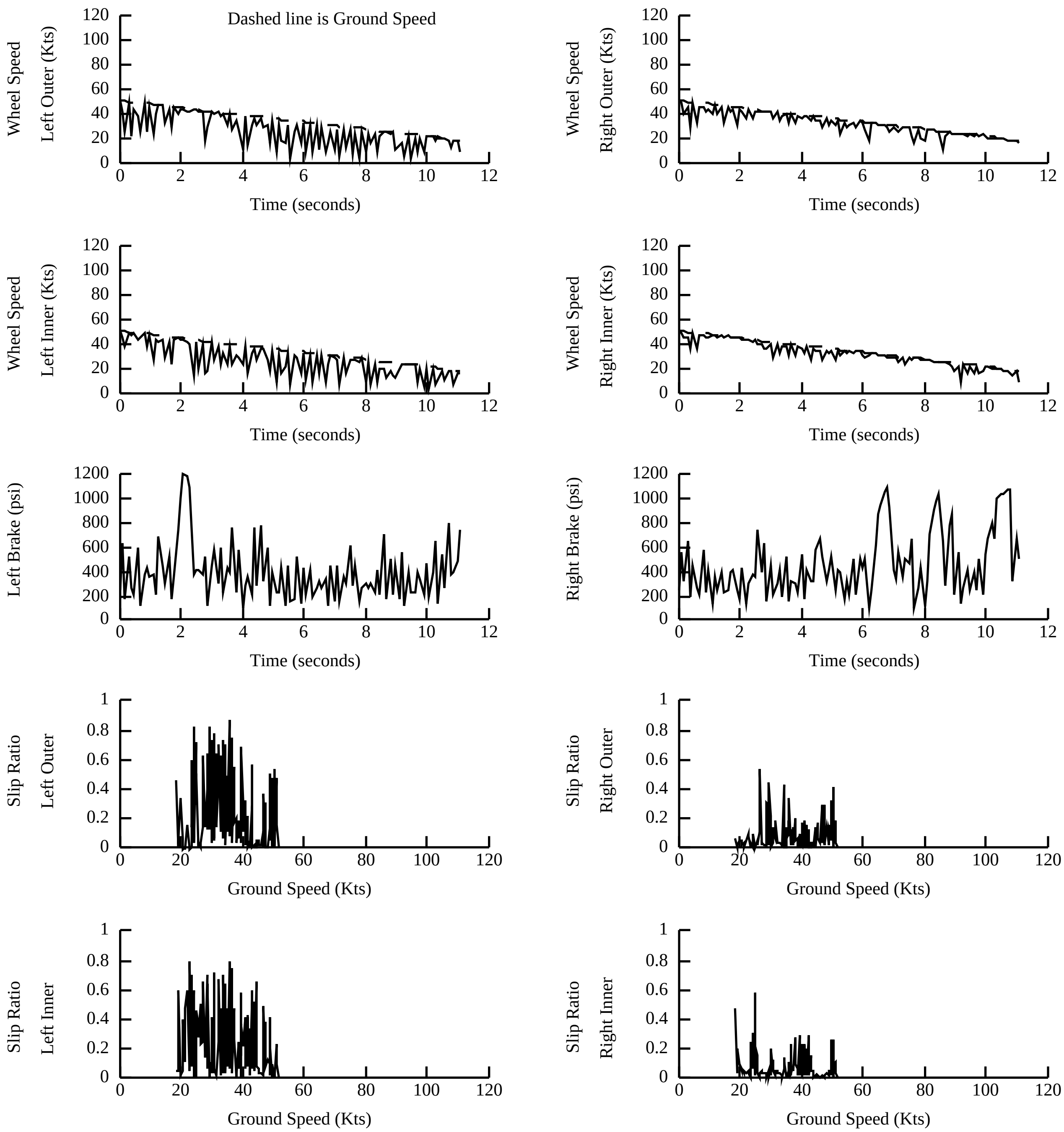


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

Flight 99/04, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.29

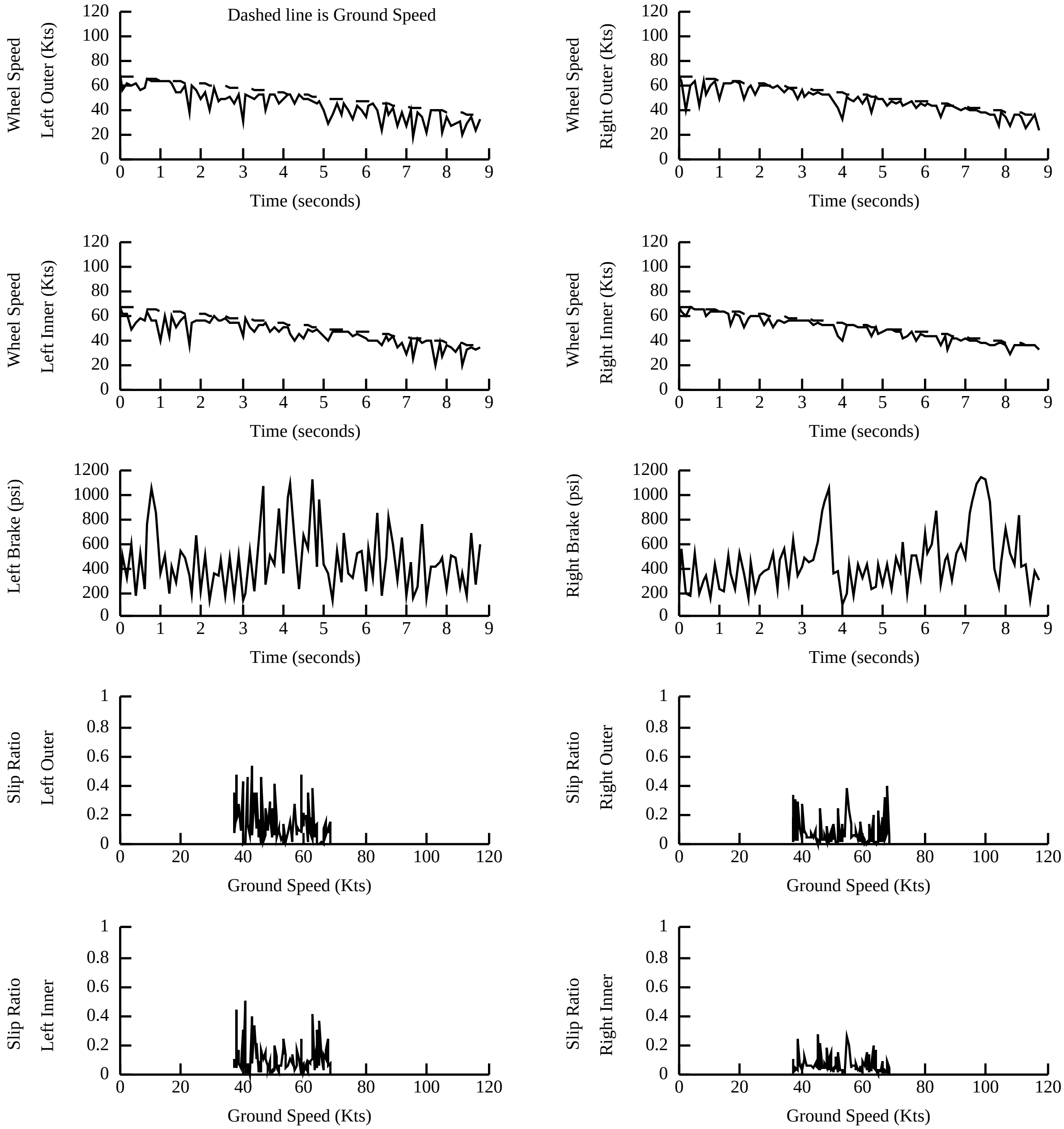


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

Flight 99/04, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.30

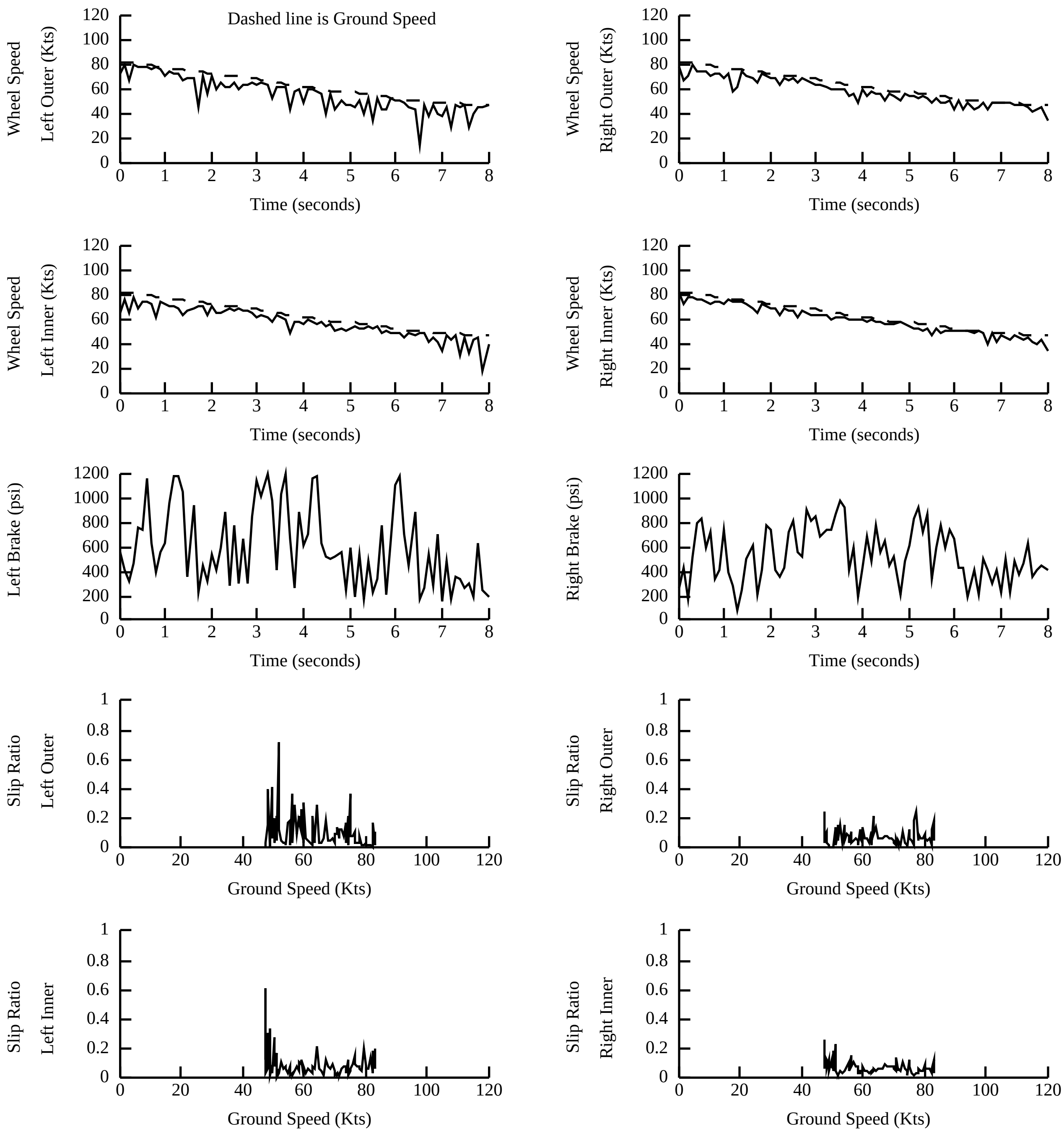


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

Flight 99/04, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.31

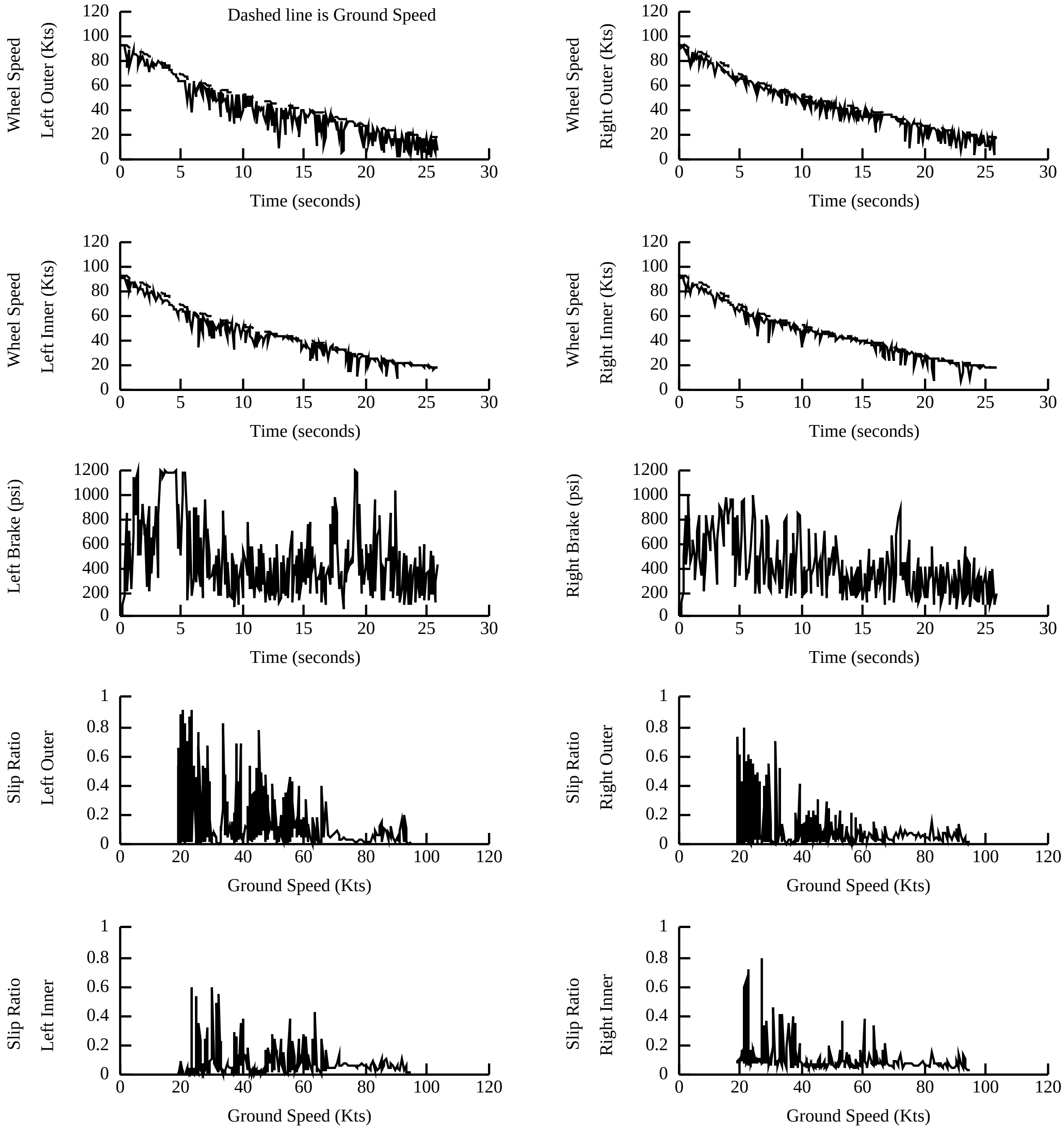


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

Flight 99/04, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.30

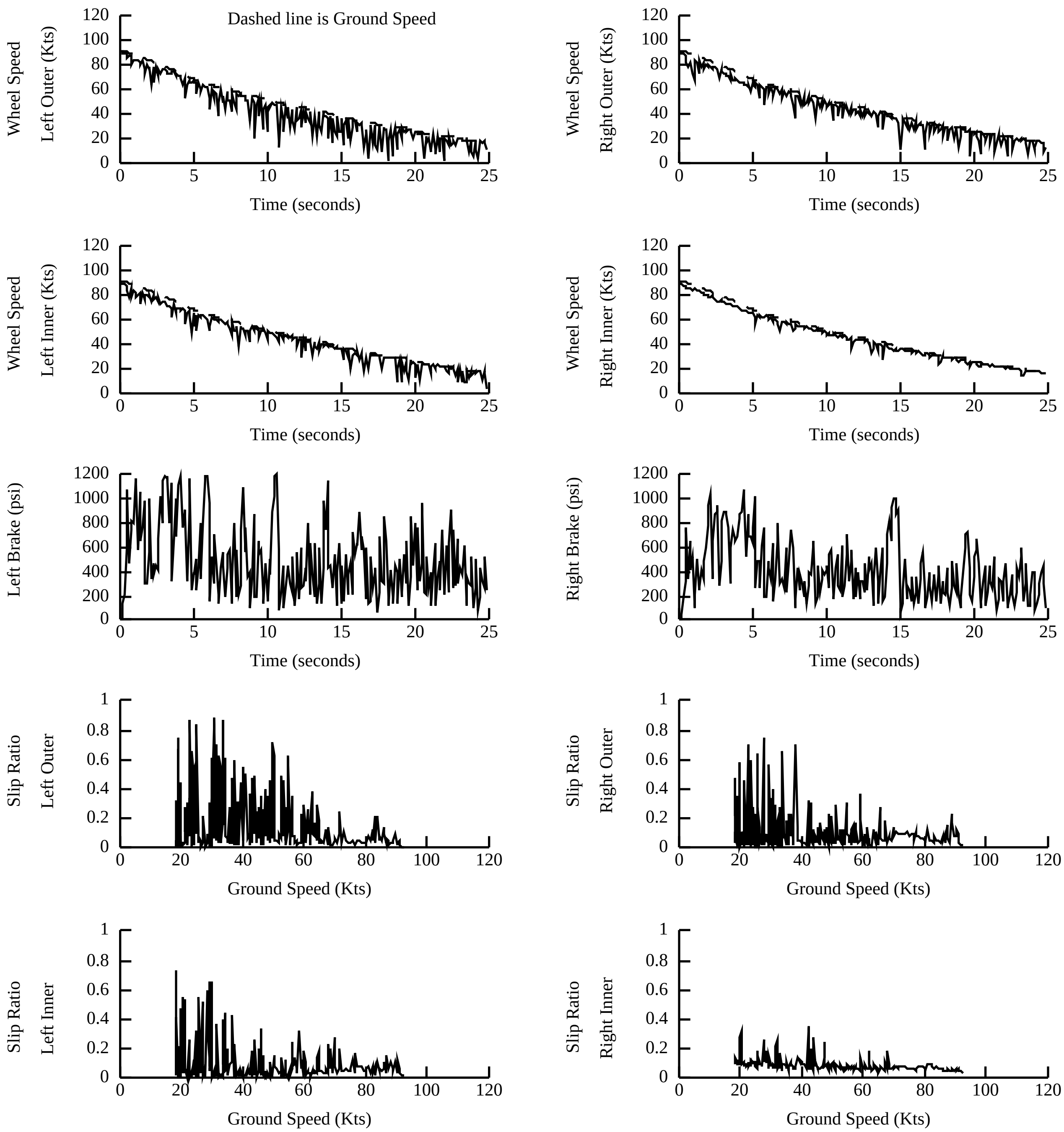


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

Flight 99/04, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.34

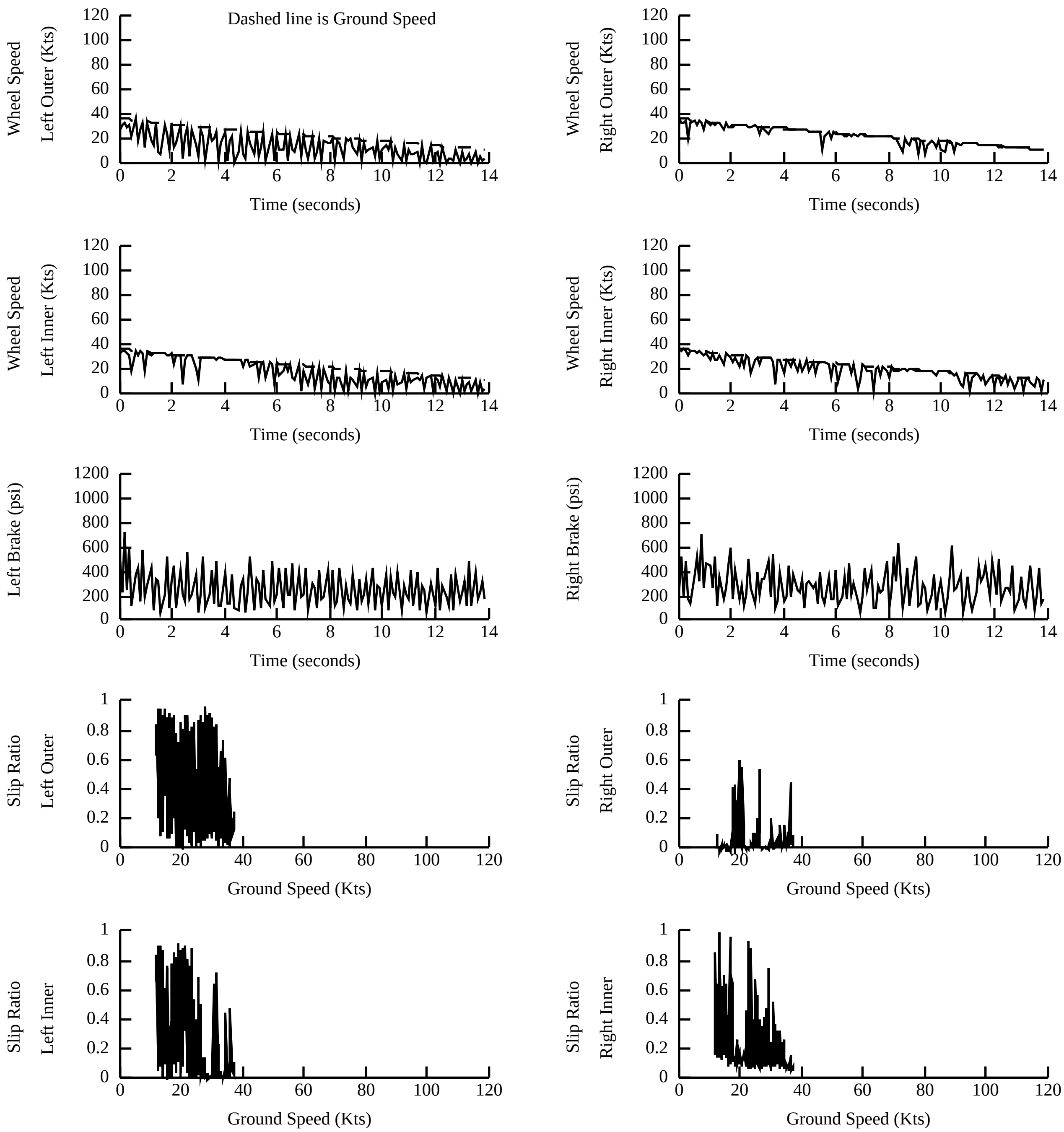


Surface: 100% Thin Ice with some Roughness from Pavement Texture

Flight 99/05, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.28

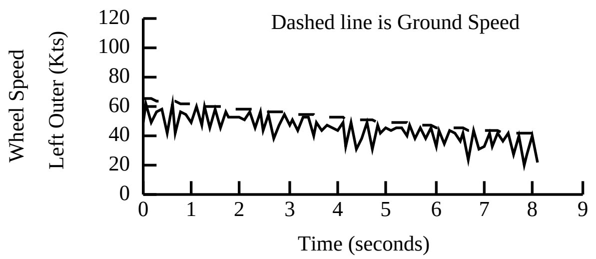


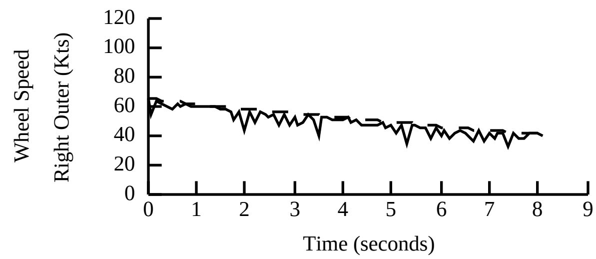
Surface: 100% Thin Ice with some Roughness from Pavement Texture

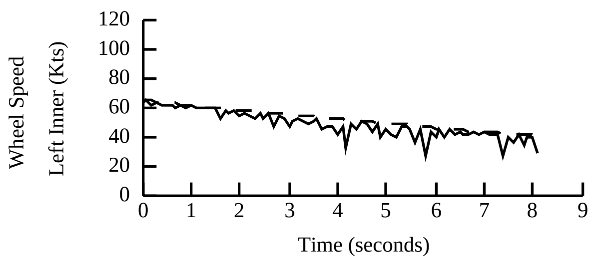
Flight 99/05, Run Number 2

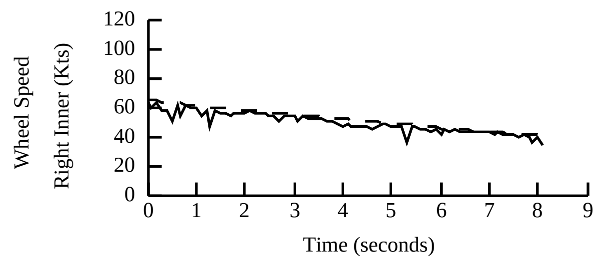
Configuration: Flaps 40, Air Brakes Out, Max Braking

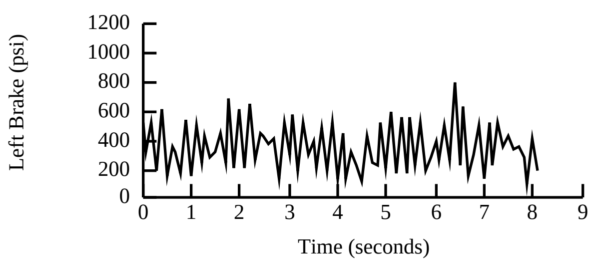
CFRI Average 0.29

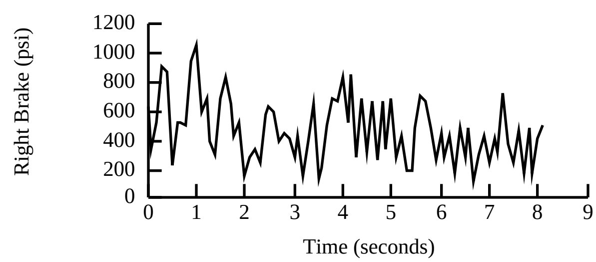


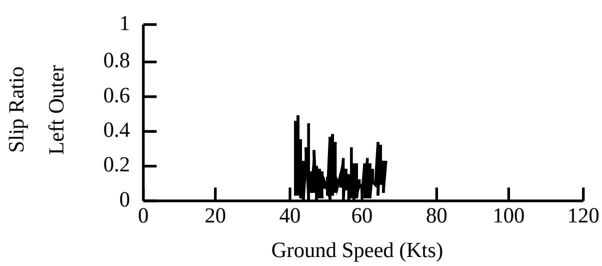



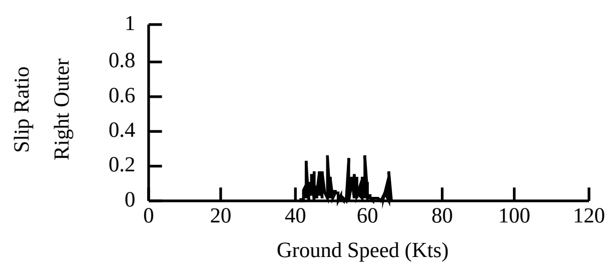



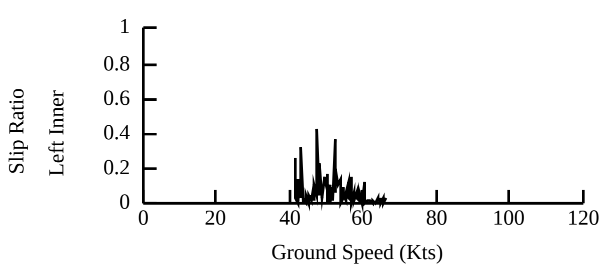



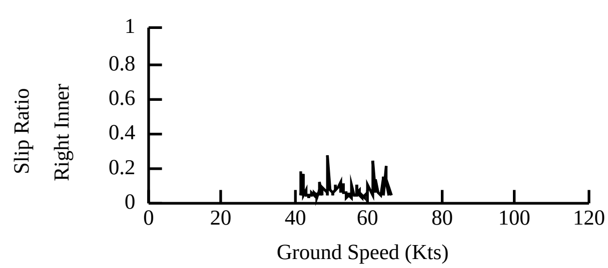



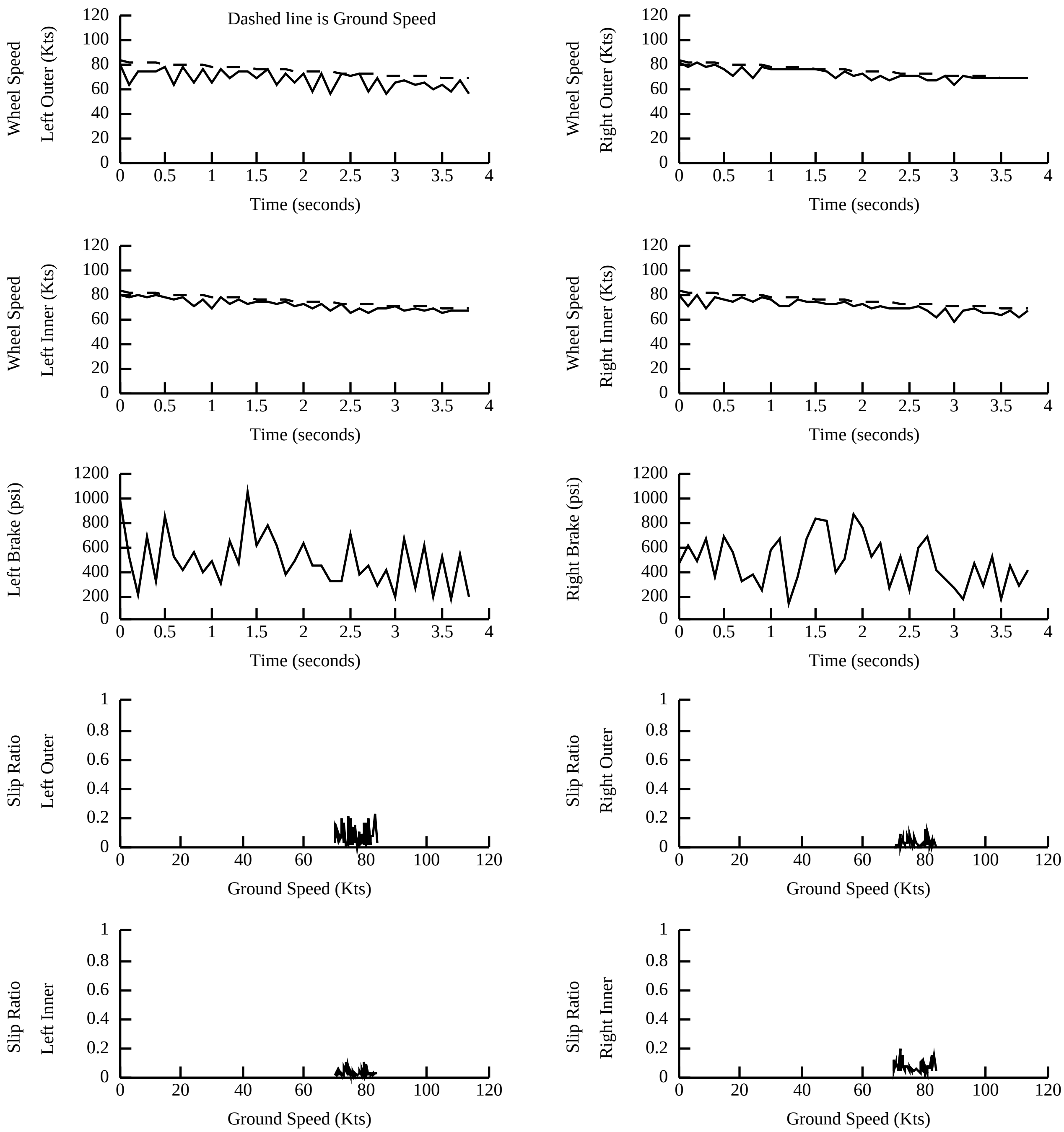



Surface: 100% Thin Ice with some Roughness from Pavement Texture

Flight 99/05, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.23

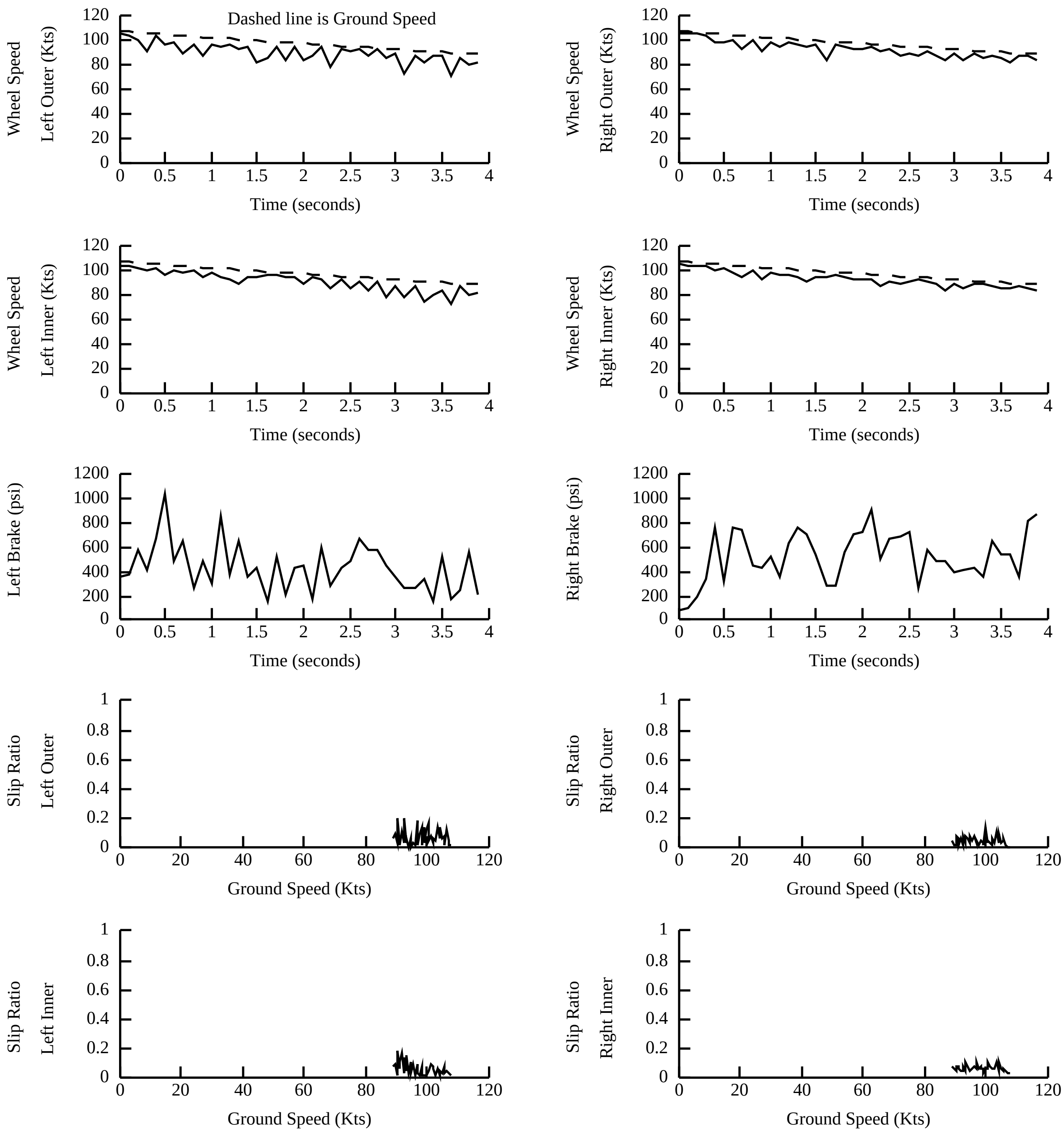


Surface: 100% Thin Ice with some Roughness from Pavement Texture

Flight 99/05, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.25

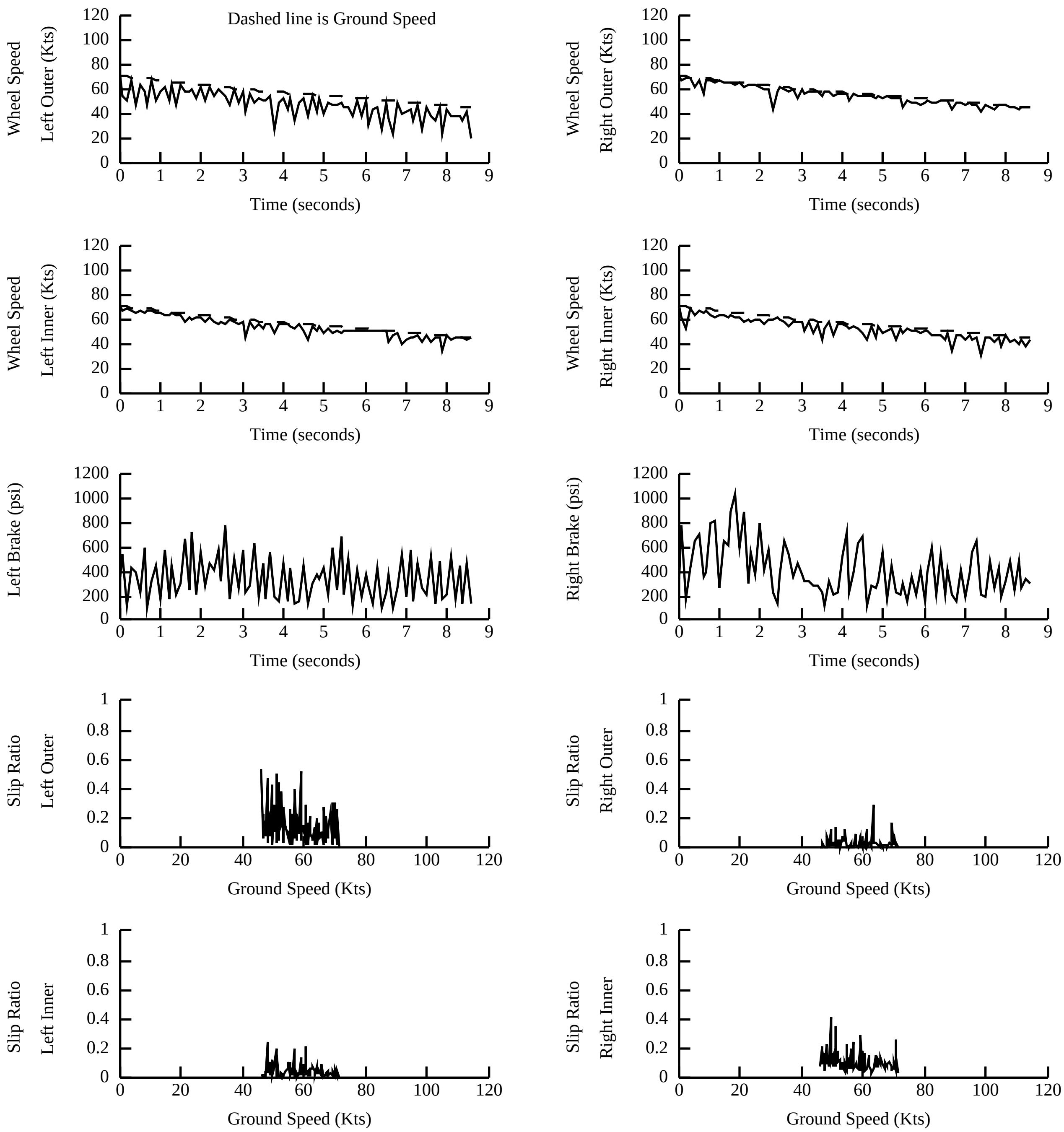


Surface: 100% Thin Ice with some Roughness from Pavement Texture

Flight 99/05, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.26

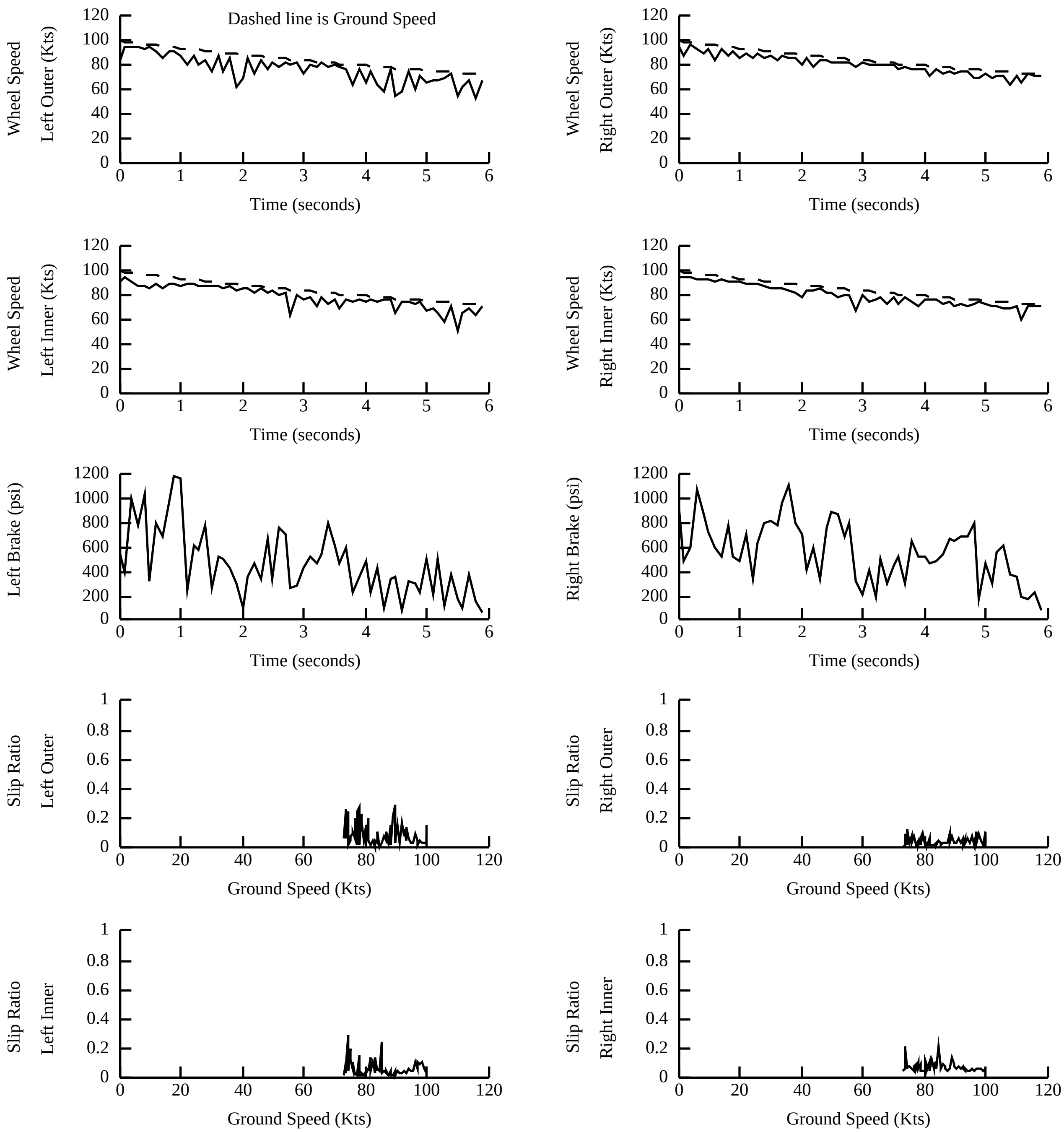


Surface: 100% Thin Ice with some Roughness from Pavement Texture

Flight 99/05, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.29

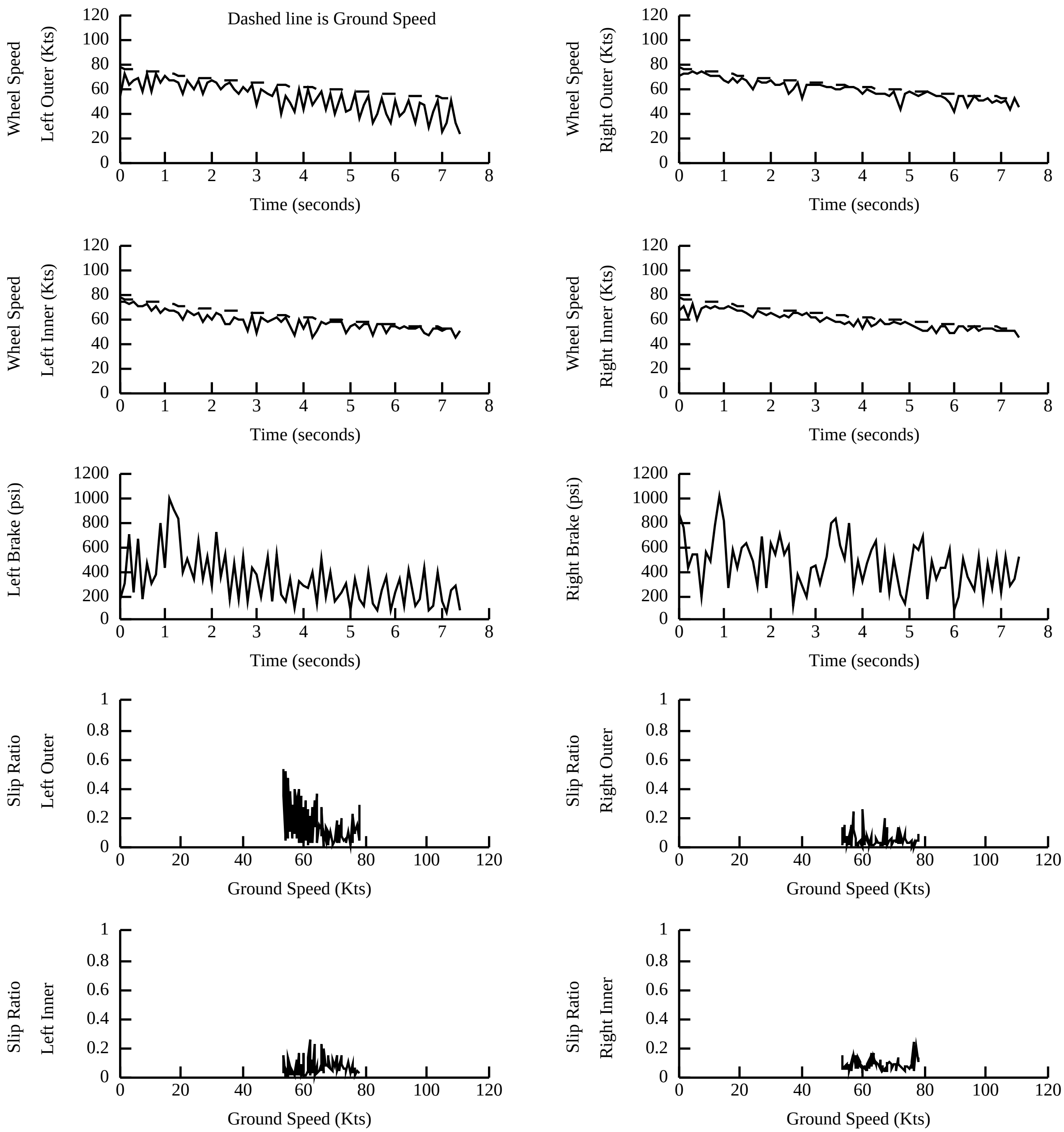


Surface: 100% Thin Ice with some Roughness from Pavement Texture

Flight 99/05, Run Number 7

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.28

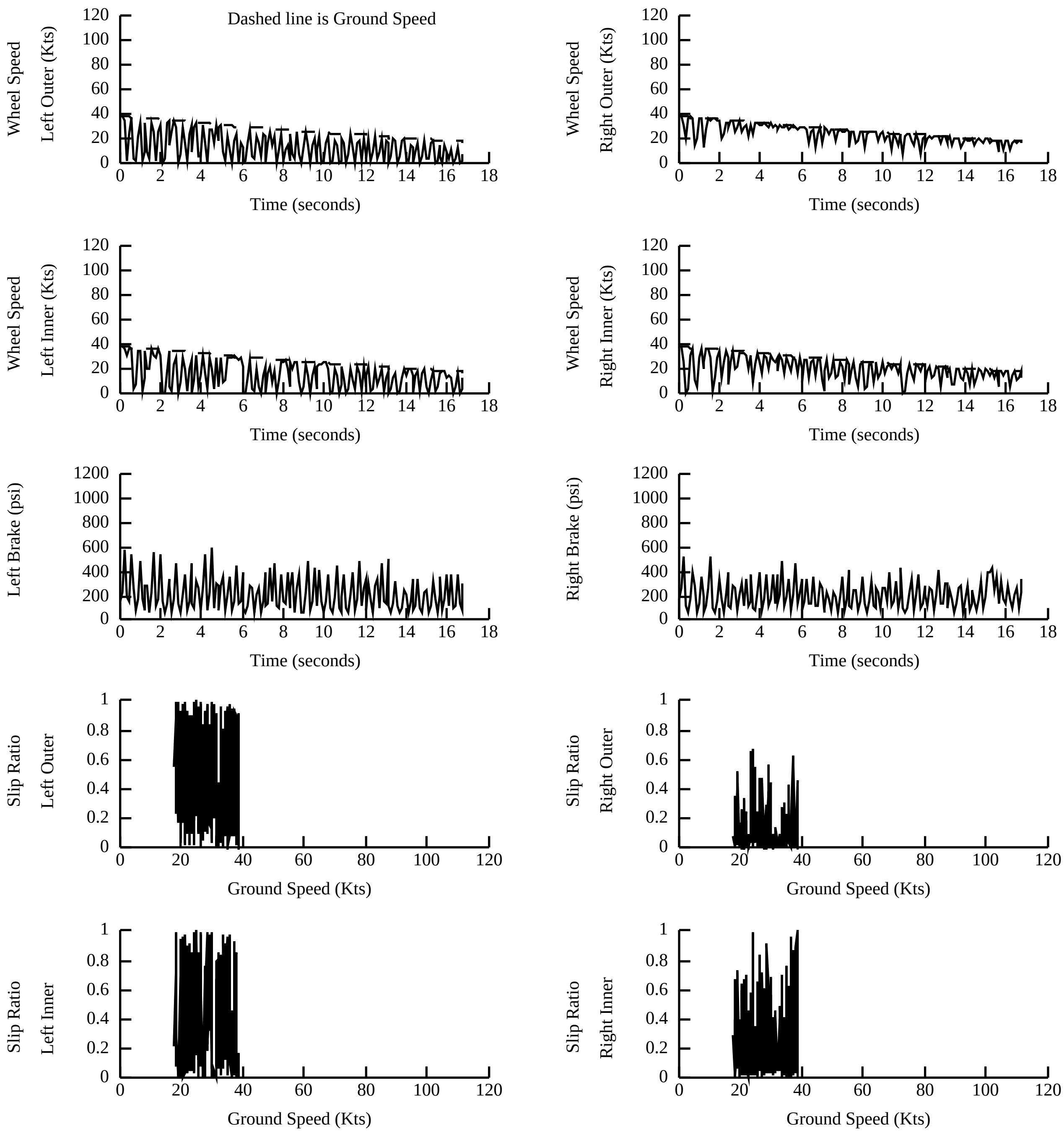


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

Flight 99/06, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.19

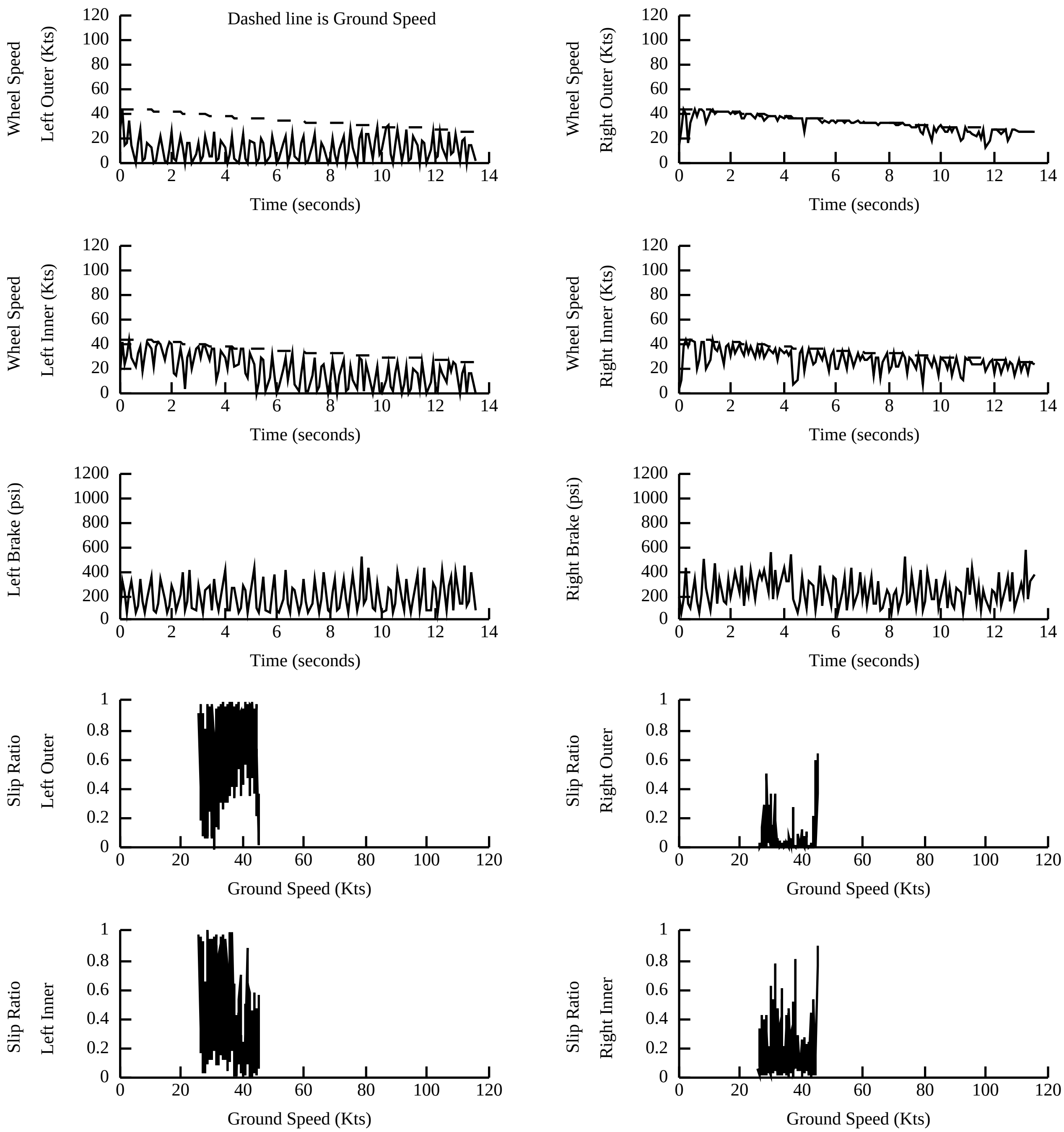


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

Flight 99/06, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.18

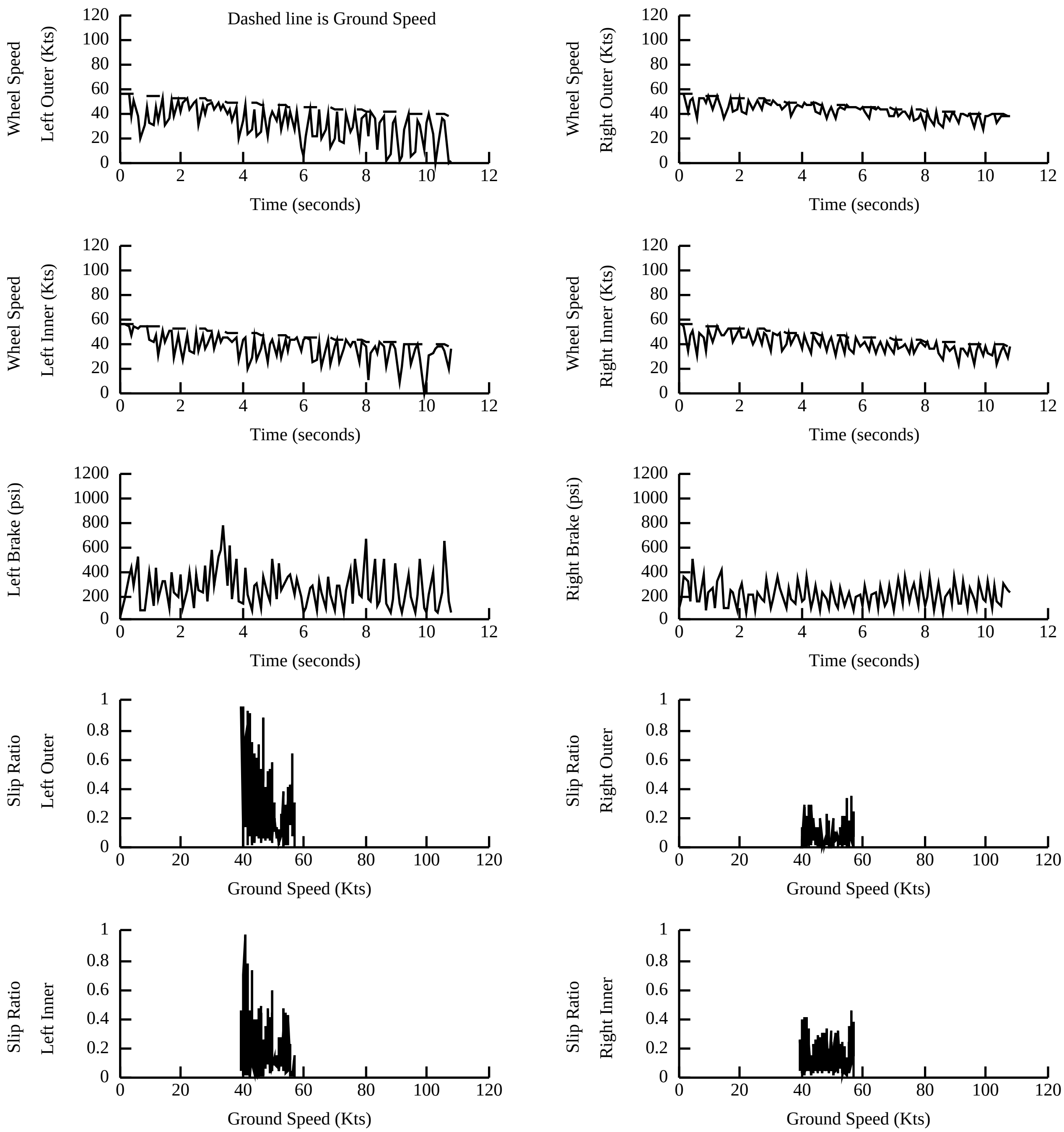


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

Flight 99/06, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.20

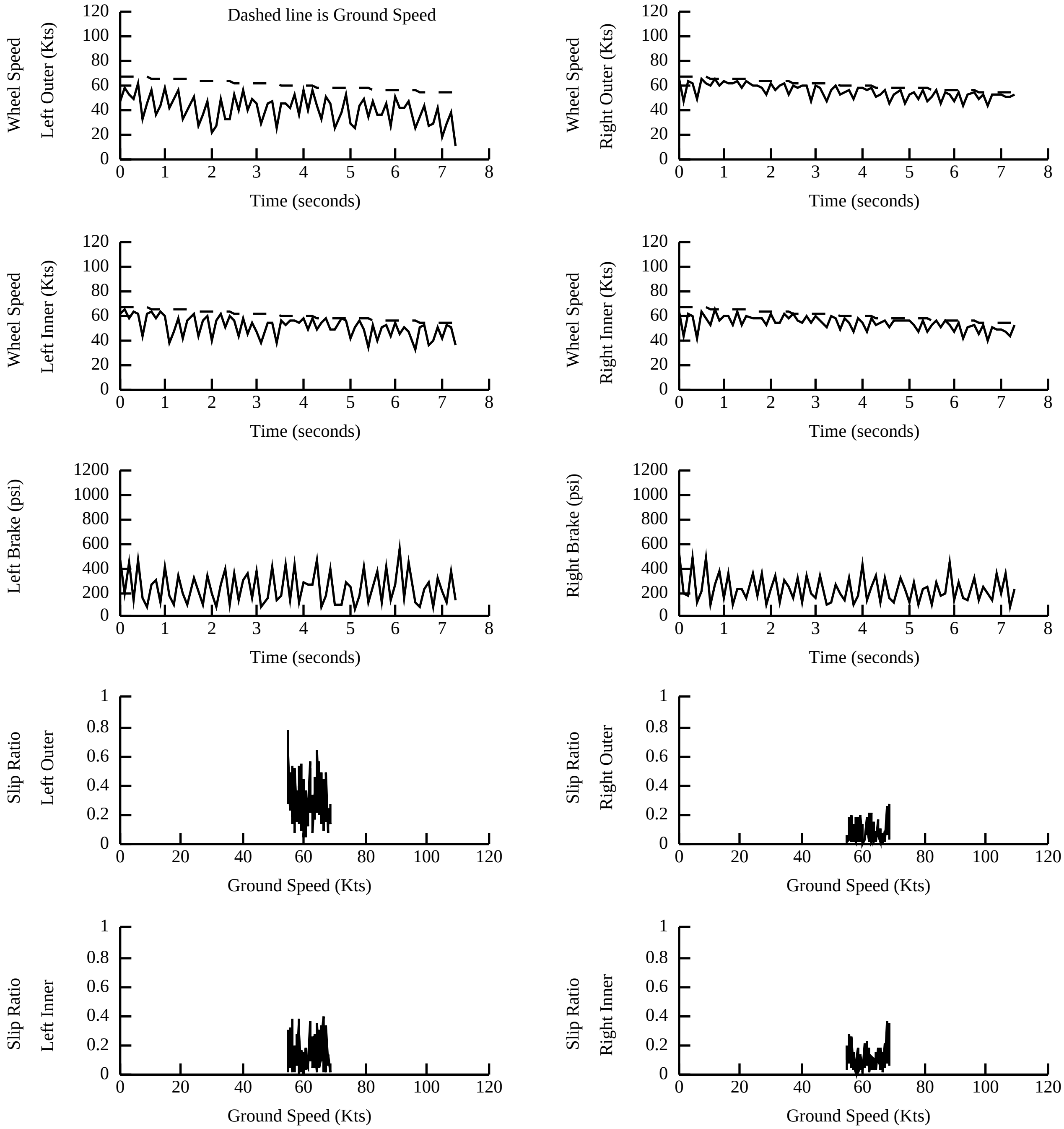


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

Flight 99/06, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.17

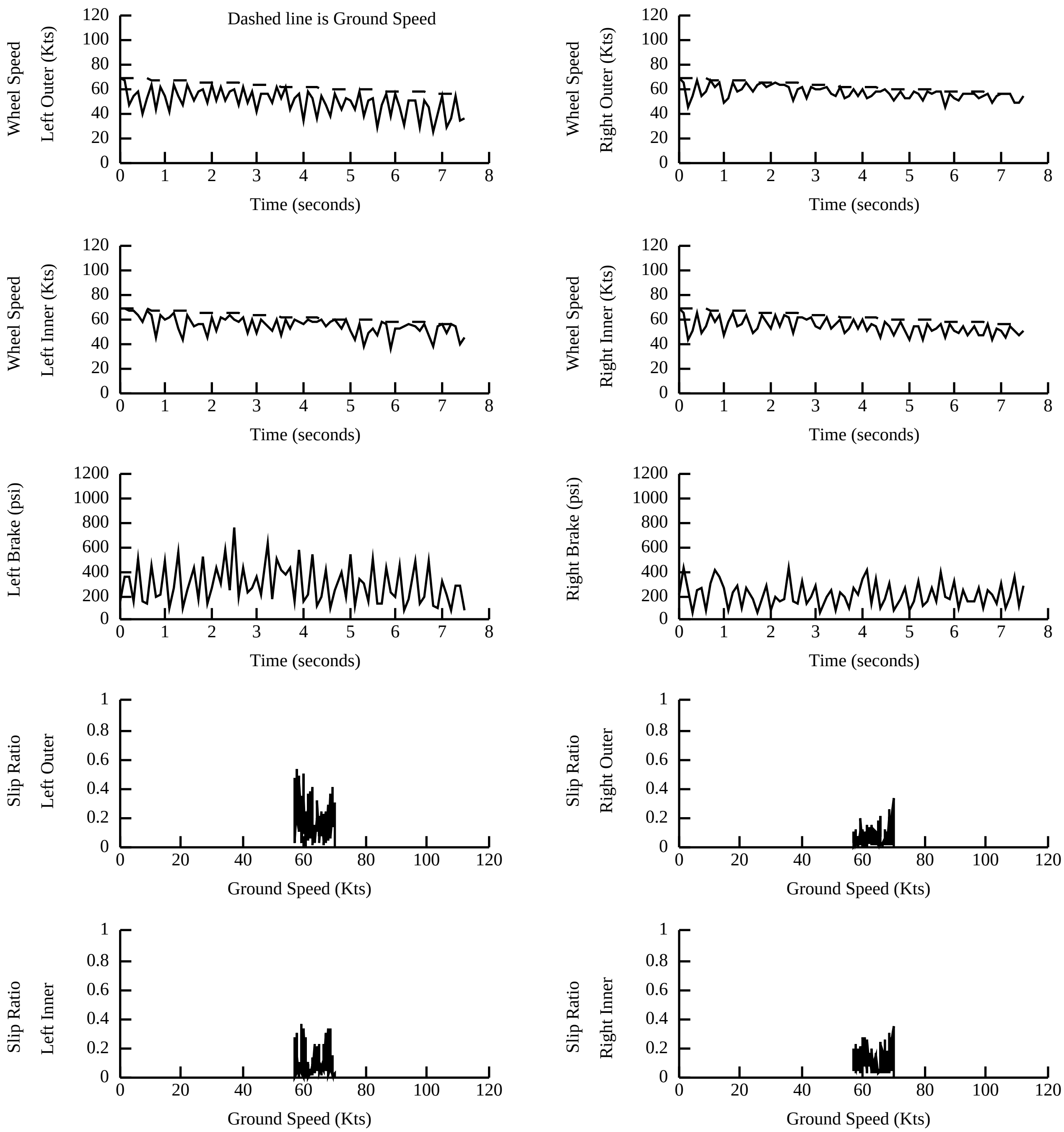


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

Flight 99/06, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.16

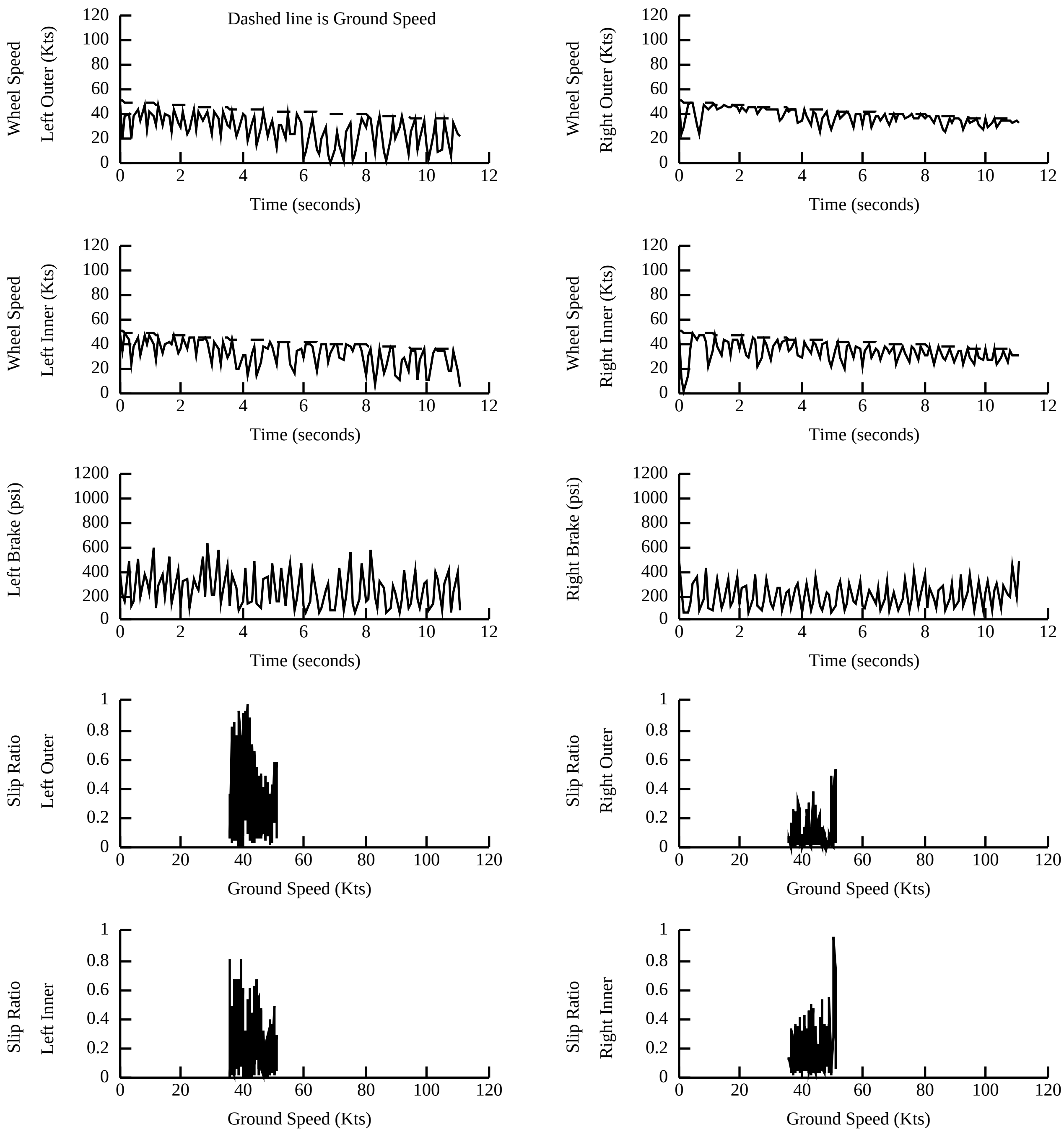


Surface: 100% Ice with One Application of Sand and Falling Loose Snow

Flight 99/06, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.19

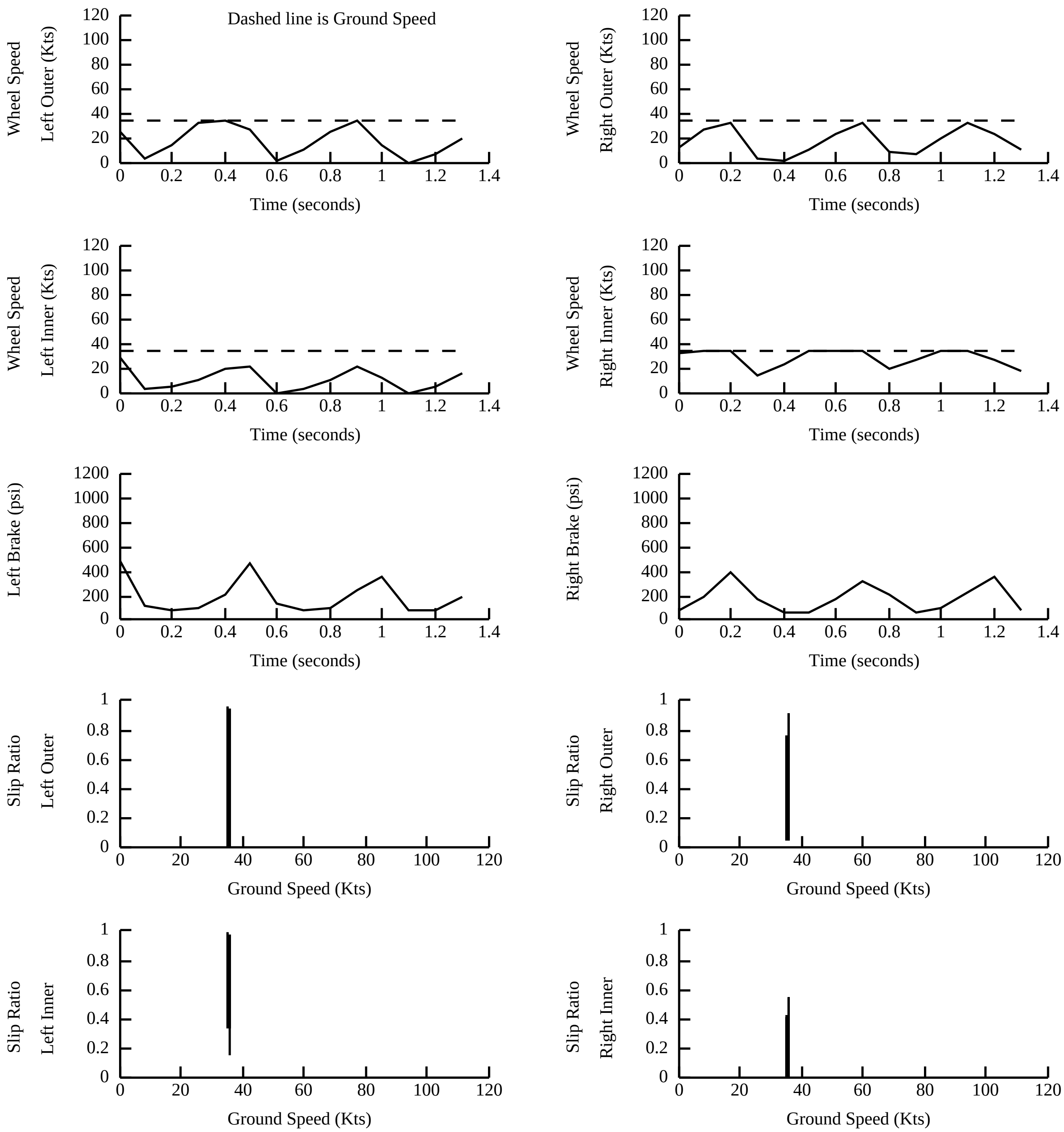


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.14

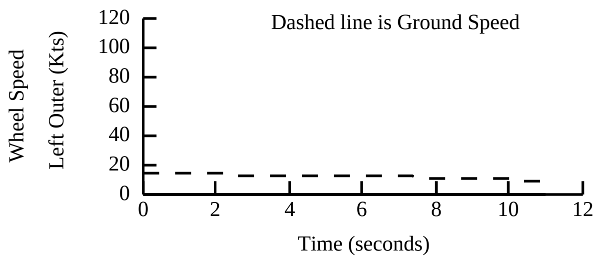


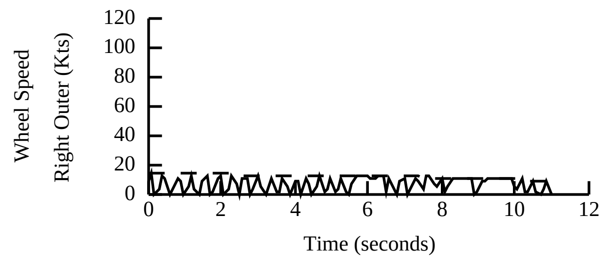
Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

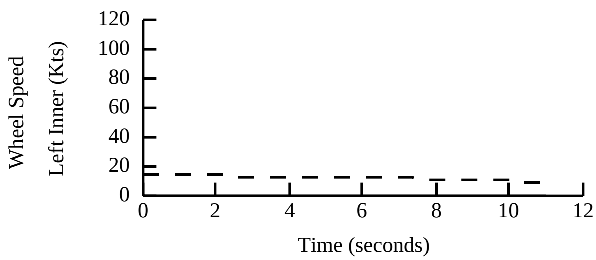
Flight 99/07, Run Number 2

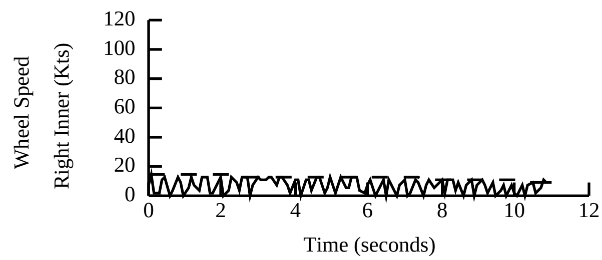
Configuration: Flaps 40, Air Brakes Out, Max Braking

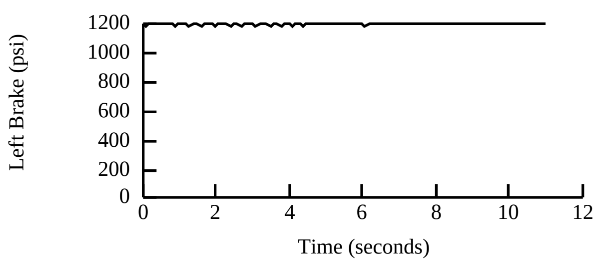
CRFI Average 0.14

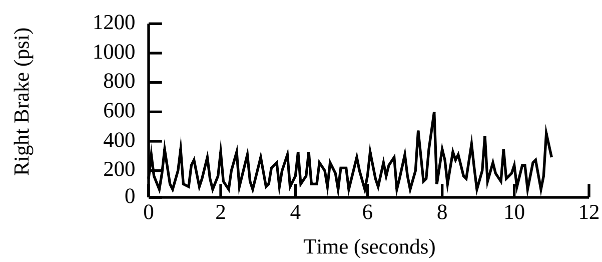


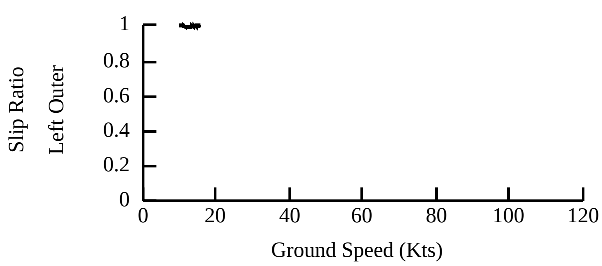



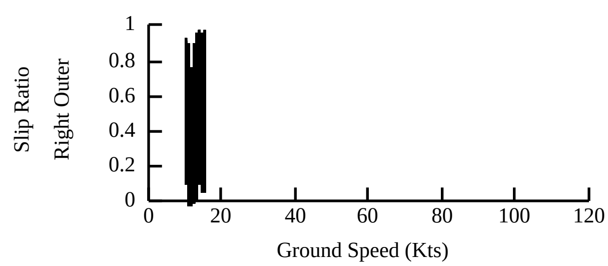



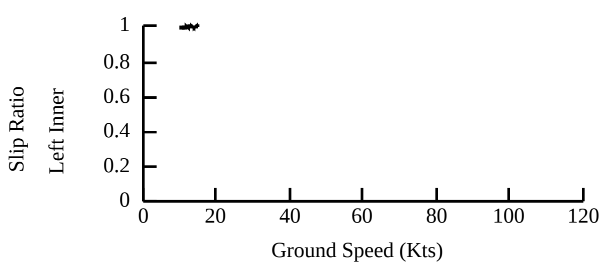



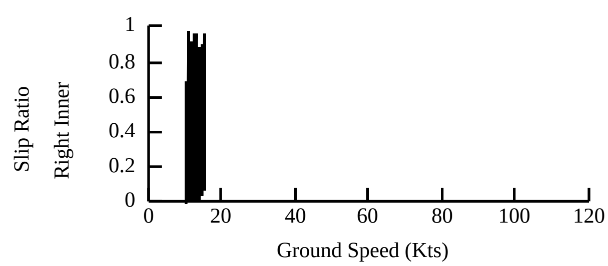



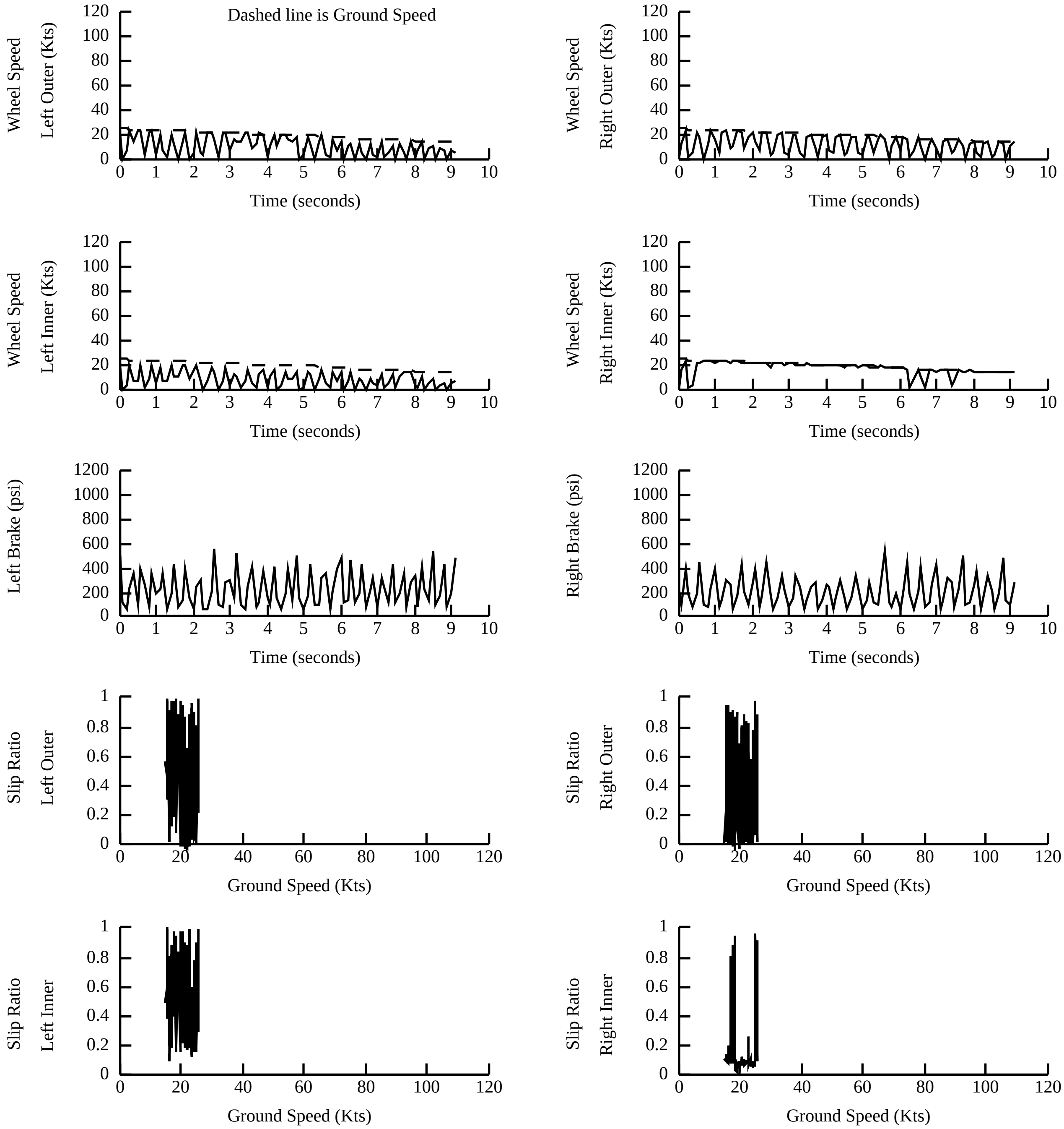



Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.17

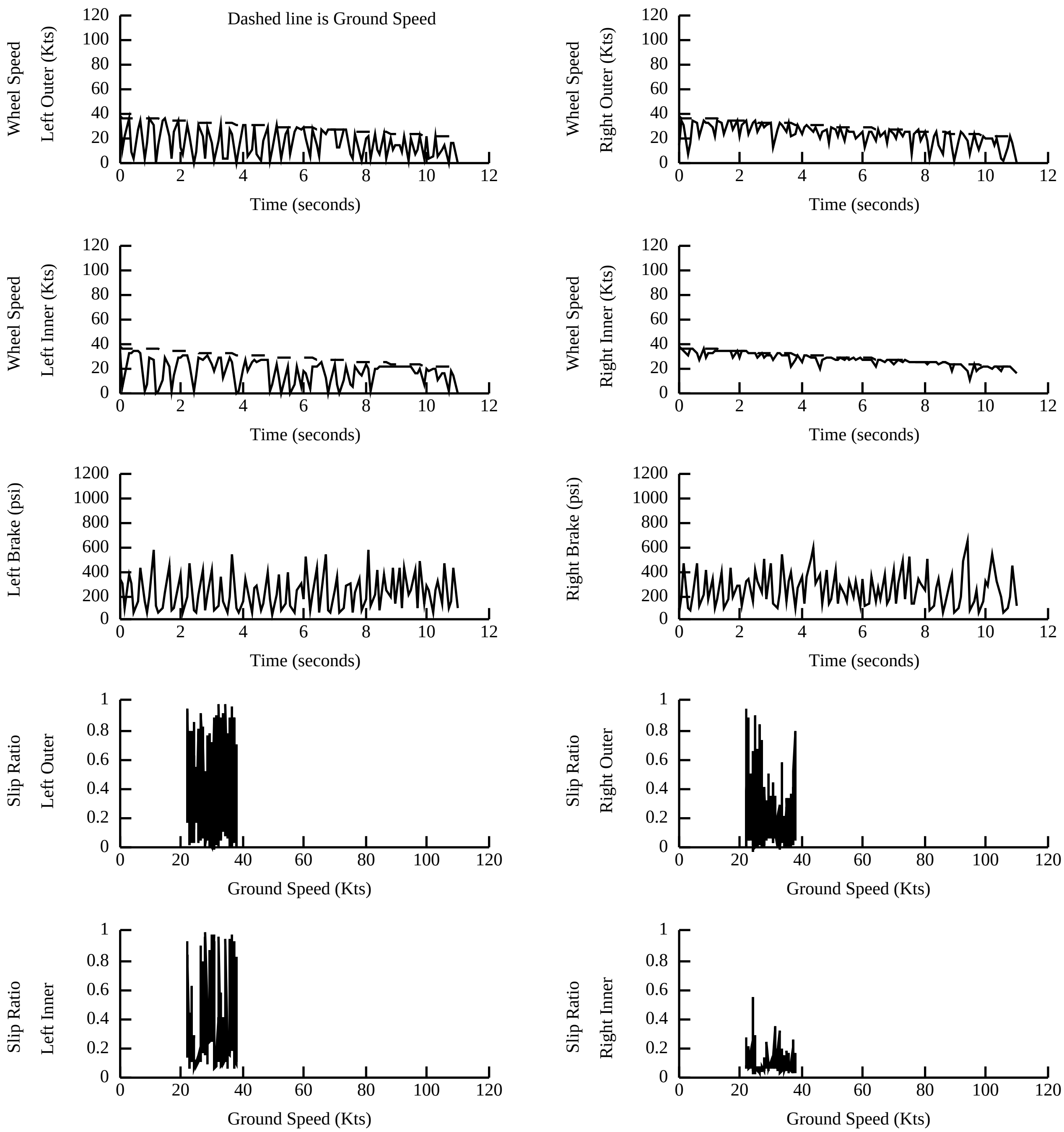


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

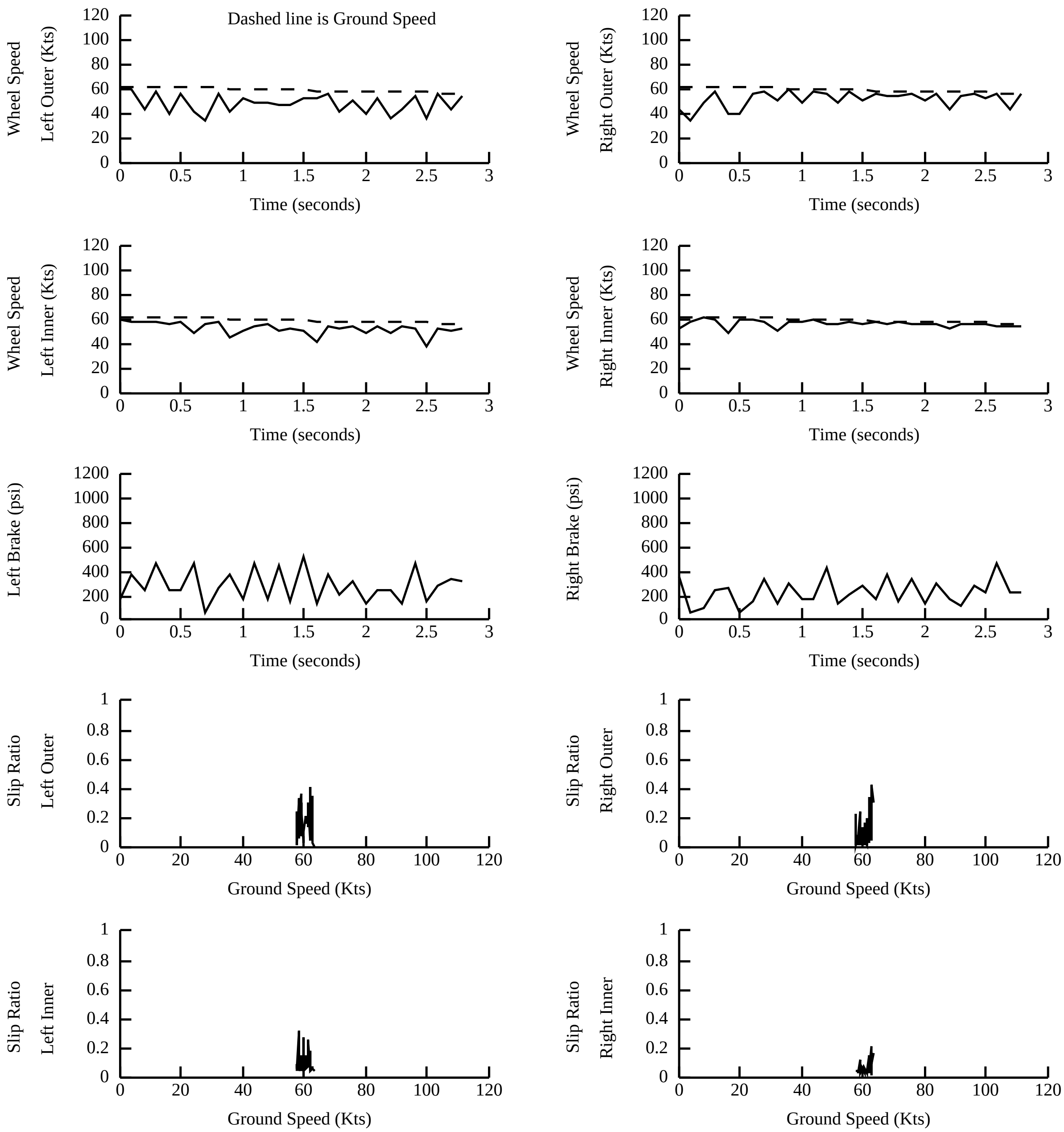


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

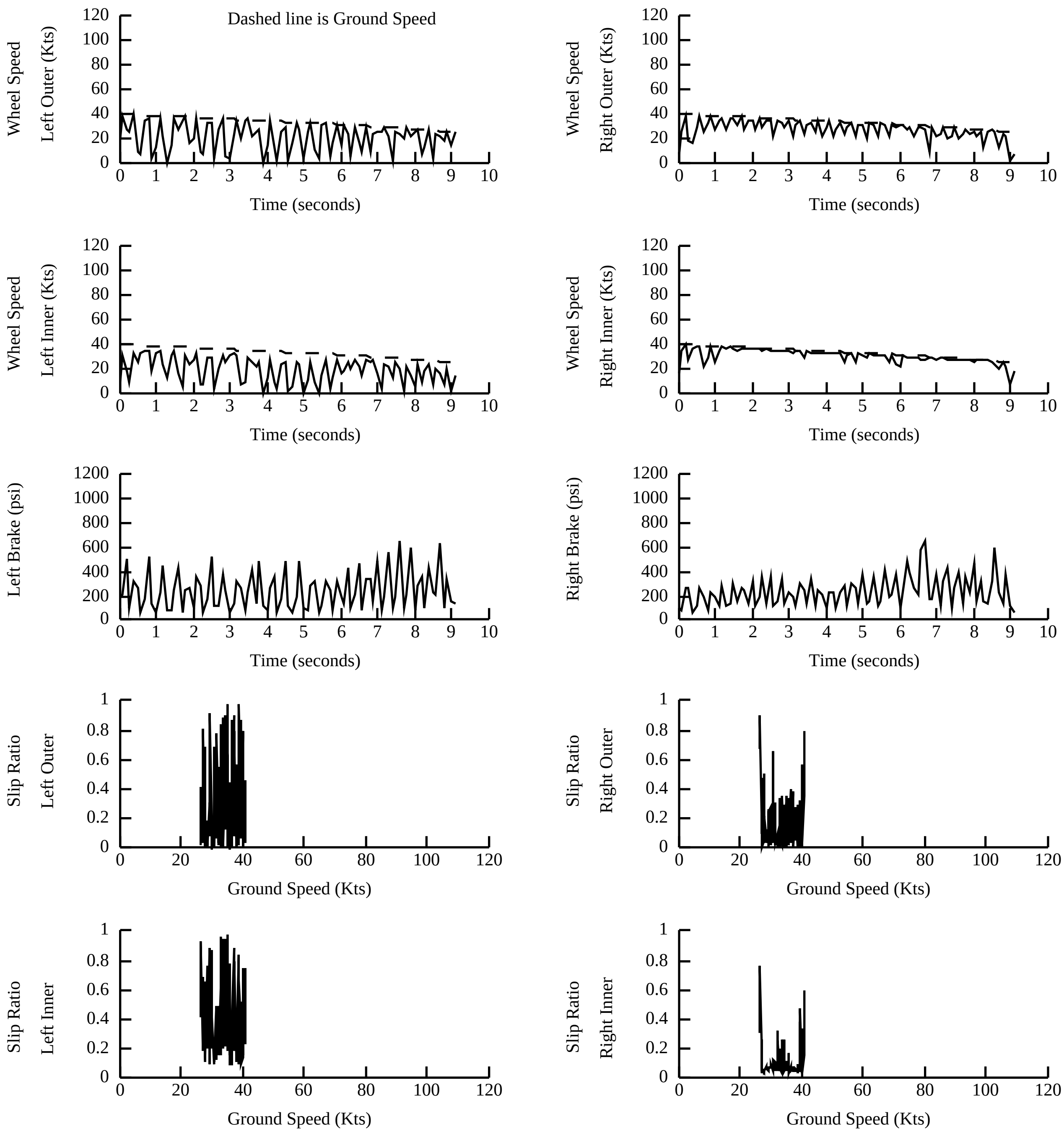


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

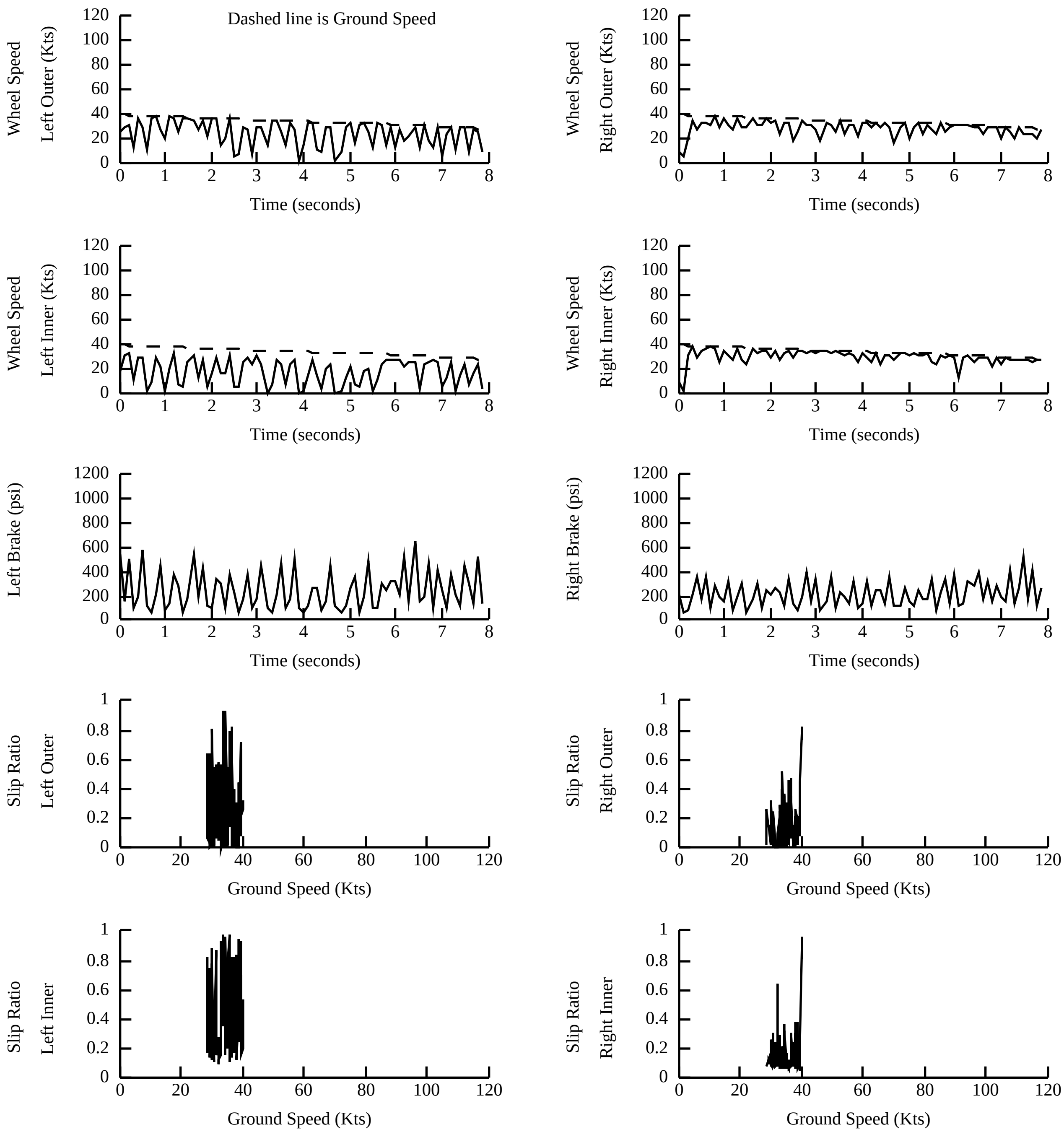


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 7

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21

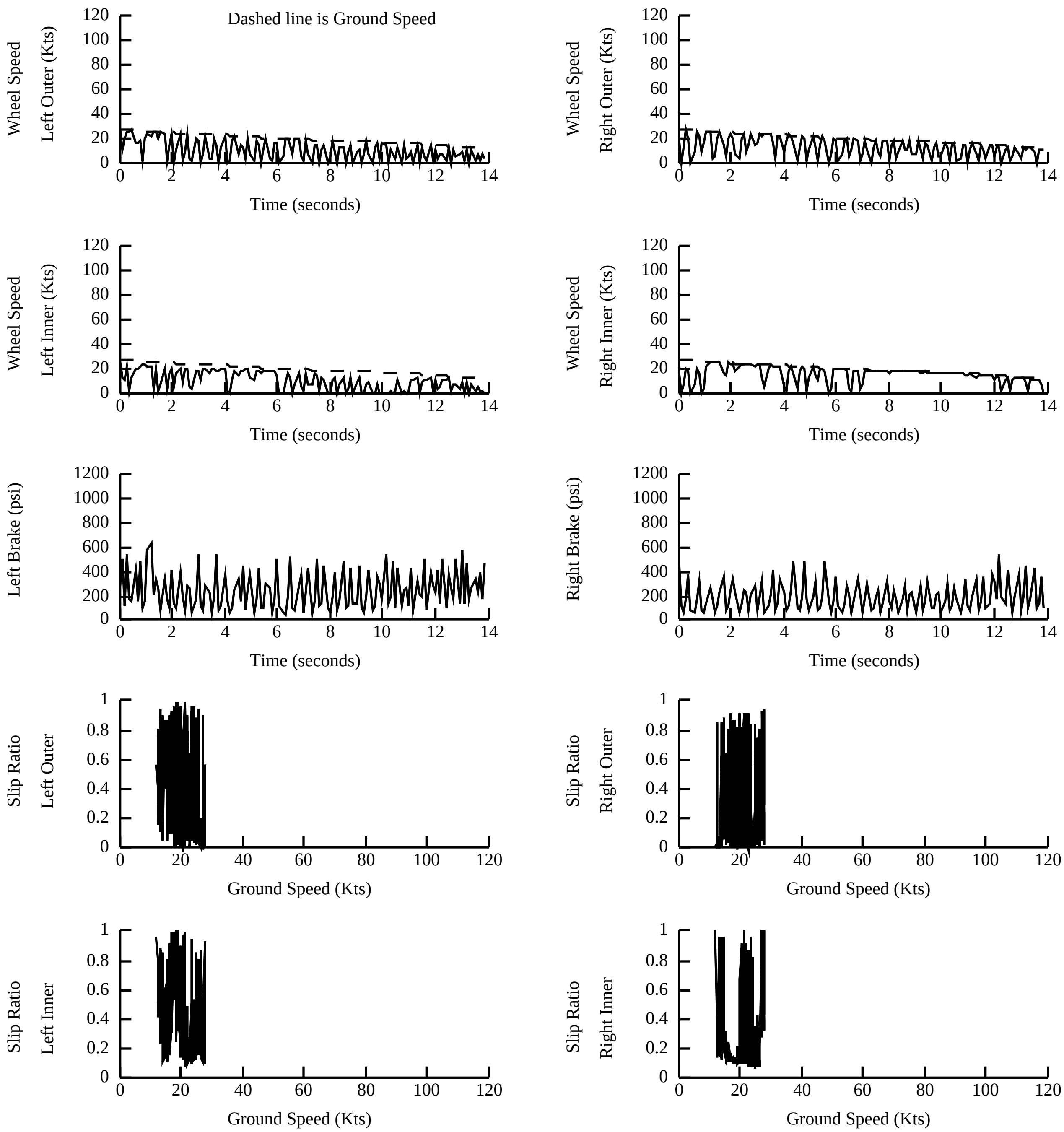


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

Flight 99/07, Run Number 8

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.22

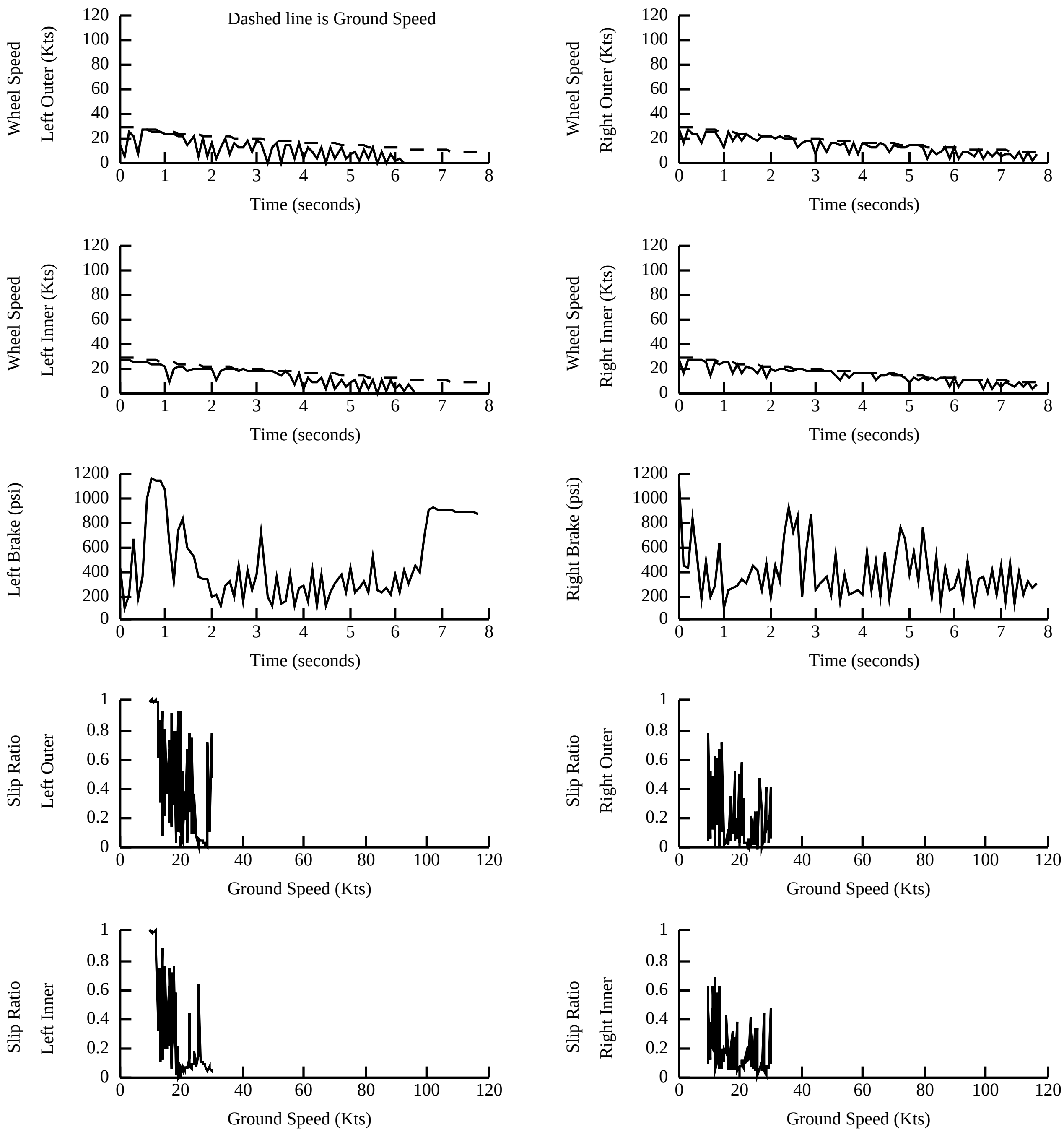


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

## Flight 99/08, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.25

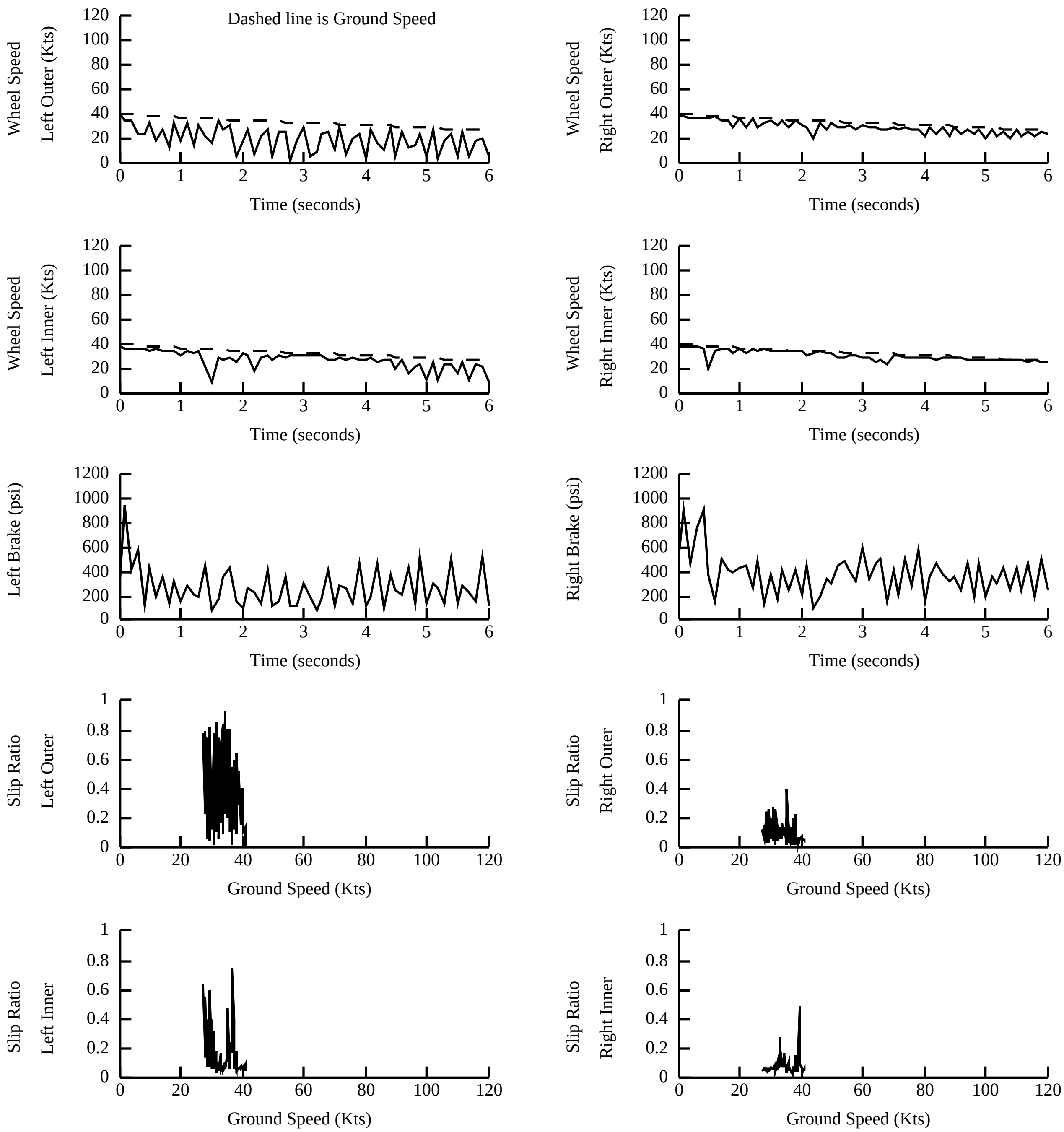


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

Flight 99/08, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

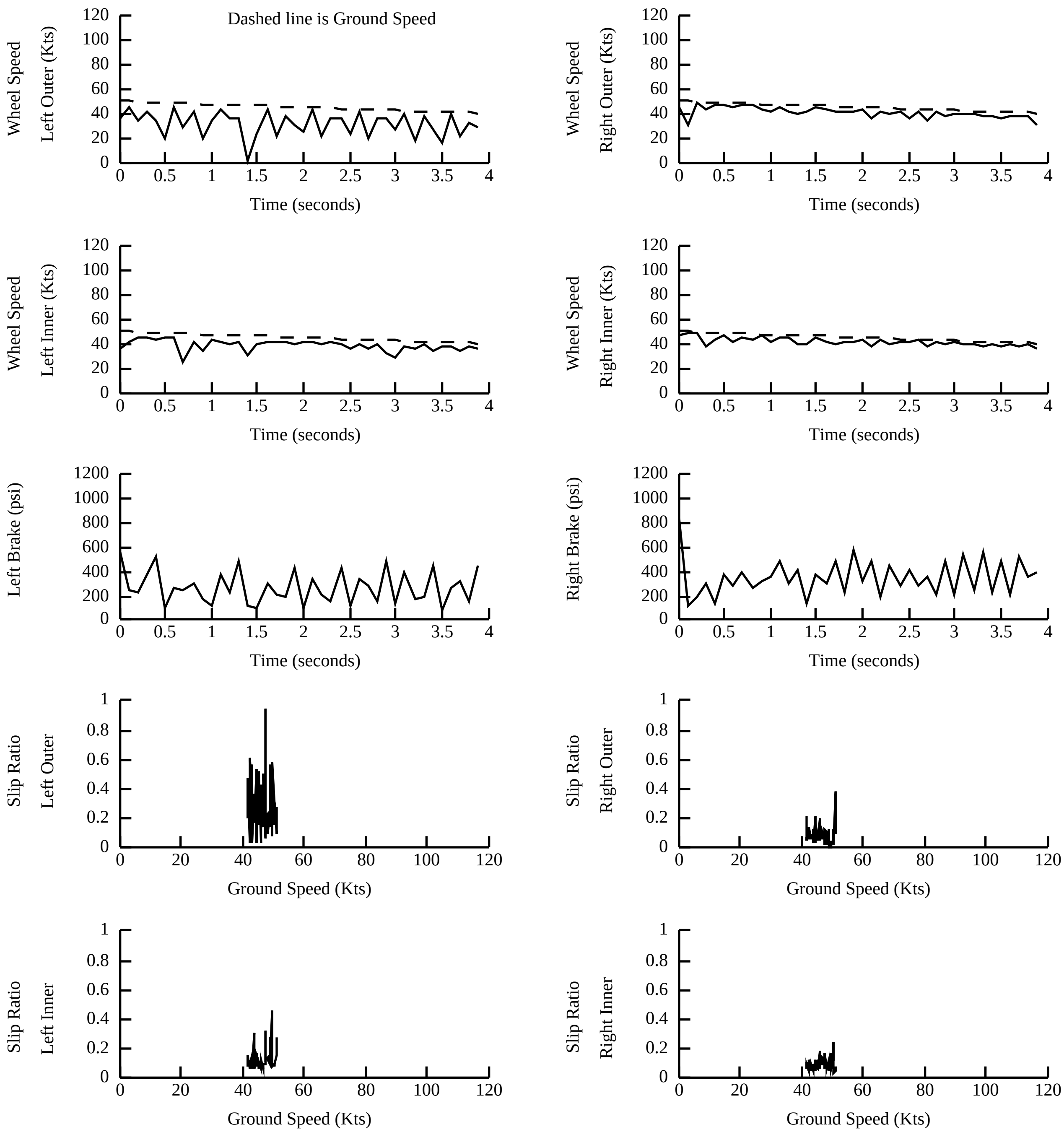


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

Flight 99/08, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

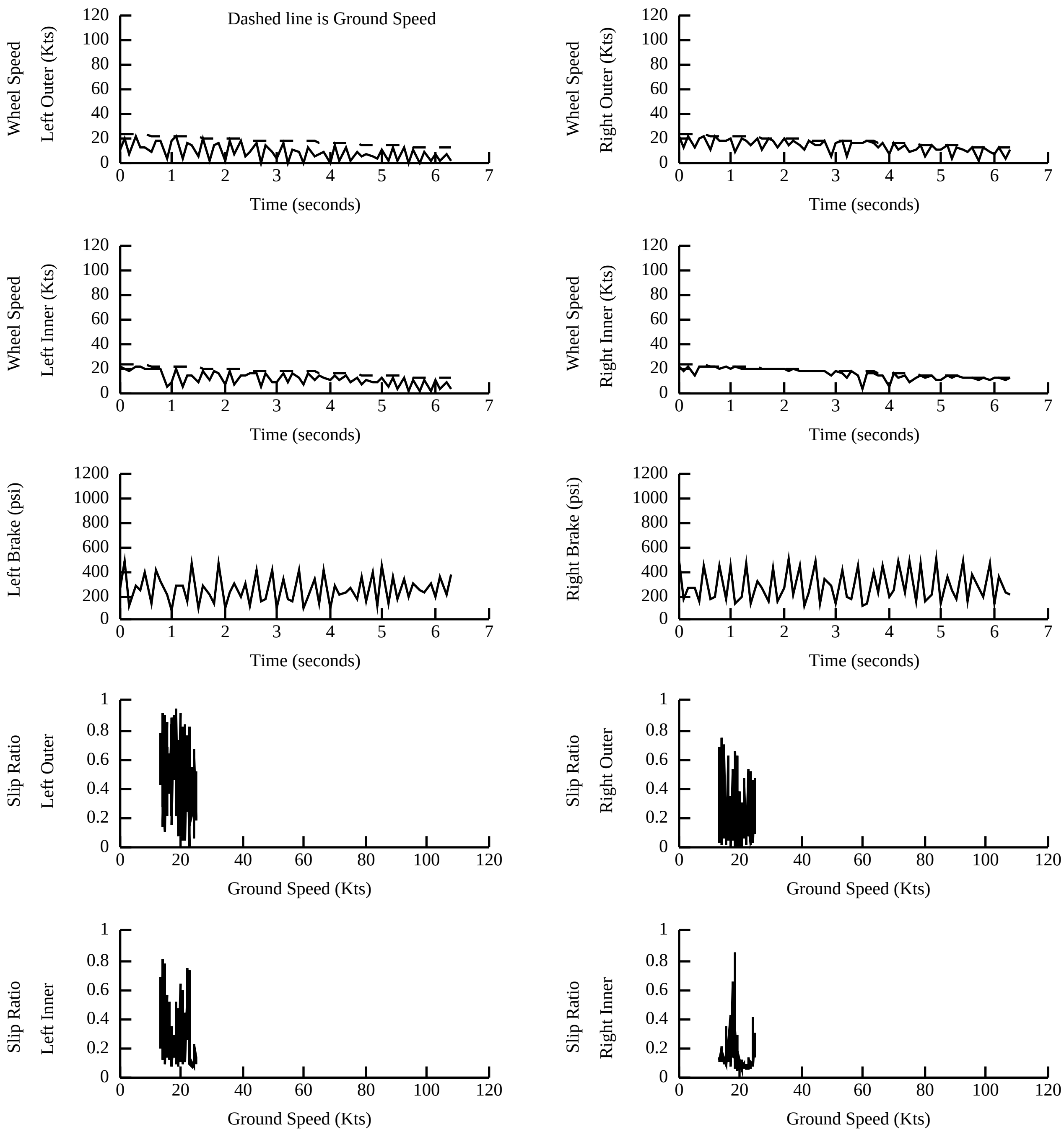


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

Flight 99/08, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

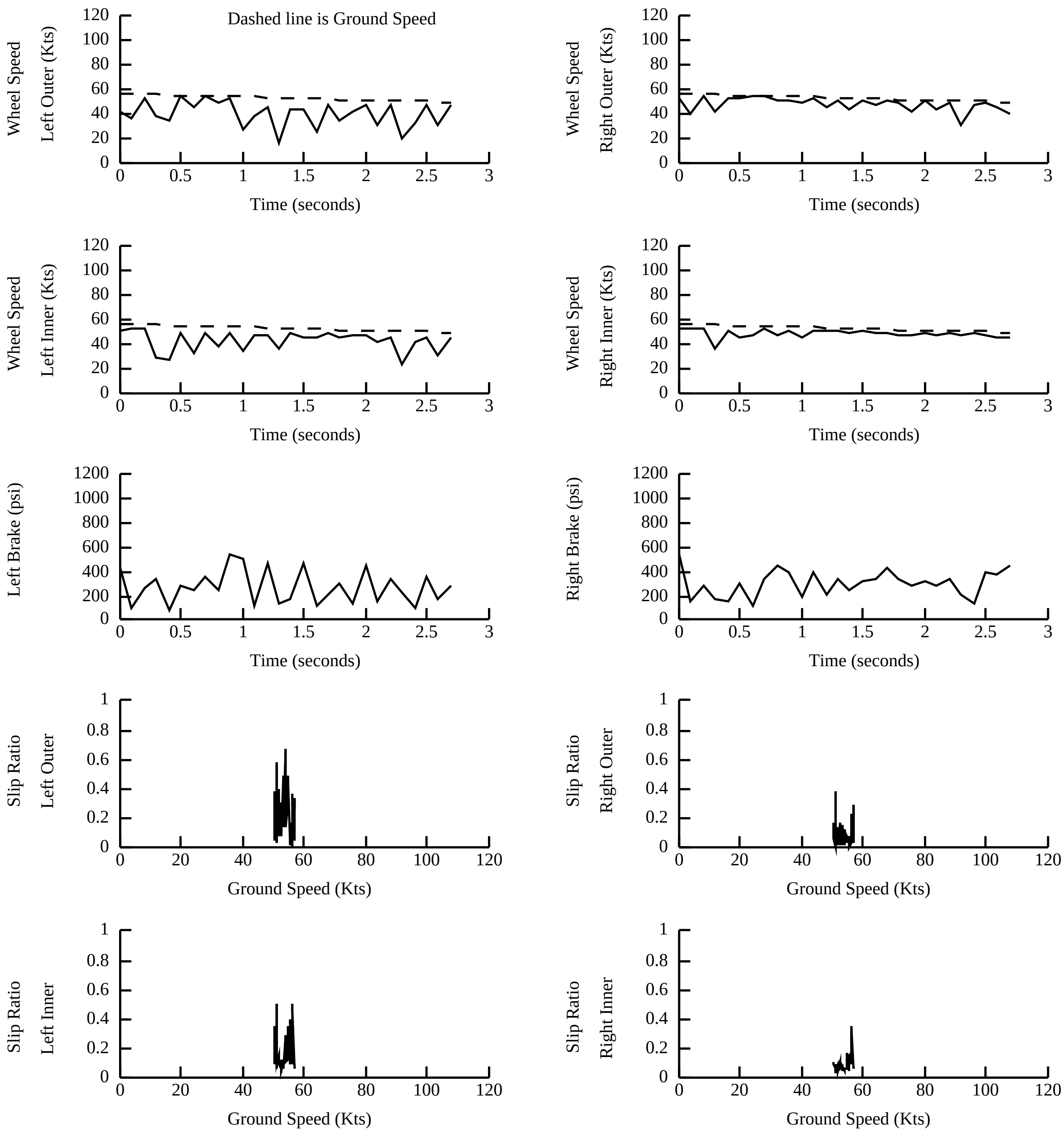


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

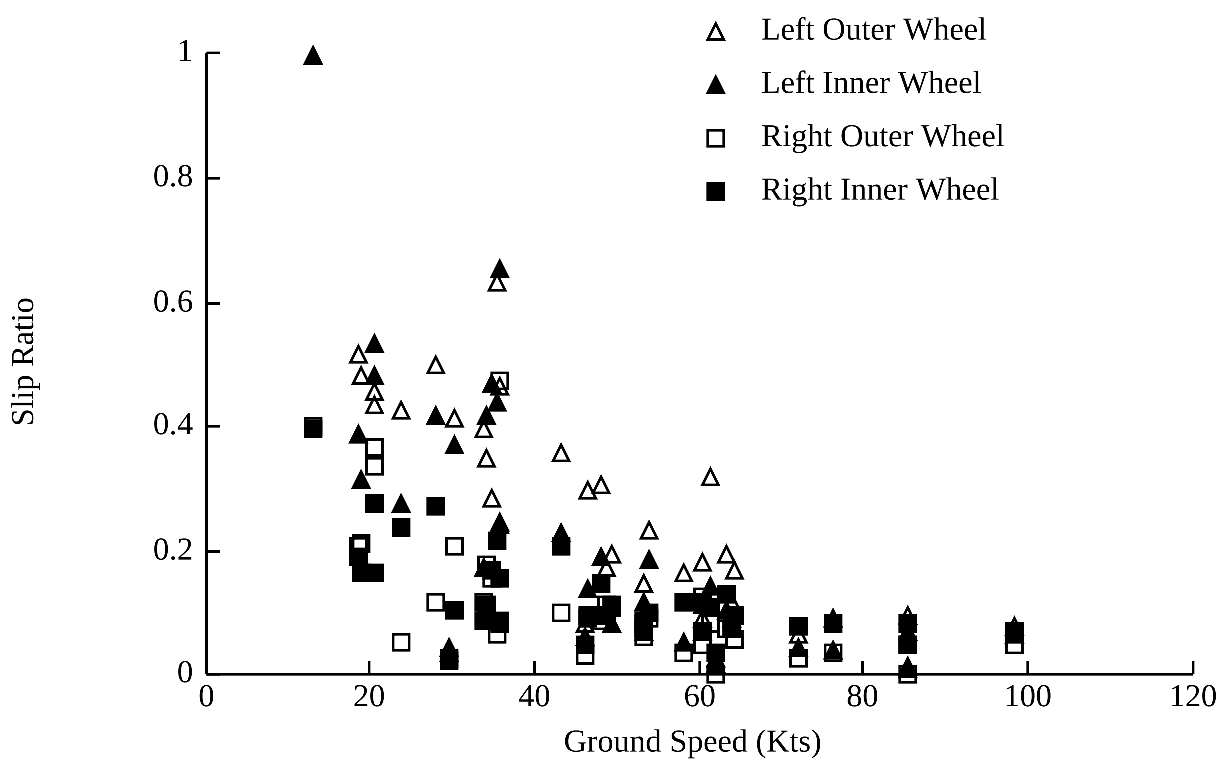
Flight 99/08, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21



# 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 ($\mu_B$) on runway surfaces with no or negligible contamination drag. Pages D3 to D13 show the variation of $\mu_B$ with ground speed for each run. The mean ground speed and mean $\mu_B$ for each run are shown in the table and on Page D14 to D15 for each runway surface condition. Page D16 shows the mean $\mu_B$ plotted against the mean CRFI value for each run, together with the results obtained from the 1996,1997, and 1998 tests and the linear fit obtained from the 1996 and 1997 tests.

| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG | WEIGHT (LB) | MEAN CRFI | MEAN SPEED (KTGS) | MEAN $\mu_B$ |
|---|---|---|---|---|---|---|---|---|
| 99/01 | 6 | 31TS | LAND | 40/OUT/B | 19250 | 0.81 (0.79 to 0.84) | 61 | 0.457 |
| | 7 | 31TS | LAND | 15/OUT/B | 18550 | 0.81 (0.79 to 0.84) | No Data | No Data |
| 99/04 | 1 | 31 | RTO | 40/OUT/B | 21450 | 0.29 (0.23 to 0.36) | 36 | 0.197 |
| | 2 | 31 | RTO | 40/OUT/B | 21350 | 0.30 (0.26 to 0.38) | 53 | 0.215 |
| | 3 | 31 | RTO | 40/OUT/B | 21250 | 0.31 (0.25 to 0.37) | 64 | 0.266 |
| | 4 | 31 | RTO | 40/OUT/B | 21000 | 0.38 (0.34 to 0.42) | No Data | No Data |
| | 5 | 31 | RTO | 15/OUT/B | 20750 | 0.30 ( 0.23 to 0.43) | 49 | 0.213 |
| | 6 | 31 | RTO | 40/OUT/B | 20400 | 0.34 (0.24 to 0.40) | 49 | 0.221 |
| 99/05 | 1 | 31TS | RTO | 40/OUT/B | 22760 | 0.28 ( 0.25 to 0.32) | 24 | 0.144 |
| | 2 | 31TS | RTO | 40/OUT/B | 22560 | 0.29 ( 0.28 to 0.30) | 53 | 0.193 |
| | 3 | 31TS | RTO | 15/OUT/B | 22310 | 0.23 (0.22 to 0.25) | 76 | 0.203 |
| | 4 | 31TS | LAND | 40/OUT/B | 21810 | 0.25 (0.21 to 0.30) | 98 | 0.226 |
| | 5 | 31TS | RTO | 15/OUT/B | 21410 | 0.26 (0.25 to 0.27) | 58 | 0.181 |
| | 6 | 31TS | LAND | 40/OUT/B | 21010 | 0.29 ( 0.24 to 0.34) | 85 | 0.250 |
| | 7 | 31TS | RTO | 40/OUT/B | 20660 | 0.28 ( 0.22 to 0.34) | 64 | 0.199 |
| 99/06 | 1 | 31TS | RTO | 40/OUT/B | 22900 | 0.19 (0.15 to 0.22) | 28 | 0.105 |
| | 2 | 31TS | RTO | 40/OUT/B | 22600 | 0.18 ( 0.16 to 0.20) | 35 | 0.111 |
| | 3 | 31TS | RTO | 40/OUT/B | 22500 | 0.20 (0.19 to 0.22) | 48 | 0.112 |
| | 4 | 31TS | RTO | 40/OUT/B | 22350 | 0.17 (0.14 to 0.19) | 61 | 0.115 |
| | 5 | 31TS | RTO | 15/OUT/B | 22150 | 0.16 (0.13 to 0.20) | 63 | 0.114 |
| | 6 | 31TS | RTO | 15/OUT/B | 21900 | 0.19 (0.15 to 0.23) | 43 | 0.106 |
| 99/07 | 1 | 31TS | RTO | 40/OUT/B | 21490 | 0.14 (0.12 to 0.16) | 36 | 0.073 |
| | 2 | 31TS | RTO | 40/OUT/B | 21390 | 0.14 (0.12 to 0.16) | 13 | 0.070 |
| | 3 | 31TS | RTO | 40/OUT/B | 20490 | 0.17 (0.16 to 0.17) | 21 | 0.108 |

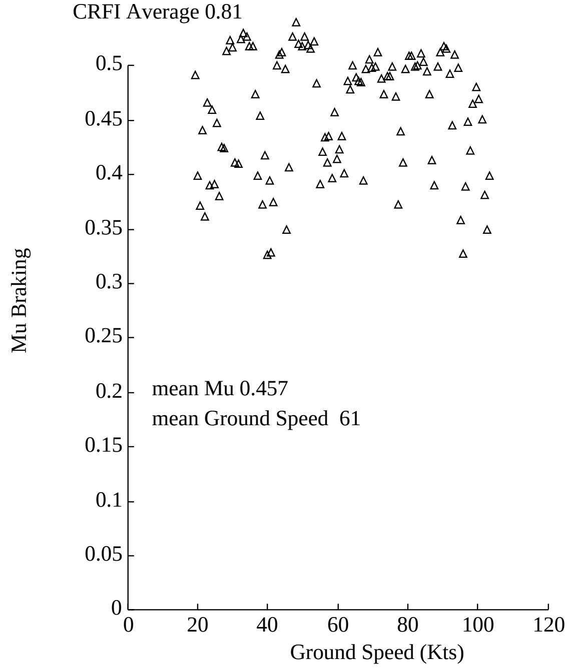
| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG | WEIGHT (LB) | MEAN CRFI | MEAN SPEED (KTGS) | MEAN $\mu_B$ |
|---|---|---|---|---|---|---|---|---|
| | 4 | 31TS | RTO | 40/OUT/B | 20340 | 0.22 (0.17 to 0.28) | 30 | 0.123 |
| | 5 | 31TS | RTO | 40/OUT/B | 20010 | 0.22 (0.17 to 0.31) | 61 | 0.131 |
| | 6 | 31TS | RTO | 40/OUT/B | 19490 | 0.22 (0.17 to 0.31) | 34 | 0.126 |
| | 7 | 31TS | RTO | 15/OUT/B | 18740 | 0.21 (0.16 to 0.26) | 35 | 0.125 |
| | 8 | 31TS | RTO | 15/OUT/B | 18540 | 0.22 (0.17 to 0.30) | 21 | 0.117 |
| 99/08 | 1 | 31TS | RTO | 40/OUT/B | 22040 | 0.25 (0.20 to 0.29) | 19 | 0.182 |
| | 2 | 31TS | RTO | 40/OUT/B | 21840 | 0.22 (0.20 to 0.25) | 34 | 0.154 |
| | 3 | 31TS | RTO | 40/OUT/B | 21640 | 0.22 (0.20 to 0.25) | 46 | 0.159 |
| | 4 | 31TS | RTO | 40/OUT/B | 21540 | 0.22 (0.20 to 0.25) | 19 | 0.145 |
| | 5 | 31TS | RTO | 15/OUT/B | 21440 | 0.21 (0.21 to 0.22) | 54 | 0.162 |

## Surface: 100% Bare and Dry

### Flight 99/01, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.81

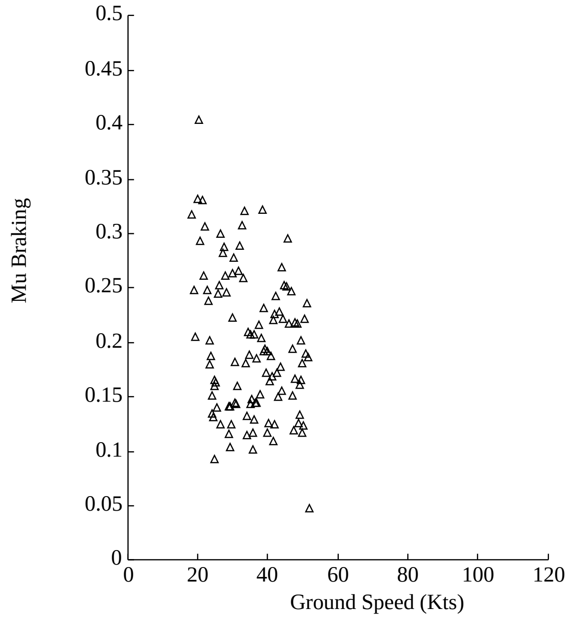


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

## Flight 99/04, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

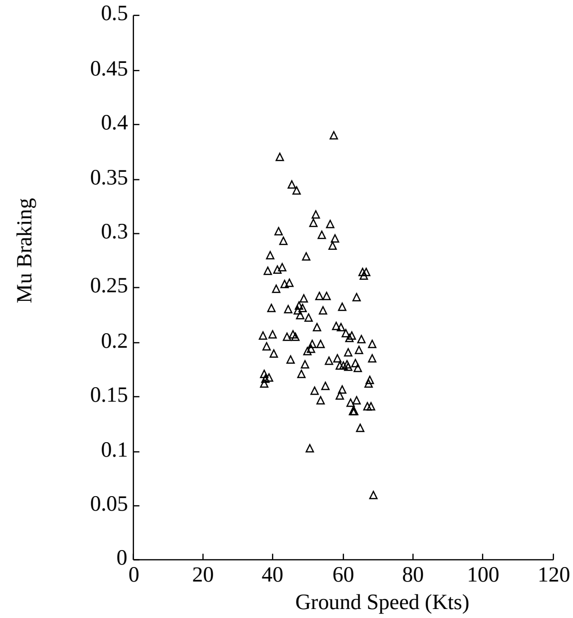
CRFI Average 0.29




## Flight 99/04, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

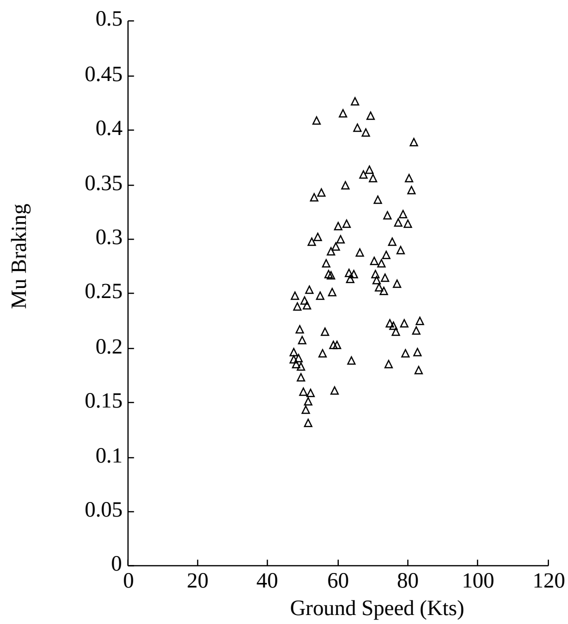
CRFI Average 0.30




## Flight 99/04, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.31

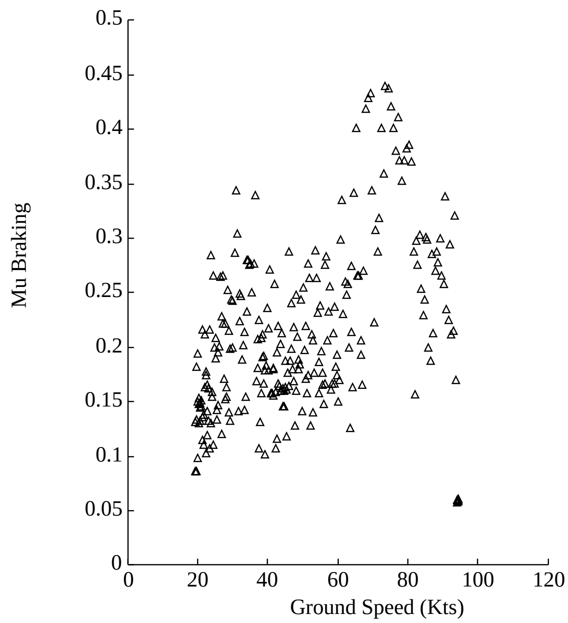


Surface: Changing conditions of Bare and Dry, Loose and Compacted Snow

Flight 99/04, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

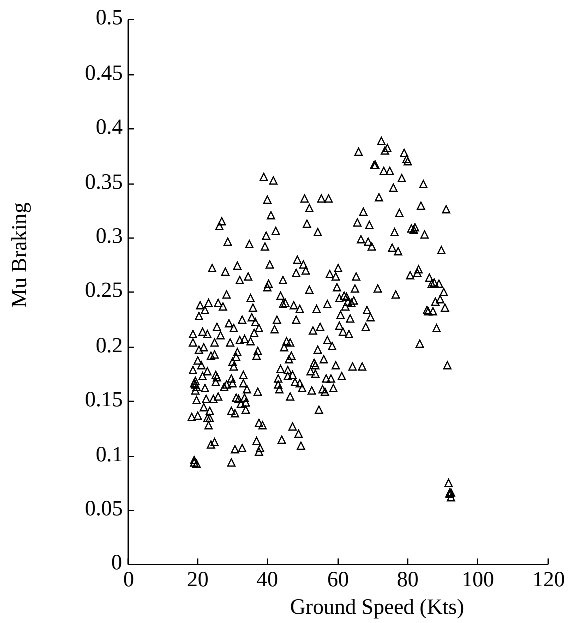
CRFI Average 0.30




Flight 99/04, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.34

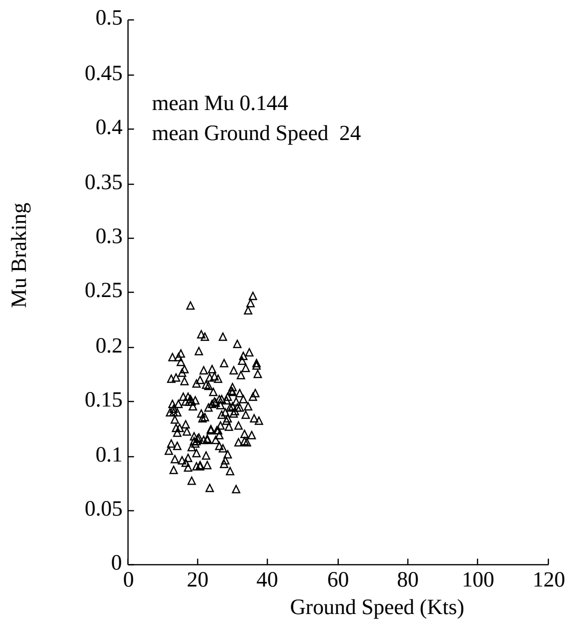


Surface: 100% Thin Ice with some Roughness from Pavement Texture

### Flight 99/05, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

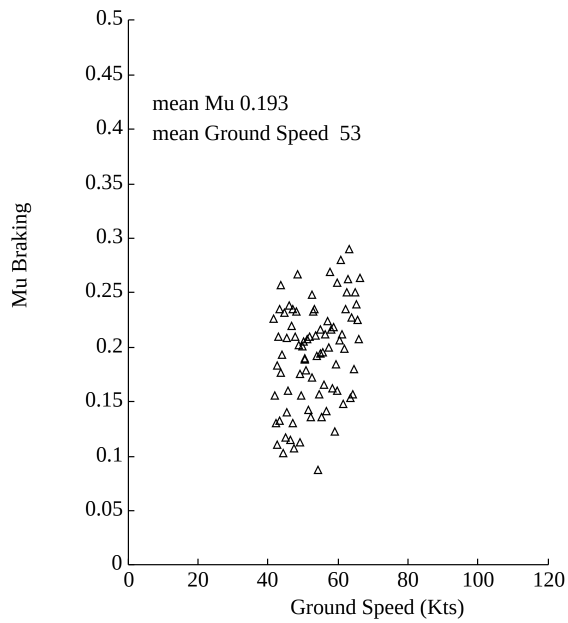
CRFI Average 0.28




### Flight 99/05, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

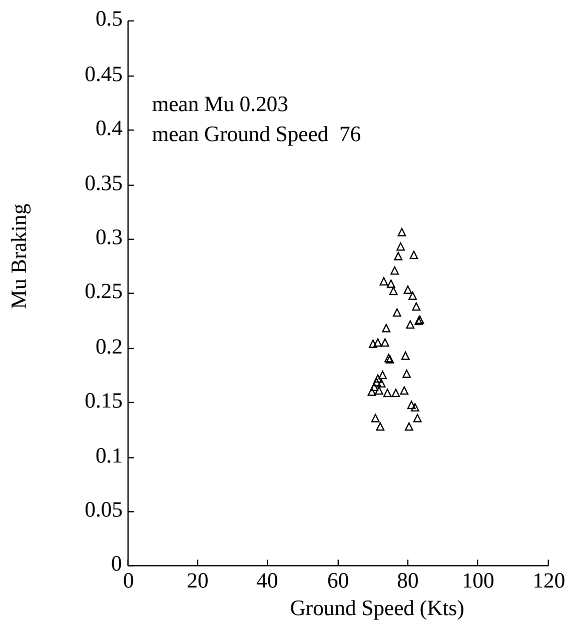
CFRI Average 0.29




### Flight 99/05, Run Number 3

Configuration: Flaps 15, Air Brakes Out, Max Braking

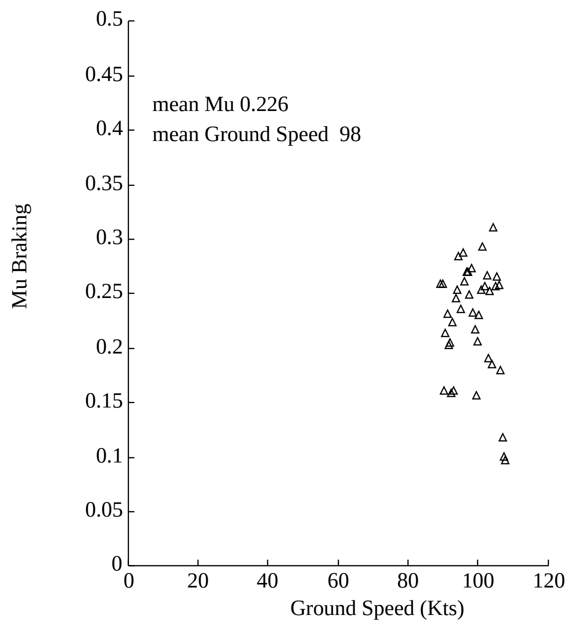
CRFI Average 0.23




### Flight 99/05, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.25

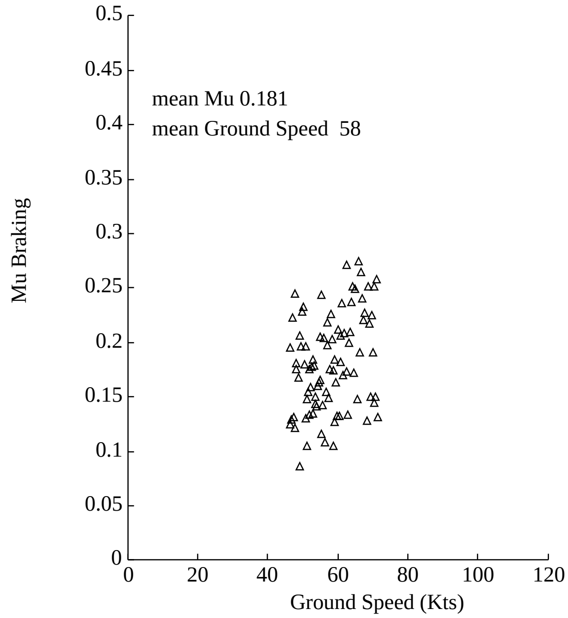


## Surface: 100% Thin Ice with some Roughness from Pavement Texture

### Flight 99/05, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

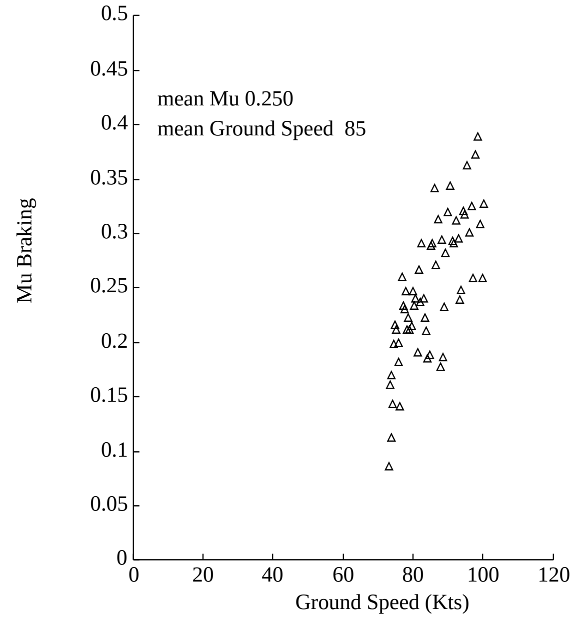
CRFI Average 0.26




### Flight 99/05, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

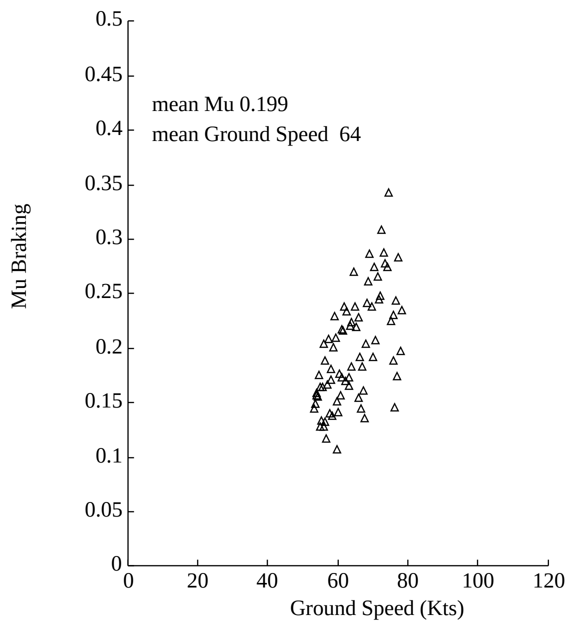
CRFI Average 0.29




### Flight 99/05, Run Number 7

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.28

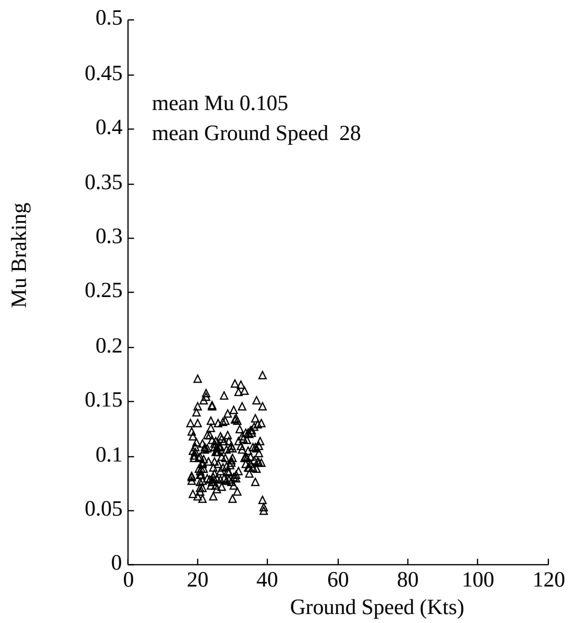


## Surface: 100% Ice with One Application of Sand and Falling Loose Snow

### Flight 99/06, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

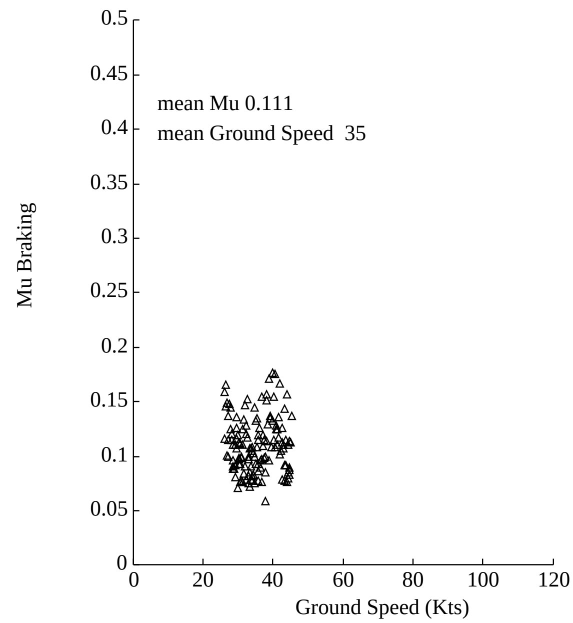
CRFI Average 0.19




### Flight 99/06, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

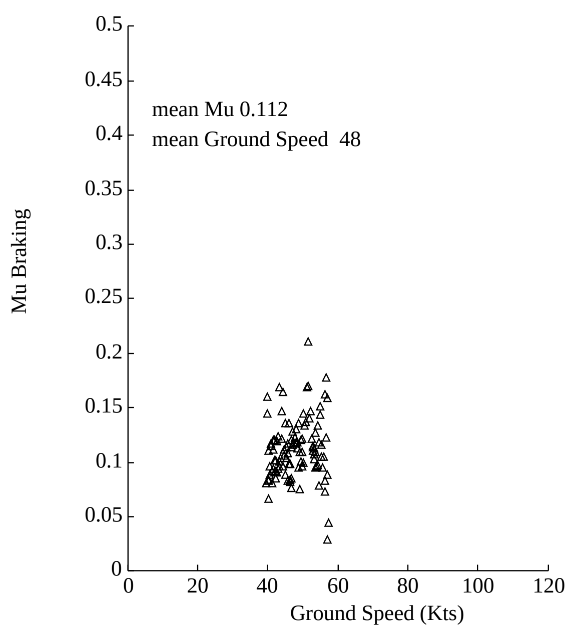
CRFI Average 0.18




### Flight 99/06, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

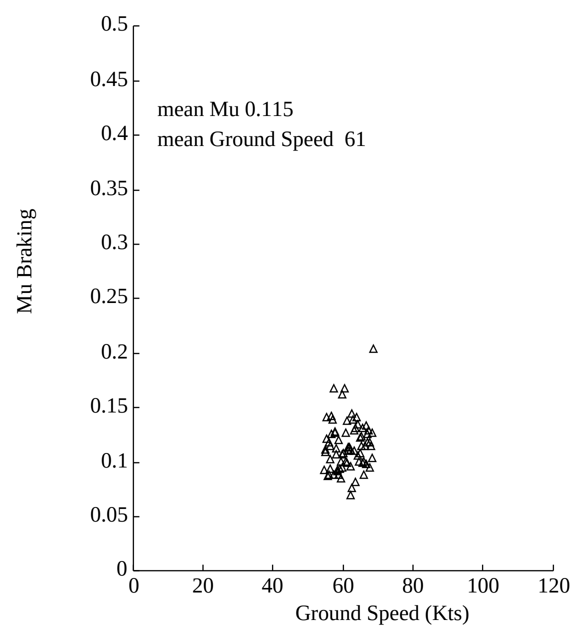
CRFI Average 0.20




### Flight 99/06, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.17

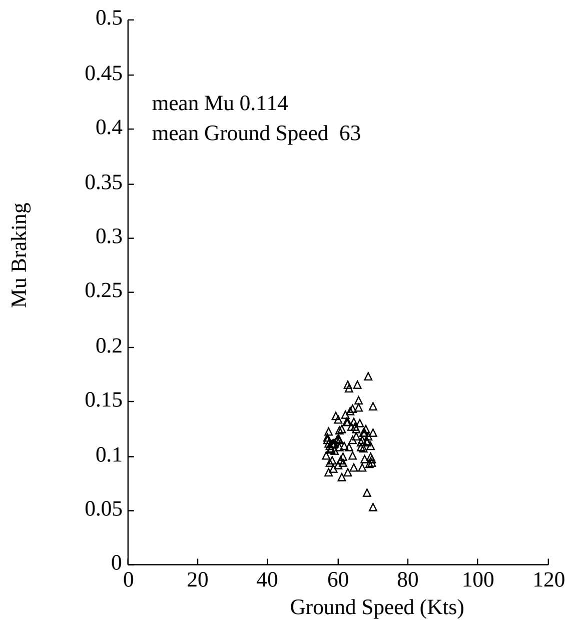


## Surface: 100% Ice with One Application of Sand and Falling Loose Snow

### Flight 99/06, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

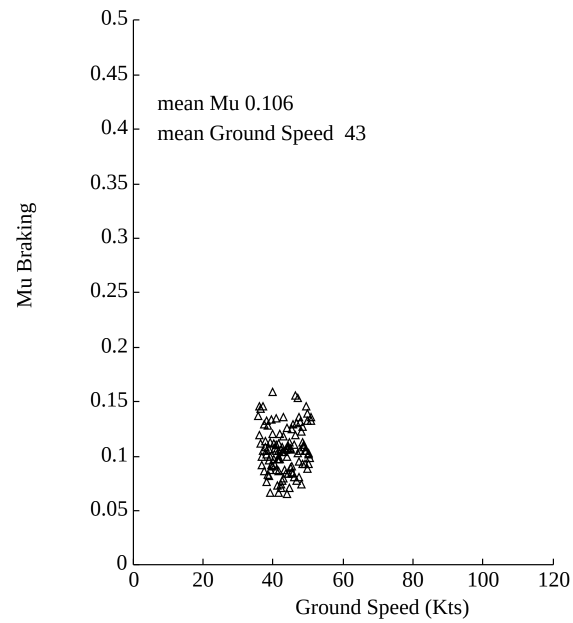
CRFI Average 0.16




### Flight 99/06, Run Number 6

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.19

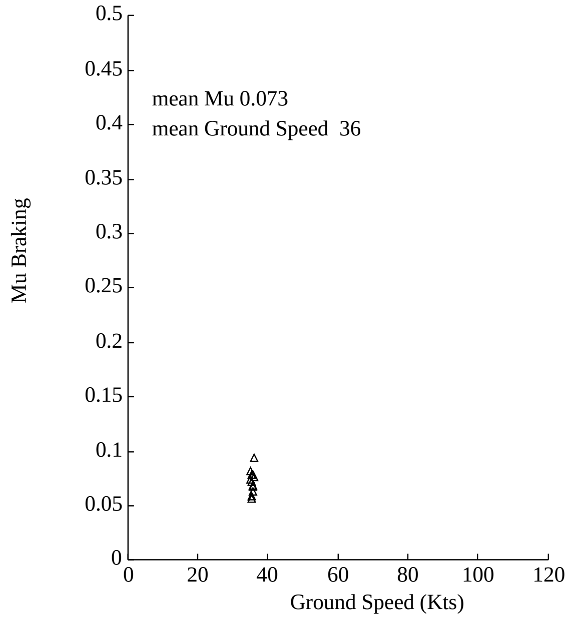


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

## Flight 99/07, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

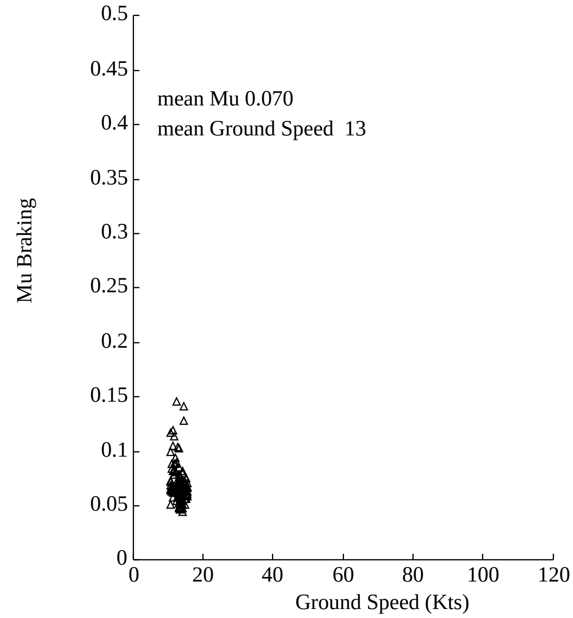
CRFI Average 0.14




## Flight 99/07, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

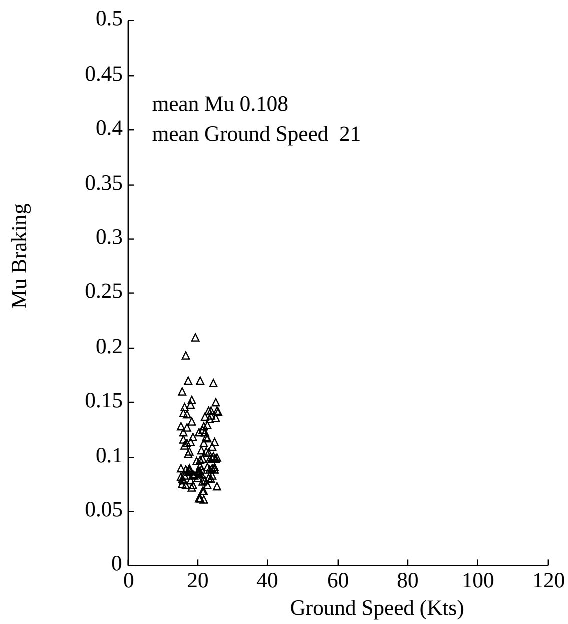
CRFI Average 0.14




## Flight 99/07, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

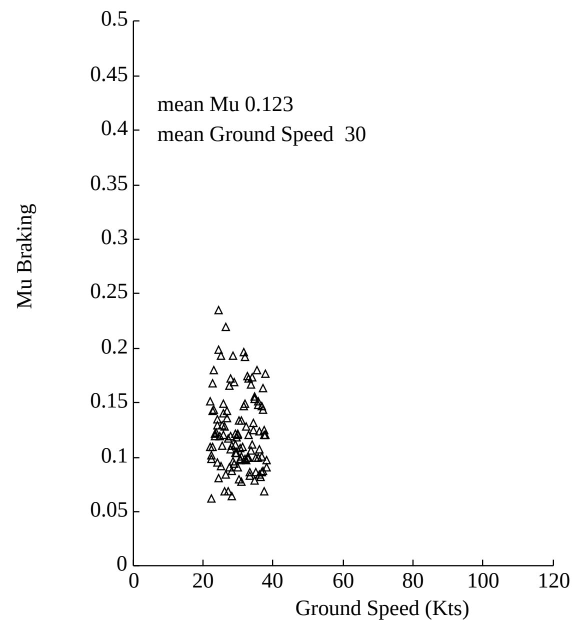
CRFI Average 0.17




## Flight 99/07, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

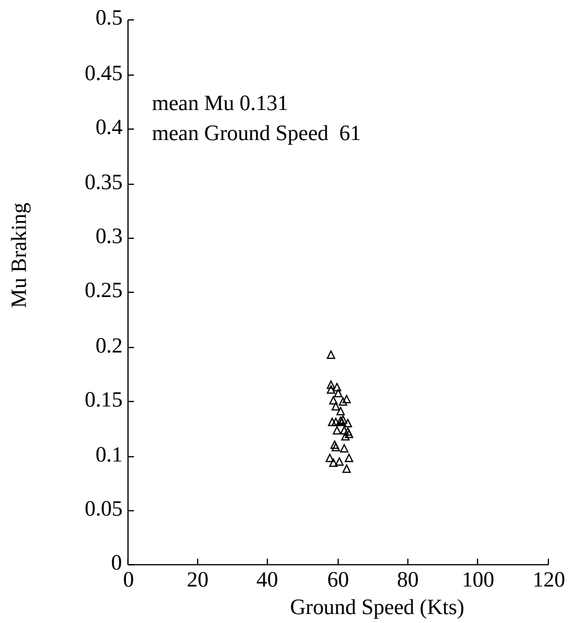


Surface: 100% Ice, Runs 1 and 2 Not Sanded, Runs 3 to 8 Sanded

## Flight 99/07, Run Number 5

Configuration: Flaps 40, Air Brakes Out, Max Braking

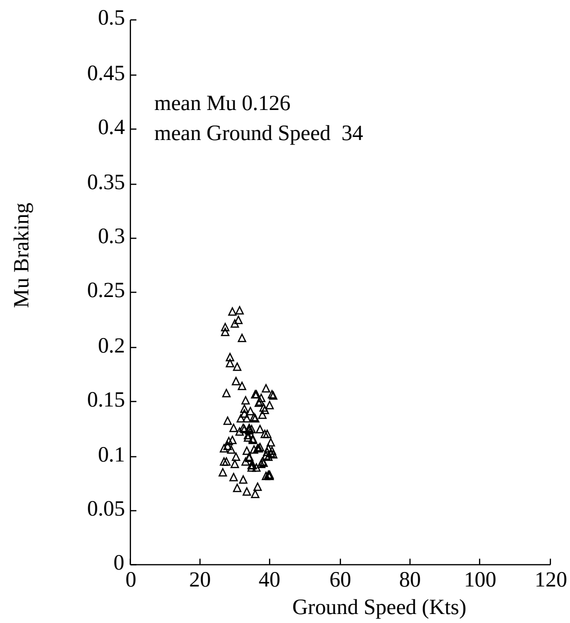
CRFI Average 0.22




## Flight 99/07, Run Number 6

Configuration: Flaps 40, Air Brakes Out, Max Braking

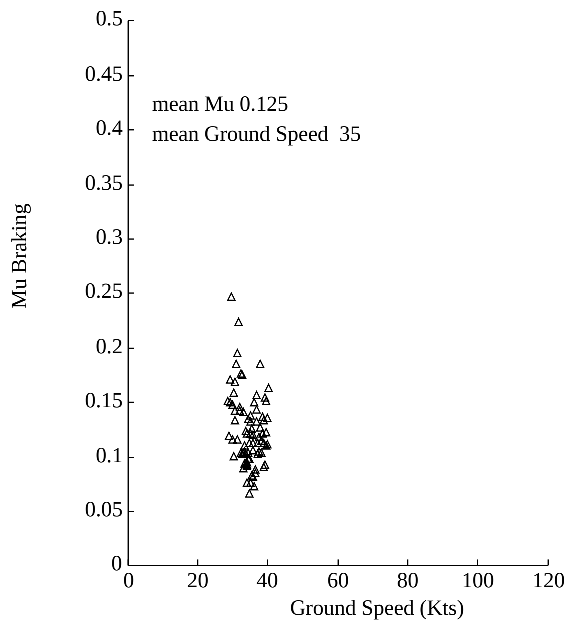
CRFI Average 0.22




## Flight 99/07, Run Number 7

Configuration: Flaps 15, Air Brakes Out, Max Braking

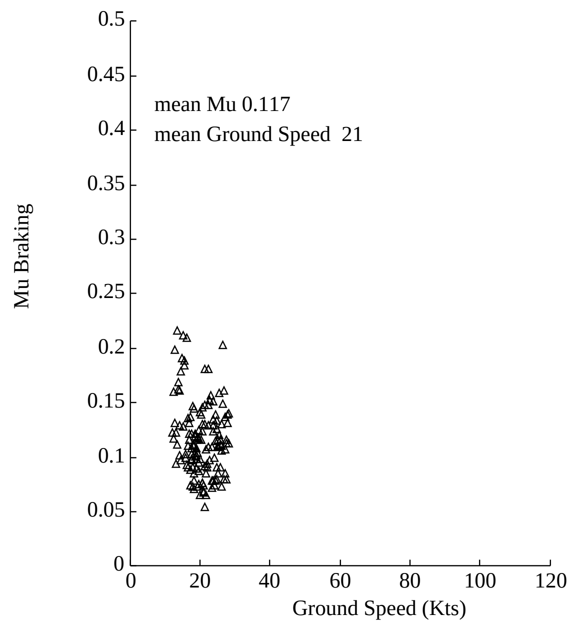
CRFI Average 0.21




## Flight 99/07, Run Number 8

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.22

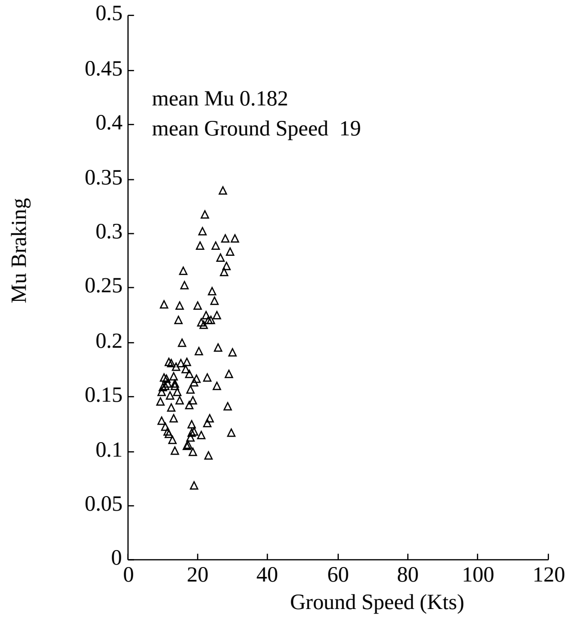


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

## Flight 99/08, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Max Braking

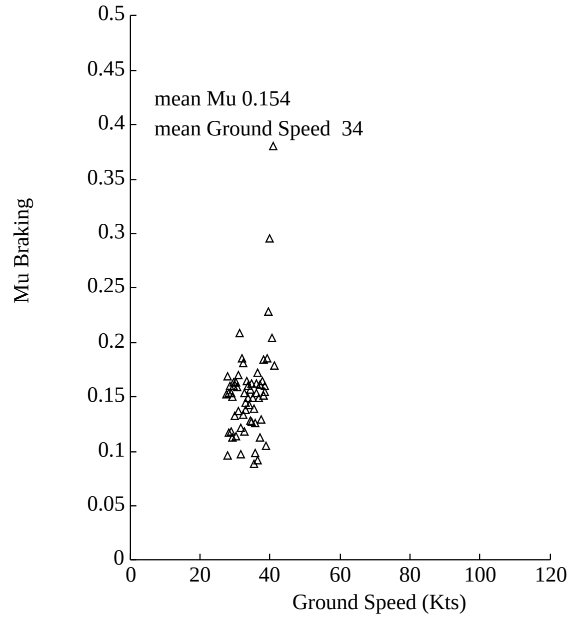
CRFI Average 0.25




## Flight 99/08, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Max Braking

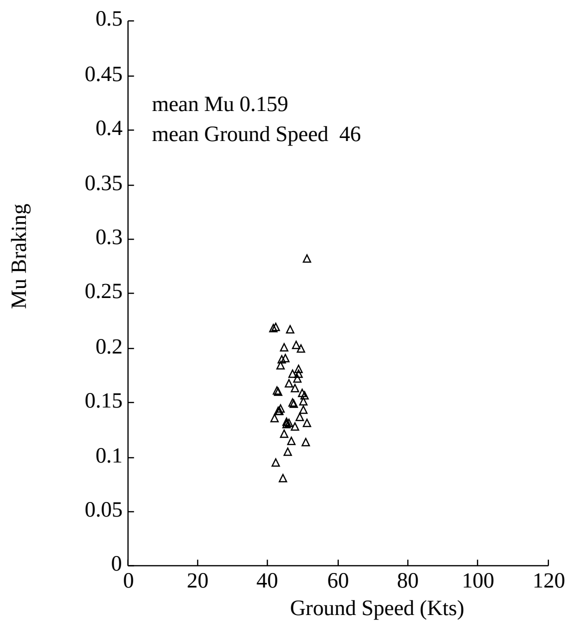
CRFI Average 0.22




## Flight 99/08, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Max Braking

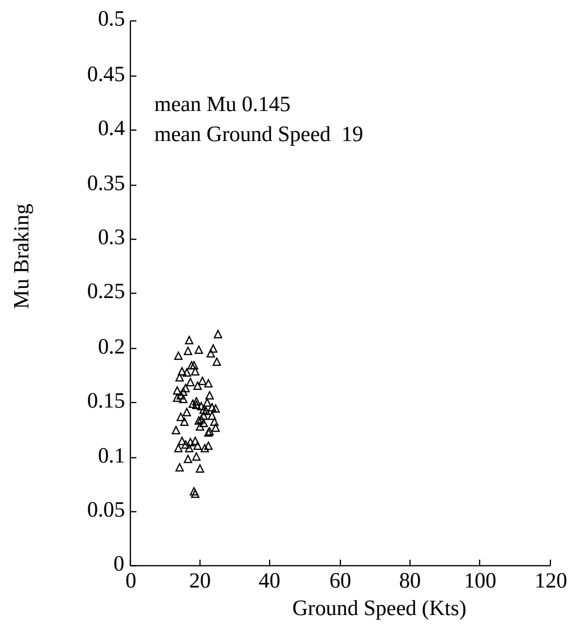
CRFI Average 0.22




## Flight 99/08, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Max Braking

CRFI Average 0.22

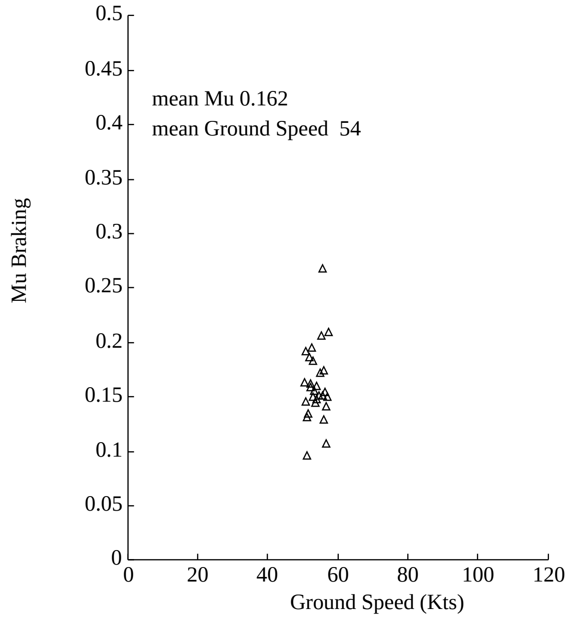


Surface: Run 1 Bare and Wet, Slush, Loose Snow, Runs 2 to 5 Moist Snow and Slush

Flight 99/08, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Max Braking

CRFI Average 0.21

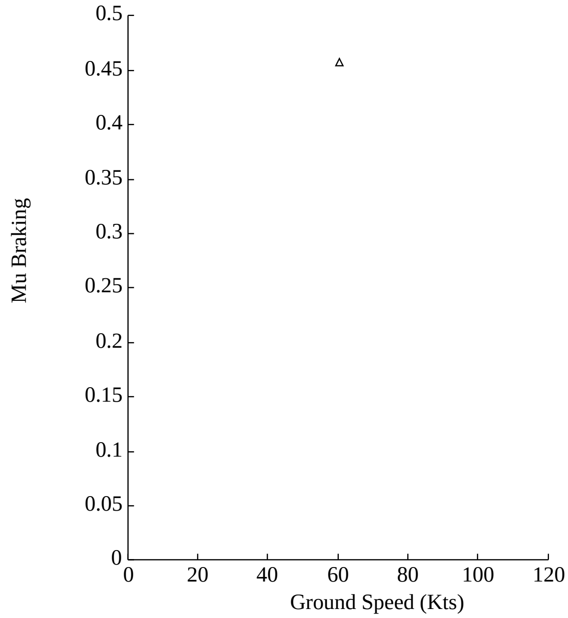


# Summary of Aircraft Mu Braking on Surfaces with No or Negligible Contamination Drag

## Flight 99/01, Run Number 6

100% Bare and Dry

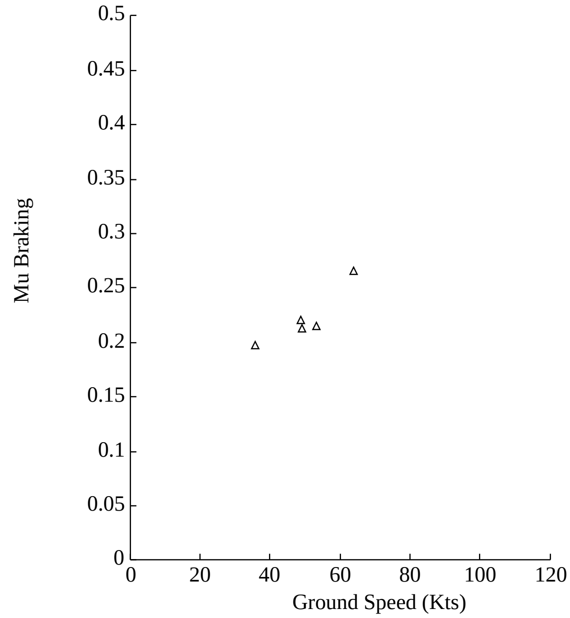
CRFI Average 0.81




## Flight 99/04, Run Numbers 1 through 6

Changing conditions of Bare and Dry, Loose and Compacted Snow

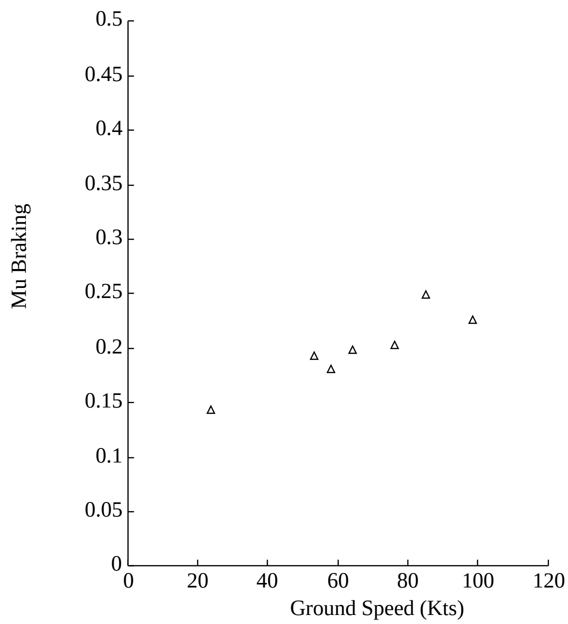
CRFI Average 0.29




## Flight 99/05, Run Numbers 1 through 7

100% Thin Ice with some Roughness from Pavement Texture

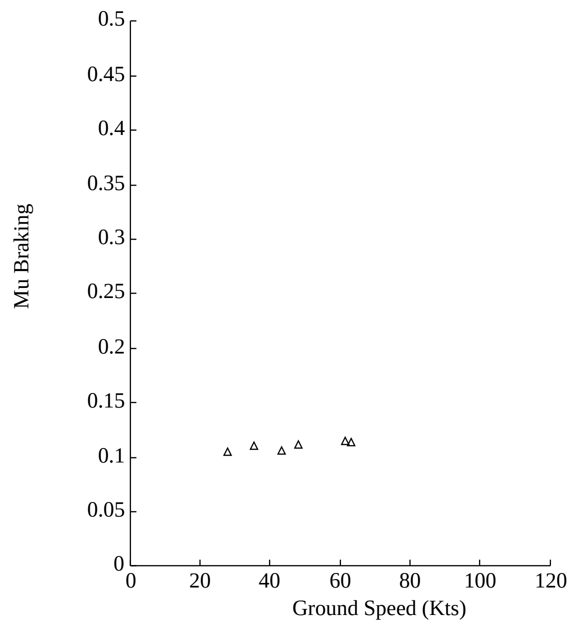
CRFI Average 0.28




## Flight 99/06, Run Numbers 1 through 6

100% Ice with One Application of Sand and Falling Loose Snow

CRFI Average 0.19

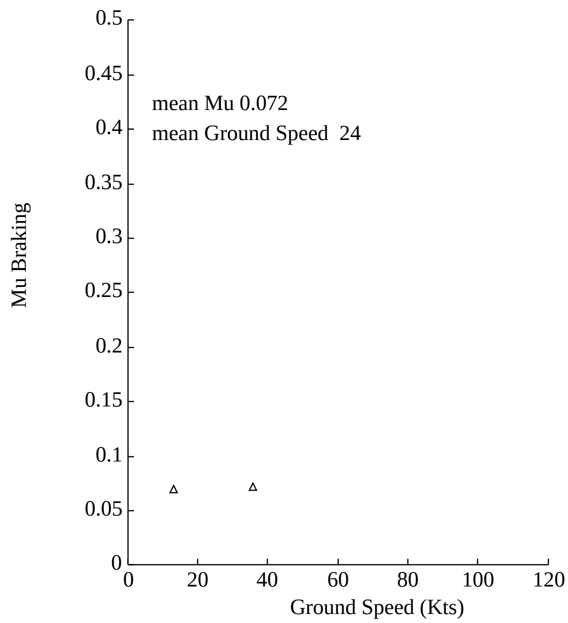


## Summary of Aircraft Mu Braking on Surfaces with No or Negligible Contamination Drag

### Flight 99/07, Run Numbers 1 and 2

100% Ice, No Sand

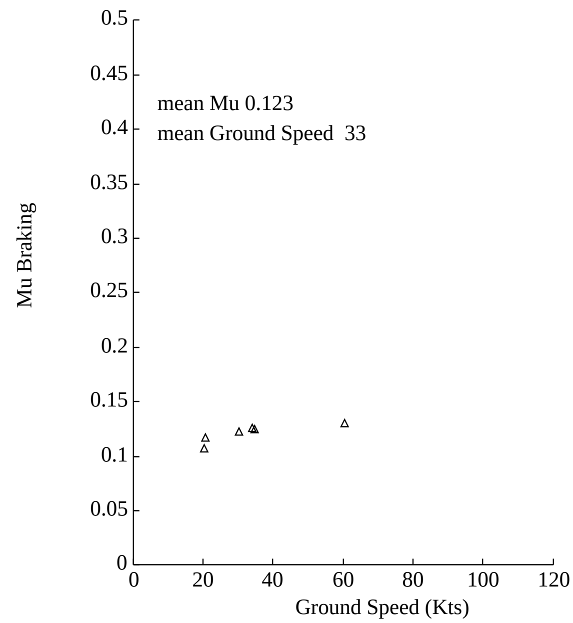
CRFI Average 0.14




### Flight 99/07, Run Numbers 3 through 8

100% Ice, Sand

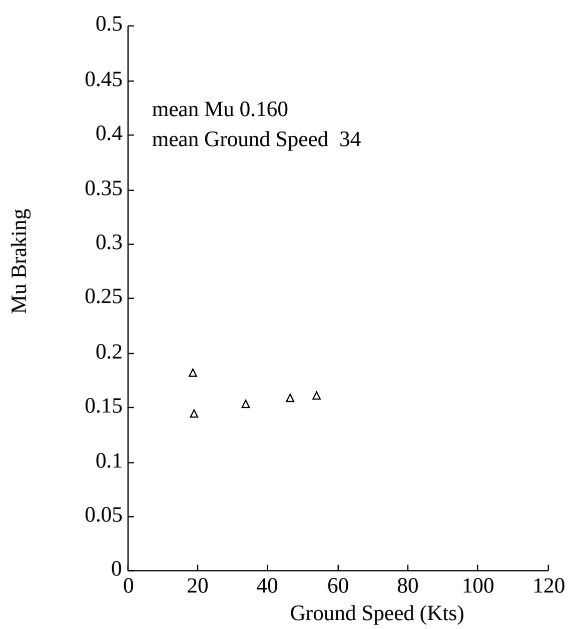
CRFI Average 0.21




### Flight 99/08, Run Numbers 1 through 5

Ice with Loose Moist Snow, Slush on Entrance, Water Patches

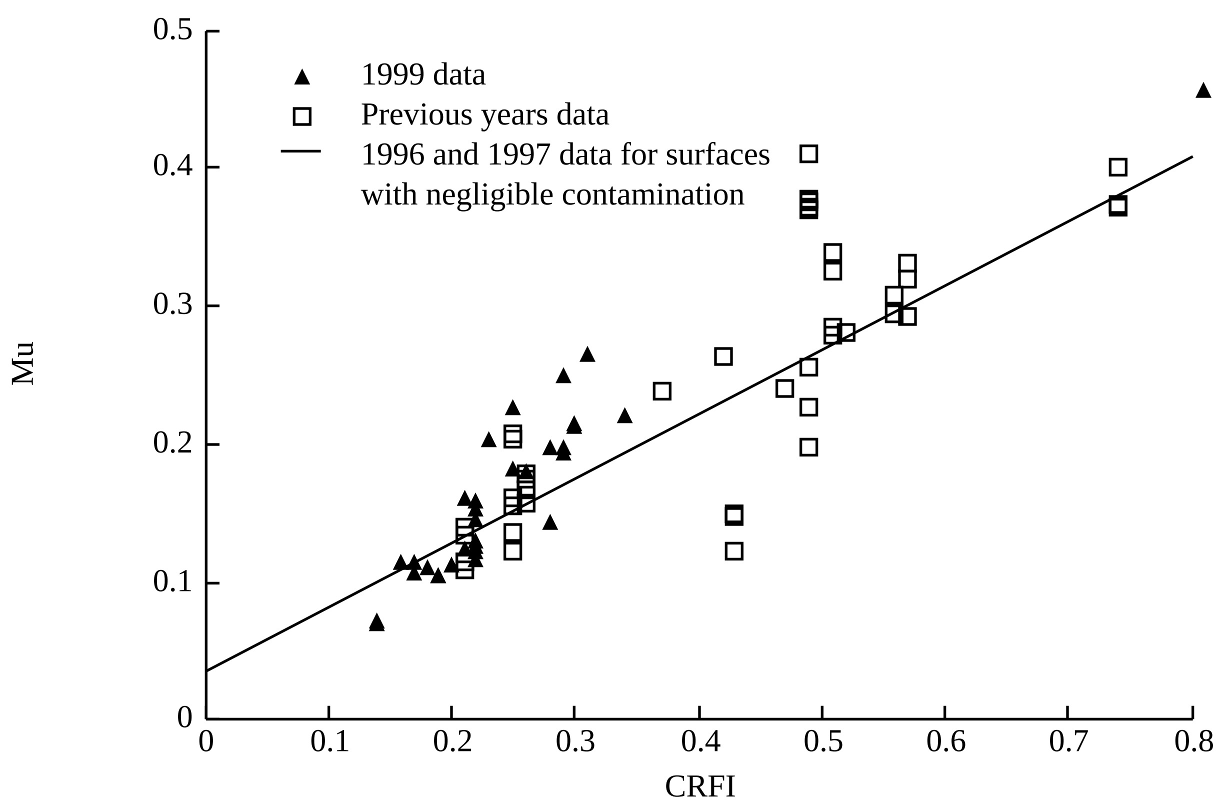
CRFI Average 0.25



# Mean Mu Braking versus CRFI

Surfaces with No or Negligible Contamination Drag

Mu Braking = 0.0354 + 0.4658 * CRFI



# APPENDIX E - TEST RUNS FOR CONTAMINATION DRAG

The following table shows the test runs used to determine the contamination drag. Pages E2 to E3 show the variation of $D_{CONTAM}/W$ with ground speed for each run. The mean ground speed and mean $D_{CONTAM}/W$ for each run are shown in the table and on Page E4. Within the data scatter, there was no significant contamination drag for the single runway surface condition tested.

| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG (see Note 1) | WEIGHT (LB) | MEAN DEPTH (INCH) | MEAN SG | MEAN SPEED (KTGS) | MEAN $D_{CONTAM}$ /W | MEAN $D_{CONTAM}$ (LB) |
|---|---|---|---|---|---|---|---|---|---|---|
| 99/03 | 1b | 08 | RTO | 40/OUT/NO | 23250 | 0.6 (see Note 1) | 0.12 | 15 | -0.002 | -50 |
| | 2b | 08 | RTO | 40/OUT/NO | 22950 | 0.6 (see Note 1) | “ | 26 | 0.018 | 410 |
| | 3b | 08 | RTO | 40/OUT/NO | 22700 | 0.7 (see Note 1) | “ | 36 | 0.000 | 0 |
| | 4b | 08 | RTO | 40/OUT/NO | 22450 | 0.8 (see Note 1) | “ | 34 | -0.013 | -290 |
| | 5b | 08 | RTO | 15/OUT/NO | 21850 | 0.8 (see Note 1) | “ | 26 | 0.010 | 220 |

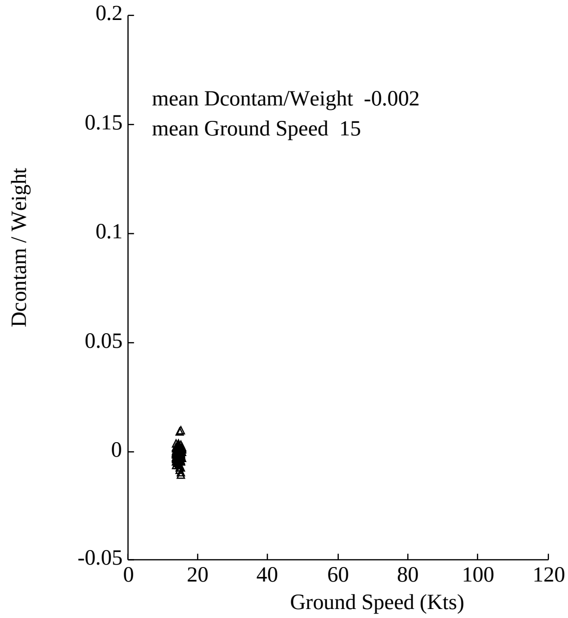
Note 1: Mean depth is an estimate from depth in drifts weighted by proportion of runway covered by drifts

Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts
SG of Snow 0.12

## Flight 99/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, No Braking

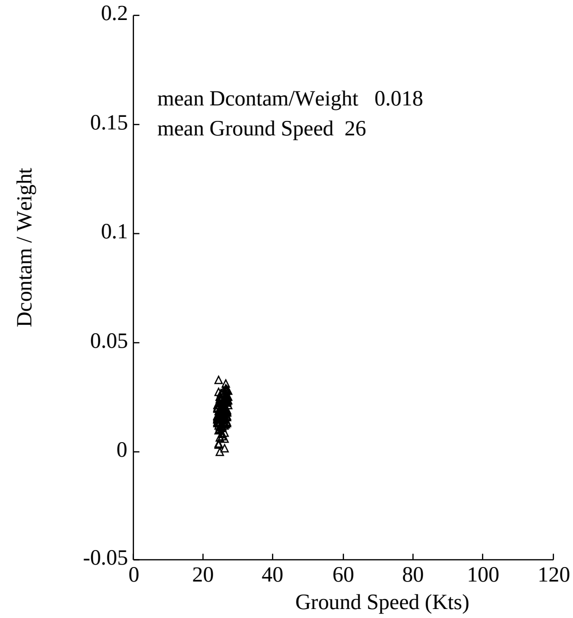
CRFI Average 0.33




## Flight 99/03, Run Number 2

Configuration: Flaps 40, Air Brakes Out, No Braking

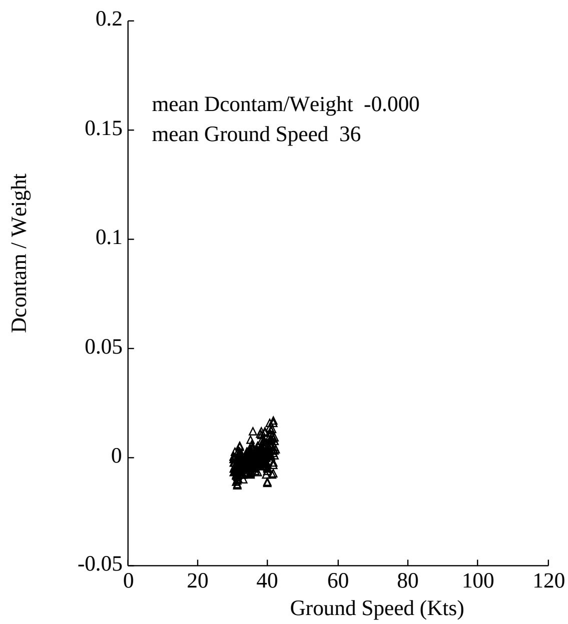
CRFI Average 0.35




## Flight 99/03, Run Number 3

Configuration: Flaps 40, Air Brakes Out, No Braking

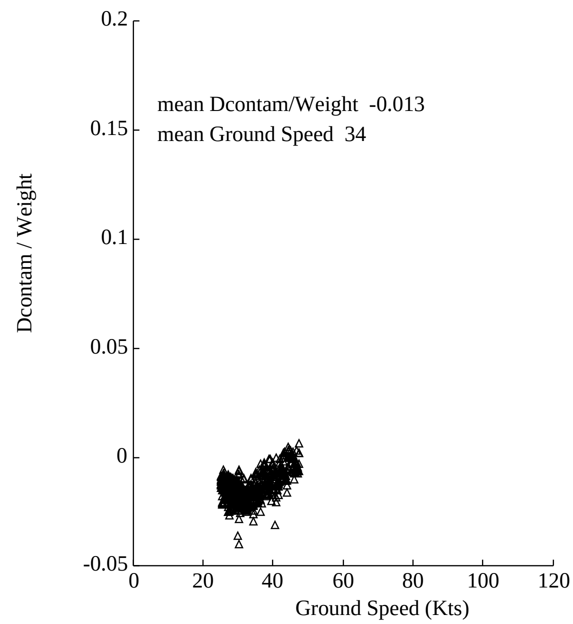
CRFI Average 0.36




## Flight 99/03, Run Number 4

Configuration: Flaps 40, Air Brakes Out, No Braking

CRFI Average 0.38

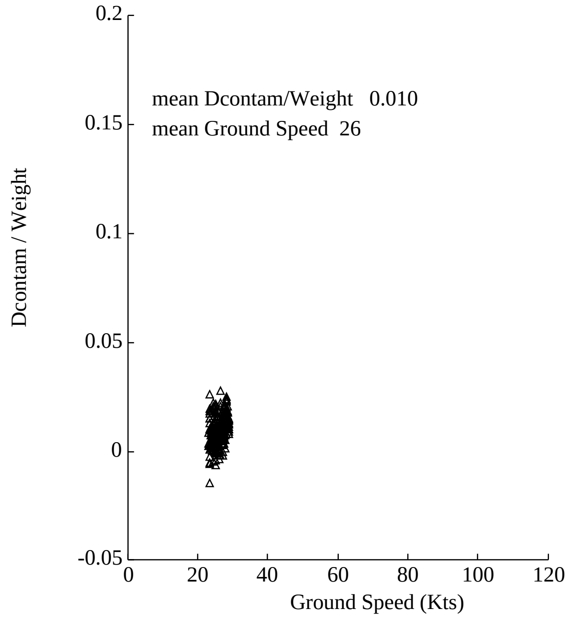


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts
SG of Snow 0.12

Flight 99/03, Run Number 5

Configuration: Flaps 15, Air Brakes Out, No Braking

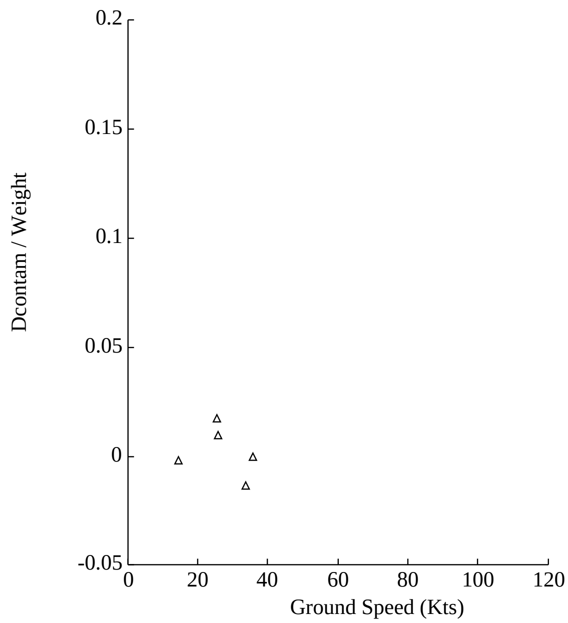
CRFI Average 0.40



# Summary of Aircraft Contamination Drag

## Flight 99/03, Run Numbers 1 through 5

Changing Conditions of Bare and Dry and Loose Snow Drifts



# 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 ($\mu_B$) on runway surfaces with contamination drag. However there was no measurable contamination drag on the single surface condition tested. Pages F2 to F3 show the variation of $\mu_B$ with ground speed for each run. The mean ground speed and mean $\mu_B$ for each run are shown in the table and on Page F4. Page F5 shows the mean $\mu_B$ plotted against the mean CRFI value for each run. This page also shows the relationship of $\mu_B$ versus CRFI on runway surfaces with no or negligible contamination drag, obtained from 1996 and 1997 tests.

| FLT | RUN | RW | TAXI/ RTO/ LAND | CONFIG | WEIGHT (LB) | MEAN $D_{CONTAM}$/ W | MEAN CRFI | MEAN SPEED (KTGS) | MEAN $\mu_B$ |
|---|---|---|---|---|---|---|---|---|---|
| 99/03 | 1a | 08 | RTO | 40/OUT/B | 23250 | | 0.33 (0.30 to 0.36) | 30 | 0.179 |
| | 2a | 08 | RTO | 40/OUT/B | 22950 | | 0.35 (see Note 1) | 46 | 0.191 |
| | 3a | 08 | RTO | 40/OUT/B | 22700 | | 0.37 (see Note 1) | 62 | 0.186 |
| | 4a | 08 | RTO | 40/OUT/B | 22450 | | 0.39 (see Note 1) | 85 | 0.216 |
| | 5a | 08 | RTO | 15/OUT/B | 21850 | | 0.40 (0.36 to 0.44) | 72 | 0.267 |

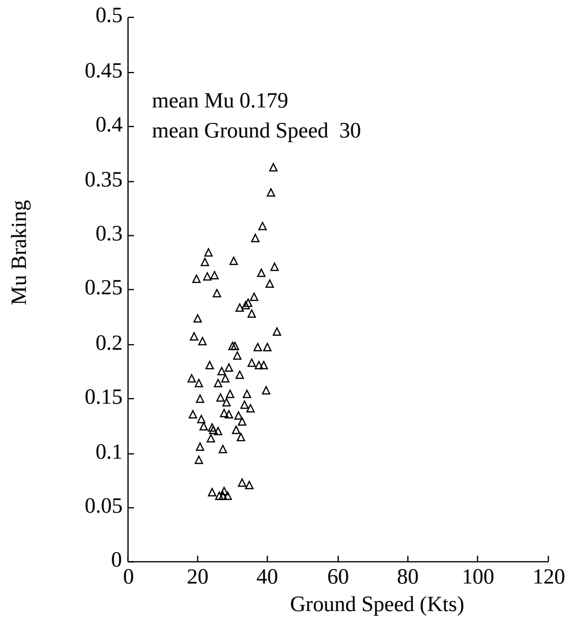
Note 1: CRFI Average obtained by interpolation from before and after aircraft tests

Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts
SG of Snow 0.12

## Flight 99/03, Run Number 1

Configuration: Flaps 40, Air Brakes Out, Split Run

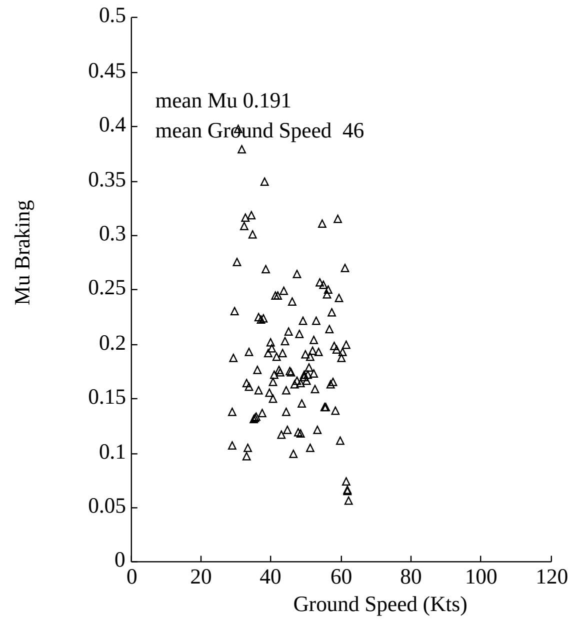
CRFI Average 0.33




## Flight 99/03, Run Number 2

Configuration: Flaps 40, Air Brakes Out, Split Run

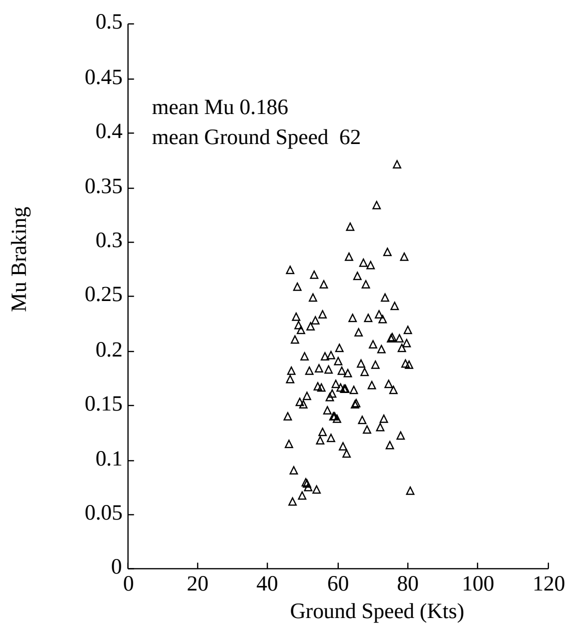
CRFI Average 0.35




## Flight 99/03, Run Number 3

Configuration: Flaps 40, Air Brakes Out, Split Run

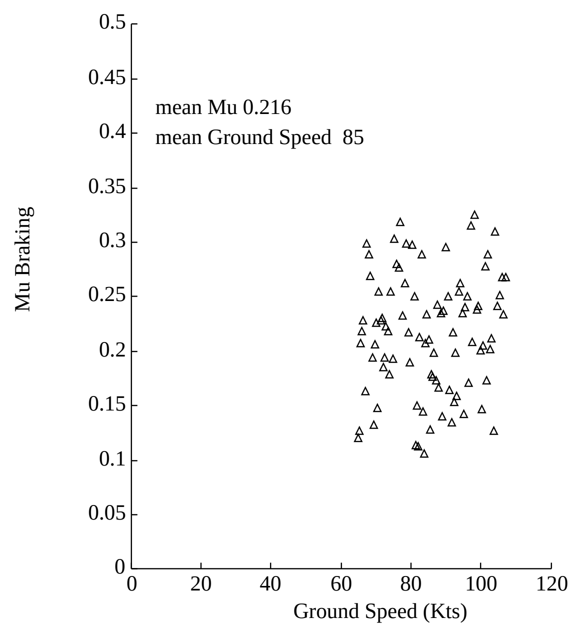
CRFI Average 0.36




## Flight 99/03, Run Number 4

Configuration: Flaps 40, Air Brakes Out, Split Run

CRFI Average 0.38

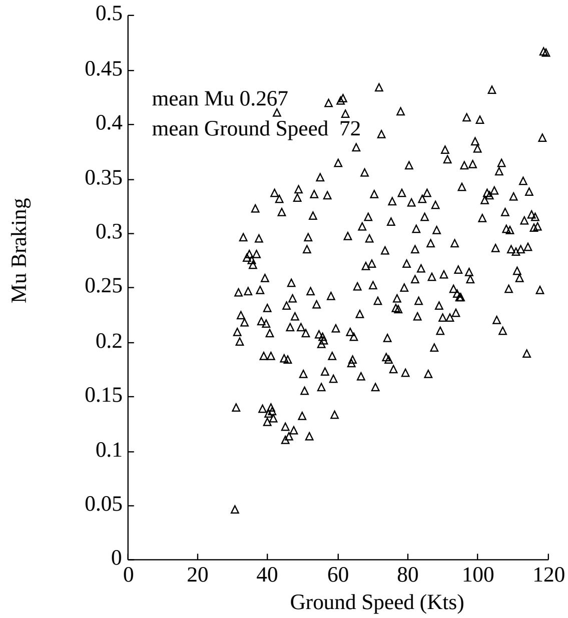


Surface: Changing Conditions of Bare and Dry and Loose Snow Drifts
SG of Snow 0.12

Flight 99/03, Run Number 5

Configuration: Flaps 15, Air Brakes Out, Split Run

CRFI Average 0.40

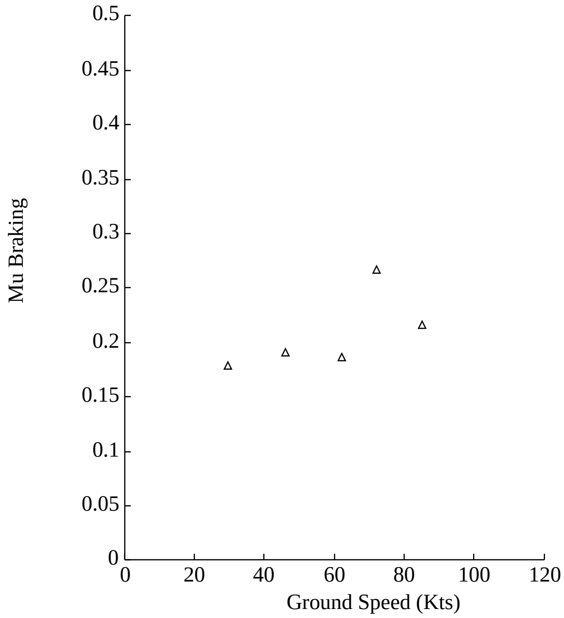


## Summary of Aircraft Mu Braking on Surfaces with Appreciable Contamination Drag

### Flight 99/03, Run Numbers 1 through 5

Changing Conditions of Bare and Dry and Loose Snow Drifts

CRFI Average 0.33



# Mean Mu Braking versus CRFI

Surfaces with Contamination Drag

Mu Braking = 0.0354 + 0.4658 * CRFI