INSTITUTE FOR
AEROSPACE RESEARCH

INSTITUT DE
RECHERCHE AÉROSPATIALE

Pages 148

Fig.
Diag. 3

REPORT
RAPPORT

FLIGHT RESEARCH LABORATORY

LABORATOIRE DE RECHERCHE EN VOL

Report
Rapport LTR-FR-185

Date August 2002

Lab. Order
Comm. Lab.

File
Dossier 46-7352-9-5

Unlimited
Unclassified

LTR-FR-185

Dash 8 Aircraft Braking Performance on Winter Contaminated Runways

Also published as Transport Canada publication no. TP13957E

Submitted by
Présenté par S.W. Baillie
Director/directeur

Author (s)
Auteur(s) M.Bastian, J.B. Croll

Approved
Approuvé W. Wallace
Director General/Le directeur général

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 13957E	2. Project No. 5136	3. Recipient's Catalogue No.
4. Title and Subtitle Dash 8 Aircraft Braking Performance on Winter Contaminated Runways		5. Publication Date August 2002
		6. Performing Organization Document No. LTR-FR-185
7. Author(s) M. Bastian and J.B. Croll		8. Transport Canada File No. ZCD2450-B-14
9. Performing Organization Name and Address National Research Council Canada Institute for Aerospace Research Flight Research Laboratory Ottawa, Ontario Canada K1A 0R6		10. PWGSC File No.
		11. PWGSC or Transport Canada Contract No.
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer Angelo Boccanfuso

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by National Research Council Canada and Transport Canada's Aerodrome Safety Branch

16. Abstract

The braking performance of a NavCanada-owned Dash 8 research aircraft was evaluated on winter contaminated runway surfaces at the North Bay airport during the months of January and March 2001. This was done as part of the Joint Winter Runway Friction Measurement Program (JWRFMP), a five-year collaborative test program involving Transport Canada, the U.S. National Aeronautics & Space Administration, National Research Council Canada, and the U.S. Federal Aviation Administration.

Aircraft braking performance was measured during full anti-skid braking runs on snow- and ice-covered runway surfaces. The aircraft-braking coefficient was compared to the Canadian Runway Friction Index and the International Runway Friction Index. Both indices were found to have a linear relationship with the aircraft-braking coefficient. The results agreed very well with those of other aircraft that had previously participated in JWRFMP testing.

17. Key Words Friction, contaminated runway, aircraft, slip speed, Dash 8, braking performance	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages vii, 17, apps	23. Price Shipping/ Handling

Transports Canada | Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 13957E	2. N° de l'étude 5136	3. N° de catalogue du destinataire
4. Titre et sous-titre Dash 8 Aircraft Braking Performance on Winter Contaminated Runways		5. Date de la publication Août 2002 6. N° de document de l'organisme exécutant LTR-FR-185
7. Auteur(s) M. Bastian et J.B. Croll		8. N° de dossier - Transports Canada ZCD2450-B-14
9. Nom et adresse de l'organisme exécutant Conseil national de recherches du Canada Institut de recherche aérospatiale Laboratoire de recherche en vol Ottawa, Ontario Canada K1A 0R6		10. N° de dossier - TPSGC 11. N° de contrat - TPSGC ou Transports Canada
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet Angelo Boccanfuso

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Coparrainé par le Conseil national de recherches du Canada et la Direction de la sécurité des aérodromes de Transports Canada

16. Résumé

On a procédé à l'évaluation des performances de freinage d'un appareil de recherche Dash 8 fourni par NavCanada pour des essais sur pistes contaminées par des conditions hivernales, à l'aéroport de North Bay, durant les mois de janvier et mars 2001. Les essais faisaient partie du Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH). Il s'agit d'un programme d'essais d'une durée de cinq ans mené avec la collaboration de Transports Canada, de la National Aeronautics & Space Administration des États-Unis, du Conseil national de recherches du Canada et de la Federal Aviation Administration des États-Unis.

Les performances de l'avion ont été mesurées durant des essais en freinage maximal sous protection de système antidérapage, effectués sur des pistes contaminées par la neige et la glace. Le coefficient de frottement obtenu a été comparé à ceux de l'Indice canadien de la glissance des pistes (CRFI, pour *Canadian Runway Friction Index*) et aux valeurs de l'Indice international de la glissance des pistes (IRFI, pour *International Runway Friction Index*). Les résultats ont démontré l'existence d'une relation linéaire entre, d'une part, les coefficients canadiens et international, et, d'autre part, le coefficient réalisé avec le Dash 8. De plus, on a noté une très bonne corrélation des valeurs de frottement du Dash 8 avec celles d'autres aéronefs ayant déjà participé à des essais dans le cadre du programme PCRGCAH.

17. Mots clés Frottement, piste contaminée, aéronef, vitesse de dérive, Dash 8, performances de freinage	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	vii, 17, ann.	Port et manutention

CDT/TDC 79-005
Rev. 96

Canadä

ABSTRACT

The braking performance of a NavCanada owned Dash 8 research aircraft was evaluated on winter contaminated runway surfaces at the North Bay airport during the months of January and March of 2001. This was done as part of the Joint Winter Runway Friction Measurement Program (JWRFMP), a five-year collaborative test program involving Transport Canada, NASA, NRC and the FAA. The aircraft braking performance was measured during full anti-skid braking runs on snow and ice covered runway surfaces. The aircraft-braking coefficient was compared to the Canadian Runway Friction Index (CRFI) and the International Runway Friction Index. Both indices were found to have a linear relationship with the aircraft-braking coefficient. The results agreed very well with those of other aircraft that had previously participated in the JWRFMP testing.

RÉSUMÉ

Au cours des mois de janvier et mars 2001, la performance en freinage d’un avion de recherche Dash 8 appartenant à NavCanada a été évaluée sur des surfaces de piste recouvertes de contamination hivernale à l’aéroport de North Bay. Cette opération a été effectuée dans le cadre du Programme de recherche conjoint sur la glissance des chaussées aéronautiques l’hiver (PRCGCAH), un programme d’essais de cinq ans mené conjointement par Transports Canada, la NASA, le CNRC et la FAA. La performance en freinage de l’avion a été mesurée pendant des courses à freinage maximal avec utilisation du système d’antidérapage sur des surfaces de piste recouvertes de neige et de glace. L’indice de freinage de l’avion a ensuite été comparé au Coefficient canadien de frottement sur piste (CRFI) et à l’International Runway Friction Index. On a pu établir une relation linéaire entre ces deux coefficients et l’indice de freinage de l’avion. Les résultats obtenus cadrent très bien avec ceux obtenus à l’aide d’autres avions ayant participé antérieurement aux essais du PRCGCAH.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF APPENDICES

GLOSSARY OF TERMS

ATIS	Automatic Terminal Information System
C_D	Aircraft Coefficient of Drag
C_L	Aircraft Coefficient of Lift
CPU	Computer Processor Unit
CRFI	Canadian Runway Friction Index
D	Aerodynamic Drag
DAS	Data Acquisition System
D_{CONTAM}	Contamination Drag
DGPS	Differential Global Positioning System
ERD	Electronic Recording Decelerometer
FAA	Federal Aviation Administration
ft	Feet
g	Gravitational Constant
GPS	Global Positioning System
HW	Headwind
IAR	Institute for Aerospace Research
IRFI	International Runway Friction Index
JAA	Joint Aviation Authority
JBI	James Brake Index
knots	Nautical miles per hour
L	Aerodynamic Lift
lbf	Pounds of force

Mu	Coefficient of friction
NASA	National Aeronautics and Space Administration
NOTAM	Notice to Airmen
RTO	Rejected Takeoff
SG	Specific Gravity
t	Time
T	Aircraft Thrust
TS	Test Section
TW	Tailwind
V	Aircraft velocity along the runway (groundspeed)
V_{EAS}	Equivalent Airspeed
V_w	Wheel speed
W	Aircraft Weight
	Runway Slope (positive uphill)
	Atmospheric Density Ratio (= / $_0$)
μ_B	Aircraft Braking Coefficient (= Braking Force/(W-L))
μ_R	Rolling Friction Coefficient (= Rolling Resistance/(W-L))
μ_S	Wheel slip ratio (= (V-V_W)/V)

Dash 8 Aircraft Braking Performance on Winter Contaminated Runways

1.0 Introduction

During two test periods in January and March of 2001, a NavCanada owned DeHavilland Dash 8 series 100 aircraft and a flight test crew participated in the Joint Winter Runway Friction Measurement Program (JWRFMP) at Jack Garland Airport in North Bay, Ontario Canada. The JWRFMP is a collaborative program between Transport Canada, NASA, NRC, and the FAA. The program's main objective is to study aircraft braking performance on winter contaminated runways and to find ways of correlating this to ground vehicle based friction measurements.

This report presents the results of the Dash 8 aircraft flight tests. The friction indices of two ground based friction-measuring devices, the Electronic Recording Device (ERD) and the IRFI (International Runway Friction Index) Reference Vehicle (IRV), are compared to the test aircraft-braking coefficient.

2.0 Test Program

2.1 Test Vehicles

Two primary test vehicles were used to measure and record the surface friction values. These were the Electronic Recording Device (ERD), and the IRFI Reference Vehicle (IRV). The ERD is a spot measuring device and measures a combined surface friction and contamination drag value. The IRV is a continuous measurement device and is capable of independent measurement of the contamination drag and the surface friction. A third test vehicle, the Saab Surface Friction Tester (SFT), was used as an independent friction measurement source in case of large discrepancies between the ERD and IRV.

In Canada, the ERD is the standard winter friction-measuring device and is available at all airports across the country. The runway surface friction is reported as the CRFI or Canadian Runway Friction Index. This information is available to pilots via. NOTAMS, ATIS, and tower advisories. The IRV measures and reports the IRFI or International Runway Friction Index. The IRFI is an ASTM standard currently under development and when fully mature, is expected to replace the CRFI in Canada. The SFT is the third friction-measuring device and is also widely used through out Canada, particularly for summer time airport operations. It is used as a third source to investigate any discrepancies between the ERD and the IRV.

2.2 Test Aircraft

The test aircraft is owned and operated by NavCanada and is used primarily for flight inspection. The Dash 8 series 100 is a twin-engine turbo prop commuter aircraft with a seating capacity of 30 passengers. The landing gear configuration on this aircraft is dual wheel bogies for all gear assemblies including the nose wheel. The tires installed on the aircraft were a Good Year flotation type tire, size H31x9.75-13. The aircraft is equipped with anti-skid braking on the two main gears. The system is capable of delivering a maximum system pressure of 3000 psi to the brakes and is modulated through four independent control valves and wheel speed transducers. There is a locked wheel crossover protection, where if a wheel pair speed differs by approximately 50%, the brake pressure to the wheels is released so as to preclude tire lockup and subsequent tire scuffing.

2.3 Aircraft Data Acquisition System

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

The following aircraft parameters were continuously recorded. Parameters marked with (*) were essential for data analysis.

T (*)	Time (sec)
Lat (*)	DGPS Latitude position
Lon (*)	DGPS Longitude
Hgt (*)	DGPS height with respect to earth ellipsoid reference
TGS (*)	DGPS speed along runway centerline (ft/sec)
Ax (*)	Aircraft longitudinal acceleration (g)
Az (*)	Aircraft vertical acceleration (g)
Phi	Aircraft roll angle (deg)
Theta	Aircraft pitch angle (deg)
Hdg (*)	Aircraft magnetic heading (deg)
LOBP (*)	Left outer Brake Pressure (psi)
LIBP (*)	Left inner Brake Pressure (psi)
ROBP (*)	Right outer Brake Pressure (psi)
RIBP (*)	Right inner Brake Pressure (psi)
LOWS (*)	Left outer wheel speed (KTGS)
LIWS (*)	Left inner wheel speed (KTGS)
RIWS (*)	Right inner wheel speed (KTGS)
ROWS (*)	Right outer wheel speed (KTGS)

The following parameters were manually recorded by the flight-test crew

ZFW	Zero fuel weight prior to each flight (lbf)
ZFCG	Zero fuel CG prior to each flight (% MAC)
Fuel	Indicated fuel load prior to each test run (lbf)
Wind	Wind speed and direction immediately prior to and after each test run (kts, deg M).
Vtest	Test section entry and exit speeds, or brakes on and off speeds.
Comment	Qualitative comments from either the pilots and/or flight-test observer.

2.4 Test Surface Description

All tests were conducted at the Jack Garland Airport (CYYB) in North Bay, Ontario Canada. During winter operations runway 13/31 is closed to regular traffic and hence could be used as a dedicated test area. Other runways were also used as surface conditions and aircraft traffic allowed. A total of twelve test surfaces were tested during the two deployments to North Bay.

The following surface descriptions are provided for the twelve test surfaces tested on:

A. 100% bare and dry.
B. 100% smooth dry ice.
C. 2 1/2 to 7 inches of loose snow (average of 4 inches) over 40% compacted snow, 40% ice patches, 20% bare and dry.

D. 1/4 inch loose snow over 40% compacted snow over ice, 40% ice patches, 20% bare and dry.
E. 1/8 inch loose dry snow over 40% compacted snow, 40% ice patches, 20% bare and dry.
F. 1/8 inch loose dry snow over bare pavement, 9 feet of C/L bare with inter- aggregate voids filled with snow.
G. 1/8 to 1/2 inch (1/4 inch average) loose snow over bare and dry pavement.
H. light sanding of loose snow up to 1/2 inch deep over 40% compacted snow, 40% ice patches, 20% bare and dry.
I. Wet snow and slush over ice patches and bare and dry pavement, 20% to 40% water puddles 1.5 to 2 inches deep.
J. 20% bare and dry, 80% bare and damp with patches of standing water.
K. 100% bare and damp of course texture with 10% to 20% standing water.
L. 100% bare and damp of course texture with 20% to 40% standing water.

The test sections typically consisted of a 100x1000 foot contaminated area. The rest of the runway was maintained at a high friction value to allow for safe aircraft handling. The runway surface condition was evaluated on a case-by-case assessment to determine if there existed adequate stopping condition outside of the test section. The test section was sufficiently displaced from the start of the runway to allow for a wide range of entry speeds to the test section. This was accomplished through either, acceleration from the threshold, to attain low speed entry or from a landing, which yielded high-speed entry to the test section. Beyond the test section sufficient runway length was maintained to safely bring the aircraft to a stop. High friction safety strips were maintained on either side of the test section for visual reference and for aircraft recovery in case of a lateral departure from the test section.

2.5 Test Plans

A number of different test plans were established to determine different aspects of the aircraft performance. All tests were conducted at either the flight idle or discing engine/propeller settings. The flight idle and discing settings on the Dash 8 are non-governed engine settings, whose residual idle thrust and propeller drag could be determined as a function of air speed, both reliably and accurately, without having to instrument the engines and use complicated engine thrust models.

The following lists the four test plans used:

YYB2001/01: Aerodynamic, rolling friction, idle thrust, and propeller discing thrust parameters will be confirmed on a bare and dry runway. Test points 1 through 4 of this test plan may also be used for runway slope determination.

YYB2001/02: The effect of groundspeed on contamination drag will be determined by a series of coasting runs at different groundspeeds.

YYB2001/03: The effect of groundspeed on braking coefficient will be determined by a series of braking runs with the braking initiated at different groundspeeds.

YYB2001/04: The effect of groundspeed on braking in the presence of contamination drag will be determined by a series of alternating coasting and braking runs at different groundspeeds.

In general the following test sequence was used for each contaminated surface.

A. Ground friction test devices recorded the surface friction prior to aircraft runs.
B. On surfaces with appreciable contamination drag, aircraft coasting runs were made for the determination of contamination drag.
C. Full anti-skid aircraft braking runs were made for the determination of the aircraft braking friction coefficient.
D. Ground friction test vehicles recorded the test surface friction after the aircraft runs. On test surfaces where the friction was deemed to be changing, the test vehicles made measurements after each aircraft run.

3.0 Test Results and Discussion

3.1 Analysis Methods

The analysis methods and equations used are fully developed in Reference 2 Appendix A, the final equations used are reproduced here for completeness.

It should be noted that for the purpose of calculating the braking coefficient, the aircraft weight is assumed to be entirely on the main wheels. This convention is consistent with the industry and with the other aircraft that have participated in the JWRFMP.

General equations of motion:

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

$$D_F = \mu_R (W\cos\varepsilon - L) \qquad \textbf{(2)}$$

$$L = \frac{1}{2}\rho_o V_{EAS}^2 S C_L$$
$$D = \frac{1}{2}\rho_o V_{EAS}^2 S C_D \qquad \textbf{(3)}$$

Where:

W	aircraft weight
G	gravitational constant
dV/dt	aircraft acceleration
D_P	combined drag from the propellers and residual idle thrust

$\mathbf{D_F}$	wheel braking friction
D	aerodynamic drag
L	aerodynamic lift
$\mathbf{D_{CONTAM}}$	contamination drag
	runway slope
μ_R	coefficient of rolling friction
μ_B	coefficient of braking friction
μ_S	wheel slip ratio coefficient
$\mathbf{V_{EAS}}$	equivalent airspeed
S	wing surface area
Cl	coefficient of lift in ground effect
Cd	coefficient of drag in ground effect
$\mathbf{V_{GS}}$	aircraft ground speed
$\mathbf{V_W}$	wheel speed
$_0$	Air density, correct to sea level

For small angles of , cos ( ) = 1, and sin ( ) = , the general equation then becomes:

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

Determination of flight idle and discing thrust:

Setting $D_{CONATAM}$ in the general equation to zero and solving for the propeller drag $D_{P,}$ the equation (1) becomes:

$$\frac{D_P}{W} = -\frac{D}{W} - \varepsilon - \mu_R(1 - \frac{L}{W}) - \frac{1}{g}\frac{dV}{dt} \qquad \textbf{(5)}$$

The value used for the aircraft rolling friction was supplied by the manufacturer (μ_R = 0.025).

Determination of slip ratio:

$$\mu_S = (V_{GS} - V_W)/V_{GS} \qquad \textbf{(6)}$$

Determination of braking coefficient:

On surfaces with no or negligible contamination drag:

$$\mu_B = (-\frac{D}{W} - \frac{D_P}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \qquad \textbf{(7)}$$

On surfaces with appreciable contamination drag:

$$\mu_B = (-\frac{D}{W} - \frac{D_P}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}) \Big/ (1 - \frac{L}{W}) \quad \textbf{(8)}$$

Determination of contamination drag:

$$\frac{D_{CONTAM}}{W} = -\frac{D}{W} - \frac{D_P}{W} - \varepsilon - \mu_R (1 - \frac{L}{W}) - \frac{1}{g}\frac{dV}{dt} \qquad \textbf{(9)}$$

3.2 Summary of Test Runs

In Appendix A, the data for each test run is presented in tabular form on pages A1 to A3 and graphically on pages A4 to A39. On these graphs the aircraft ground speed, acceleration, and four brake pressures are plotted. A total of 69 test runs were made in 8 test flights (flight 2001/01 to flight 2001/08).

3.3 Runway Slope Determination

The runway slope profiles at the North Bay airport varied significantly along the length of each runway, some of these changes occurring within a test section. This necessitated the requirement to accurately map the runway slope profile for each runway. Previous flight test programs involving an NRC Falcon 20 had established the runway slope profiles for most of the runways (see reference 2). The previously established runway slope profiles were used for this test program with the exception of runway 18/36, which had not yet been profiled. Flight 2001/01 runs 3 and 4 were used to determine this slope profile. The runway slope is established by performing a slow speed aircraft taxi down the length of a runway. The vertical height information from a differential GPS and the along track distance down the runway are then modeled to determine runway slope.

3.4 Aircraft Propeller Drag

In order to determine the aircraft braking performance the propeller drag and engine thrust components (D_P) must be known so that the aircraft-braking coefficient can be computed from equations 7 and 8. It was not feasible for this test program to instrument the engine and determine a full dynamic thrust/drag model. All flight-testing was therefore done at a fixed non-governed engine setting. Special test runs were made on a bare and dry runway to determine the combined engine thrust and propeller drag (D_P) as a function of equivalent air speed. The Dash 8 has two non-governed engine settings, and both are used during routine landing procedures, flight idle and discing. Both the flight idle and the discing drag as a function of equivalent air speed models were determined using equation 5. The combined propeller drag and engine thrust models are presented in Appendix B. Page B1 summarizes each of the data runs in tabular form. Pages B2 to B6 shows each individual run graphically. Page B7 shows the relationship between equivalent air speed and the flight idle drag. A least squares second order fit was applied to the data with the resulting coefficients shown on the graphs. Note that at 63 knots and below the drag is negative. This is due to the forward pitch setting of the propellers in the flight idle setting and, hence, the drag term becomes a thrust term. Appendix B, Page B8 shows the relationship between the equivalent air speed and the propeller discing drag. A second order equation was also found to best fit the data, with the coefficients shown on the graph. Note that the drag term is slightly negative at zero ground speed.

Figure 1 and Figure 2 contrast the experimentally derived propeller drag models with the drag models supplied by DeHavilland. Both the flight idle and discing derived models differ only slightly from the aircraft manufacturer's models. At the higher speeds (roughly 60 to 100 knots) the DeHavilland model matches very closely to the experimentally derived models. At the lower speeds the experimentally derived model under estimates the drag by up to about 800 lbs. This is true for both the flight idle and discing drag models. The most plausible explanation for the slight divergence in the models, is that the DeHavilland models contain solely propeller drag and, the derived models contain a number of additional factors that are all lumped together and labeled "propeller drag". The dominant of the all these combined factors would be the residual idle thrust from the engines. Another possible reason for the difference in the models is that the manufacturer must, by necessity, be conservative in its determination of the propeller drag. Therefore, the slight divergence between the DeHavilland and the experimentally derived models of propeller drag is not of concern. The experimentally derived models were used for the subsequent data reduction.

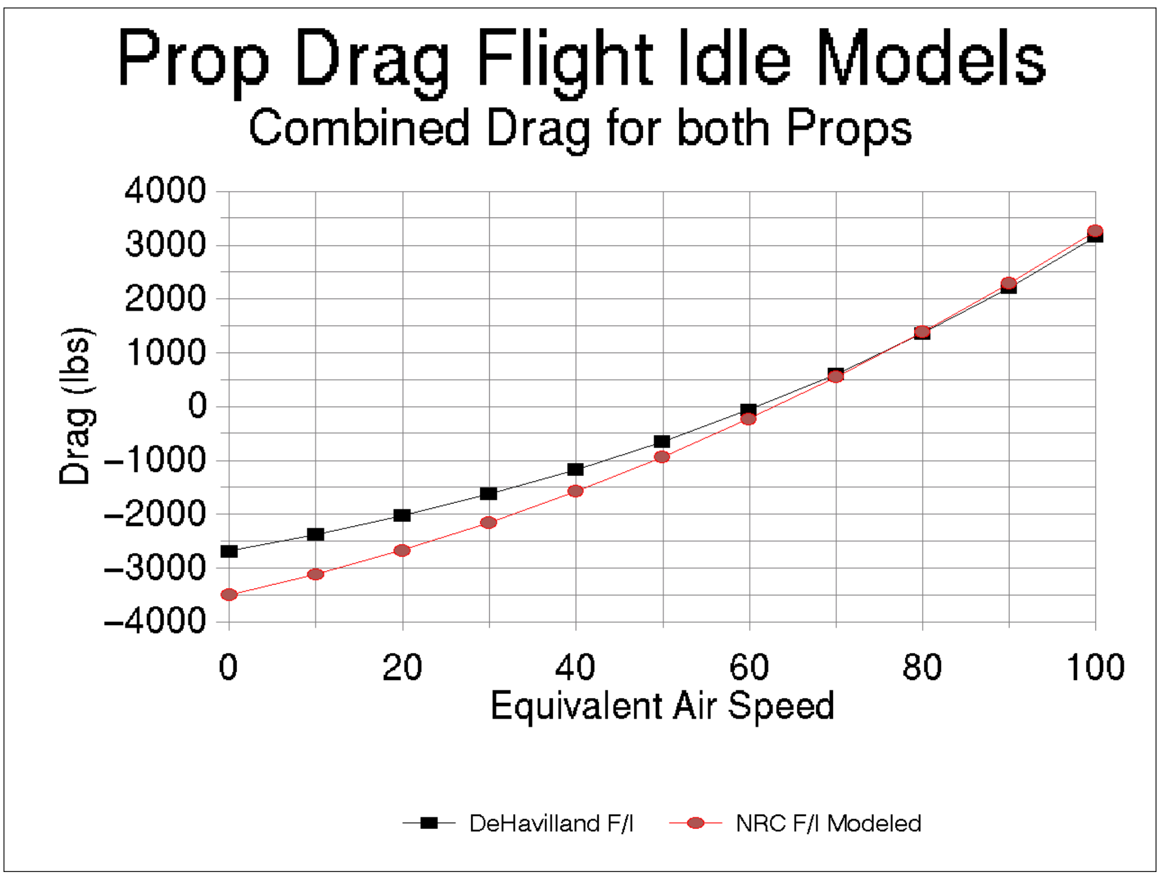


Figure 1

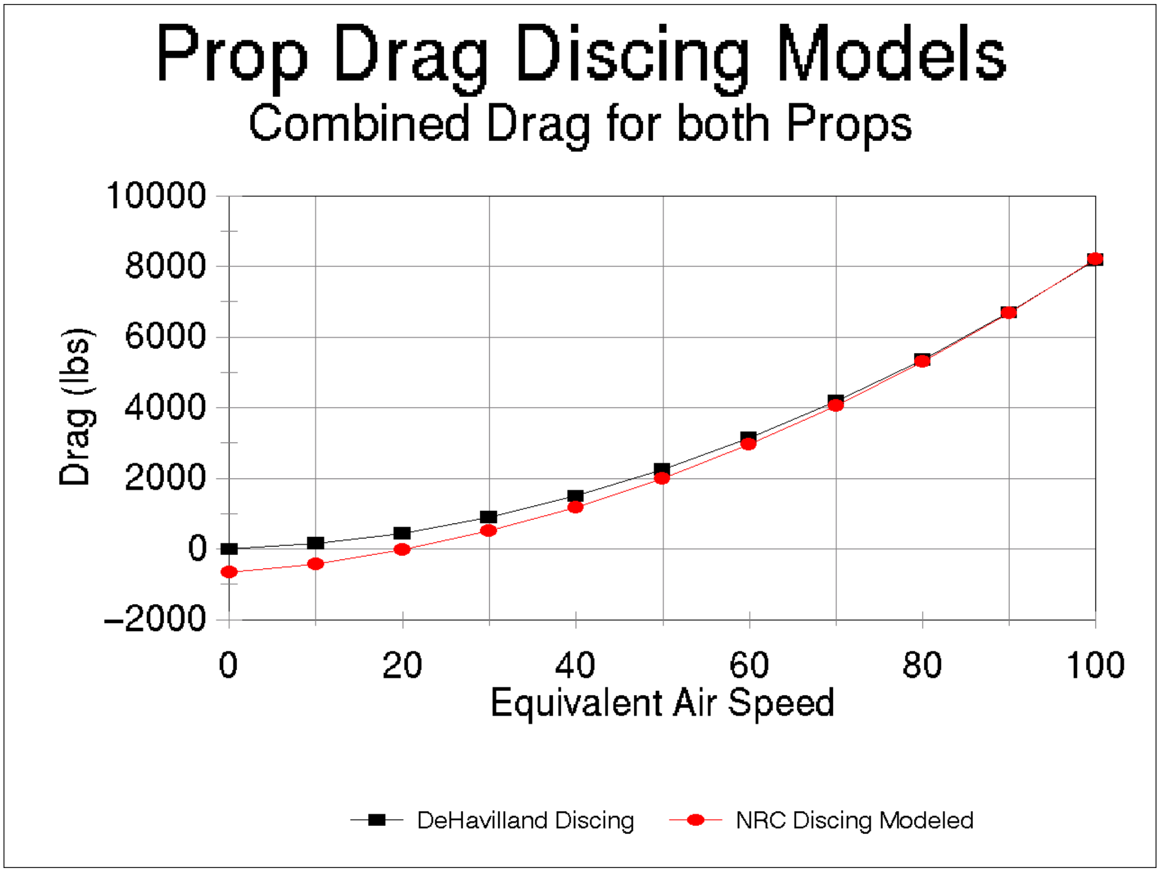


Figure 2

3.5 Anti-skid Braking Slip Ratio

The slip ratios for each of the four wheels is shown in Appendix C. Pages C1 and C2 show the tabular data for each test point. Pages C3 to C48 show the data for each test point graphically. Shown are the wheel speeds, brake pressures and slip ratios for all four wheels. Note that the top four rows of graphs are plotted against time and the lower two rows of graphs are plotted against ground speed. On page C49 the average slip ratio for each wheel is plotted against the average ground speed. The slip ratios are a good measure of how well the anti-skid system of the aircraft is operating. A slip ratio of zero indicates that the tires are freewheeling and a slip ratio of one indicates a locked wheel condition. In general the Dash 8 anti-skid system worked very well for a wide variety of surface conditions. The average slip ratio for the four main wheels in the table on page C1 and C2 is 10%, which is considered the optimal slip ratio for maximum braking.

In the following discussion, typical anti-skid braking performance will be discussed for three representative test surfaces, a high, a medium, and a low surface friction.

In Appendix C, page C46, a high surface friction case can be seen. It is flight 2001/08 run number 1 and was conducted on a bare and wet runway surface. From the four brake pressure traces, it is apparent that all four brake pressures are modulated independently by the anti-skid system using the same control laws. After the initial application of the brakes, the brake pressures quickly rise to about 1500 psi. The aircraft is capable of delivering a maximum system pressure of 3000 psi. At this point all four wheels start into a deep skid. A deep skid can be characterized as a wheel speed that differs significantly from the ground speed of the aircraft, producing a slip ratio of greater than 20%. The anti-skid system responds by reducing the brake pressures to the four wheels. The pressures are reduced to the point, where the wheels recover from the impending skid (i.e. it's wheel speed increases and starts to match that of the aircraft ground speed). The brake pressures are then re-applied to the wheels but only at a percentage of that which caused the skid. The brake pressure is then rapidly increased until another impending skid is detected, and the cycle is repeated. The brake pressure traces resemble that of a saw-tooth pattern, as clearly seen for all the brake pressure traces on page C46. It should be noted that through out this time the pilot has both brake pedals firmly engaged and any brake pressure modulations are a result of the anti-skid system.

There is an anomaly in the data recording system that shows up on careful examination of the data presented on the page C46. It is quite evident that the four brake pressure traces are quite distinct however careful examination of the slip ratios reveals only three distinct traces. It appears that the left inner wheel speed is really a duplicate of the left outer wheel speed; this is true for the entire data set. The error likely occurred at the electrical pickup points on the anti-skid controller box.

In Appendix C, page C12, a medium surface friction case can be seen. It is flight 2001/02 run number 13 and was conducted on a runway surface of 60% loose snow over ice and 40% ice patches. On this reduced friction surface the anti-skid system is having a harder time preventing the wheels from entering a skid a deep skid. On the bare and wet surface there are several instances of a deep skids, where as on this surface there is an increase in the number of deep skid onsets. Note that the left brake pressures are significantly lower than the right brake pressures. The pilot did not indicate any adverse handling qualities of the aircraft for this particular test. The reported winds during this test were from 30 degrees left of the runway heading at a speed of seven knots. This is not sufficient to cause a significant wind blown ridging/thinning effects on the test surface. However with a left crosswind, more weight could be distributed on the right hand wheels, which would allow the right-hand wheels to support greater braking forces.

In Appendix C, page C38 a test surface condition of 100% smooth dry ice is presented. On this extremely low surface friction condition the anti-skid system is continually trying to keep the wheels from entering deep skids, as evidenced by the wheel speed traces. The brake pressures never rise above 400 psi and continually oscillate between 400 and 0 psi, indicating that the wheels are either in a state of entering a deep skid or recovering from one. The braking action on this surface would be characterized as poor to nil.

The relationship of the slip ratio and the ground speed is shown in Appendix C, Page C49. This graph plots the average slip ratio against the average ground speed for a given test run. There appears to be a significant effect of ground speed on the slip ratio, namely, that as the ground speed increase the slip ratio will tend to decrease slightly. A linear correlation of 59% was observed between the two. It is not clear if this relationship is a design feature of the anti-skid system or simply an artifact of the highly dynamic interaction between the tire and braking surface. However, one must also be careful in drawing conclusions from this because the slip ratio is also dependent on the surface friction, to a certain extent.

3.6 Aircraft Braking Coefficient on Surfaces with No or Negligible Contamination Drag

The majority of all test runs performed were for the determination of the aircraft-braking coefficient (Mu braking or μ_B). These were calculated using equation number 7. Appendix D shows the results of these tests. Pages D1 and D2 show the tabular results of the test runs. Pages D3 to D15 plot the graphical results for each of the individual test runs, and pages D16 to D18 show the averages of each test run, grouped by test surface. Page D19 compares the aircraft Mu Braking with the measured CRFI and page D20 compares the aircraft Mu Braking with the measured IRFI.

As noted earlier, for full anti-skid braking runs, the brake pressure traces resembled that of a saw tooth pattern. The period of these saw tooth patterns are on the order of 1 second. The aircraft data acquisition system collected data at 64Hz and the instantaneous braking coefficient was calculated at this same sample rate. However, the anti-skid system of the aircraft is continuously varying the brake pressures. As a result, the instantaneous unfiltered traces of μ_B contained noticeable variations due to the anti-skid action. It was decided therefore to use a 1.5-second moving window average on the data. This smoothed the data out over one and a half cycles of the saw tooth patterns. This was sufficient to average out the anti-skid cycles and yet leave variations with ground speed and runway friction.

Some of the data runs would indicate a strong inverse relationship between the braking coefficient and ground speed (page D15) and other a strong increasing relationship (page D7, run 4) and others none at all (page D11). It is not known why these conflicting variations are present and why they would suggest any correlation at all. However, the data set, taken as a whole, shows that there is no correlation between the braking coefficient of the aircraft (μ_B) and the ground speed.

Through out the JWRFMP program the CRFI has consistently correlated better with the aircraft Mu Braking than the IRFI has. The ERD is a locked wheel device where as the IRV is a variable speed/slip device. The aircraft anti-skid system is a constant slip device. One would expect the aircraft to correlate better with the IRV, however this is not the case. One possible explanation is that the ERD more closely emulated the physical effects seen by the aircraft, namely the deceleration of a large mass.

The most important relationship to come out of the entire Joint Winter Runway Friction Measurement Program is relationship between aircraft braking coefficient (μ_B) and the ground vehicle measured friction (CRFI and IRFI).

Page D19 shows the relationship between Aircraft μ_B and CRFI. The correlation factor between these two variables is 95% and exhibits typical scatter as seen by other aircraft (See references 1 through 8). The scatter can be attributed to two main causes. The first is due to measurement of the aircraft deceleration non-uniform test surfaces. All of the surfaces tested on were natural and not man made surfaces, with the exception of smooth glare ice. Natural snow covered surfaces were therefore subject to wind blown effects such as ridging and thinning. Secondly, the scatter is due to the ERD, which averages values from three discreet spot measurements along the test section. This becomes particularly evident for non-uniform surfaces. The ERD operator must be careful to not under estimate the friction by choosing the three "worst" locations at which to make spot measurements.

The following figure compares the Dash 8 aircraft braking performance with that of all the other aircraft that have participated in the Joint Winter Runway Friction Measurement Program. This data has been compiled from references 1 through 8 and summarizes in reference 11.

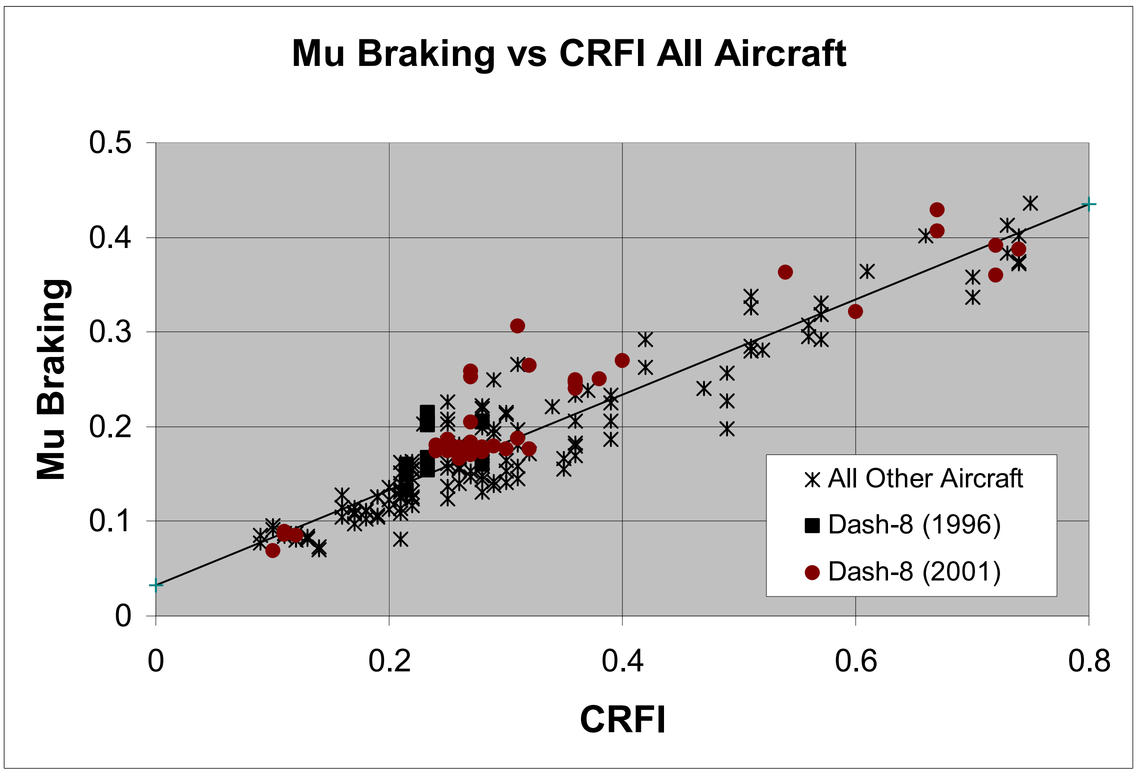


Figure 3

As can be seen from this figure the Dash 8 braking performance compares very well with that of the other aircraft. As stated earlier the Dash 8 data scatter lies within the data scatter of the other aircraft. It is important to note the wide range of aircraft compared (B757, B737, B727, Dash8, DU328, and Falcon 20). Despite the aircraft size and type variations the results when compared at this level show that all these aircraft have the same braking performance.

Page D20 shows the relationship between Aircraft μ_B and the IRFI. The correlation factor between the two is quite good at 91%. In the past, the IRFI has not correlated this well with other aircraft (see ref. 10) however, as stated, the correlation with the Dash 8 is quite good. This raises the question of, has something changed on the IRFI test vehicle so that it now correlates well with the aircraft and similarly, why did it not correlate well in the past? To date no change has been identified on the IRFI test machine. However the correlation shown is a very positive and important step towards the development and acceptance of an International Runway Friction Index.

3.7 Contamination Drag

There arose two opportunities for the determination of contaminant drag on the aircraft, flights 2001/02 and 2001/05. The results of these test runs are shown in Appendix E. The contamination drag was calculated using equation number 9. Page E01 shows the tabular results and pages E02 and E03 show the graphical results for each test run. Page E04 summarizes the results by test surface.

Page E02 shows the results for flight 2001/02 on a test surface with 4 inches of loose snow. This is a rather severe test condition and (hopefully) not representative of regular flight operations. This snow depth did not cause any adverse handling of the aircraft. The snow thrown forward and back from the main landing gear stayed well clear of the propellers and engine intake. In fact there was no impingement drag from the main landing gear. The nose wheel threw up a considerable amount of snow, and snow was compacted inside the nose gear bay, requiring careful cleaning.

The data for flight 2001/02 indicates that there is no conclusive ground speed effect in the determination of contamination drag. Runs 1 and 2 suggest that no relationship exits and runs 3 and 4 show the contrary. Therefore, due to the variable results it is not possible to draw any conclusion as to if any speed effects exist. The data from other aircraft that have participated in the program (references 2-8,10) have concluded that there is no significant ground speed effect. The contamination drag was modeled for flight 2001/05 as a single average value, with only one run conducted, page E04 shows this result.

3.8 Aircraft Braking Coefficient on Surfaces with Appreciable Contamination Drag

Appendix F summarizes the test runs made to determine the aircraft-braking coefficient (μ_B) on runway surface with appreciable contamination drag. The μ_B was determined using equation number 8.

Two surfaces were tested on that contained a significant amount of contamination (flight 2001/02 and flight 2001/05). However only one of these was considered safe to perform braking runs on, flight 2001/05. Page F02 shows the test results for each individual run, where the braking coefficient (μ_B) data is plotted against ground speed. An examination of this data shows the same inconclusive speed effects as noted previously (compare page F02 with page D04).

In the previous section it was determined that the contamination drag was a constant. Having removed the effect of contamination drag, the aircraft-braking coefficient (μ_B) should be comparable to that of the μ_B calculated for surfaces with negligible contamination drag. Page F03 shows the Mu braking plotted against the CRFI. The solid line is that of best straight-line fit calculated for surfaces with no or negligible contamination drag. One can see that the μ_B is almost right on the line and well within the scatter of the data (see page D19). Page F04 shows the μ_B plotted against the IRFI. Here too the data falls very close to the line and lies within the scatter of the data for surfaces with no or negligible contamination drag (see page D20).

It is interesting to note that despite the presence of 1.5 to 2.5 inches of water puddles over 20% to 40% of the test surface, the contamination drag is only 0.033 for these test runs, where as the braking coefficient is 0.178. The drag is almost insignificant compared to the braking coefficient. The ERD is a deceleration device and cannot distinguish between contamination drag and braking friction. It would be valid therefore, to add the drag component to the braking coefficient together when comparing with the CRFI. If one were to do this, the data points on page F03 would lie directly on the solid line as determined on page D19.

4.0 Conclusions

A. The experimentally derived propeller drag differed slightly from the manufacturer-supplied model. However this was not considered significant as a number of drag sources were lumped together under the term propeller drag for the experimentally derived model.

B. The anti skid system of the aircraft proved to be very effective at adapting to the different surfaces tested on.

C. The slip ratio, maintained by the anti skid system, exhibited a slight inverse linear relationship with ground speed.

D. The aircraft-braking coefficient (μ_B) did not exhibit any clear relationship with ground speed.

E. Aircraft braking coefficient (μ_B) correlated well with both the CRFI and IRFI. Both ground test vehicles were able to predict aircraft braking performance on winter-contaminated surfaces.

F. Dash 8 braking performance matched those of the other test aircraft that have participated in the Joint Winter Runway Friction Program, namely a Falcon 20, Boeing 727, 737, and 757.

G. The Dash 8 test results confirm the universality of the "CRFI tables" of recommended aircraft landing distance, as detailed in references 1,8 and 9.

H. There was insufficient data to support any conclusions on the relationship between the ground speed of the aircraft and the contamination drag.

I. The Mu braking (μ_B) calculated on surface with appreciable contamination drag was directly comparable to that of surfaces with no or negligible contamination. Stated differently, the contamination drag was successfully modeled and it's effect removed in the determination of μ_B.

5.0 Acknowledgements

The authors are indebted to the hard work done by numerous individuals who made this project a success, the NavCanada flight crew, for their professionalism and enthusiastic support, Innotech aviation, for the quick and efficient installation of additional sensors. Finally, to Mike Pygas of NRC, who expertly installed and wired all the inputs to the data acquisition system.

6.0 References

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

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

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

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

5. M. Doogan, E. Herrmann, P. Lamont — Dash 8 Aircraft Performance Testing on Contaminated Runway Surfaces (Winter 1997.1998), Bombardier Aerospace, DHC-D4547-98-06, June 1998.

6. M. Bastian, P. Lamont — Braking Friction Coefficient and Contaminated Drag of a B727 on Contaminated Runways, National Research Council Canada, LTR-FR-147, TP 13258E, June 1998.

7. J.B. Croll, J.C.T. Martin, M. Bastian — Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces Durint the Winter of 1997/1998, National Research Council Canada, LTR-FR-151, TP 13338E, December 1998.

8. J.B. Croll, J.C.T. Martin, M. Bastian — Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1998/1999, National Research Council Canada, LTR-FR-158, TP 13557E, December 1999.

9. J.C.T. Martin — Proposed Amendment to the CRFI Recommended Landing Distance Table for Aircraft with Thrust Reverser or Propeller Reversing System, Transport Canada Aircraft Cerfification Flight Test Division, January 1999.

10.	M.Bastian J.B. Croll J.C.T. Martin	Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1999/2000, National Research Council Canada, LTR-FR-174, TP 13833E, November 2001.
11.	J.B.Croll M. Bastian J.C.T. Martin P. Carson	Evaluation of Aircraft Braking Performance On Winter Contaminated Runways and Prediction of Aircraft Landing Distance Using the Canadian Runway Friction Index, National Research Council Canada, LTR-FR-183, TP 13943E, June 2002.

APPENDIX A - SUMMARY OF TEST RUNS

The following table shows the test conditions for all test runs. Pages A4 to A39 show the time histories of ground speed, acceleration, left brake pressures (inner and outer) and right brake pressures (inner and outer) for each run. Note that for coasting runs, the brake pressure is zero.

FLT/ DATE	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK (see Note 1)	Weight (LB)	TWR WIND (KT)	SURFACE DESCRIPTION (see Note 2)	Avg CRFI	Avg IRFI
2001/01 29/01/01	1 14:35	26	TAXI	15/IDLE/NO	31950	245/15	100% Bare and Dry		
	2 14:41	08	TAXI	15/IDLE/NO	31875	250/15	“		
	3 14:51	36	TAXI	15/IDLE/NO	31750	240/13	“		
	4 14:54	18	TAXI	15/IDLE/NO	31700	230/15	“		
	5 15:07	26	LAND	15/IDLE/NO	31500	235/15	“		
	6 15:26	26	LAND	15/DISC/NO	31350	235/15	“		
	7 15:39	08	RTO	15/DISC/NO	31200	240/12	“		
	8 15:42	26	RTO	15/IDLE/B	31150	240/11	100% Bare and Dry Air temperature –3C Surface temperature –2C	0.67	0.87
	9 15:53	26	LAND	15/IDLE/B	31050	240/12	“	0.67	0.87
	10 15:57	26	RTO	15/REV/NO	31000	240/10	“		
2001/02 31/01/01	1 14:19	31N	RTO	15/IDLE/NO	32500	060/5	2.5 to 7.0 inches of loose snow (4 inch average) at SG = 0.15, over 40% compacted snow, 40% ice patches, 20% bare and dry.		
	2 14:27	31N	RTO	15/IDLE/NO	32420	060/7	“		
	3 14:34	31N	RTO	15/IDLE/NO	32350	050/4	“		
	4 14:40	31N	RTO	15/IDLE/NO	32290	060/6	“		
	5 14:45	31TS	RTO	15/IDLE/B	32240	060/4	1/8 inch of loose dry snow over 40% compacted snow, 40% ice patches, 20% bare and dry. Air temp –8C, Surface temp –6C	0.28	0.19
	6 15:03	31TS	RTO	15/IDLE/B	32060	050/6	“	0.28	0.20
	7 15:13	31TS	RTO	15/IDLE/B	31960	050/6	“	0.27	0.21
	8 15:20	31TS	RTO	15/IDLE/B	31890	060/8	“	0.27	0.22
	9 15:32	31TS	RTO	15/DISC/B	31770	060/7	“	0.26	0.22
	10 15:38	31TS	RTO	15/DISC/B	31710	050/7	“	0.25	0.21
	11 15:43	31TS	RTO	15/DISC/B	31660	060/7	“	0.24	0.20
	12 15:57	26	RTO	15/IDLE/NO	31520	055/8			
	13 16:04	08TS	RTO	15/IDLE/B	31450	050/7	1/8 inch loose dry snow over bare pavement, 3 metre C/L bare with inter-aggregate voids filled with snow. Air temp –8C, surface temp –6C	0.31	0.38
	14	08	RTO	15/IDLE/NO	31380	050/7			

FLT/ DATE	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK (see Note 1)	Weight (LB)	TWR WIND (KT)	SURFACE DESCRIPTION (see Note 2)	Avg CRFI	Avg IRFI
	16:11								
	15 16:16	26	RTO	15/DISC/NO	31330	060/8			
	16 16:25	08TS	RTO	15/DISC/B	31240	060/8	"	0.31	0.38
	17 16:36	08	RTO	15/DISC/NO	31130	050/7			
	18 16:39	08TS	RTO	15/IDLE/B	31100	050/7	"	0.32	0.37
2001/03 01/02/01	1 10:47	36N	RTO	15/IDLE/B	30700	250/5	1/8 to ½ inch (¼ inch average) loose snow over bare pavement. Air temp –10C, surface temp –6C	0.27	0.18
	2 10:52	36N	RTO	15/IDLE/B	30650	250/5	"	0.26	0.20
	3 11:02	36N	RTO	15/IDLE/B	30560	230/5	"	0.25	0.21
	4 11:09	36N	RTO	15/DISC/B	30500	230/5	"	0.27	0.21
	5 11:52	31TS	RTO	15/IDLE/B	30150	230/5	¼ inch loose snow over 40% compacted snow, 40% ice patches, and 20% bare and dry. Air temp –9C, surface temp –7C	0.24	0.19
	6 11:58	31TS	RTO	15/IDLE/B	30090	240/5	"	0.25	0.19
	7 12:04	31TS	RTO	15/IDLE/B	30030	230/6	"	0.26	0.20
	8 12:15	31TS	LAND	15/IDLE/B	29880	230/5	"	0.26	0.20
	9 12:22	31TS	LAND	15/DISC/B	29780	230/7	"	0.27	0.20
	10 12:26	31TS	LAND	15/DISC/B	29720	230/5	"	0.27	0.20
	11 12:31	31TS	LAND	15/DISC/B	29650	230/5	"	0.27	0.20
2001/04 01/02/01	1 14:46	31TS	RTO	15/IDLE/B	30730	240/3	Light sanding of loose snow up to ½ inch deep over 40% compacted snow, 40% ice patches, 20% bare and dry. Air temp –7C, snow temp –6C	0.40	0.35
	2 14:50	31TS	RTO	15/IDLE/B	30700	230/4	"	0.38	0.35
	3 14:54	31TS	RTO	15/IDLE/B	30660	250/4	"	0.36	0.36
	4 15:02	31TS	LAND	15/IDLE/B	30520	250/4	"	0.36	0.36
	5 15:08	31TS	LAND	15/DISC/B	30440	250/2	"	0.36	0.36
	6 15:15	31TS	LAND	15/DISC/B	30350	250/2	"	0.36	0.35
2001/05 21/03/01	1 14:11	31N	RTO	15/IDLE/B	31210	235/4	Wet snow and slush over ice patches and bare pavement, 20-40% water puddles 1.5-2.5 in deep	0.32	0.36
	2 14:24	31N	RTO	15/IDLE/B	31100	235/5	"	0.30	0.39
	3 14:35	31N	RTO	15/IDLE/B	31000	240/4	Aborted due to loss of aircraft directional control	0.28	0.41
	4 14:42	31N	RTO	15/IDLE/B	30940	230/4	"	0.29	0.39
	5 14:57	31N	RTO	15/IDLE/NO	30810	245/3	"		
	6	26	TAXI	15/IDLE/NO	30750	250/5	100% Bare and Dry		

FLT/ DATE	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK (see Note 1)	Weight (LB)	TWR WIND (KT)	SURFACE DESCRIPTION (see Note 2)	Avg CRFI	Avg IRFI
	15:05								
	7 15:10	08	TAXI	15/IDLE/NO	30710	250/6	"		
	8 15:15	26	RTO	15/IDLE/NO	30670	250/6	"		
	9 15:18	08	RTO	15/IDLE/NO	30650	250/6	"		
	10 15:22	26	RTO	15/DISC/NO	30610	255/6	"		
	11 15:27	08	RTO	15/DISC/NO	30560	255/6	"		
2001/06 22/03/01	1 07:25	31N	RTO	15/DISC/B	30450	050/6	100% smooth dry ice, Air Temp -4ºC	0.10	0.16
	2 07:30	31N	RTO	15/DISC/B	30410	050/6	"	0.11	0.15
	3 07:40	31N	RTO	15/DISC/B	30330	050/6	"	0.11	0.14
	4 07:45	31N	RTO	15/DISC/B	30290	045/6	"	0.11	0.13
	5 07:55	31N	RTO	15/IDLE/B	30210	050/6	"	0.11	0.14
	6 08:00	31N	RTO	15/IDLE/B	30170	065/6	"	0.12	0.15
	7 08:13	31N	RTO	15/IDLE/B	30060	065/8	"	0.11	0.15
	8 08:17	31N	RTO	15/IDLE/B	30030	060/7	"	0.11	0.15
2001/07 22/03/01	1 10:08	31N	RTO	15/IDLE/B	29810	050/10	20% bare and dry, 80% bare and damp with patches of standing water, Air Temp +5ºC	0.54	0.59
	2 10:12	31N	RTO	15/IDLE/B	29780	055/11	"	0.60	0.72
2001/08 23/03/01	1 11:28	31TS	RTO	15/IDLE/B	29300	030/11	100% bare and damp on a coarse texture, with 10-20% standing water, Air Temp +2ºC	0.74	0.72
	2 11:32	31TS	RTO	15/IDLE/B	29270	005/6	"	0.72	0.74
	3 12:02	31TS	RTO	15/IDLE/B	29030	020/13	100% bare and damp on a coarse texture, with 20-40% standing water, Air Temp +4ºC	0.72	0.73

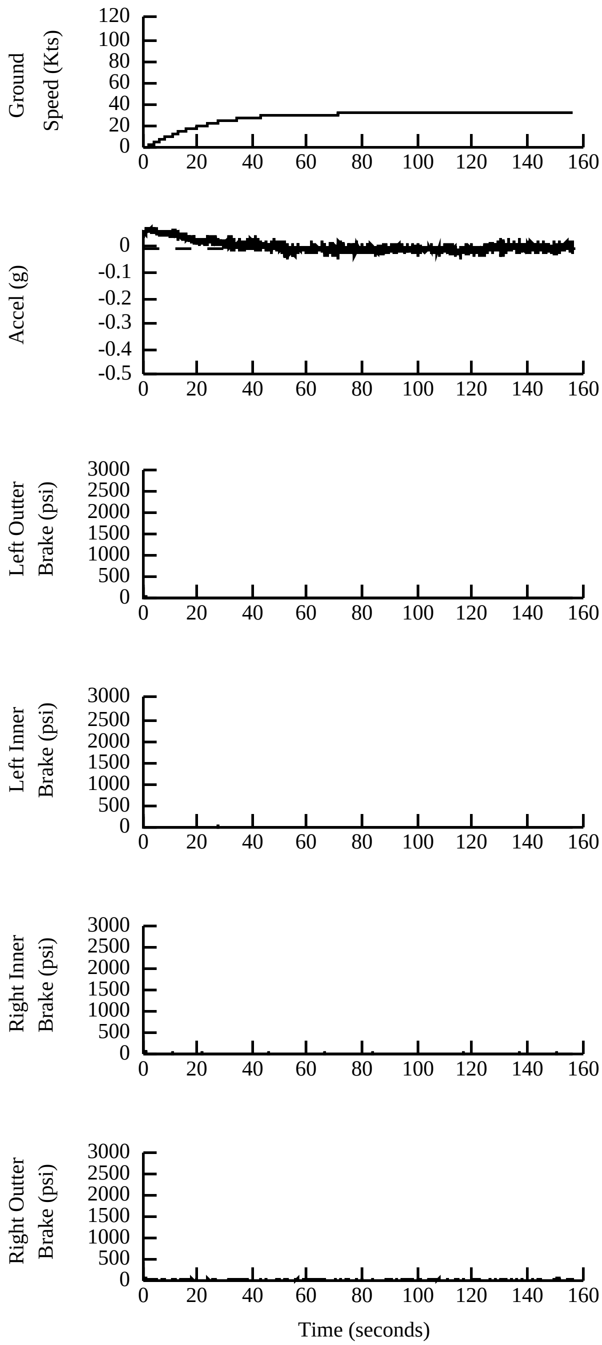
Note 1: Indicates flap setting (15 or 35), power setting (Flight Idle, Discing or Full Reverse), and pilot braking (NO for no braking, B for maximum anti-skid braking)

Note 2: Temperatures in degrees Celsius.

Surface: 100% Bare and Dry

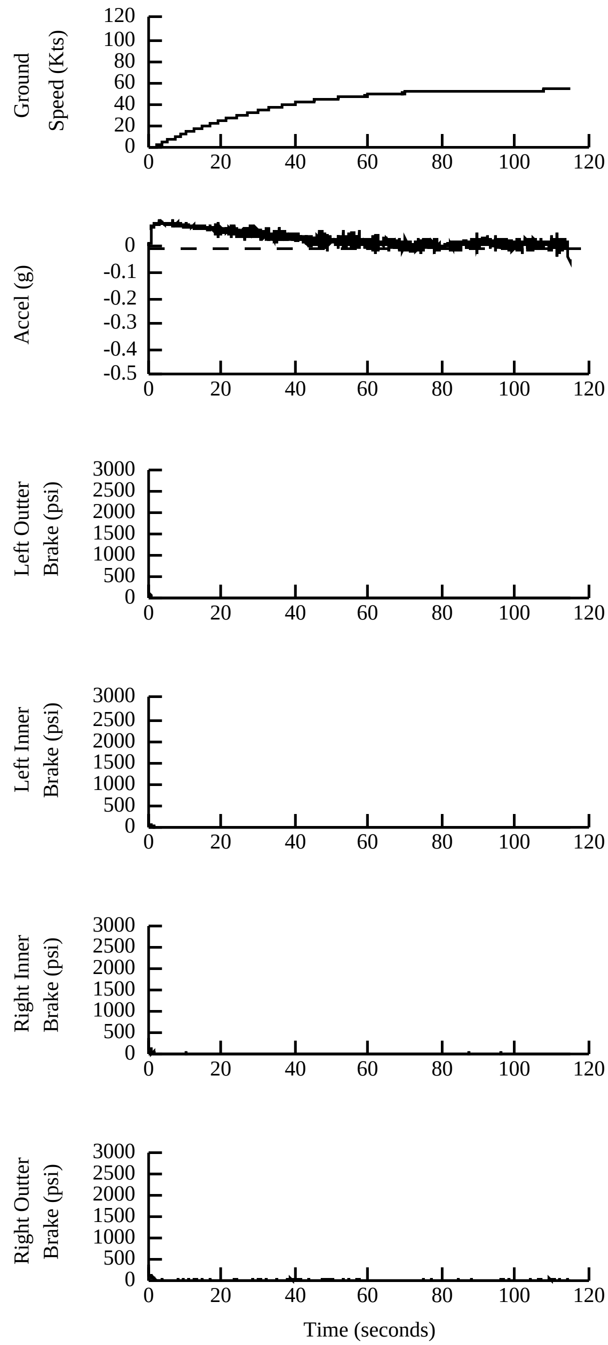
Flight 2001/01, Run Number 1

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/01, Run Number 2

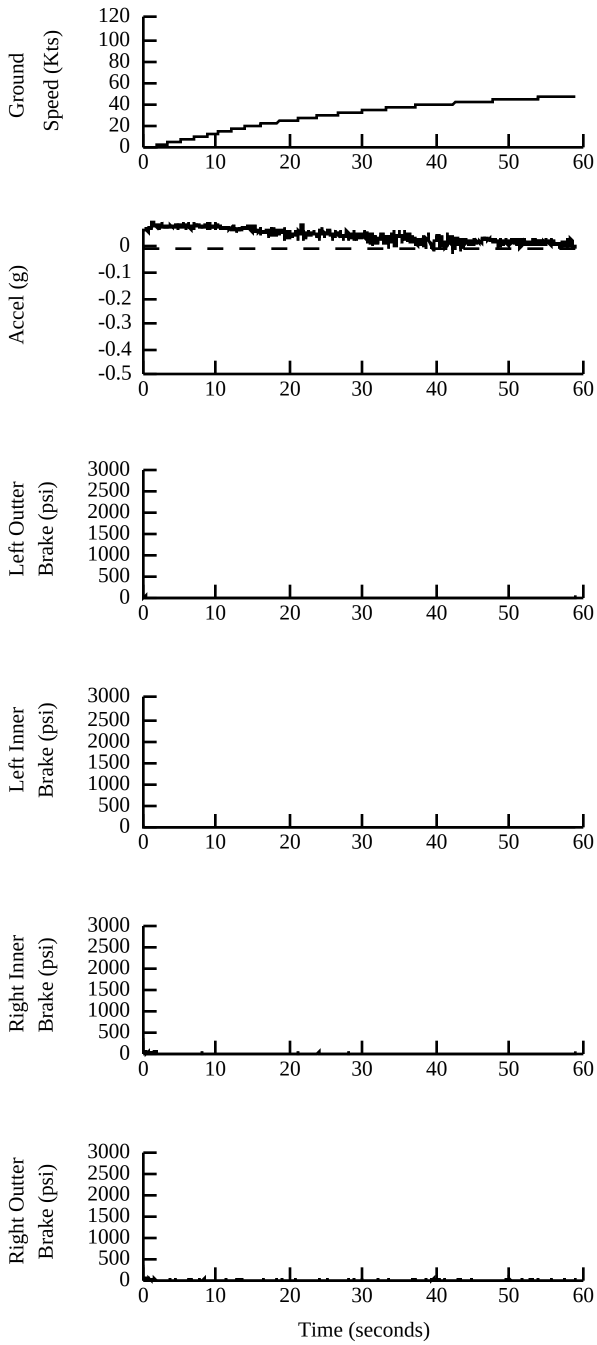
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 100% Bare and Dry

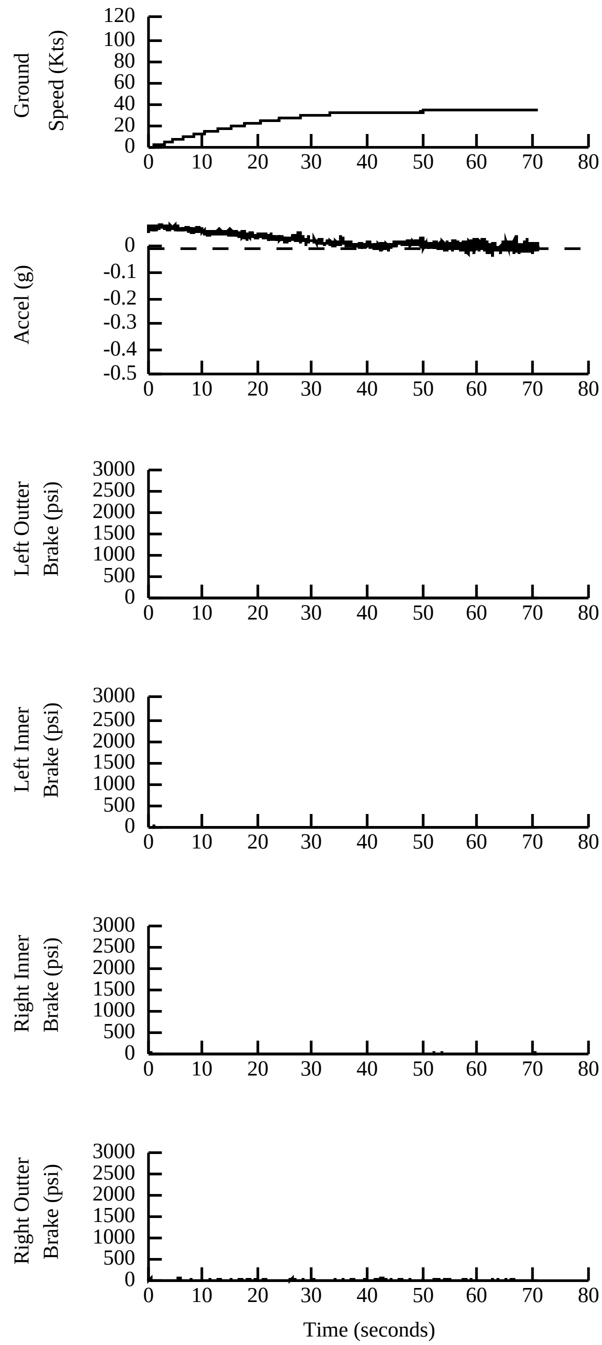
Flight 2001/01, Run Number 3

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/01, Run Number 4

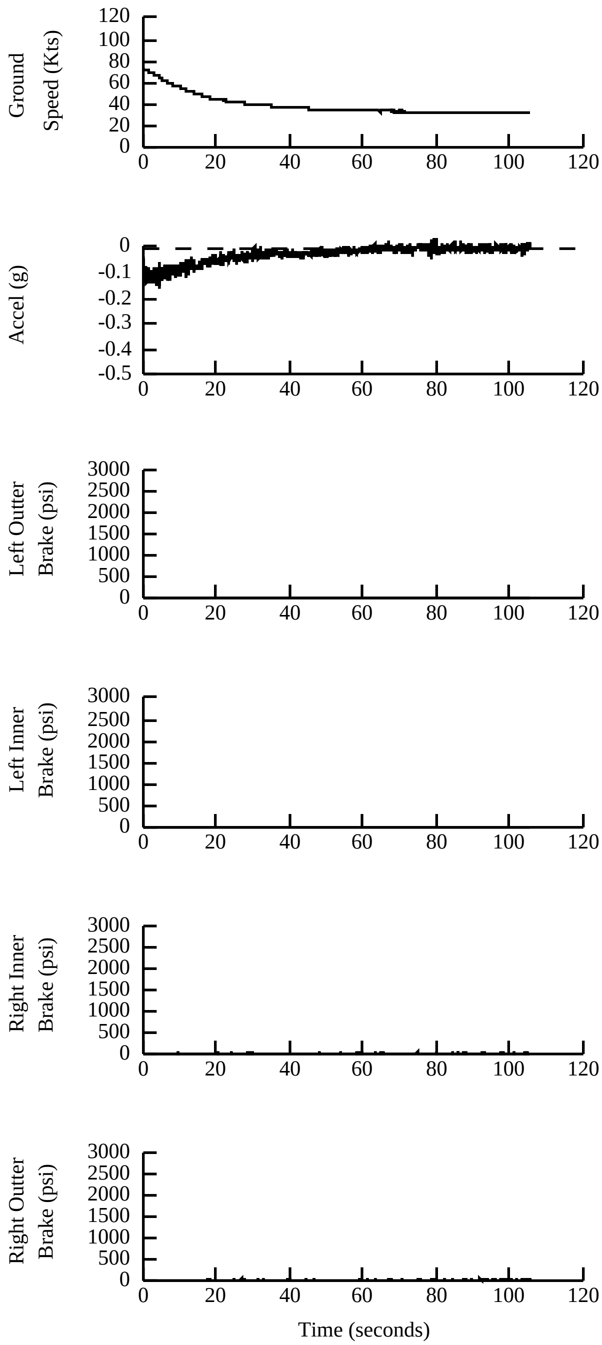
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 100% Bare and Dry

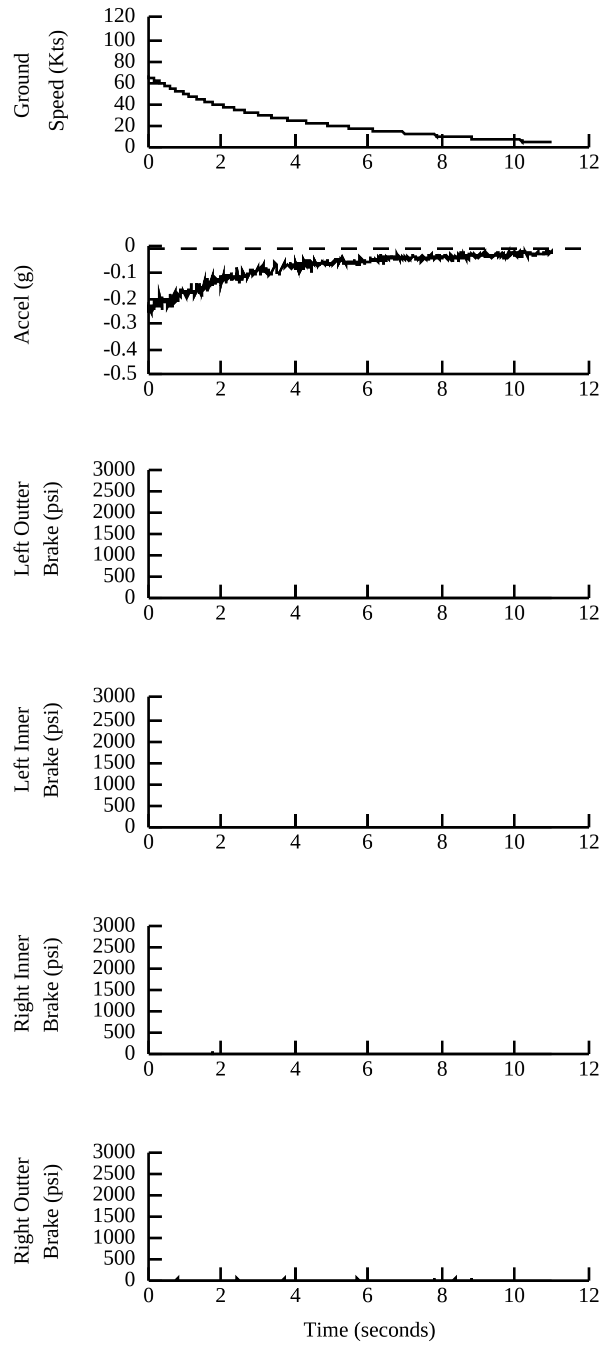
Flight 2001/01, Run Number 5

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/01, Run Number 6

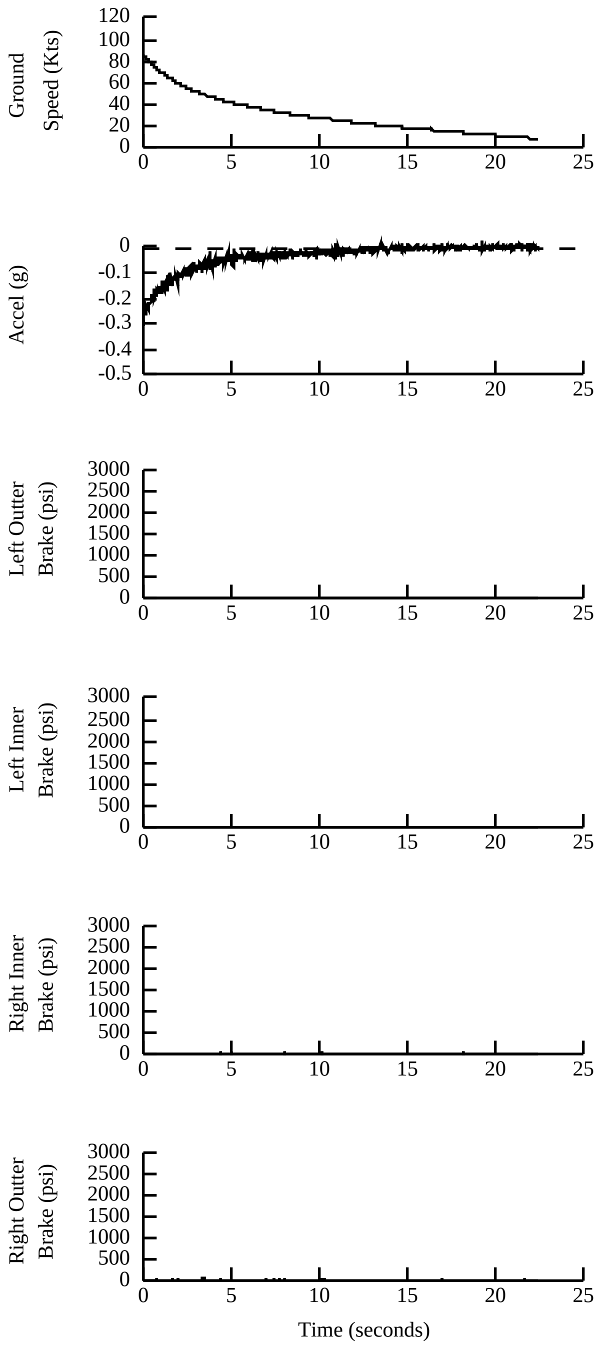
Configuration: Flaps 15, Discing, No Braking



Surface: 100% Bare and Dry

Flight 2001/01, Run Number 7

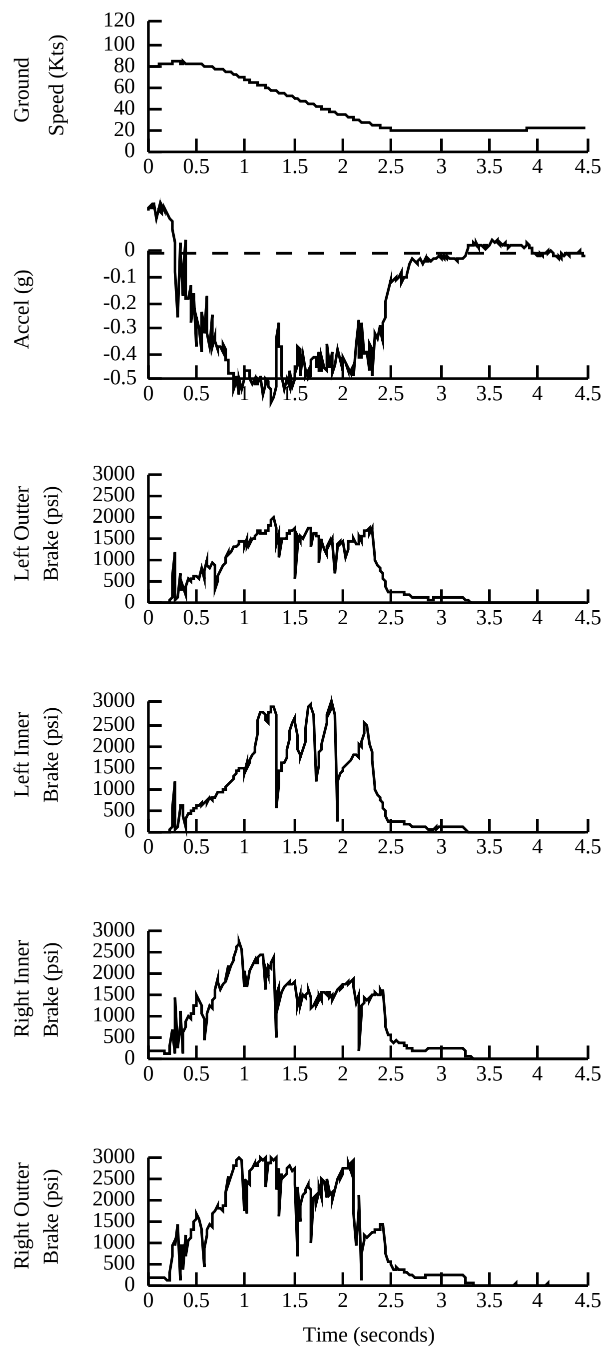
Configuration: Flaps 15, Discing, No Braking



Flight 2001/01, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.67

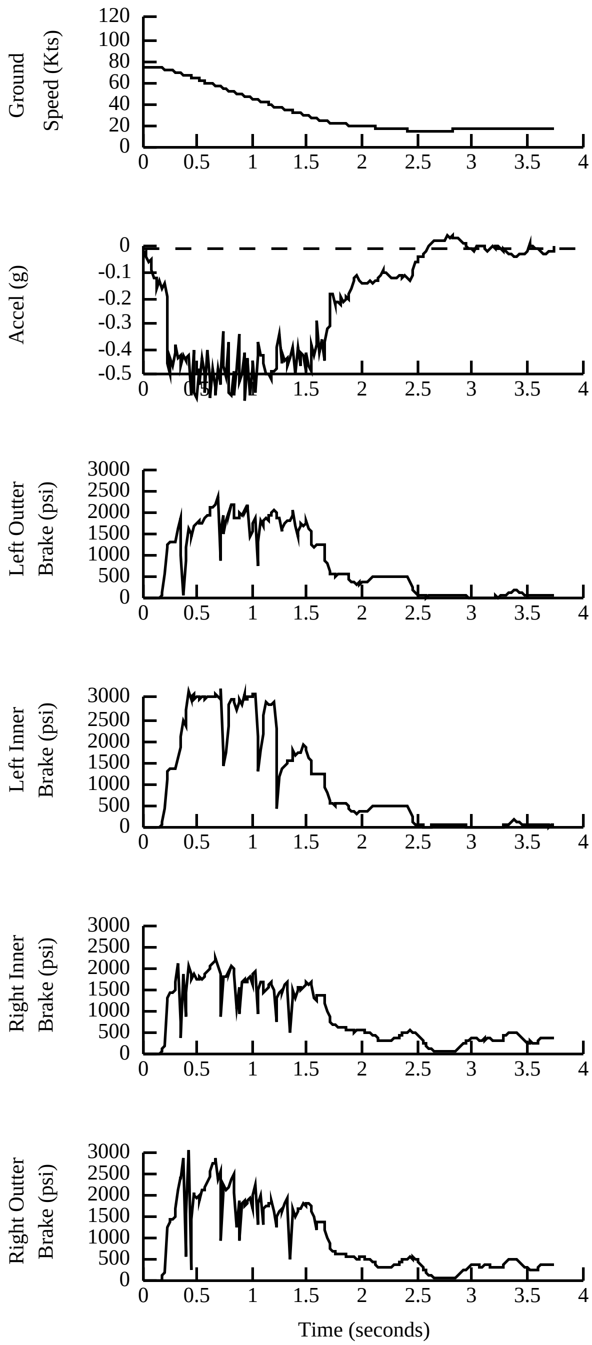


Surface: 100% Bare and Dry

Flight 2001/01, Run Number 9

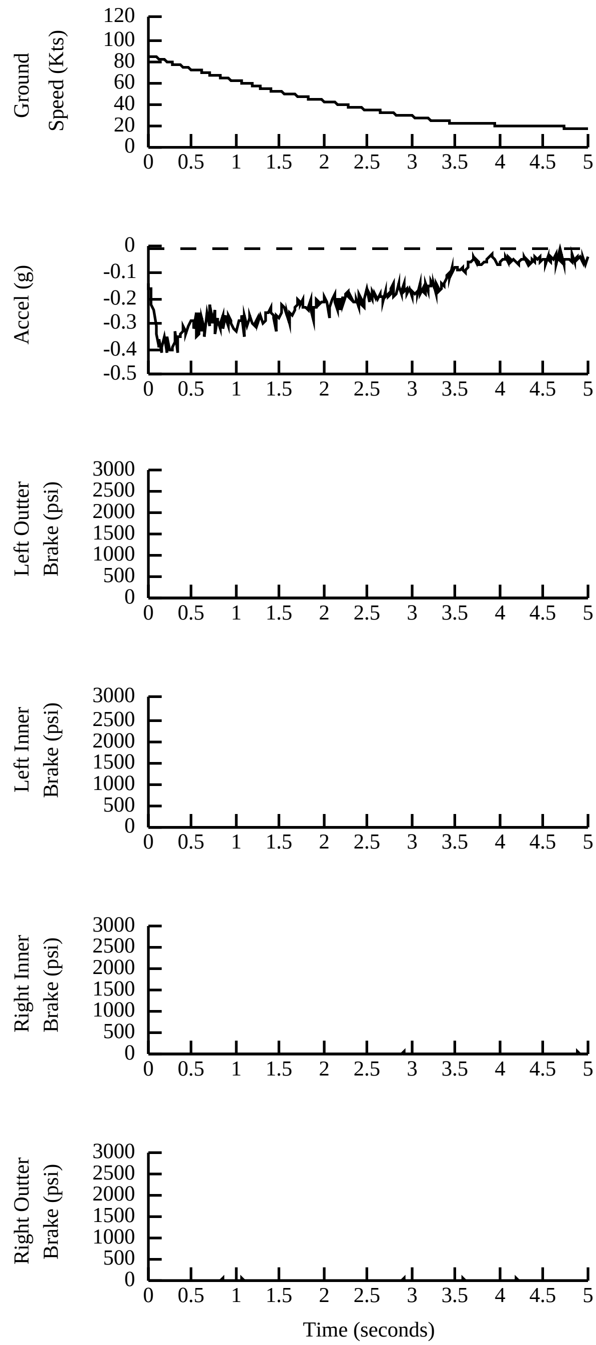
Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.67



Flight 2001/01, Run Number 10

Configuration: Flaps 15, Max Reverse

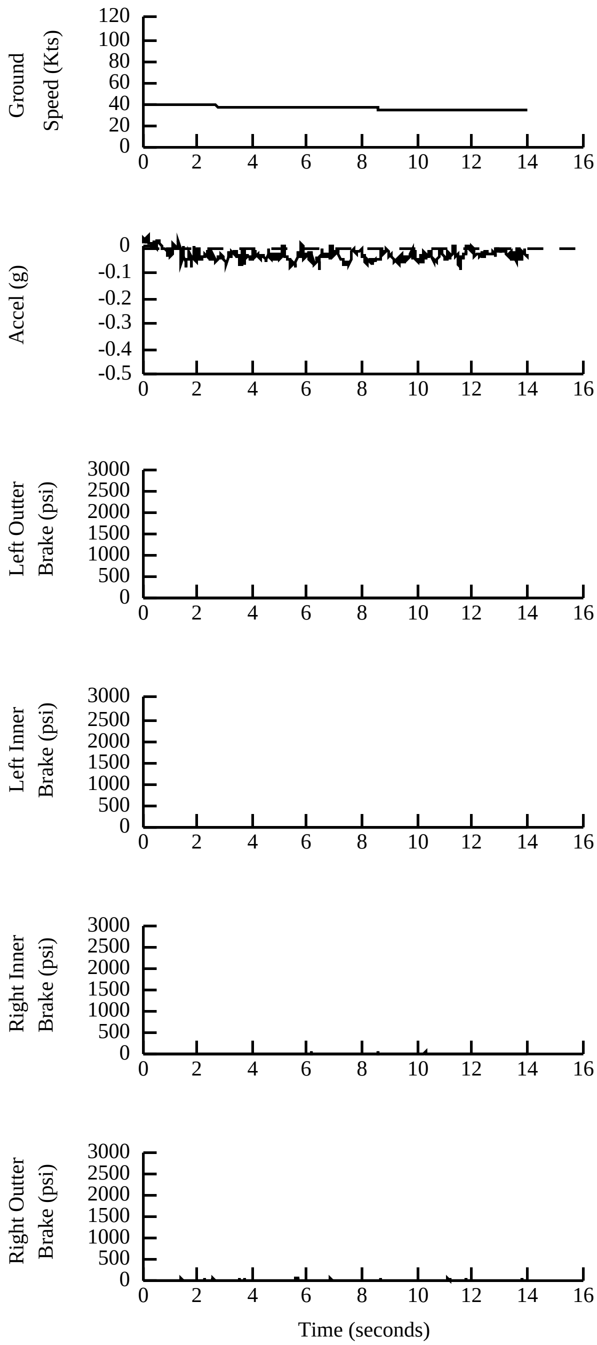


Surface: 4 inches of loose snow

Sg of snow 0.15

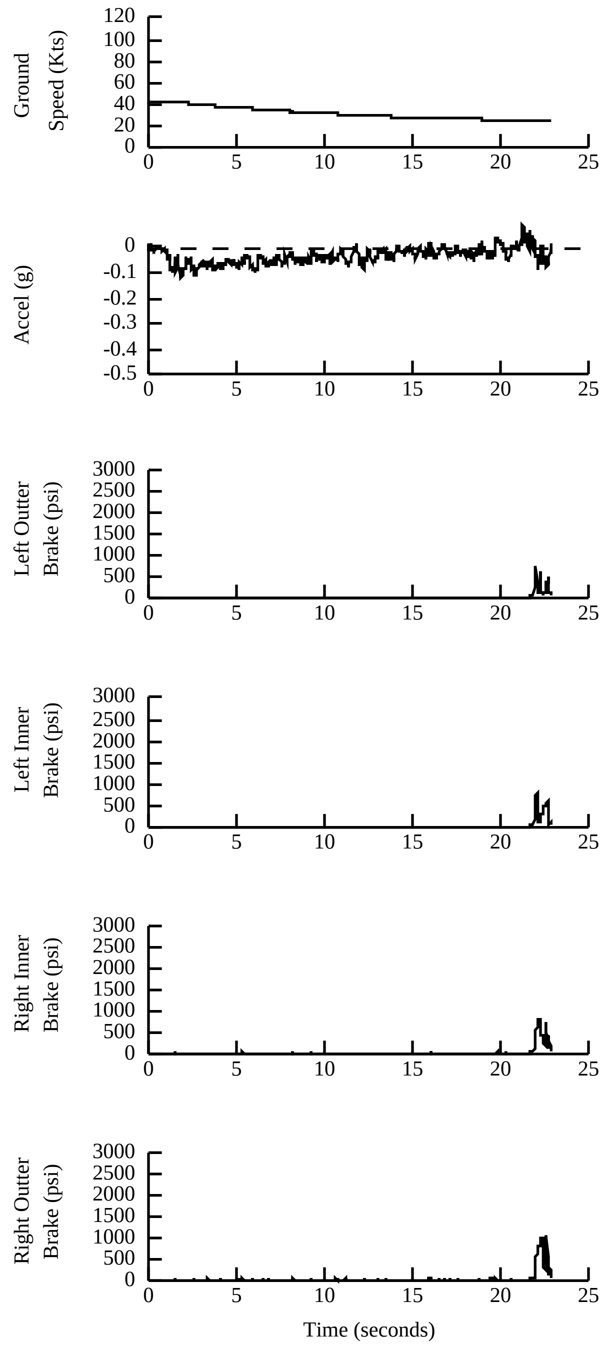
Flight 2001/02, Run Number 1

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/02, Run Number 2

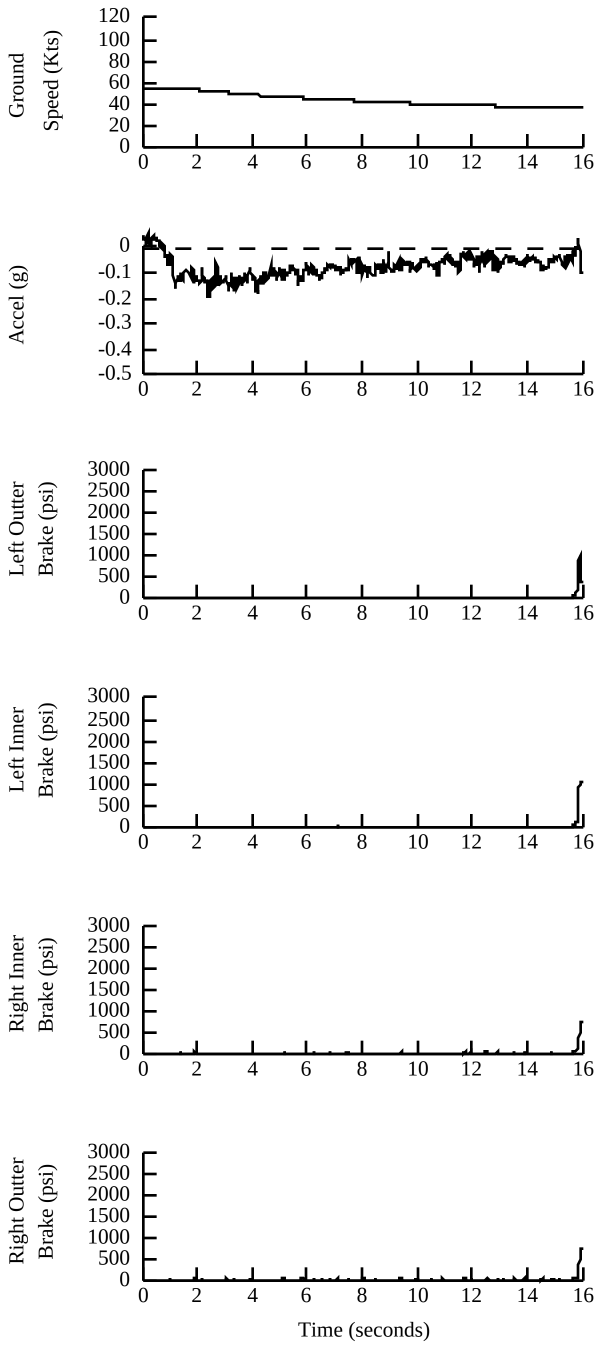
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 4 inches of loose snow
Sg of snow 0.15

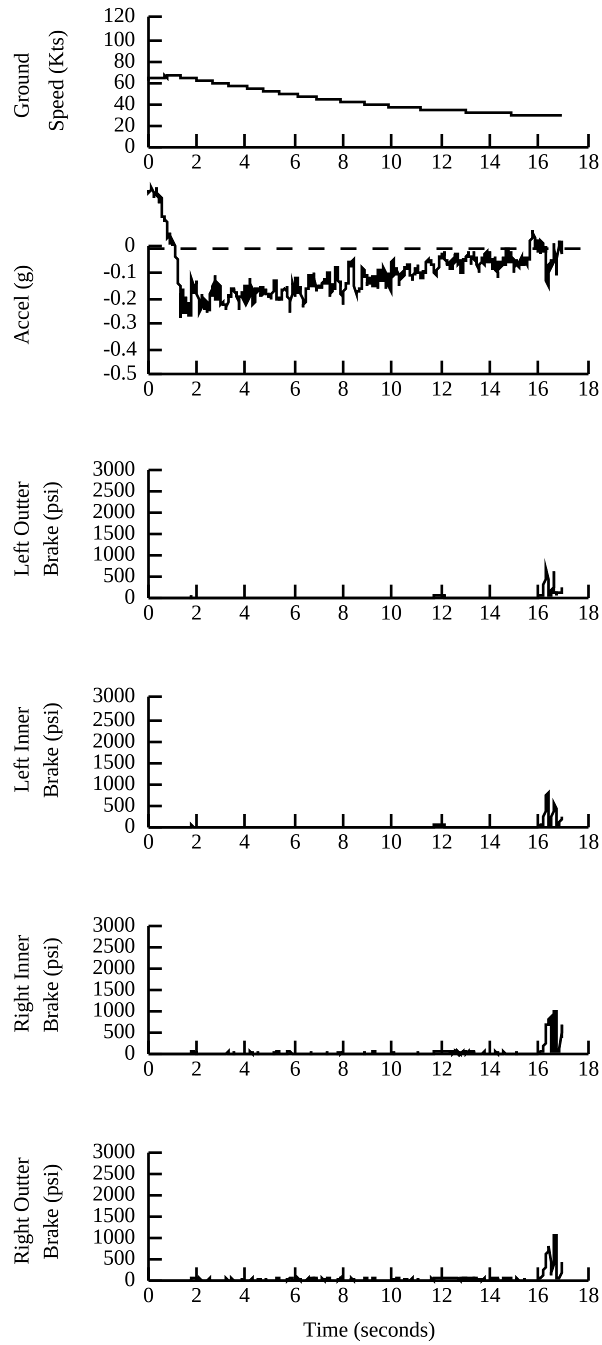
Flight 2001/02, Run Number 3

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/02, Run Number 4

Configuration: Flaps 15, Flight Idle, No Braking

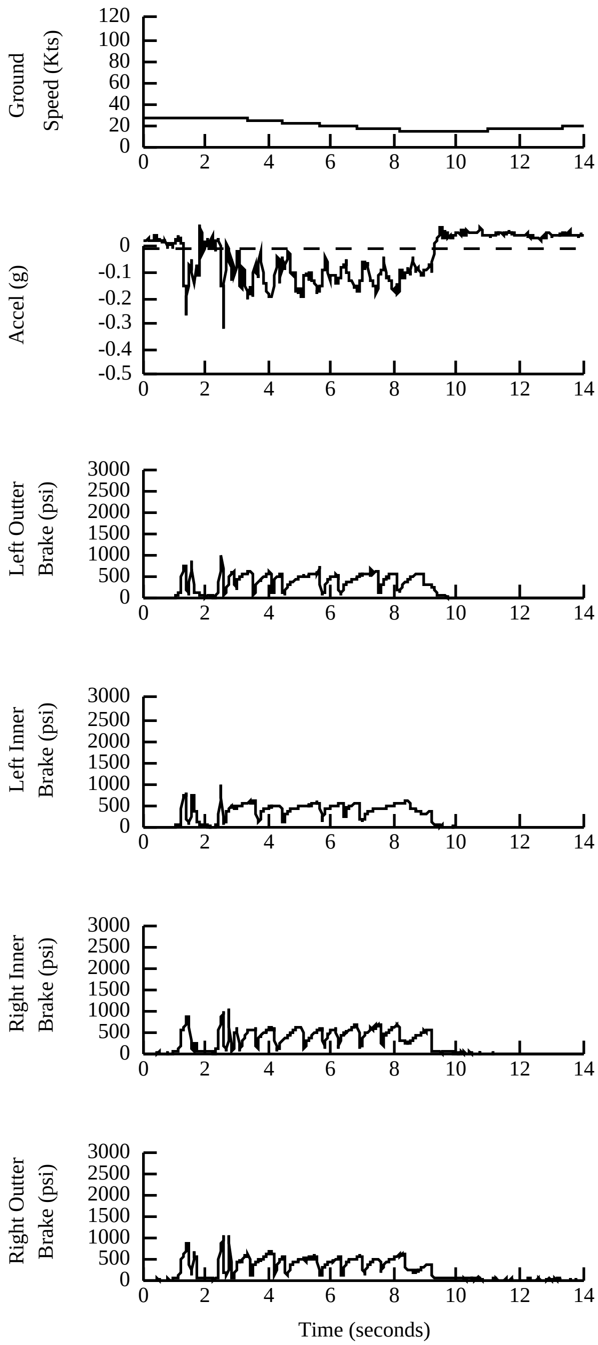


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

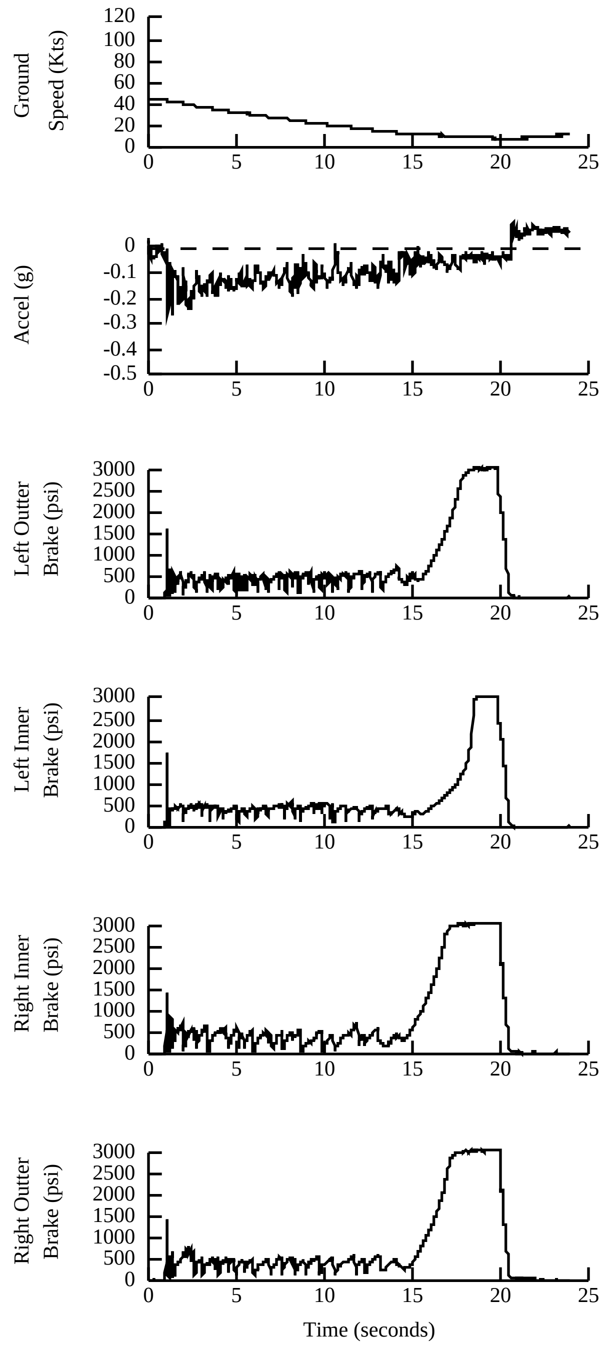
CRFI Average 0.28



Flight 2001/02, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.28

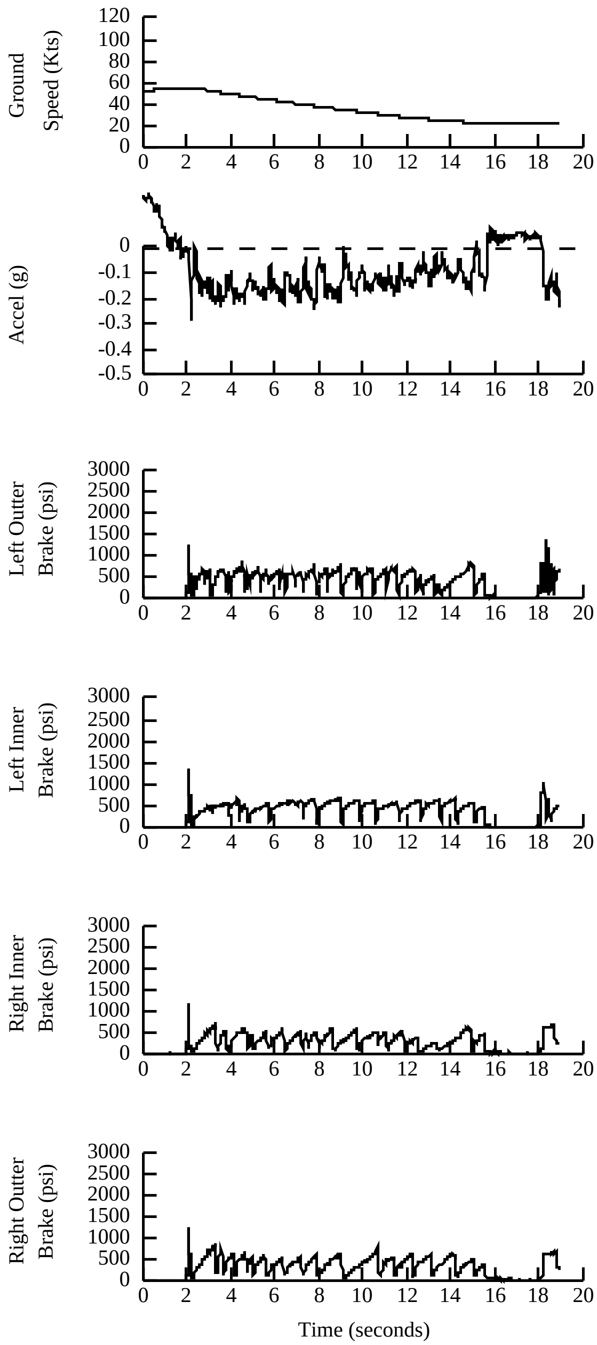


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

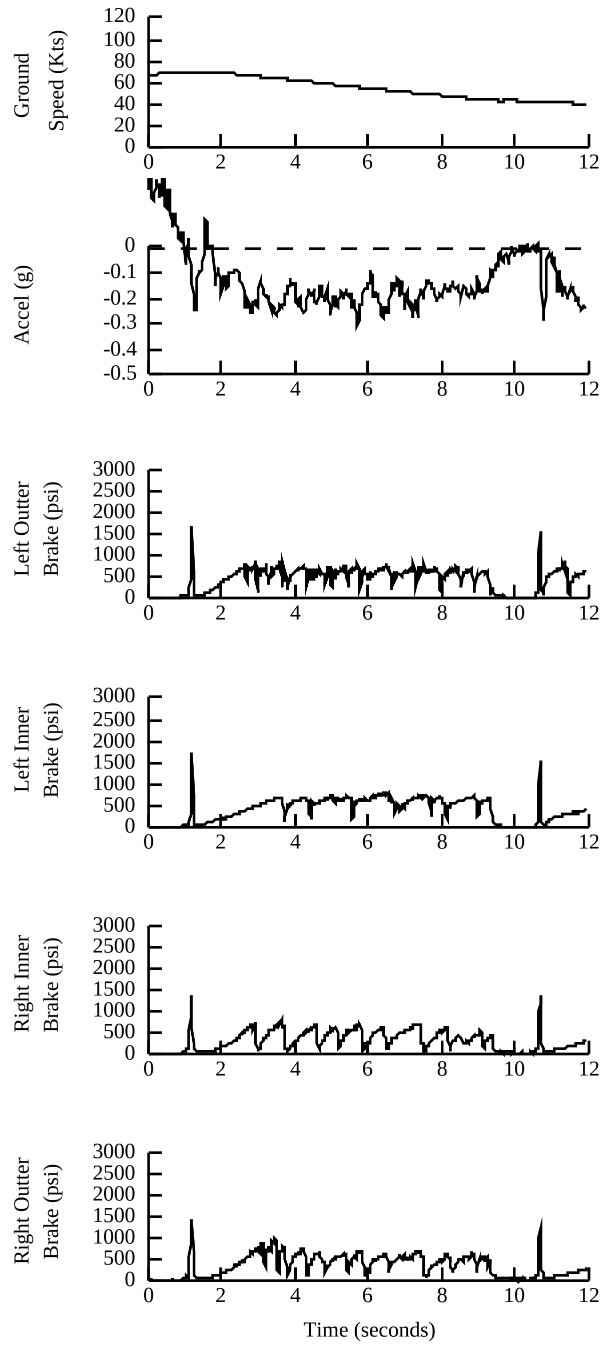
CRFI Average 0.27



Flight 2001/02, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.27

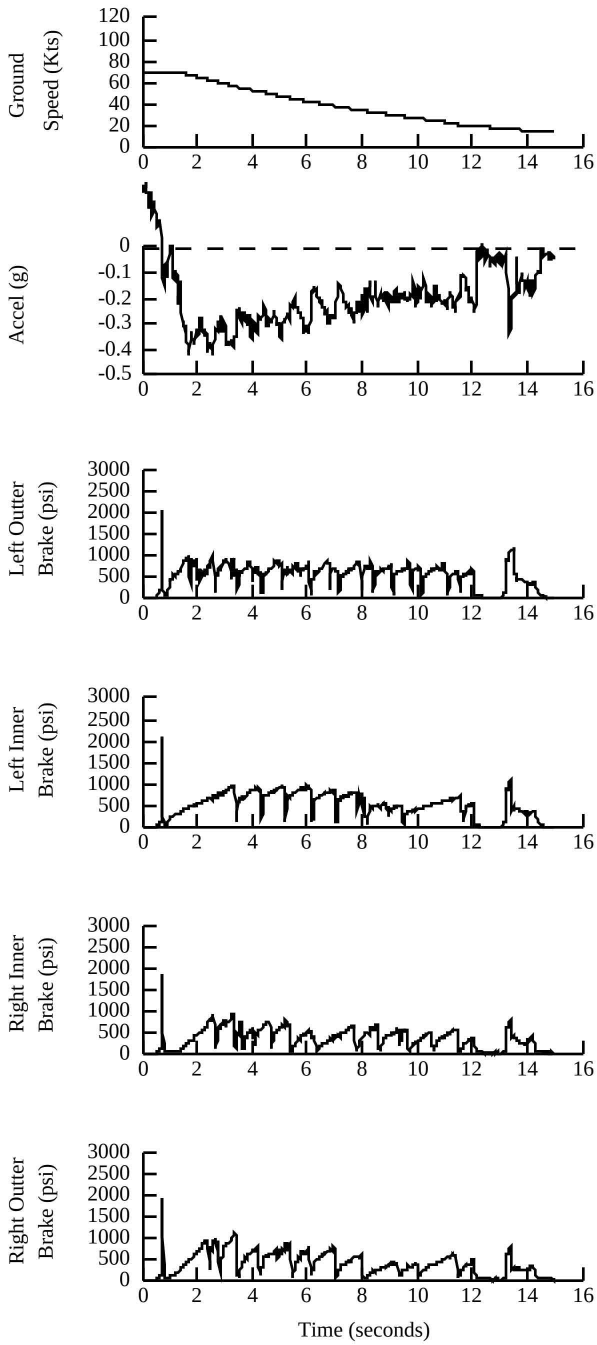


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 9

Configuration: Flaps 15, Discing, Max Braking

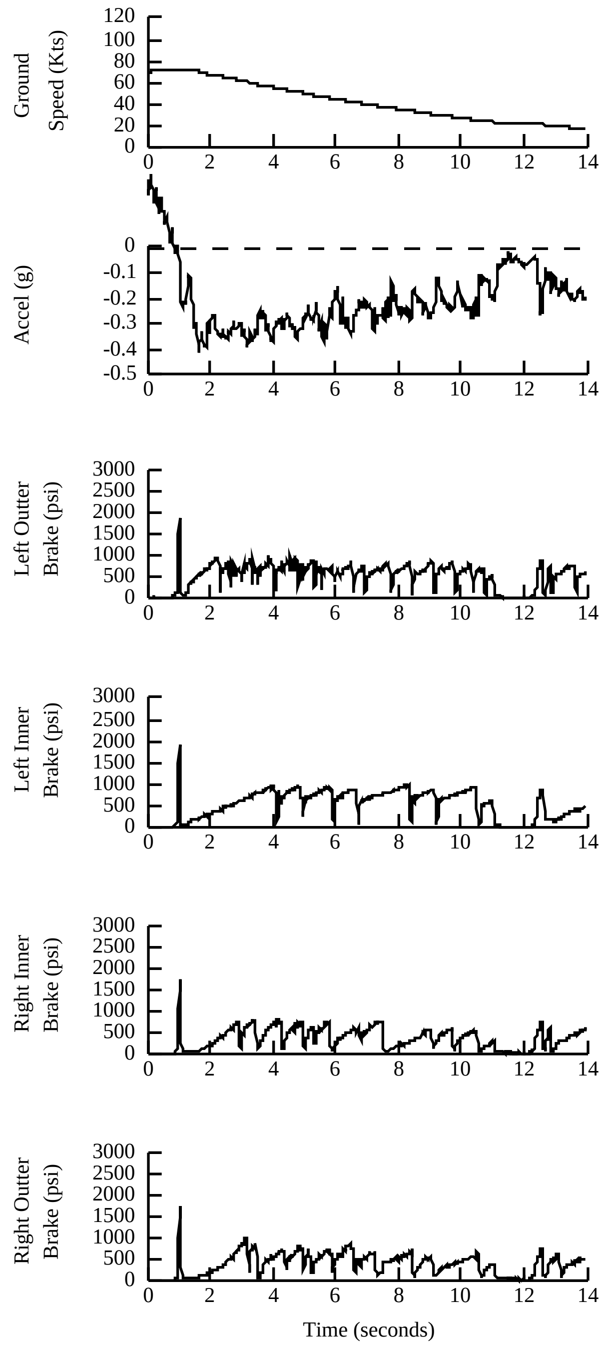
CRFI Average 0.26



Flight 2001/02, Run Number 10

Configuration: Flaps 15, Discing, Max Reverse

CRFI Average 0.25

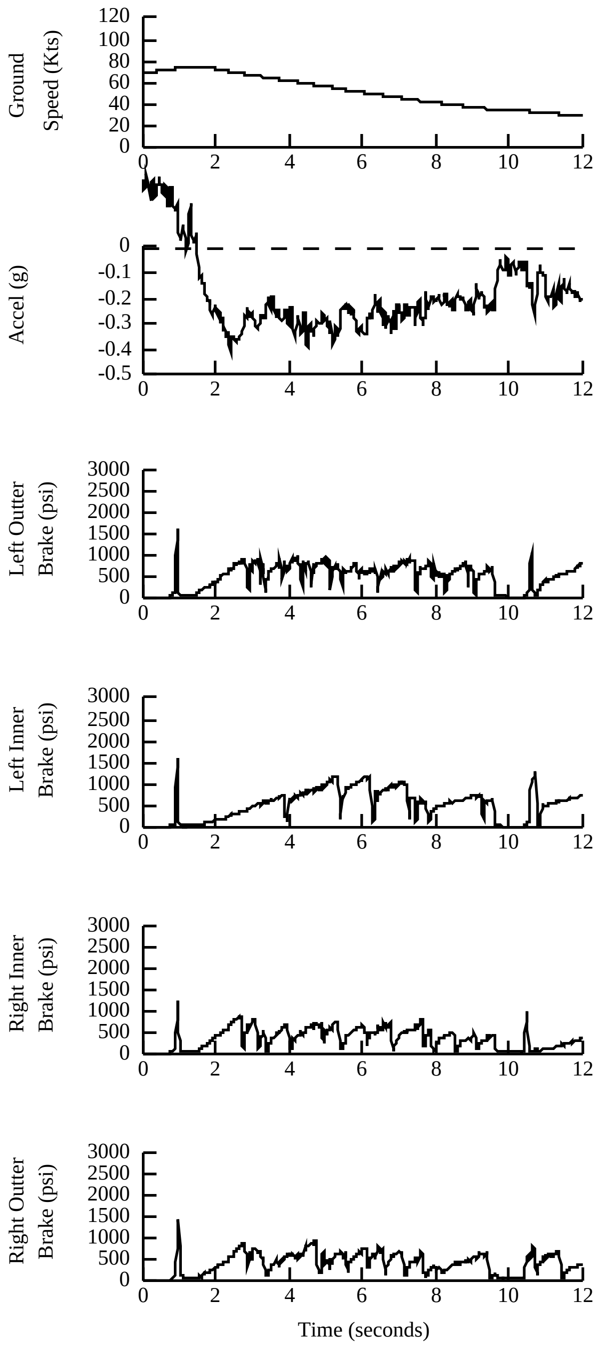


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 11

Configuration: Flaps 15, Discing, Max Braking

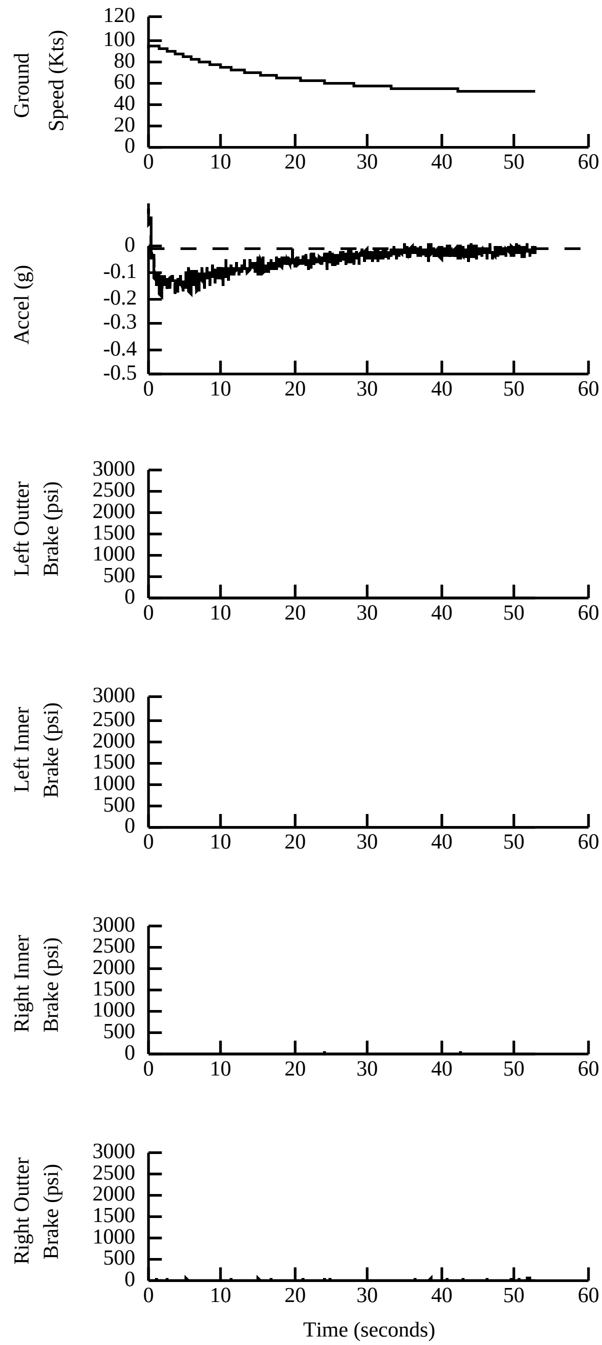
CRFI Average 0.24



Flight 2001/02, Run Number 12

Configuration: Flaps 15, Flight Idle, No Braking

CRFI Average 0.24

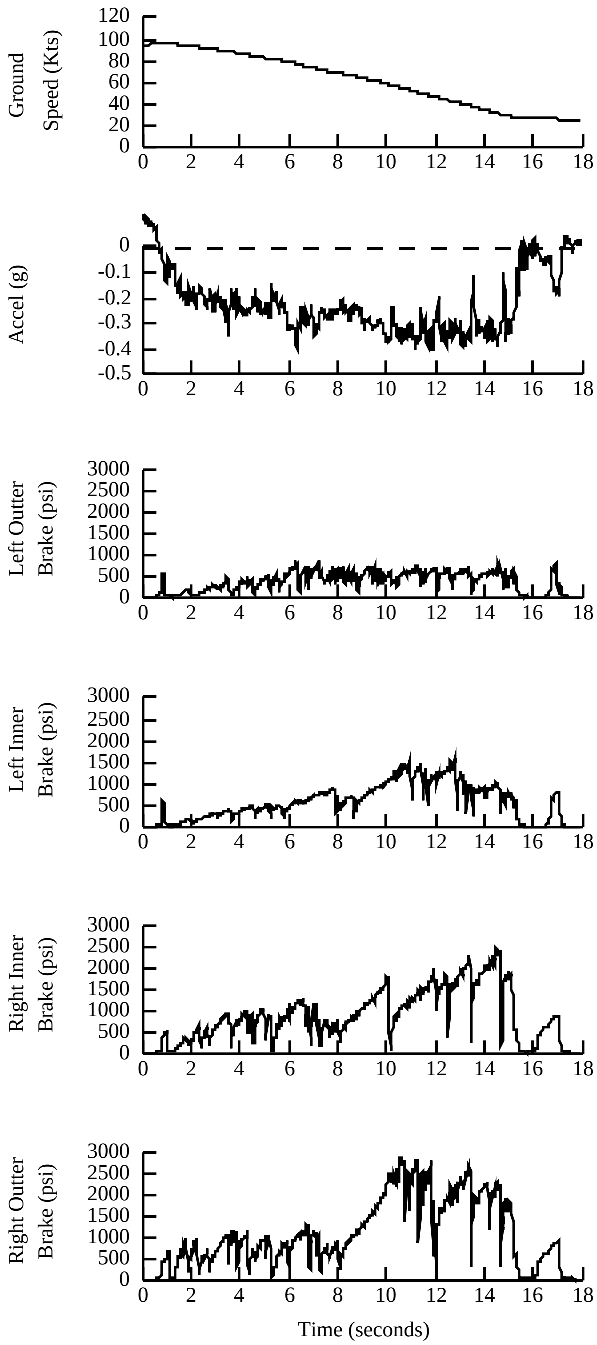


Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 13

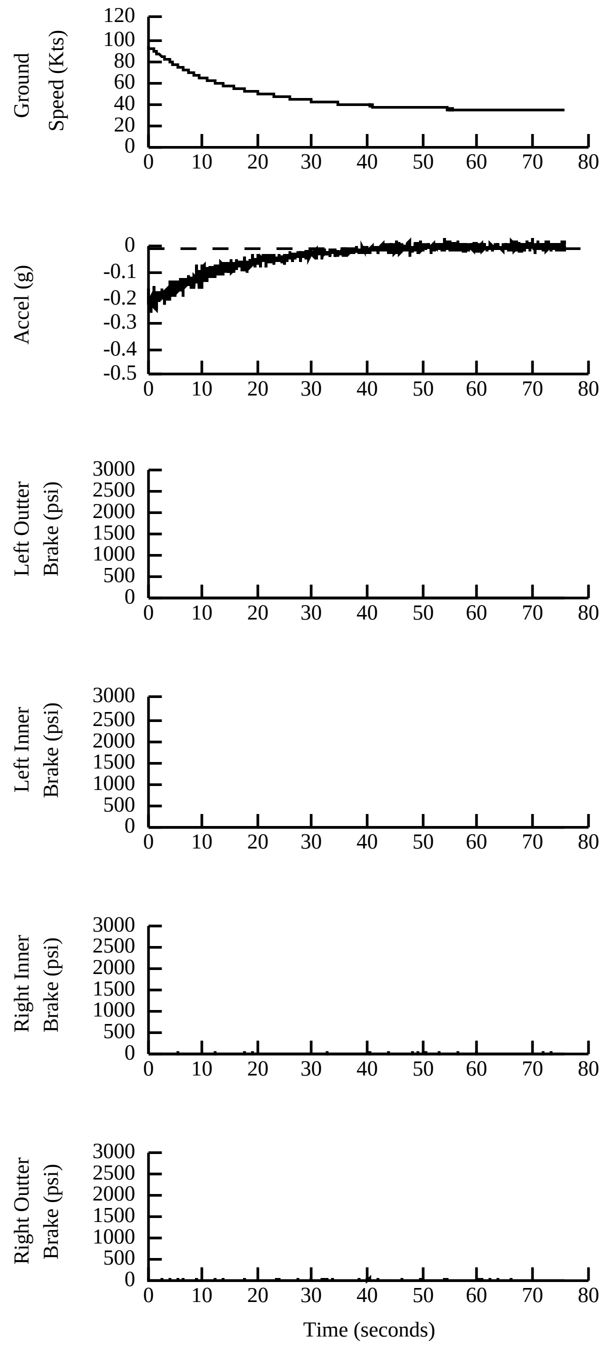
Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.31



Flight 2001/02, Run Number 14

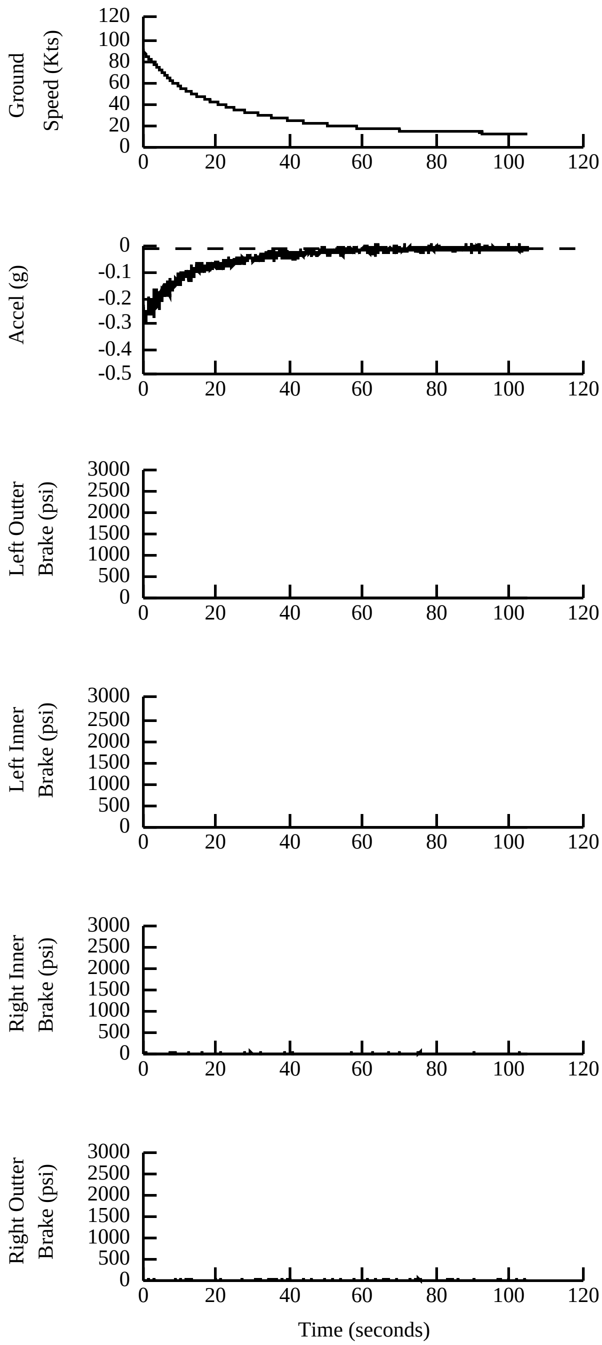
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 15

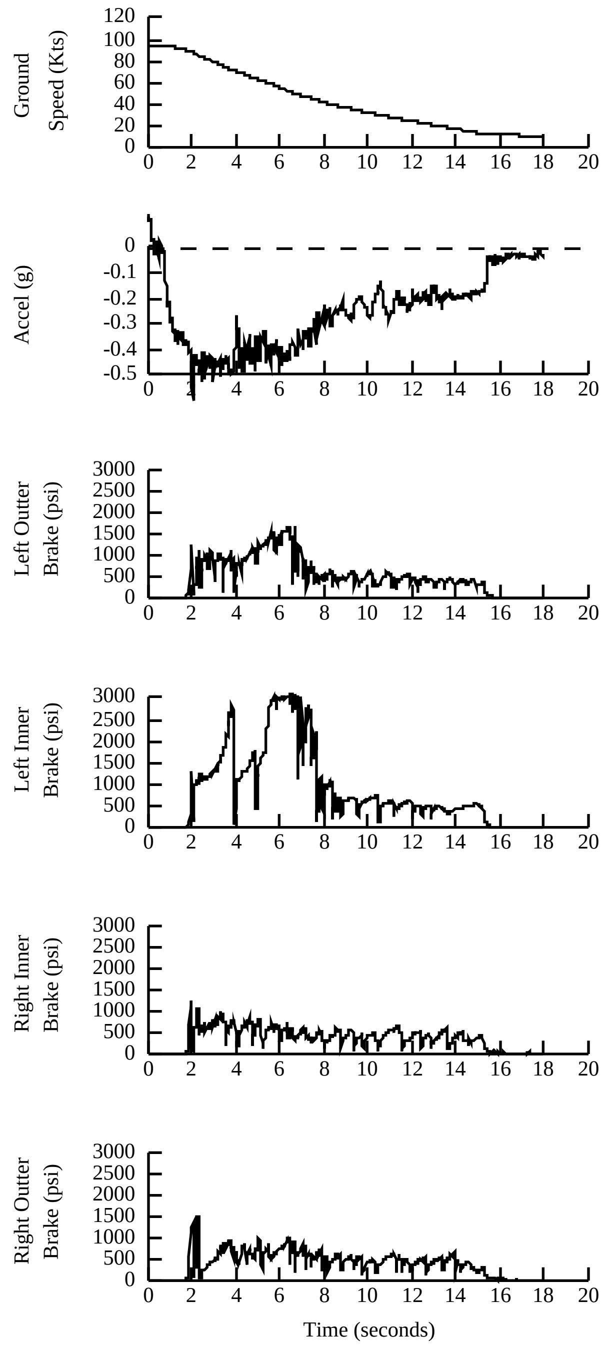
Configuration: Flaps 15, Discing, No Braking



Flight 2001/02, Run Number 16

Configuration: Flaps 15, Discing, Max Braking

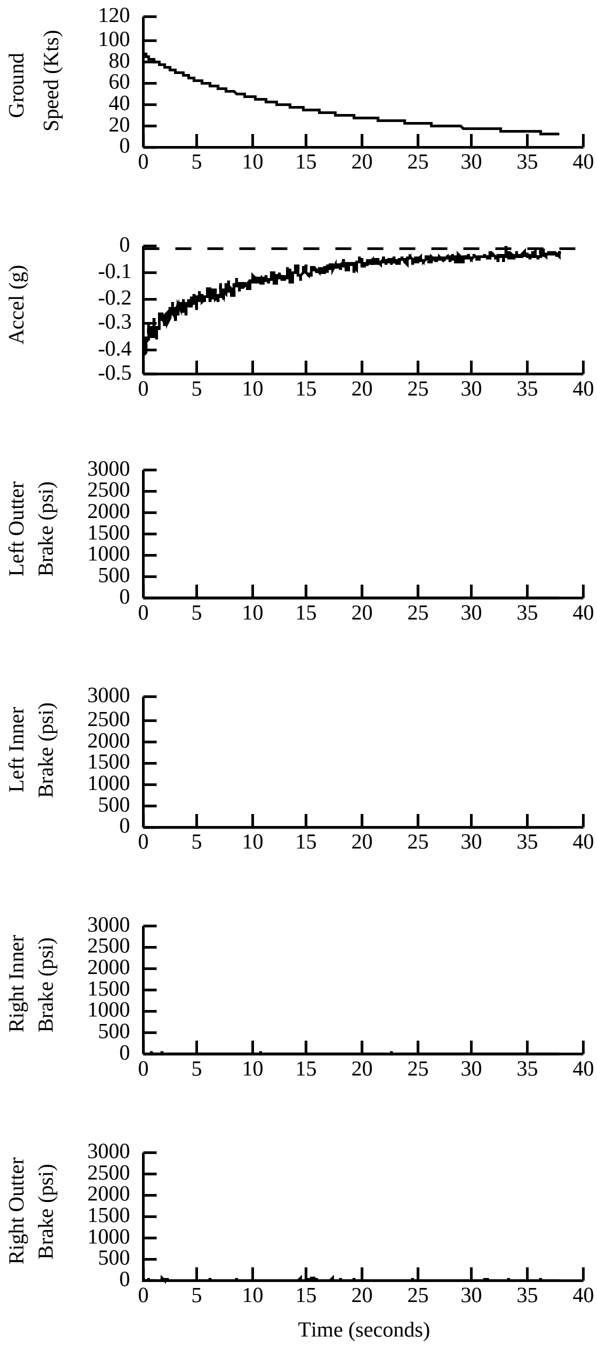
CRFI Average 0.31



Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 17

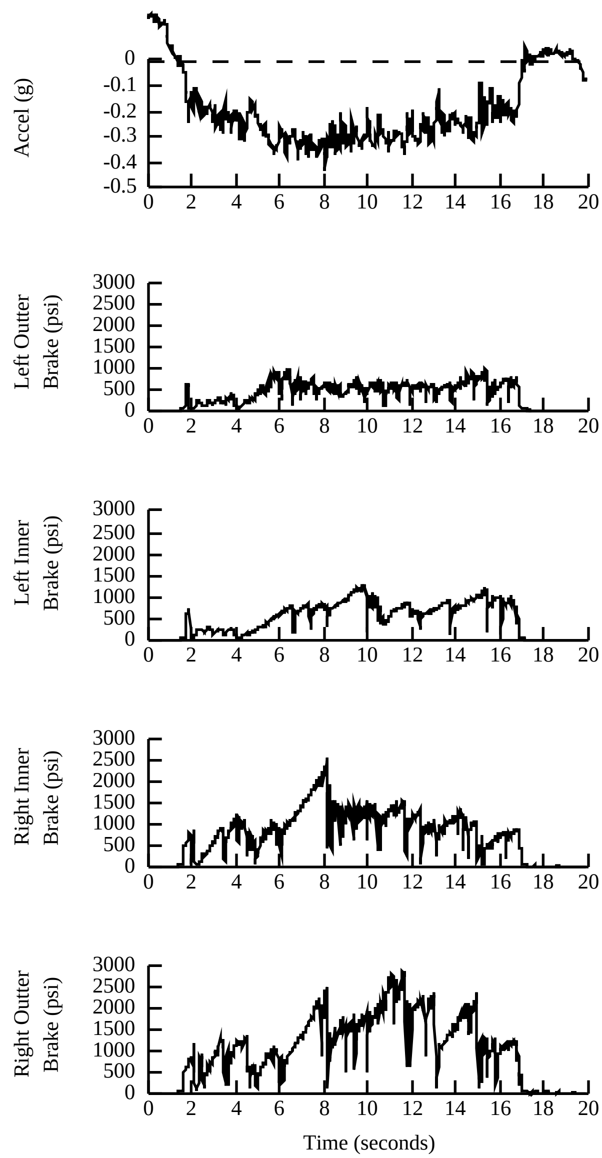
Configuration: Flaps 15, Discing, No Braking



Flight 2001/02, Run Number 18

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.32

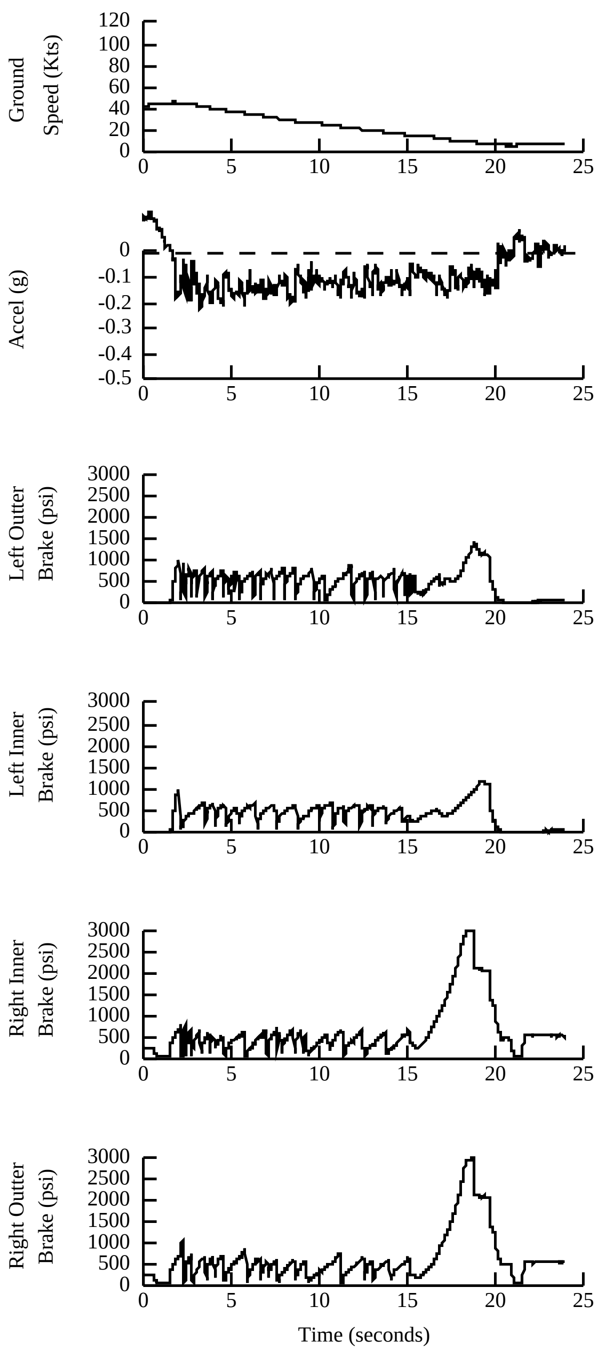


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

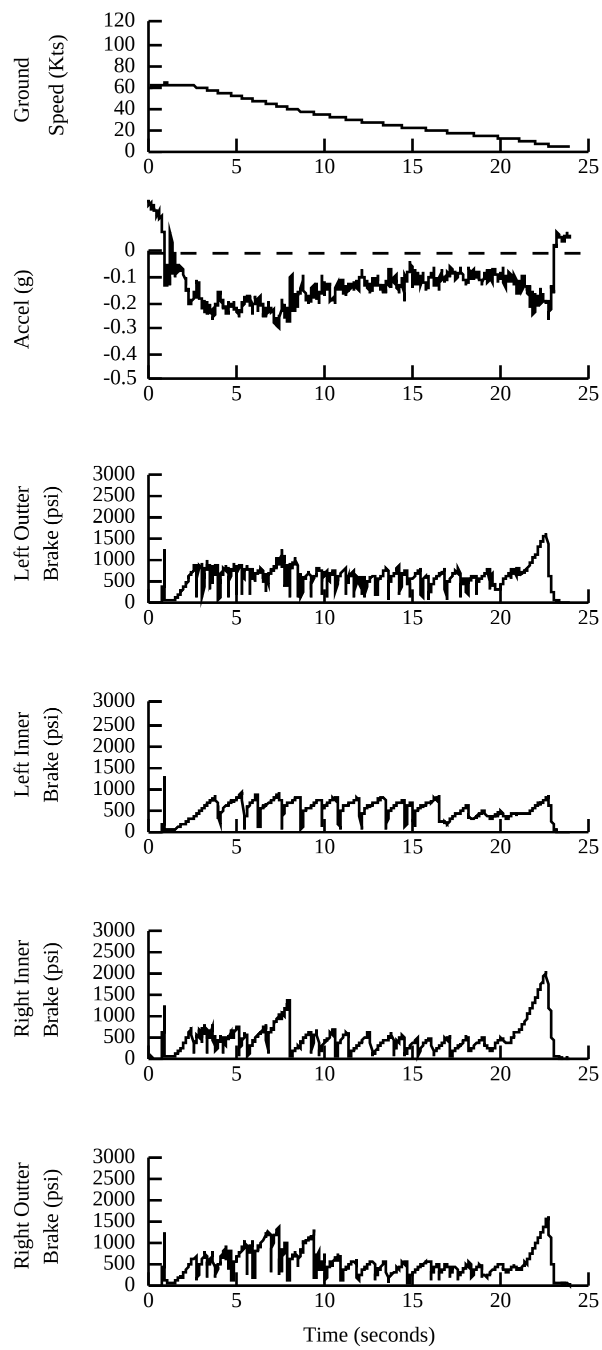
CRFI Average 0.27



Flight 2001/03, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.26

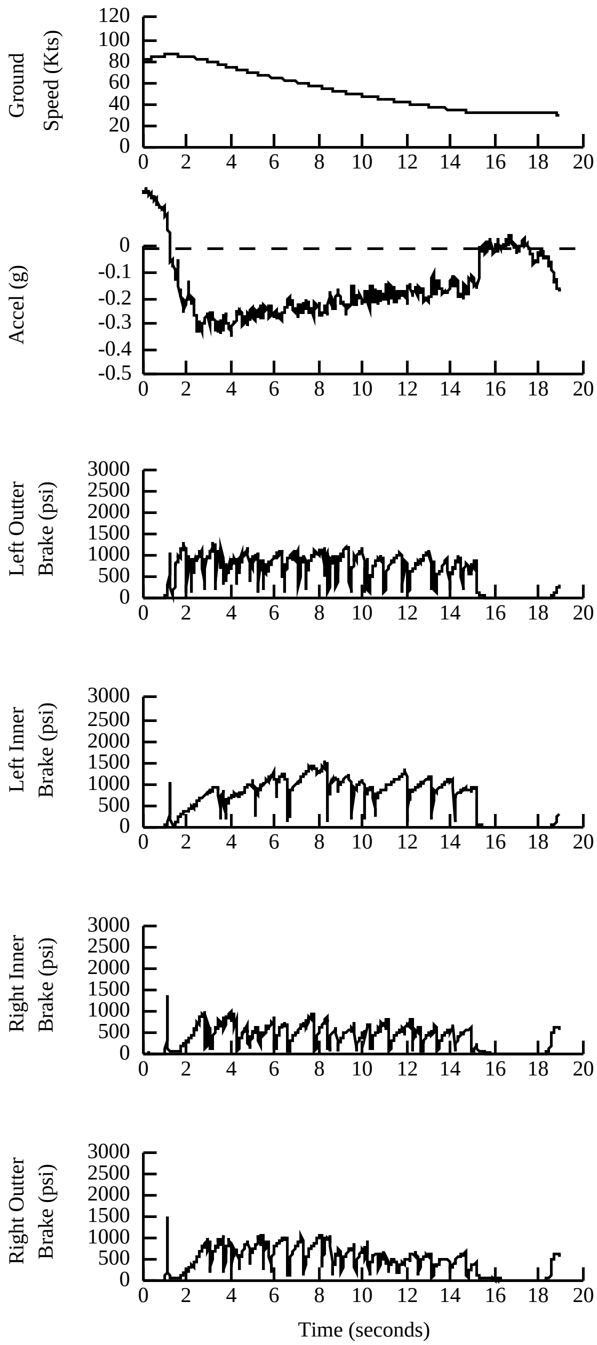


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

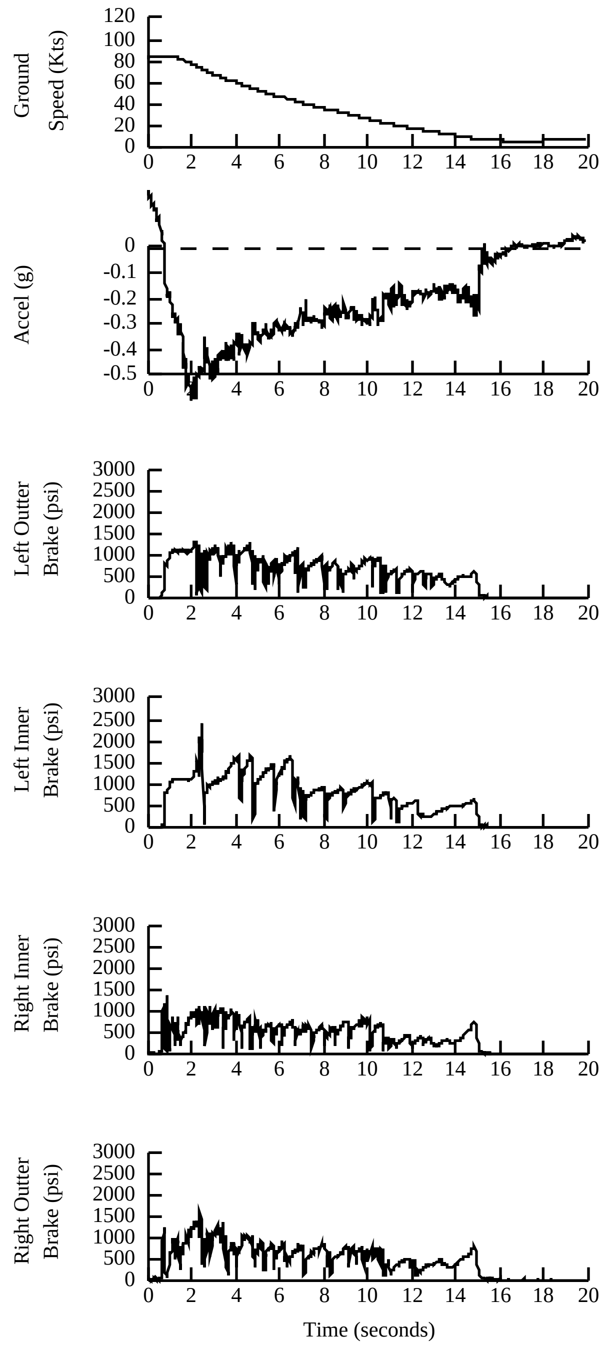
CRFI Average 0.25



Flight 2001/03, Run Number 4

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

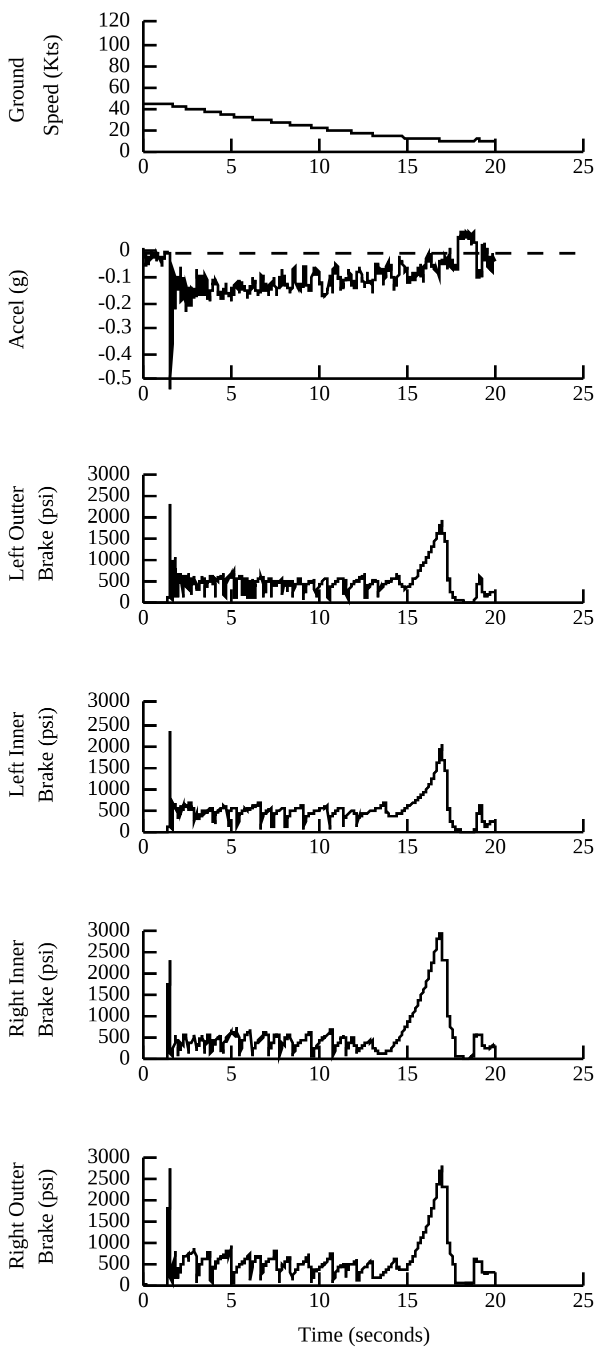


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

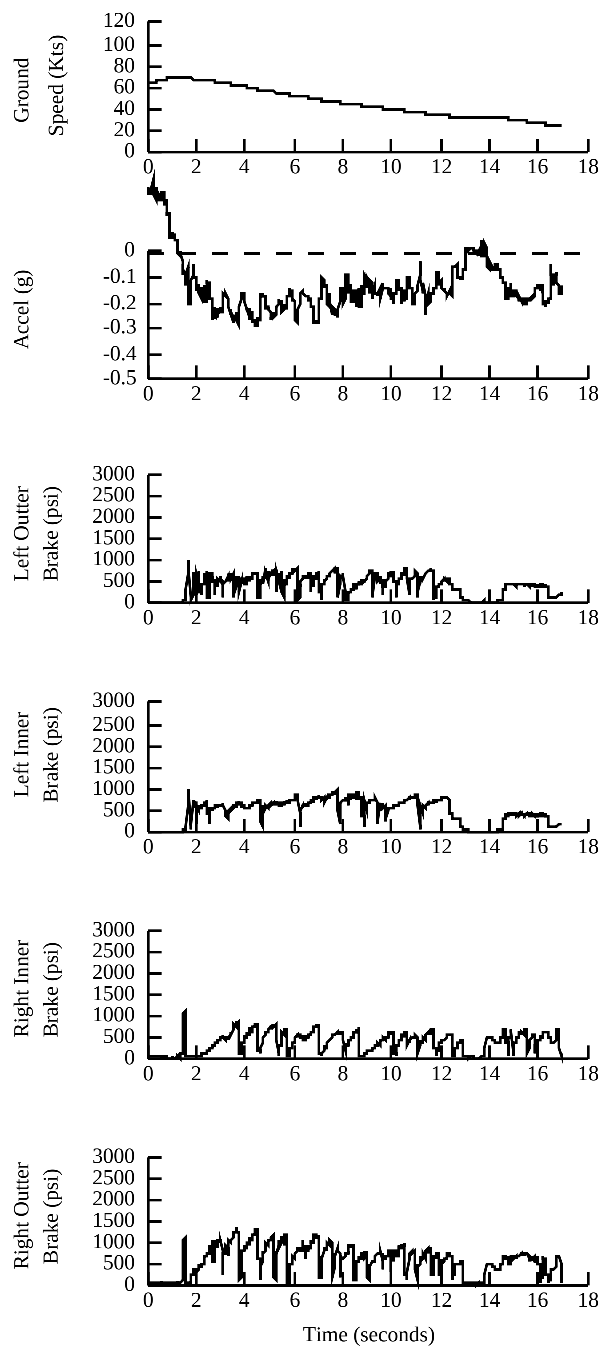
CRFI Average 0.24



Flight 2001/03, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.25

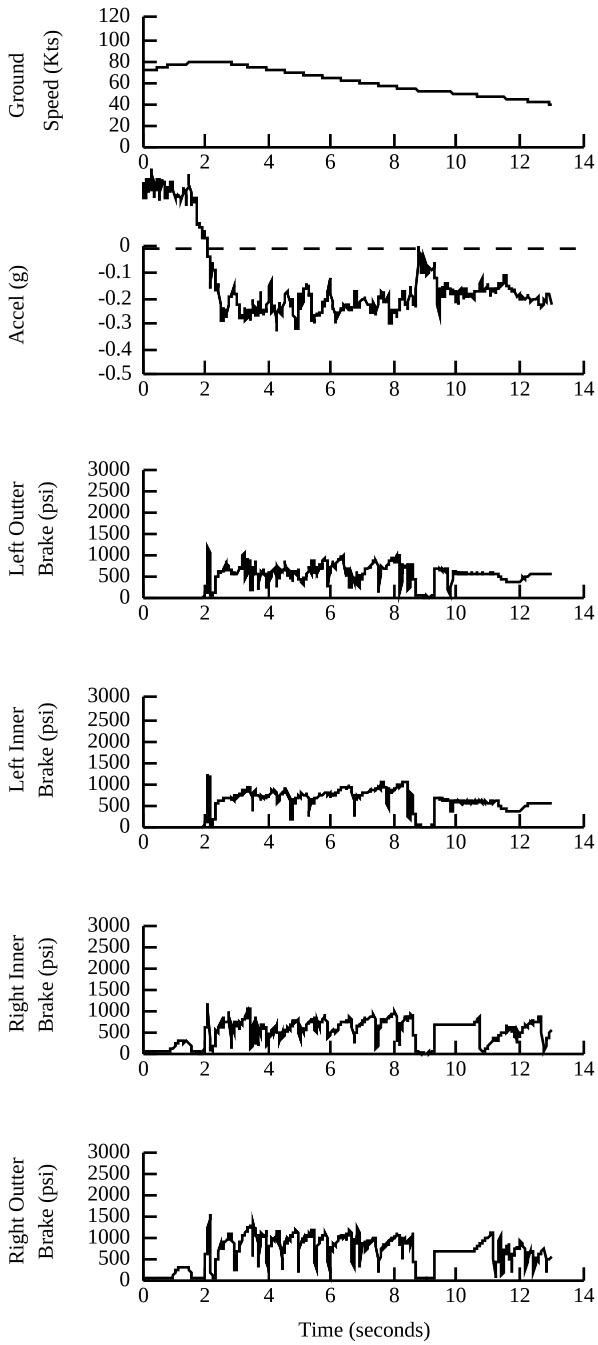


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

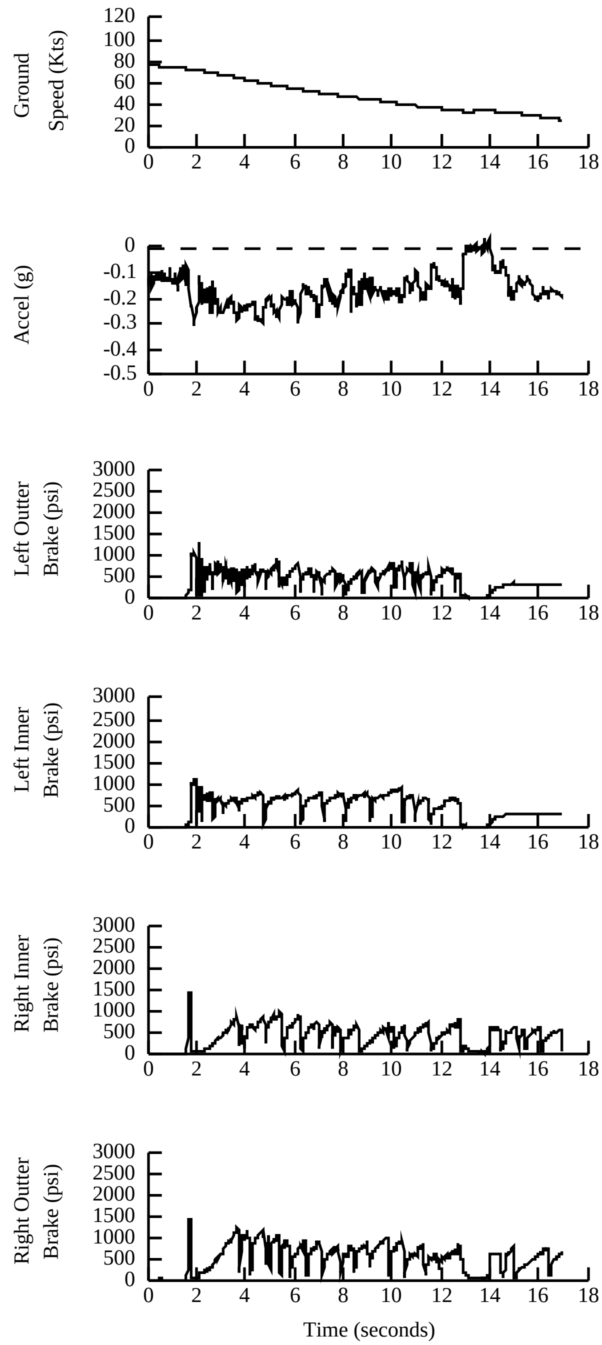
CRFI Average 0.26



Flight 2001/03, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.26

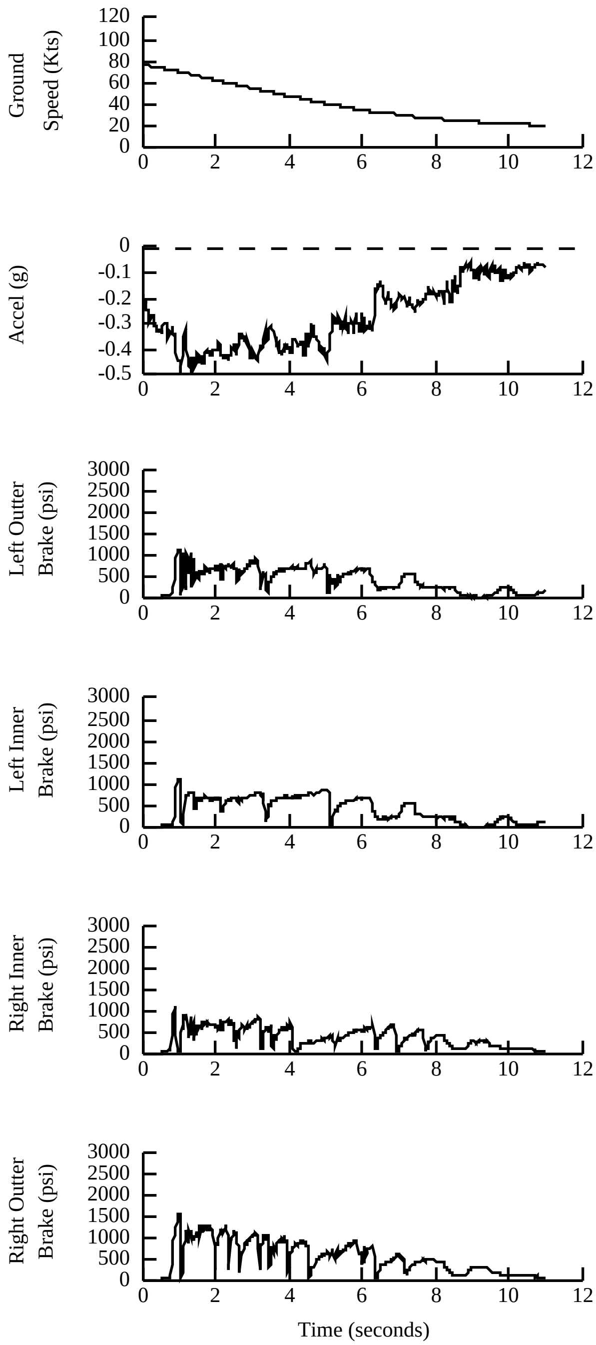


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 9

Configuration: Flaps 15, Discing, Max Braking

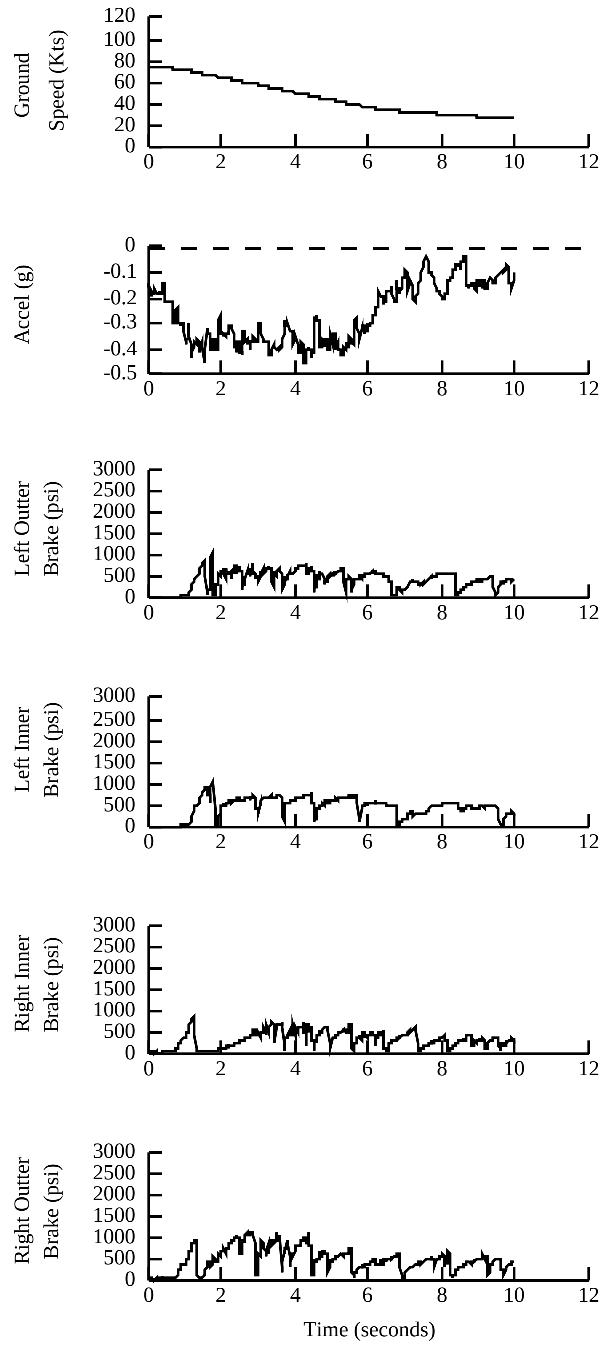
CRFI Average 0.27



Flight 2001/03, Run Number 10

Configuration: Flaps 15, Discing, Max Reverse

CRFI Average 0.27

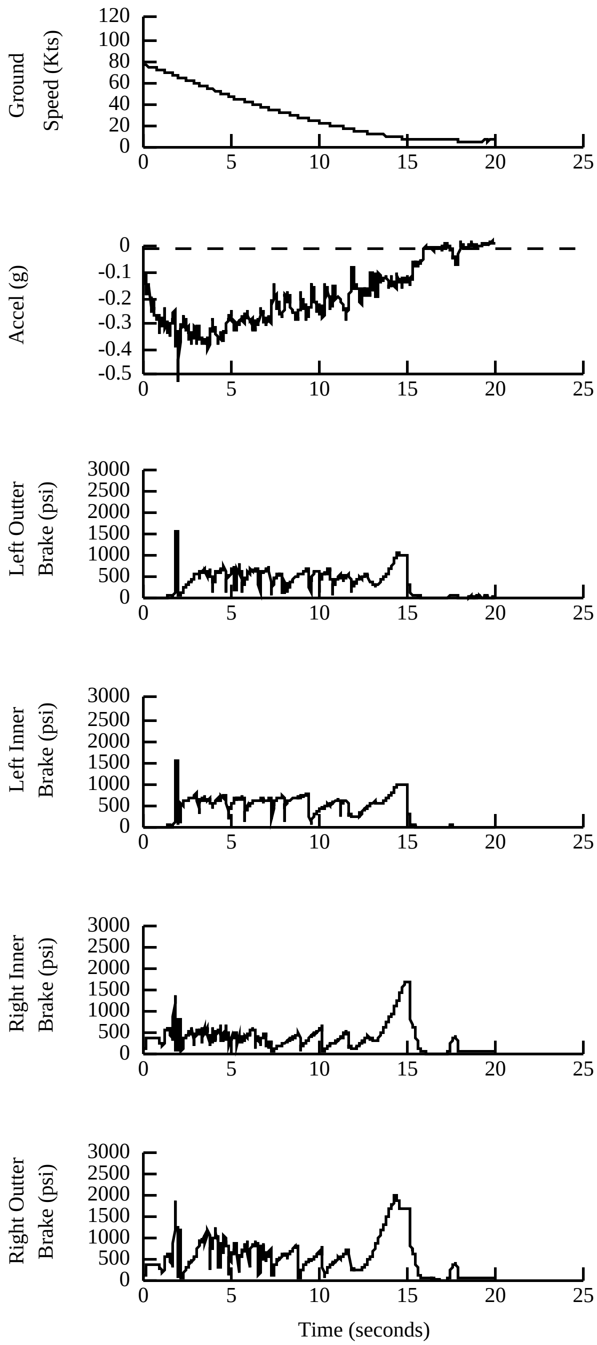


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 11

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

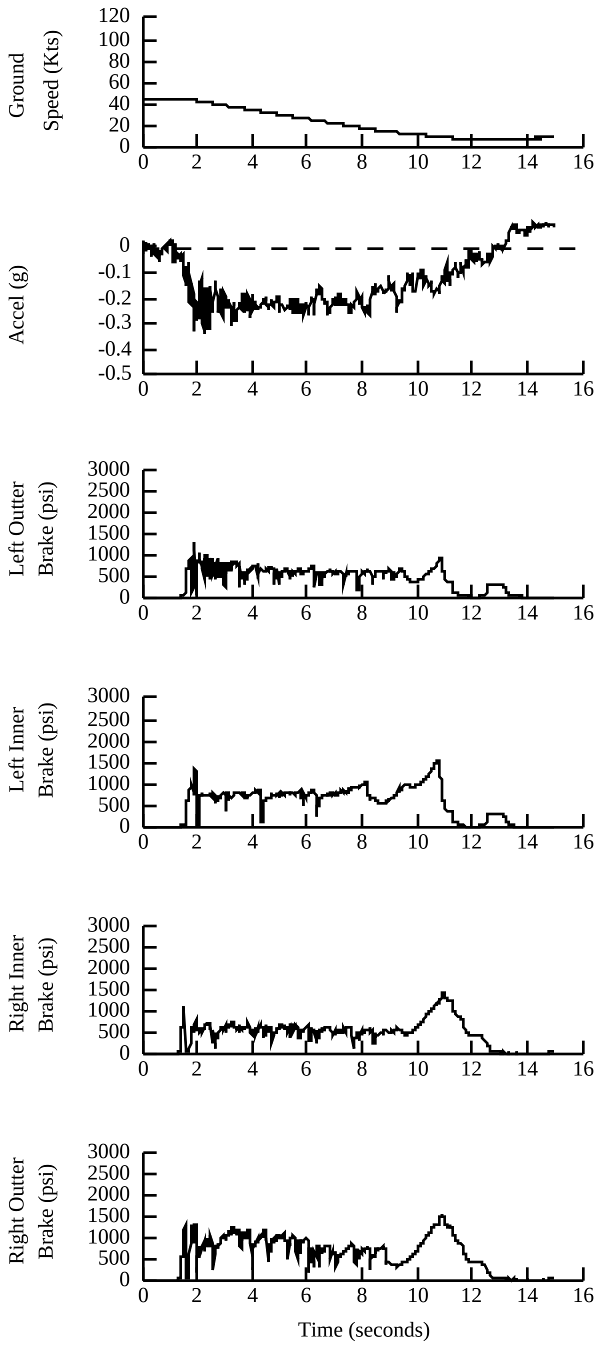


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

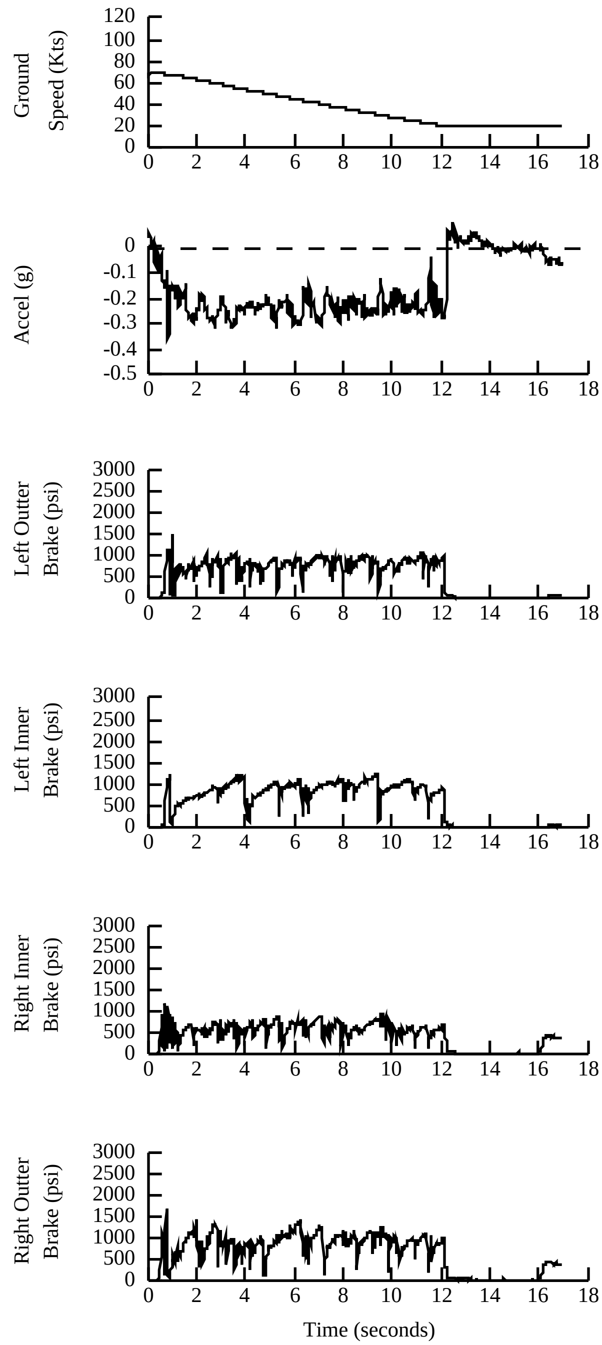
CRFI Average 0.40



Flight 2001/04, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.38

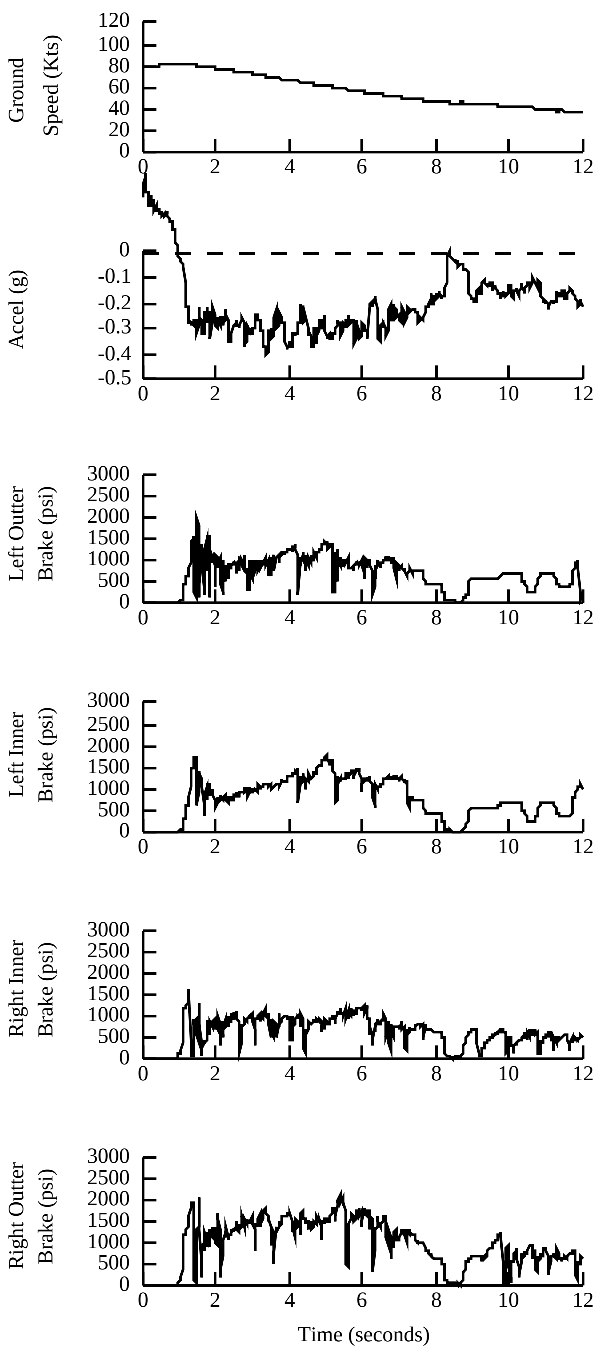


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

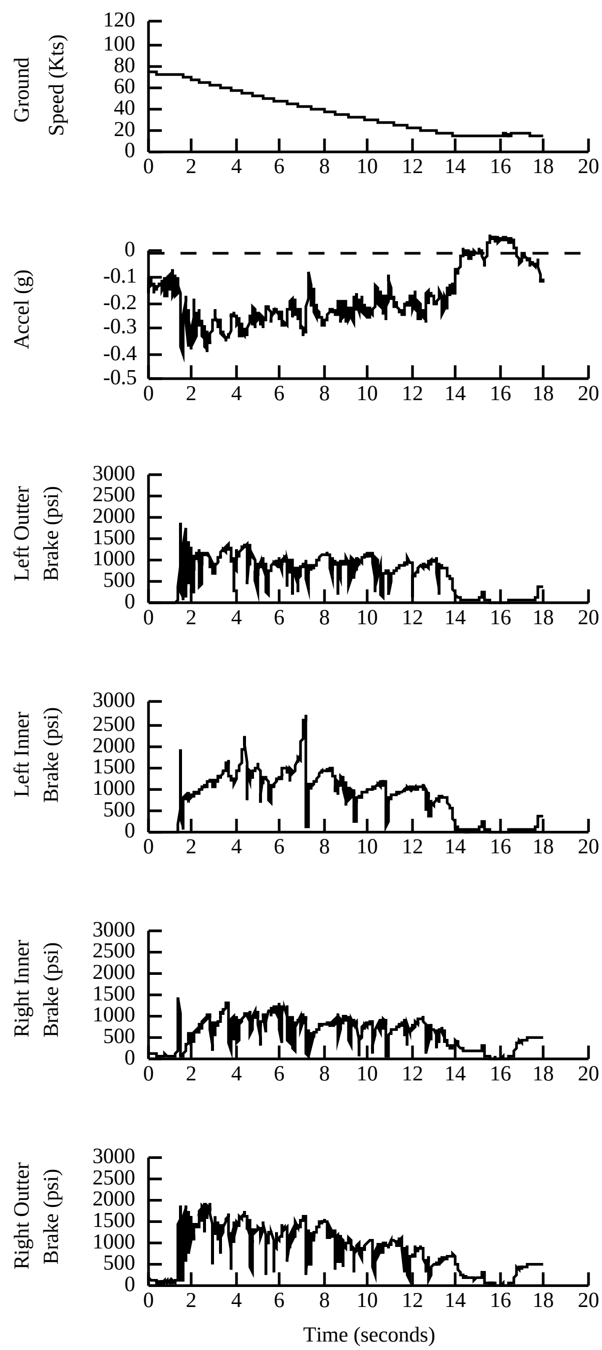
CRFI Average 0.36



Flight 2001/04, Run Number 4

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.36

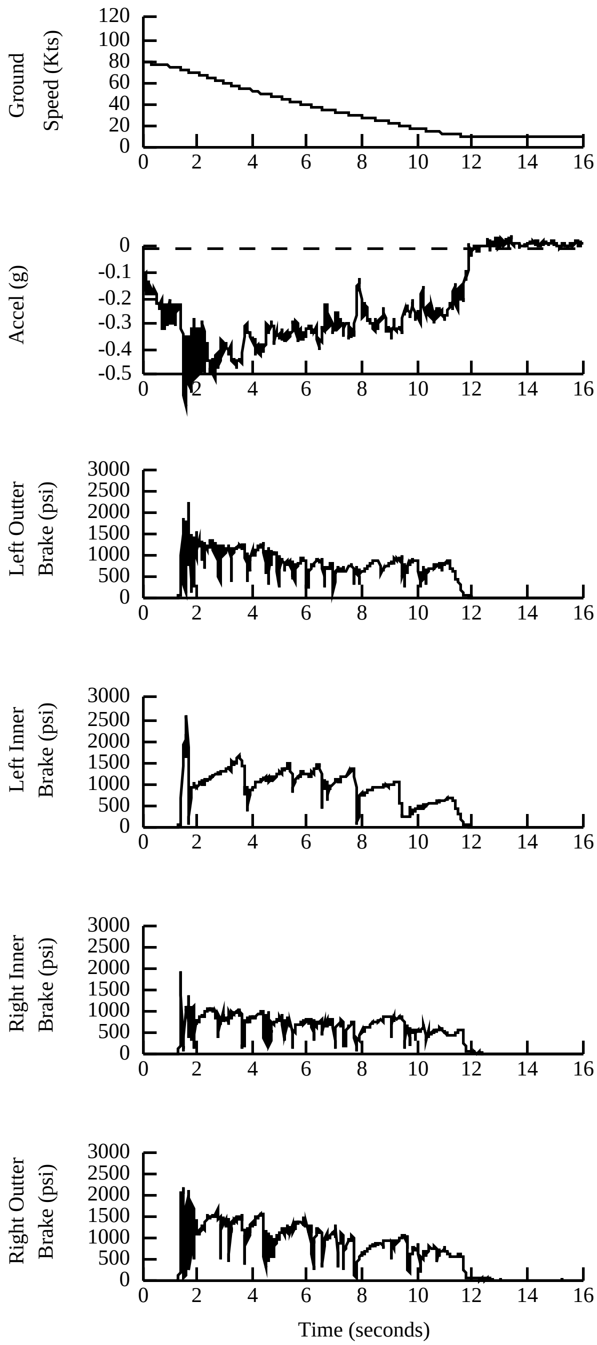


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 5

Configuration: Flaps 15, Discing, Max Braking

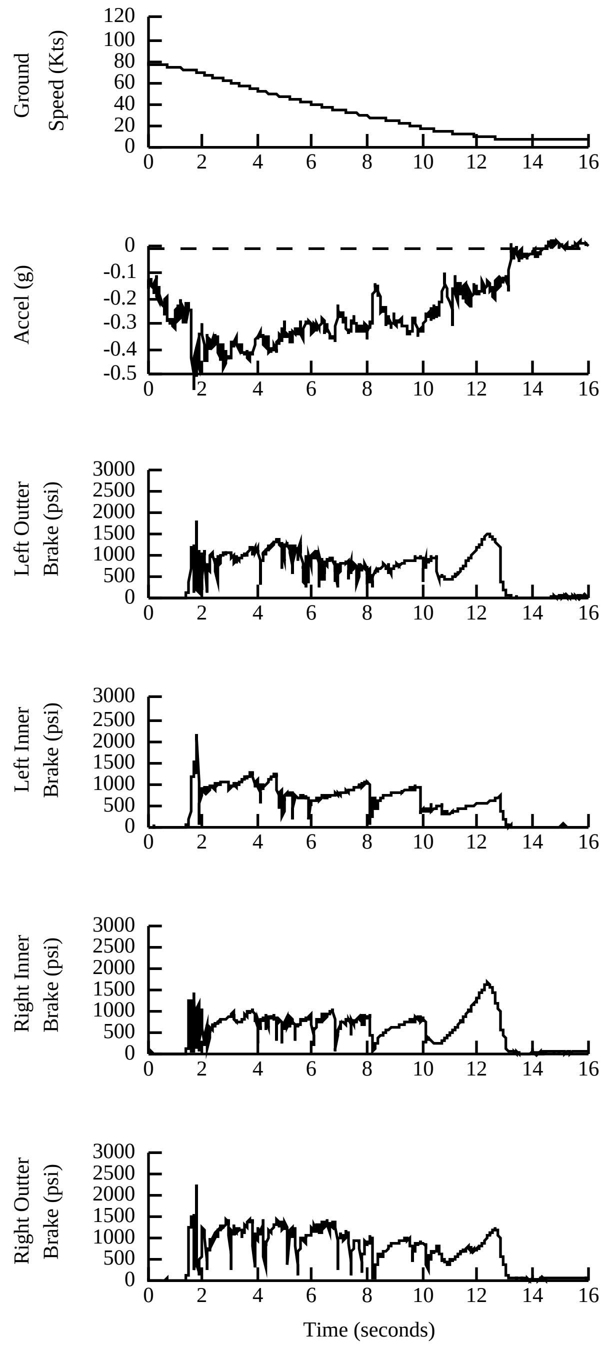
CRFI Average 0.36



Flight 2001/04, Run Number 6

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.36

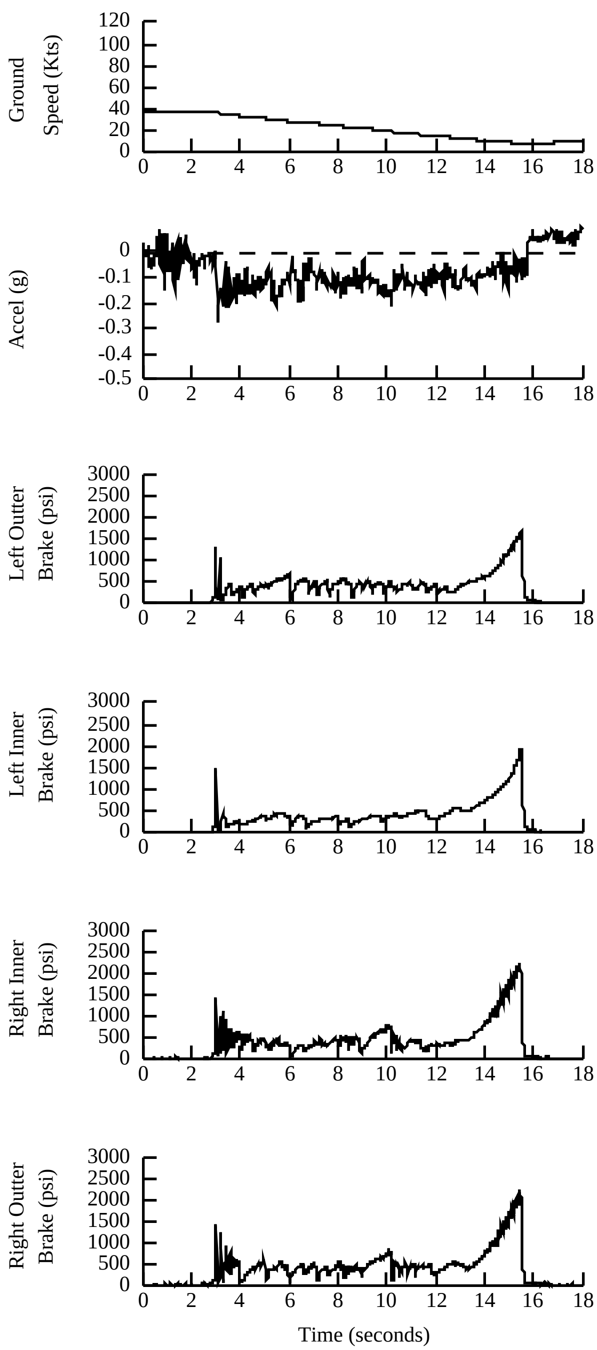


Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

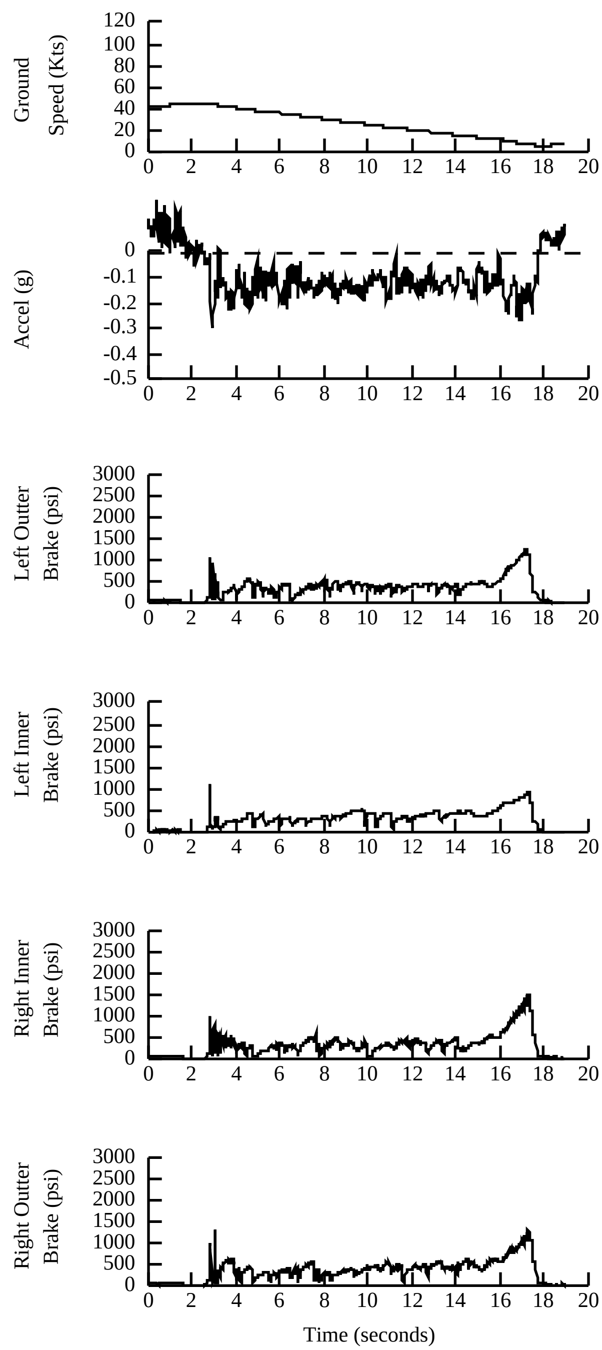
CRFI Average 0.32



Flight 2001/05, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.30

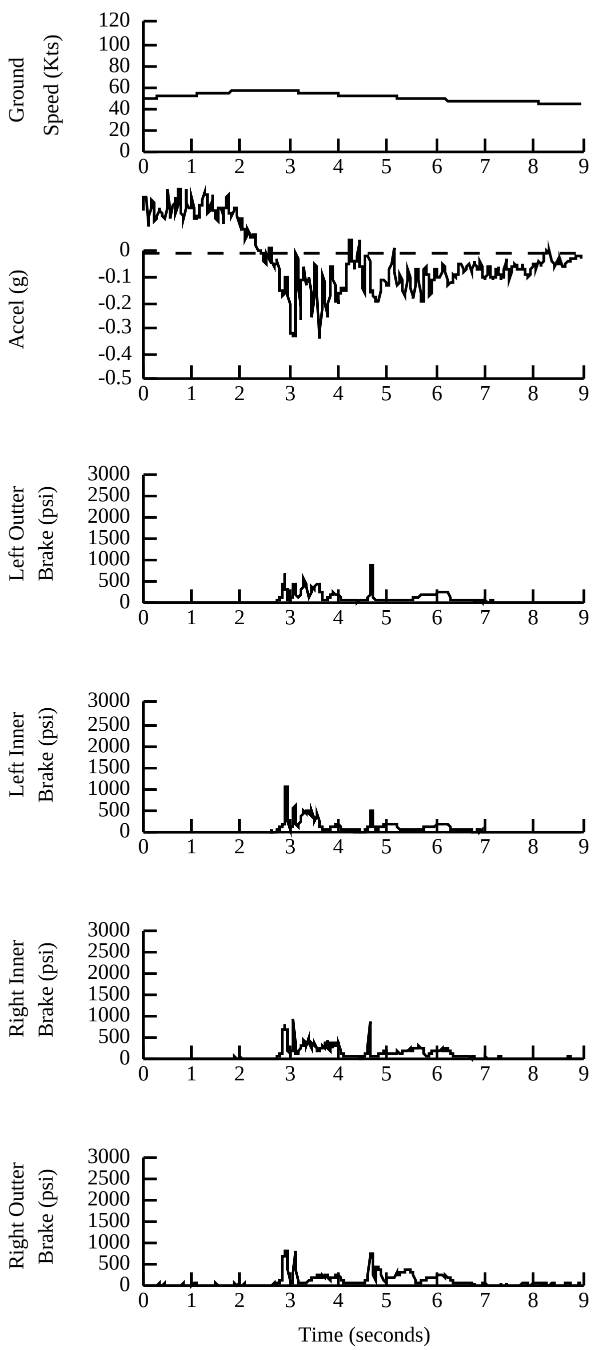


Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

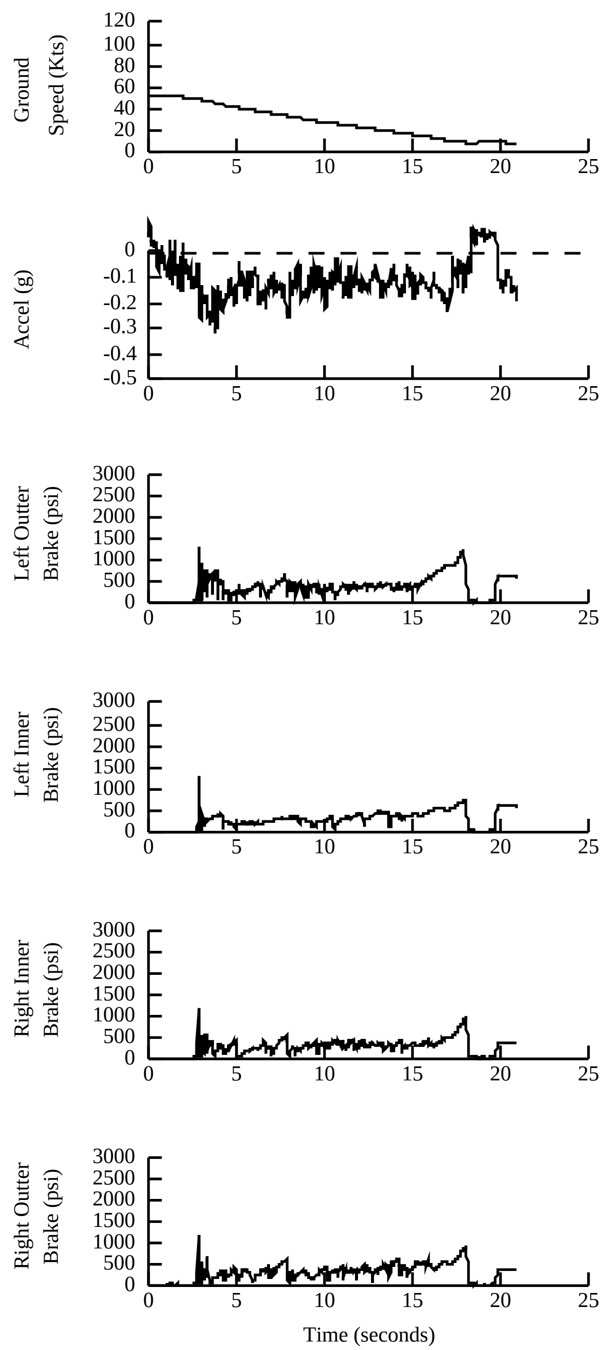
CRFI Average 0.30



Flight 2001/05, Run Number 4

Configuration: Flaps 15, Flight Idle, Max Braking

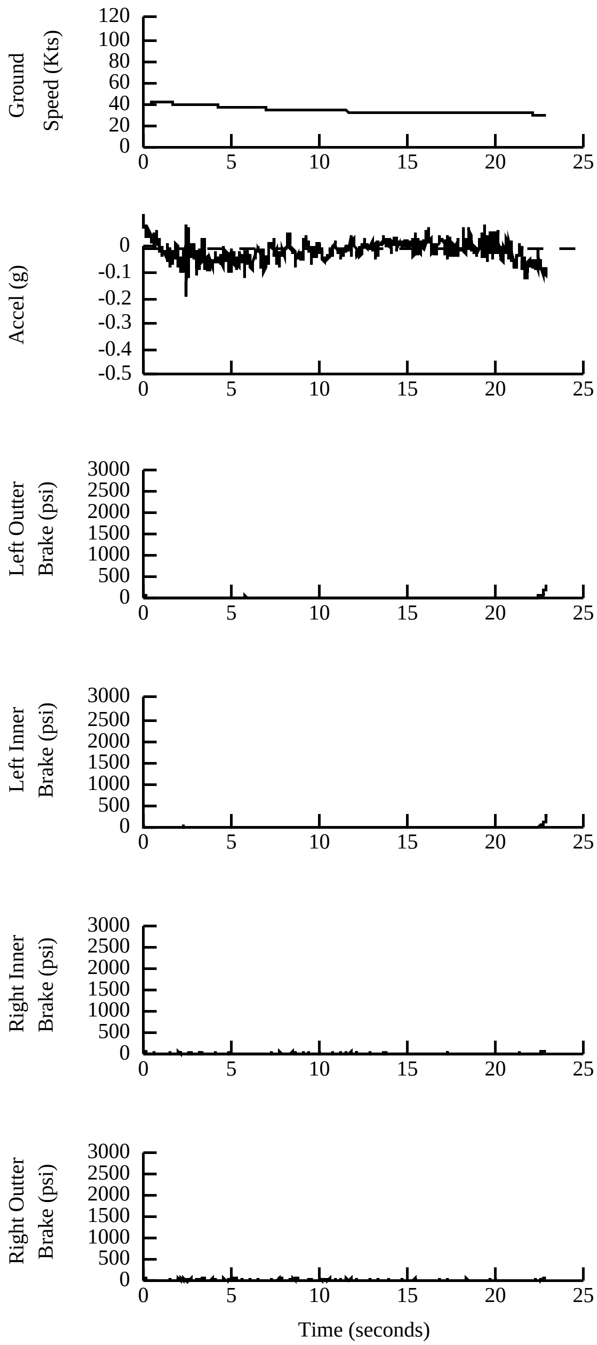
CRFI Average 0.29



Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

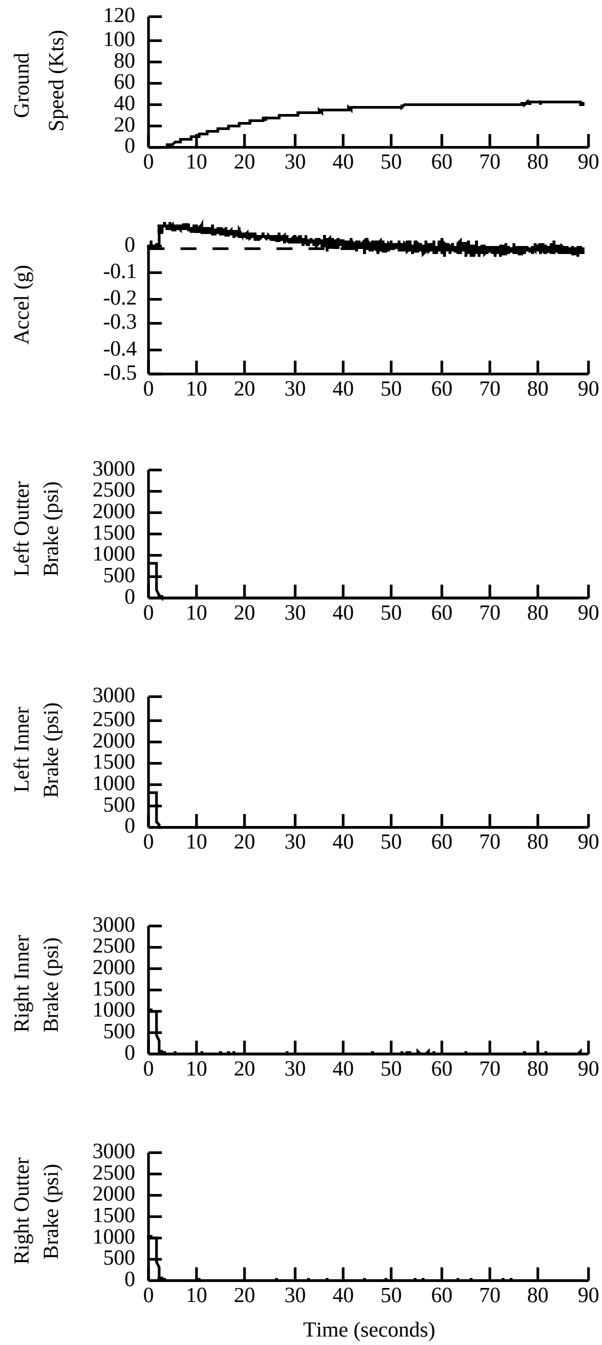
Flight 2001/05, Run Number 5

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/05, Run Number 6

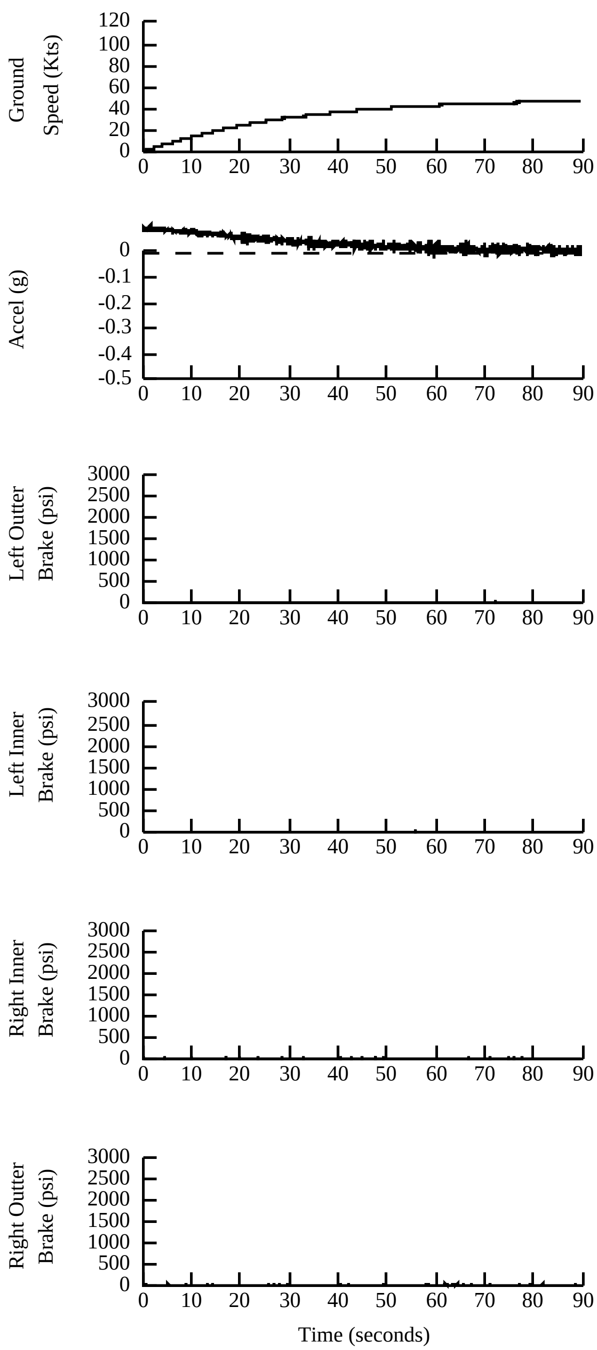
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 100% Bare and Dry

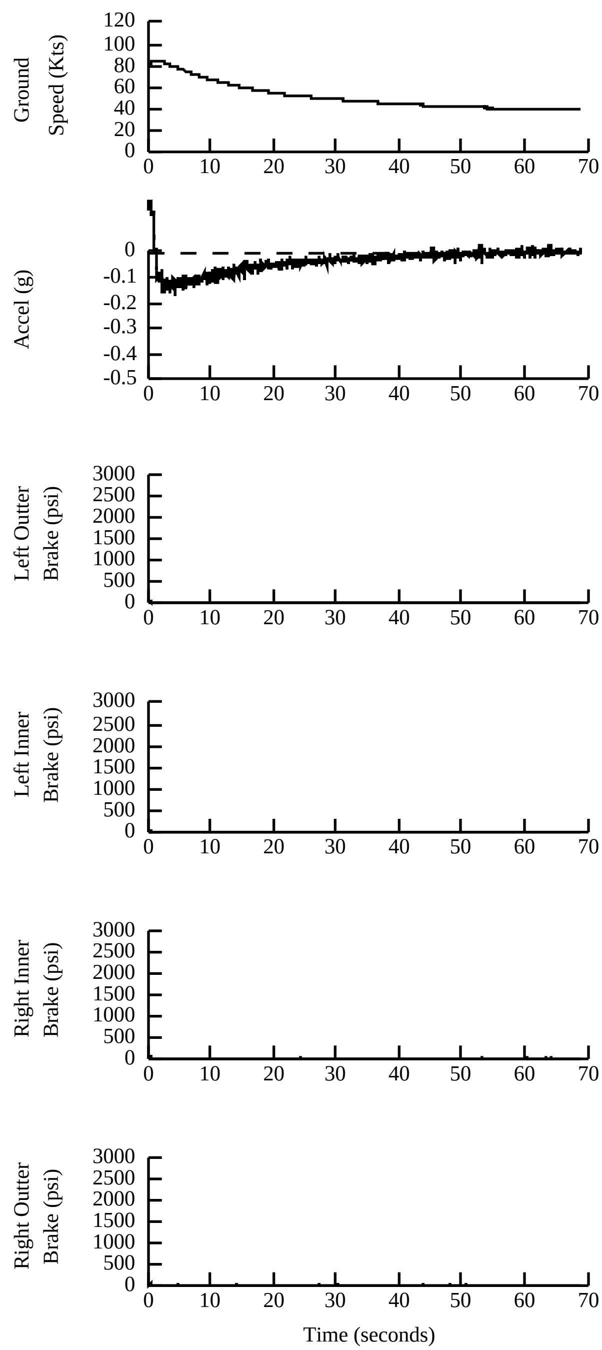
Flight 2001/05, Run Number 7

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/05, Run Number 8

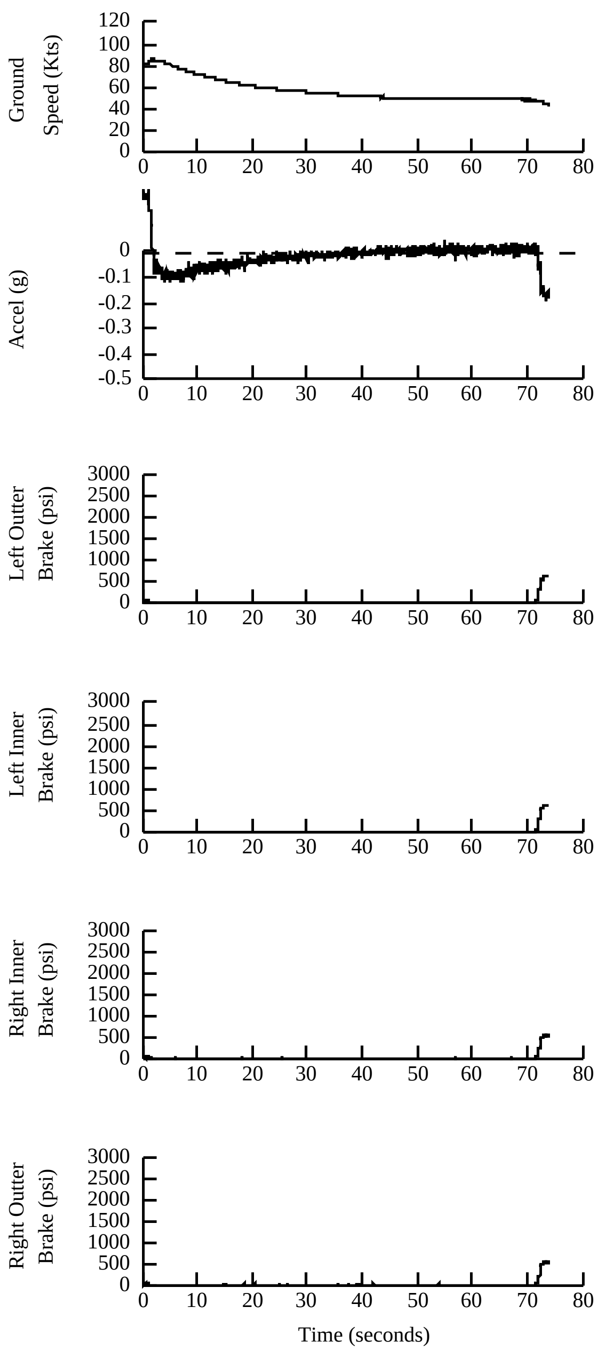
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 100% Bare and Dry

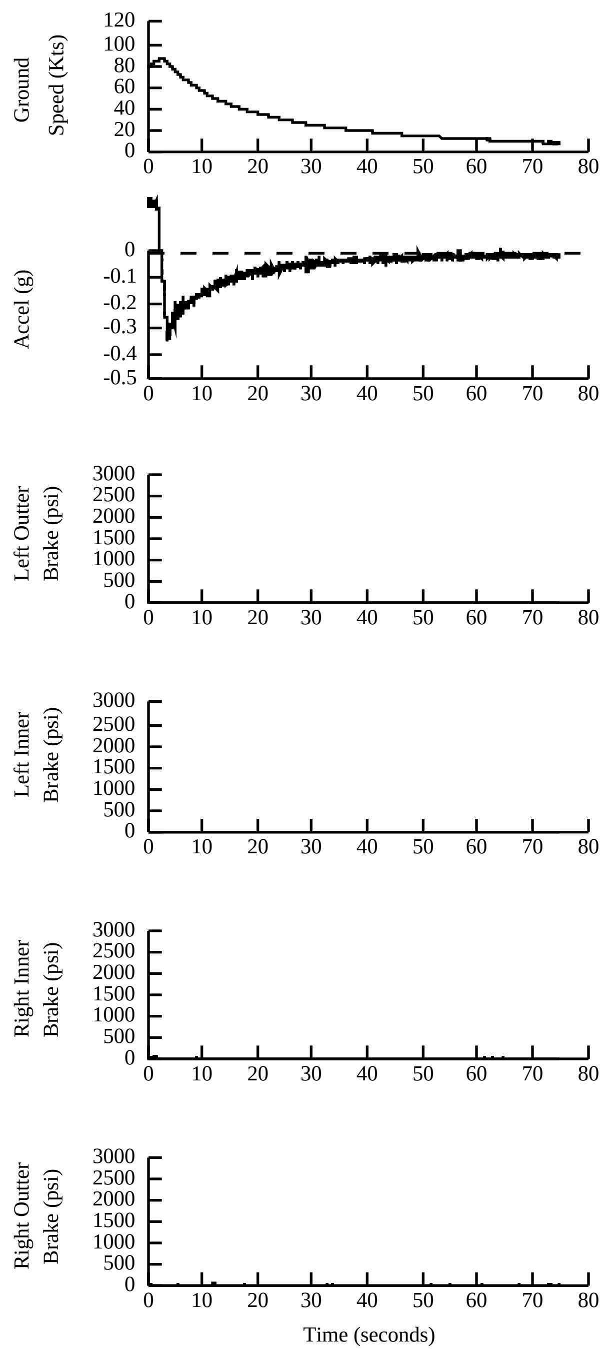
Flight 2001/05, Run Number 9

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/05, Run Number 10

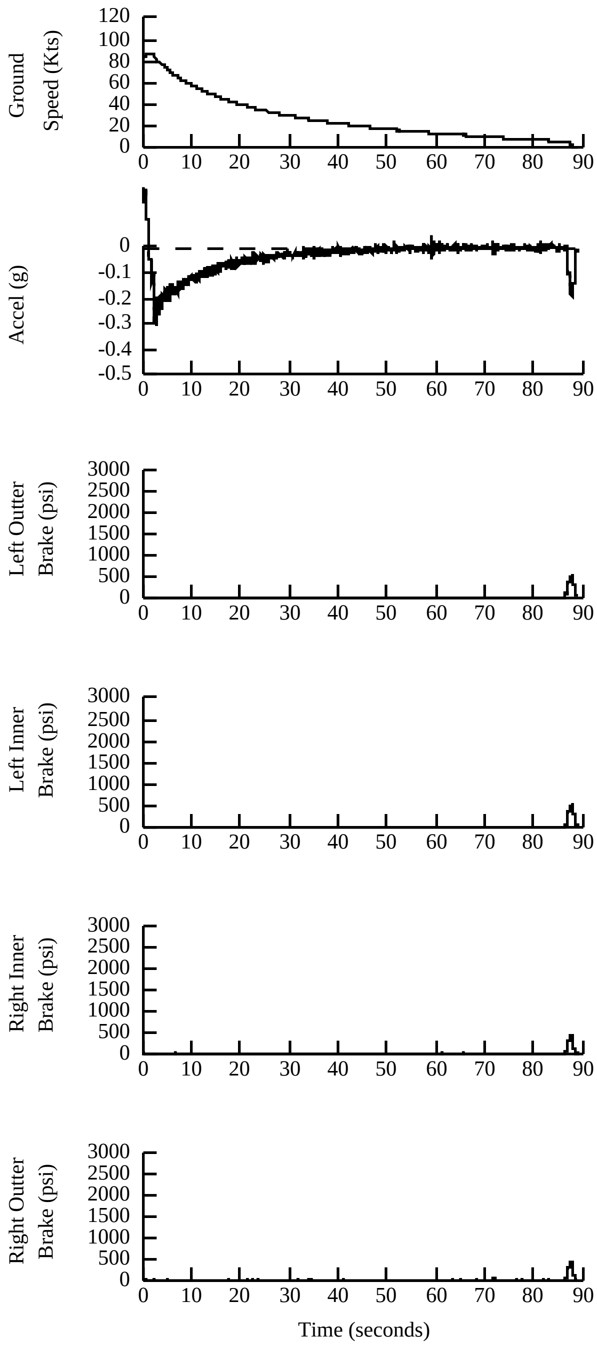
Configuration: Flaps 15, Discing, No Braking



Surface: 100% Bare and Dry

Flight 2001/05, Run Number 11

Configuration: Flaps 15, Discing, No Braking

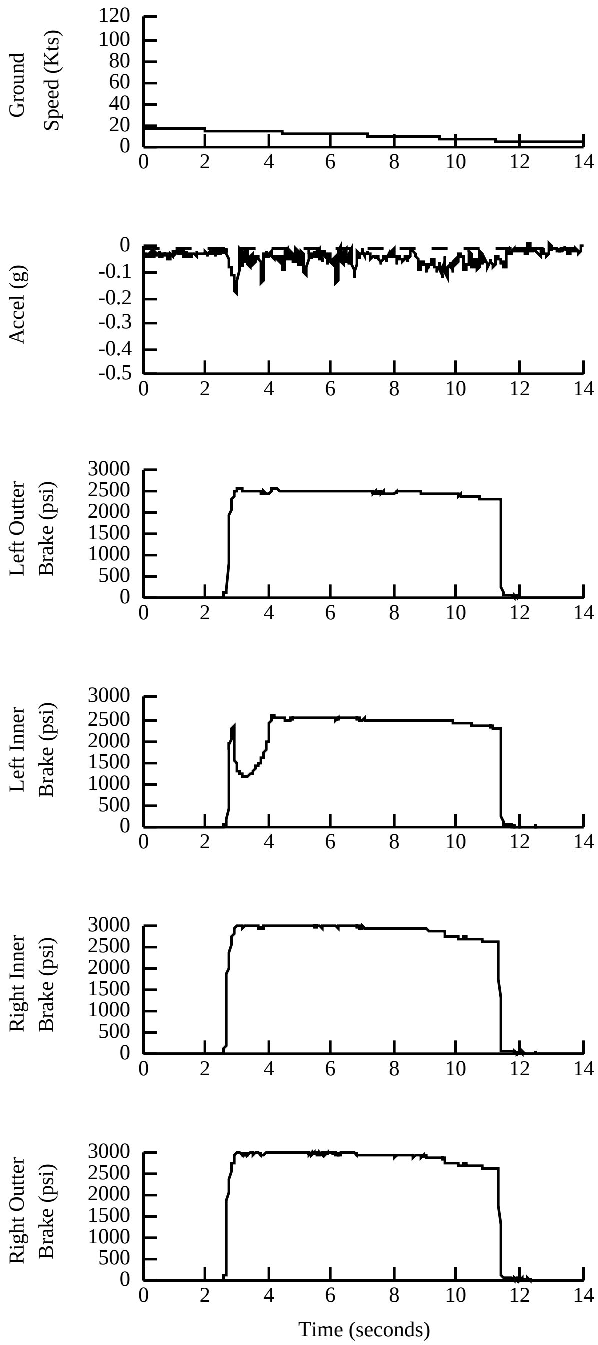


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 1

Configuration: Flaps 15, Discing, Max Braking

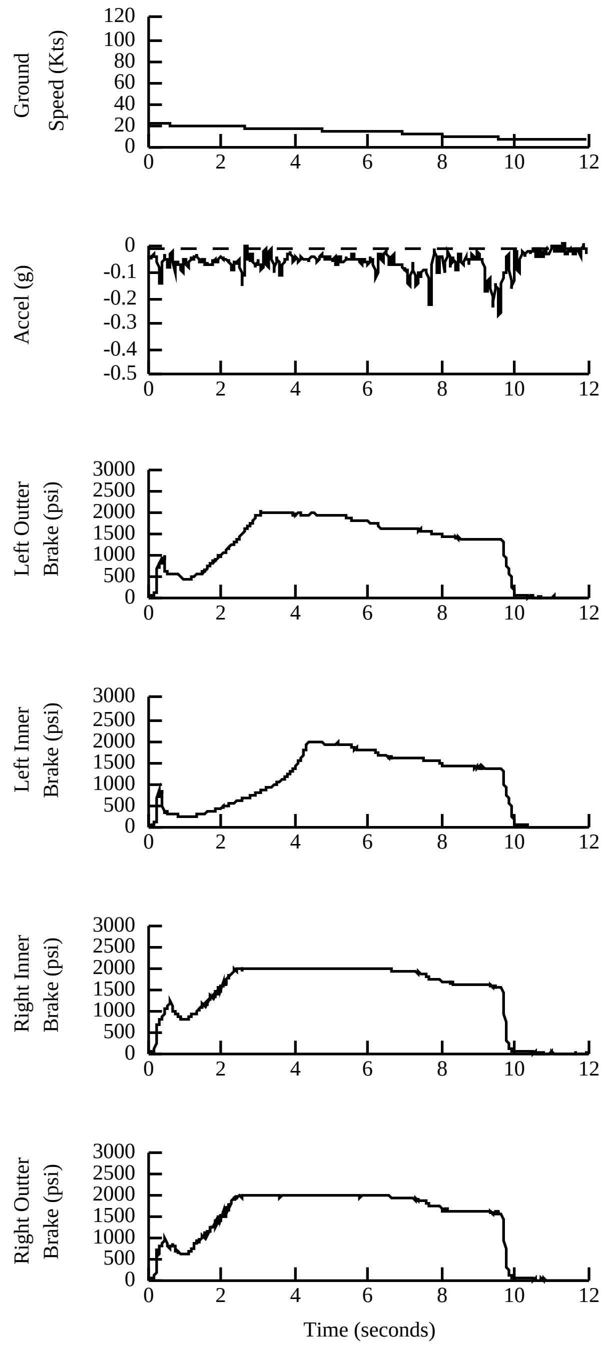
CRFI Average 0.10



Flight 2001/06, Run Number 2

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.11

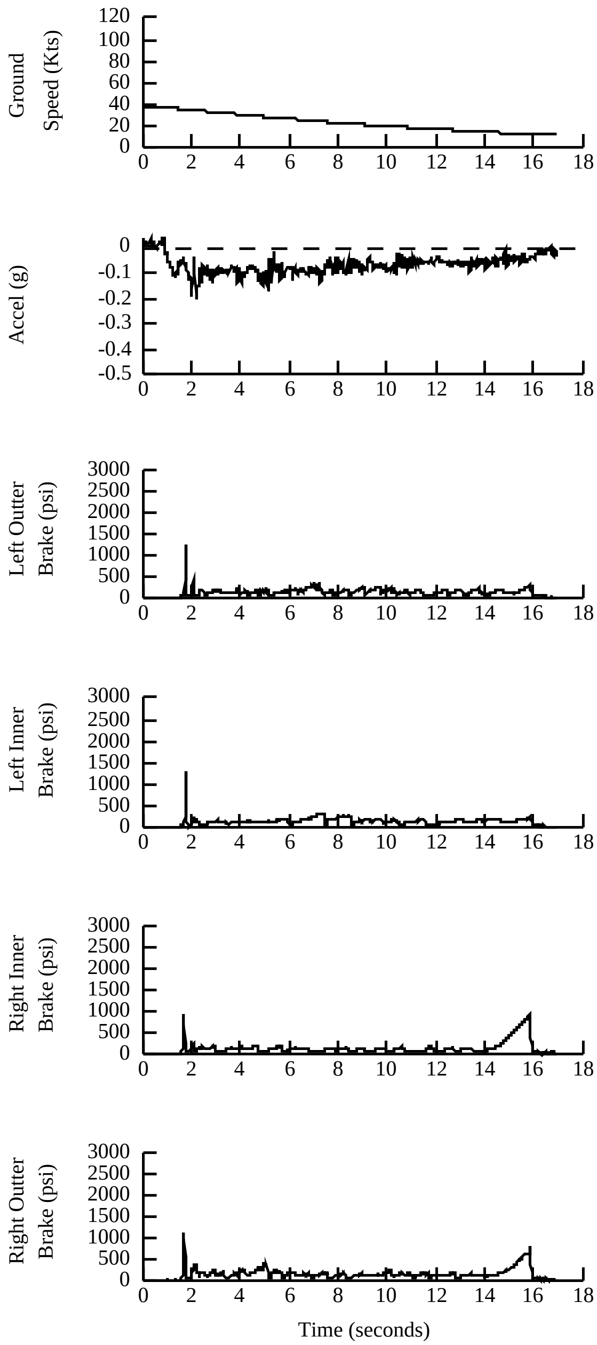


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 3

Configuration: Flaps 15, Discing, Max Braking

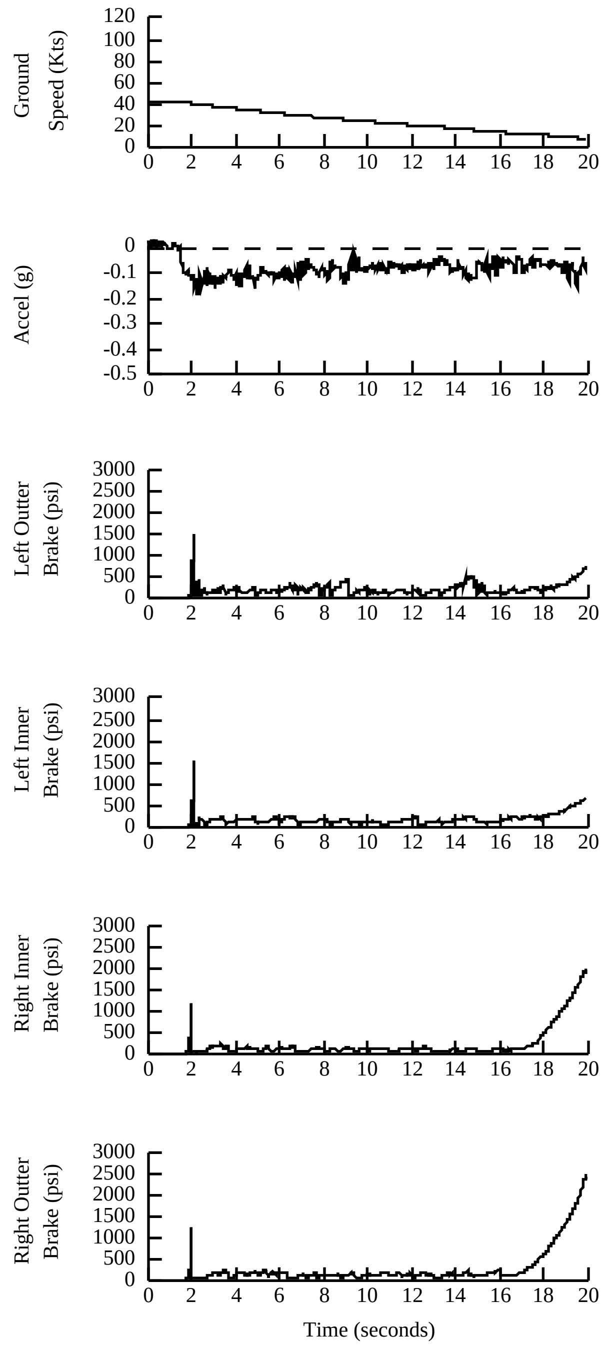
CRFI Average 0.11



Flight 2001/06, Run Number 4

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.11

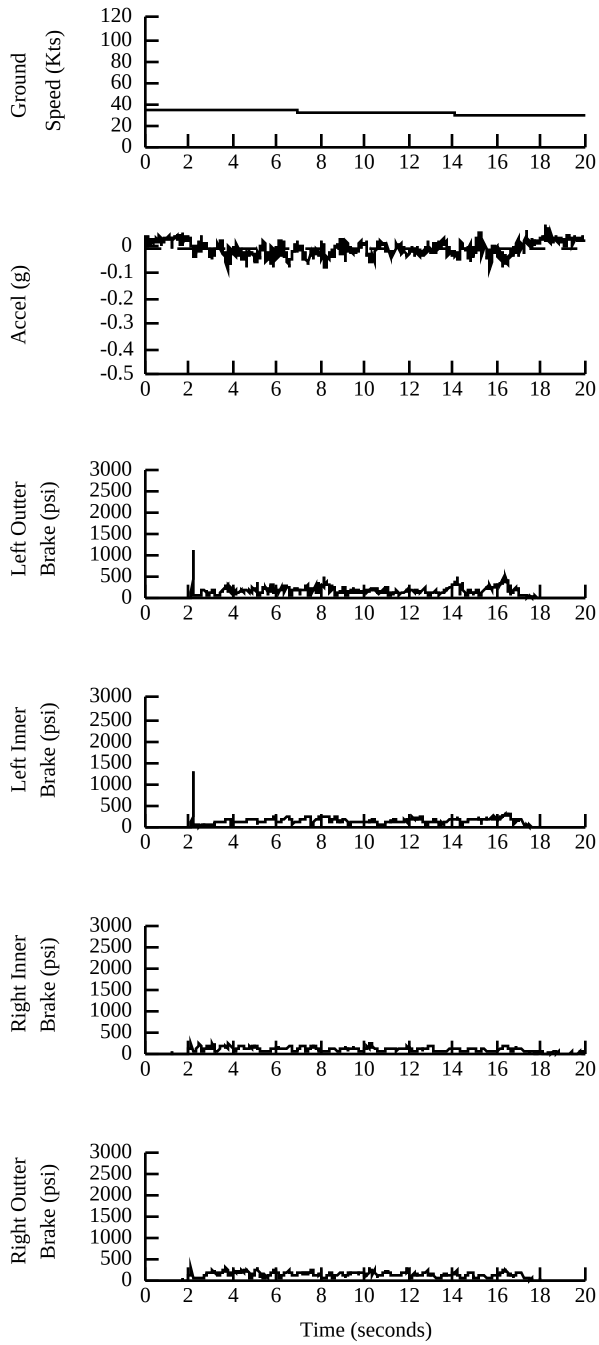


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

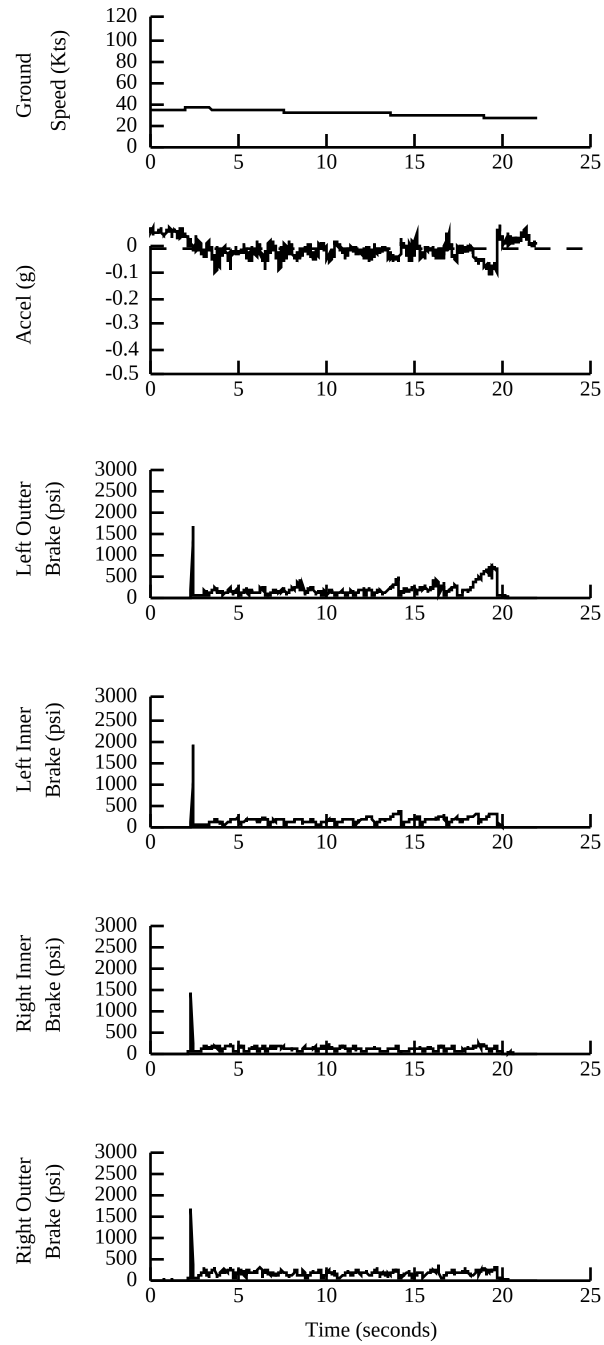
CRFI Average 0.11



Flight 2001/06, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.12

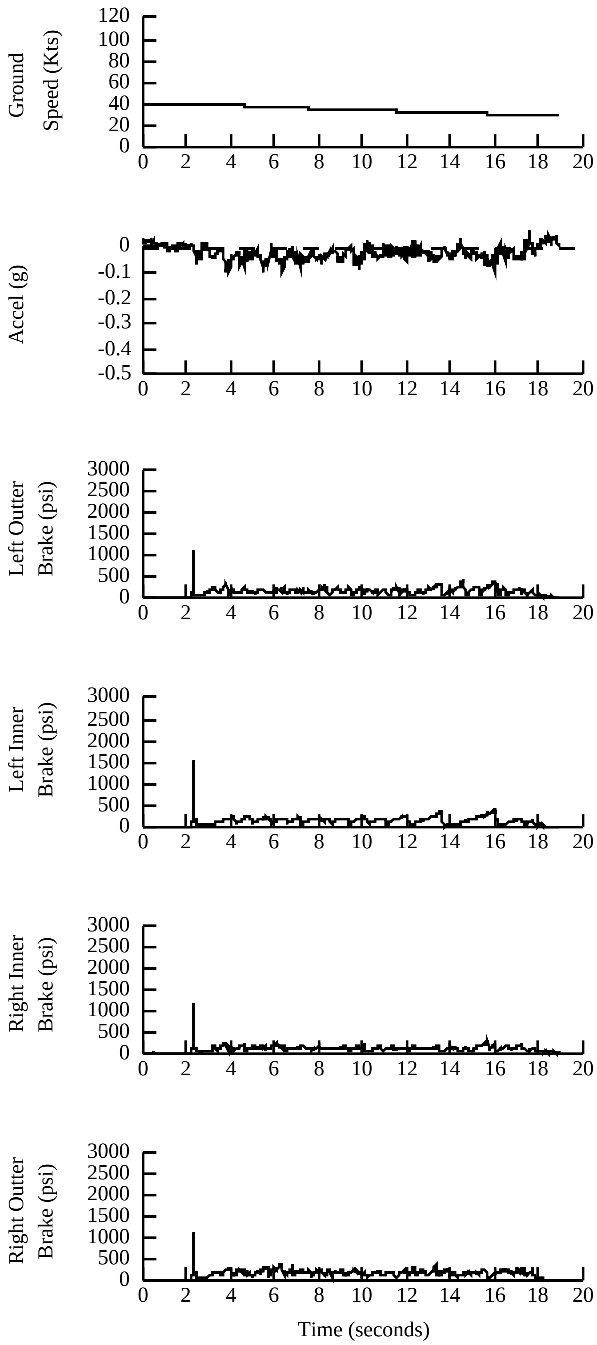


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

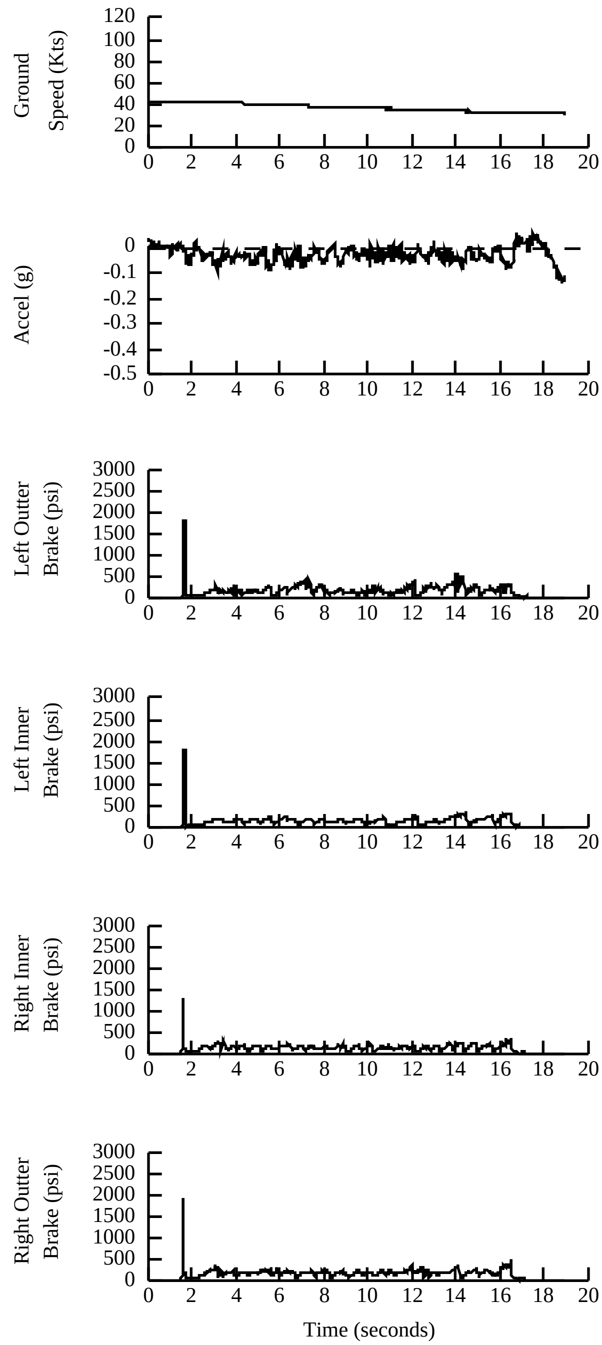
CRFI Average 0.11



Flight 2001/06, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.11

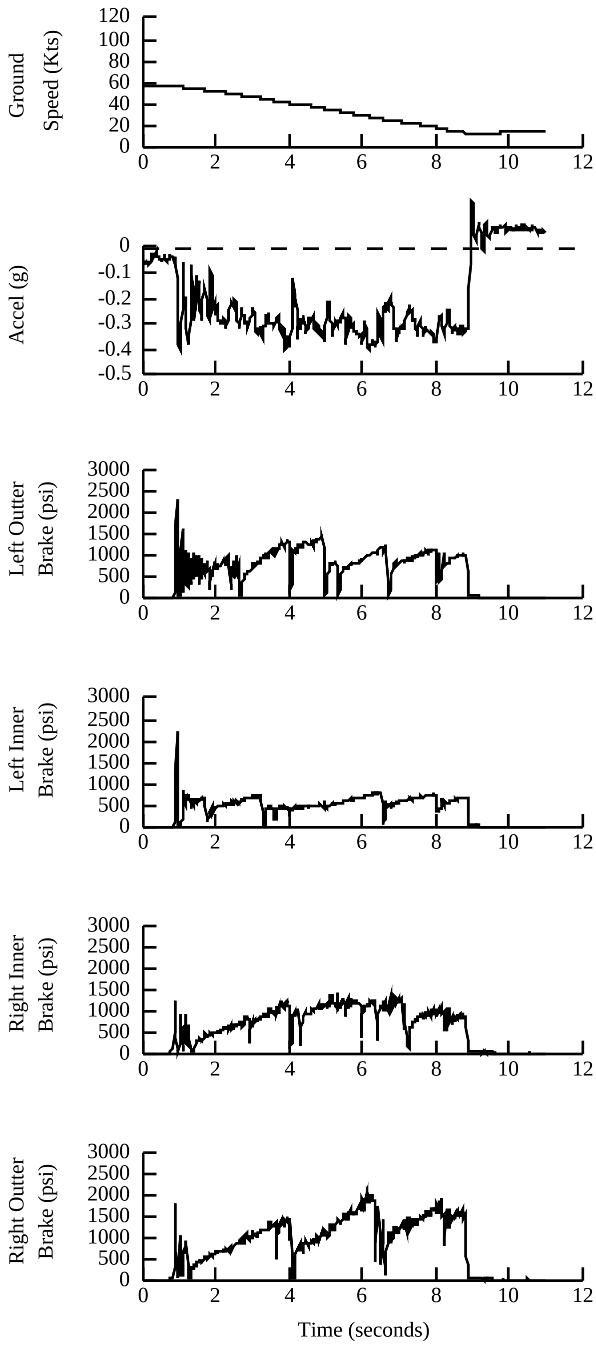


Surface: 20% bare and dry, 80% bare and damp
with patches of standing water

Flight 2001/07, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

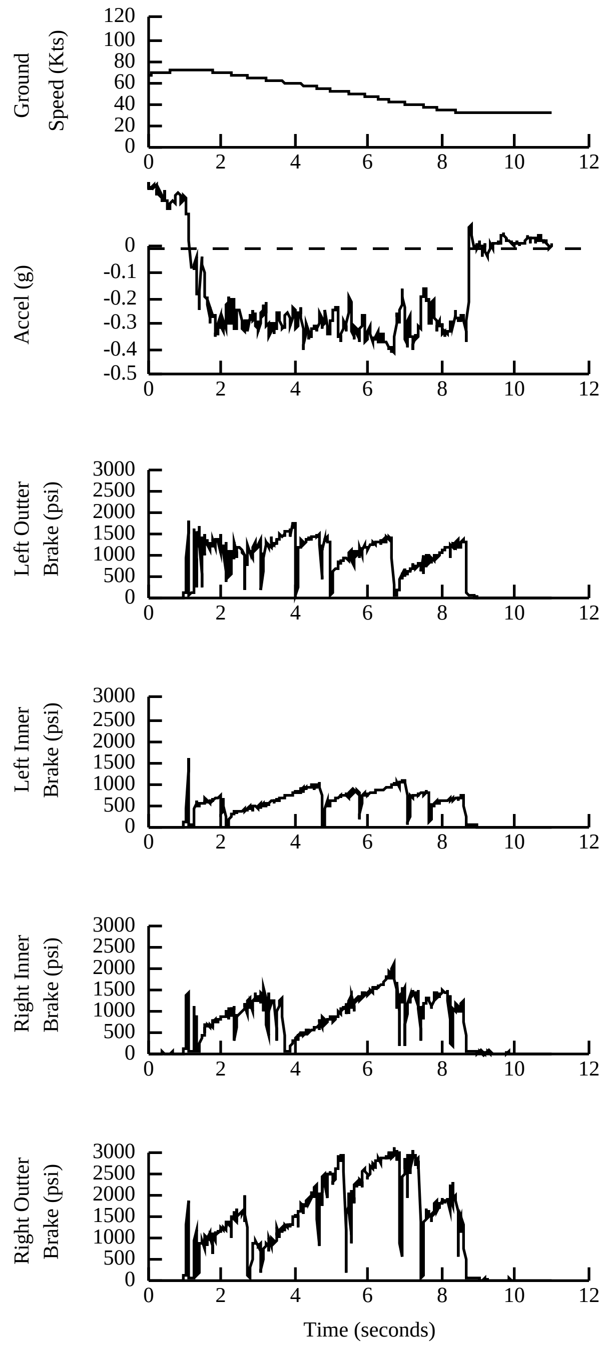
CRFI Average 0.54



Flight 2001/07, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.60

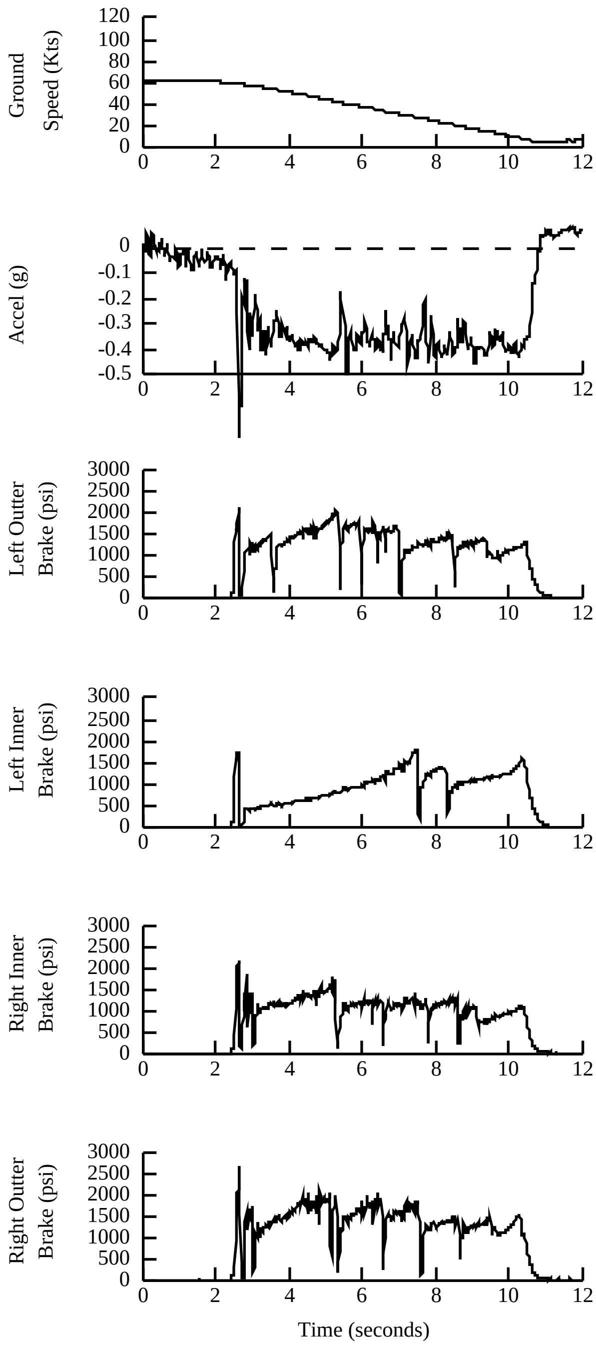


Surface: 100% bare and damp with 10-20% standing water

Flight 2001/08, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

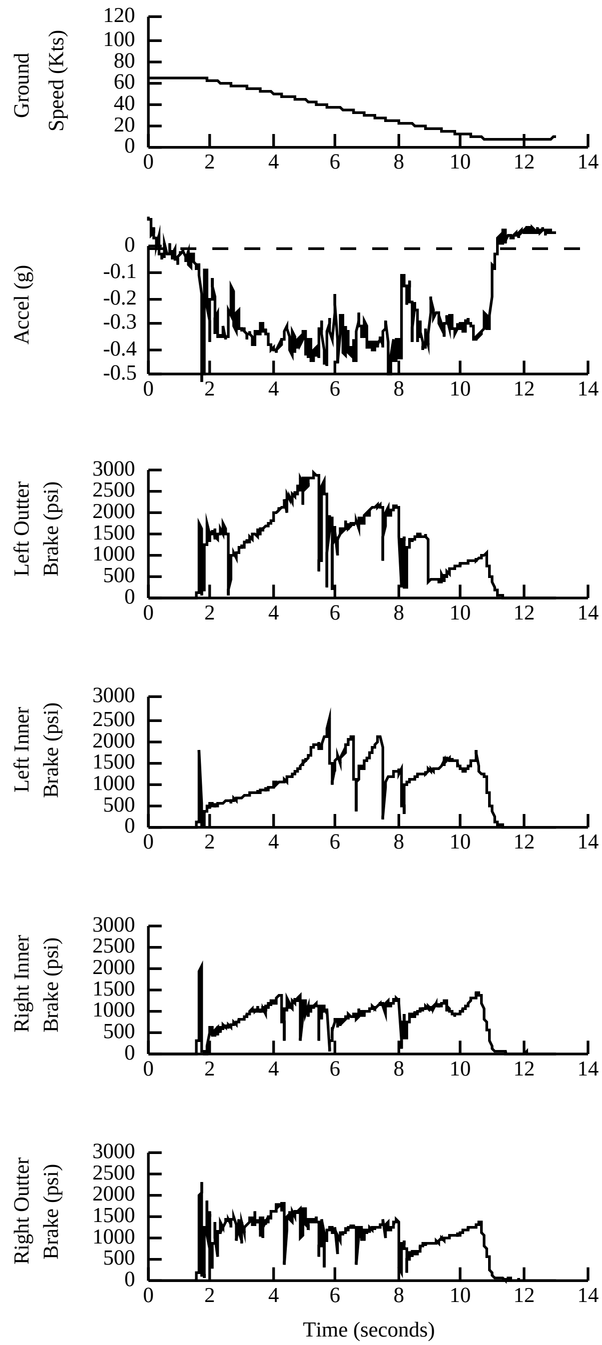
CRFI Average 0.74



Flight 2001/08, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.72

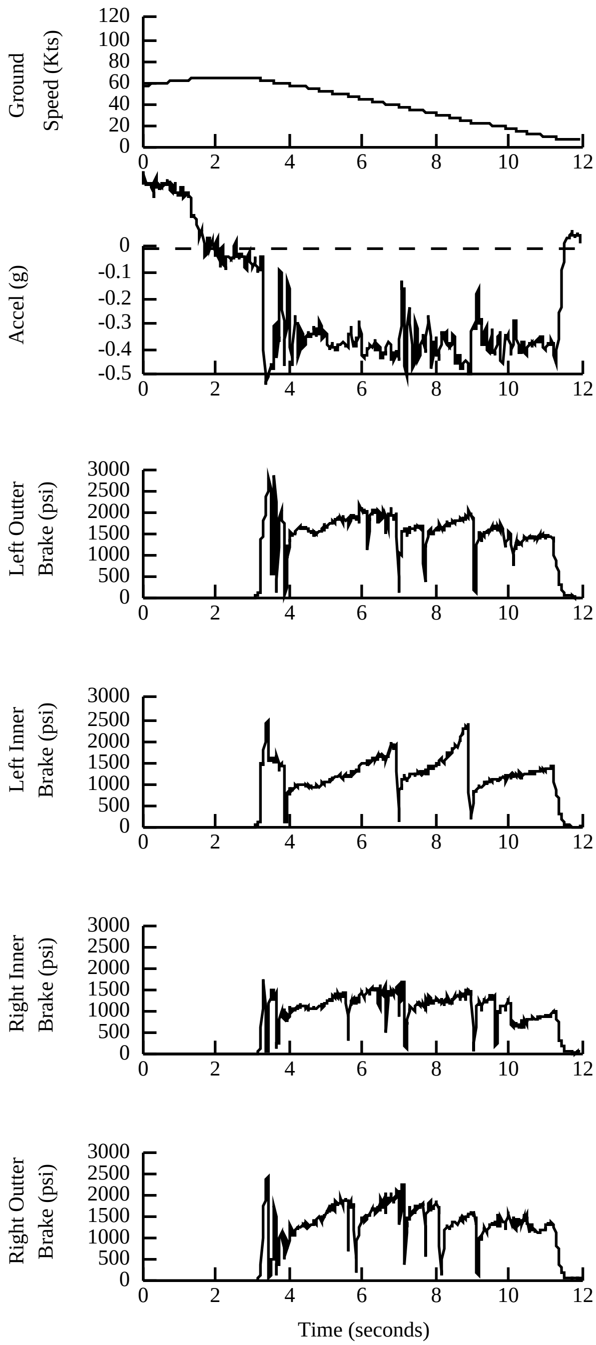


Surface: 100% bare and damp with 20-40% standing water

Flight 2001/08, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.72



APPENDIX B - TEST RUNS FOR PROPELLER DRAG FOR FLIGHT IDLE AND DISCING ENGINE SETTINGS

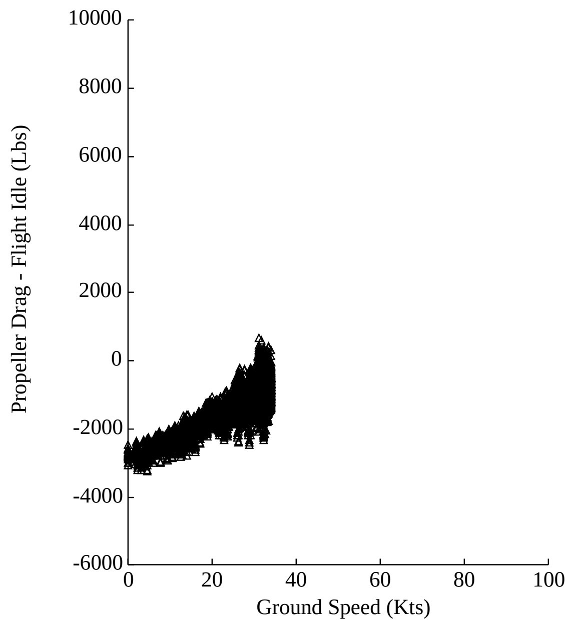
The following table shows the test runs used to model the combined propeller drag, and residual engine thrust at flight idle and discing engine throttle settings. These were performed on runway surfaces with no or negligible contamination drag. Pages B2 to B6 show the variation of propeller drag with ground speed for each run. Page B7 shows the results of all the combined discing runs and page B8 shows the combined flight idle runs.

FLT/ Date	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK	WEIGHT (LB)
2001/01 29/01/01	1 14:35	26	TAXI	15/IDLE/NO	31950
	2 14:41	08	TAXI	15/IDLE/NO	31875
	3 14:51	36	TAXI	15/IDLE/NO	31750
	4 14:54	18	TAXI	15/IDLE/NO	31700
	5 15:07	26	LAND	15/IDLE/NO	31500
	6 15:26	26	LAND	15/DISC/NO	31350
	7 15:39	08	RTO	15/DISC/NO	31200
	10 15:57	26	RTO	15/REV/NO	31000
2001/02 31/01/01	12 15:57	26	RTO	15/IDLE/NO	31520
	14 16:11	08	RTO	15/IDLE/NO	31380
	15 16:16	26	RTO	15/DISC/NO	31330
	17 16:36	08	RTO	15/DISC/NO	31130
2001/05 21/03/01	6 15:05	26	TAXI	15/IDLE/NO	30750
	7 15:10	08	TAXI	15/IDLE/NO	30710
	8 15:15	26	RTO	15/IDLE/NO	30670
	9 15:18	08	RTO	15/IDLE/NO	30650
	10 15:22	26	RTO	15/DISC/NO	30610
	11 15:27	08	RTO	15/DISC/NO	30560

Surface: 100% Bare and Dry

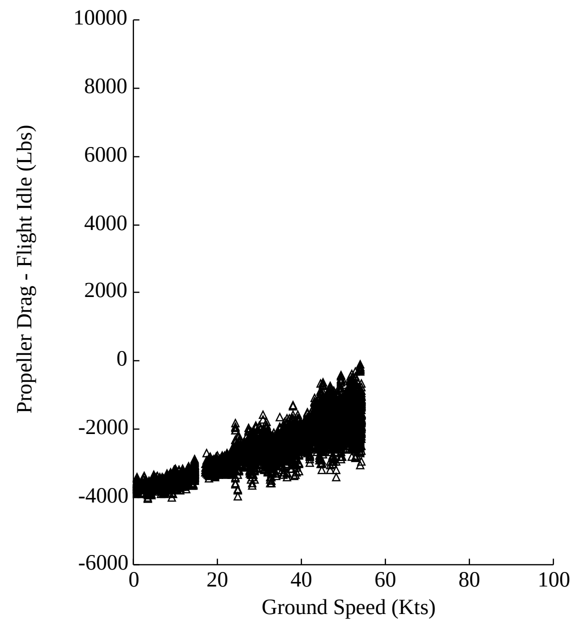
Flight 2001/01, Run Number 1

Configuration: Flaps 15, Flight Idle, No Braking



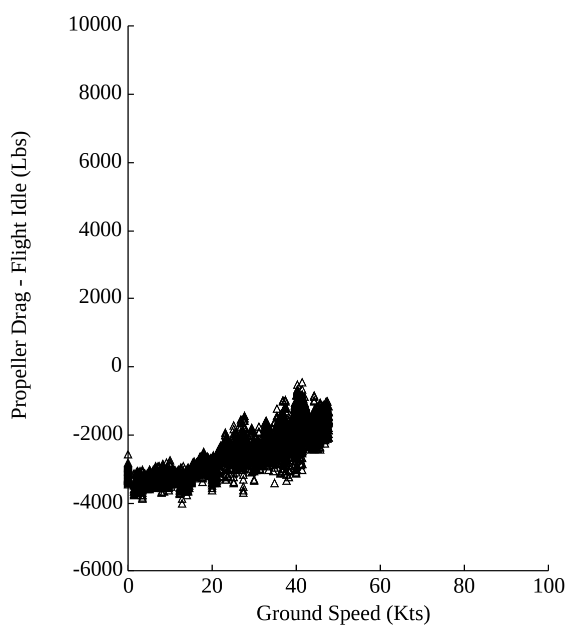
Flight 2001/01, Run Number 2

Configuration: Flaps 15, Flight Idle, No Braking



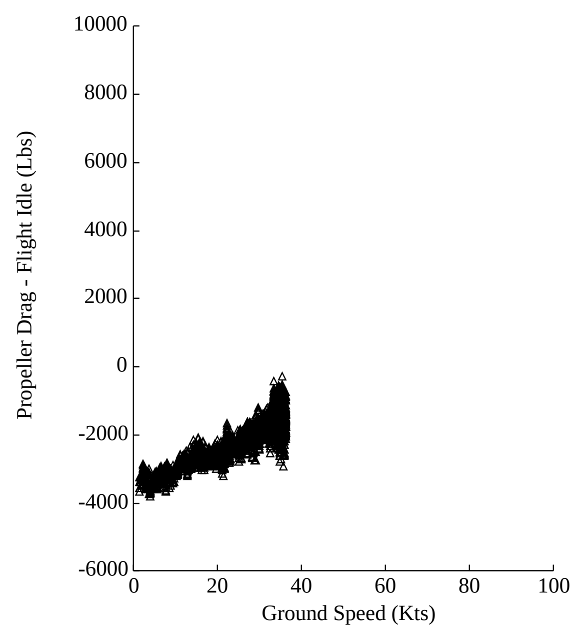
Flight 2001/01, Run Number 3

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/01, Run Number 4

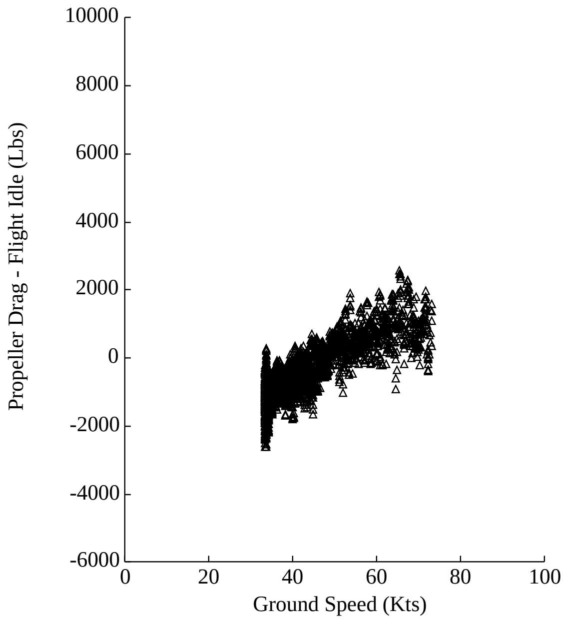
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 100% Bare and Dry

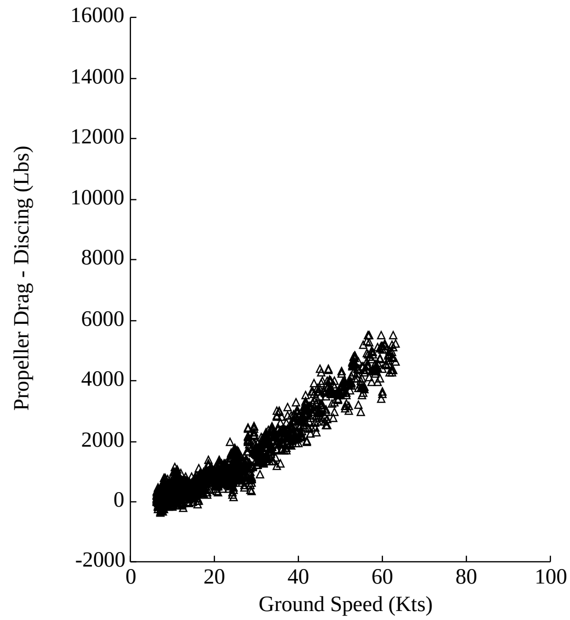
Flight 2001/01, Run Number 5

Configuration: Flaps 15, Flight Idle, No Braking



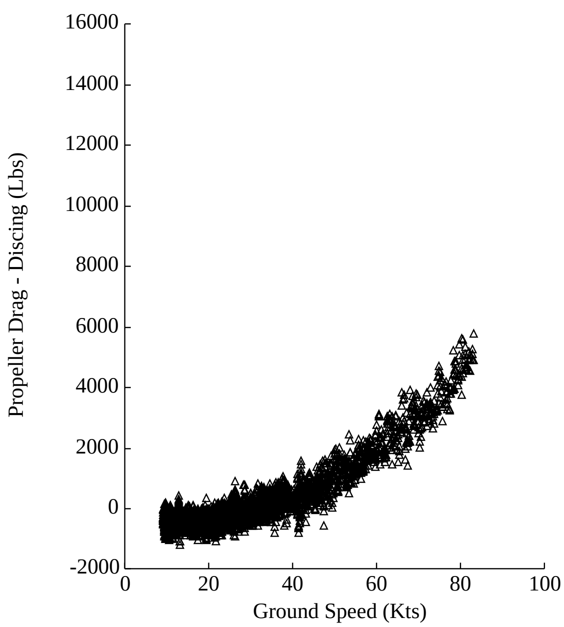
Flight 2001/01, Run Number 6

Configuration: Flaps 15, Discing, No Braking



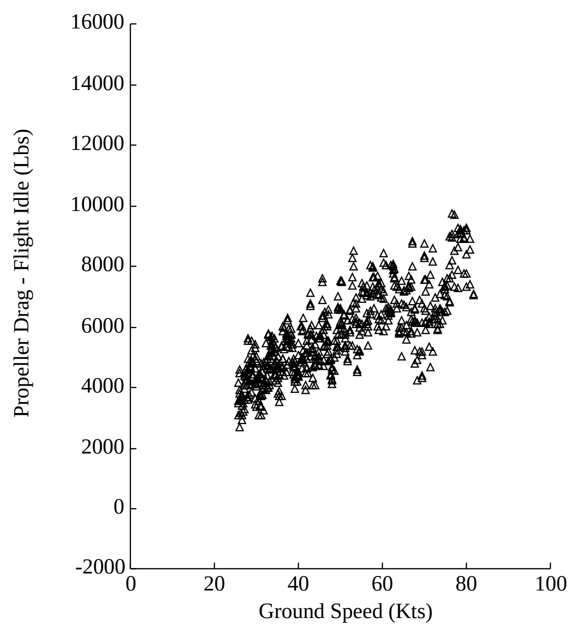
Flight 2001/01, Run Number 7

Configuration: Flaps 15, Discing, No Braking



Flight 2001/01, Run Number 10

Configuration: Flaps 15, Max Reverse

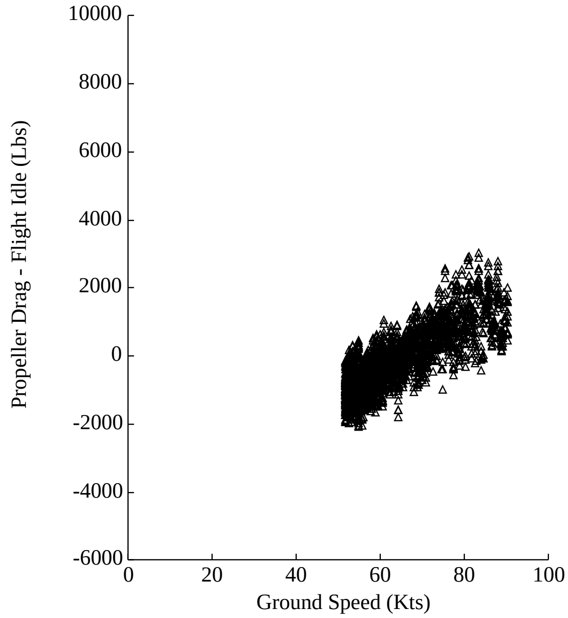


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 12

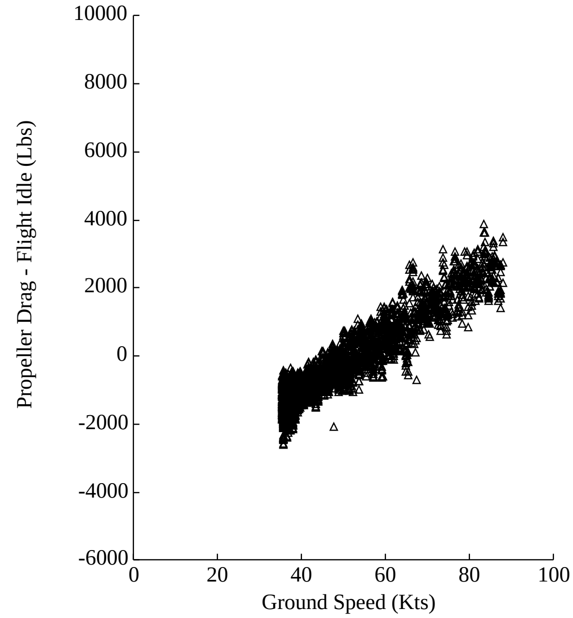
Configuration: Flaps 15, Flight Idle, No Braking

CRFI Average 0.24



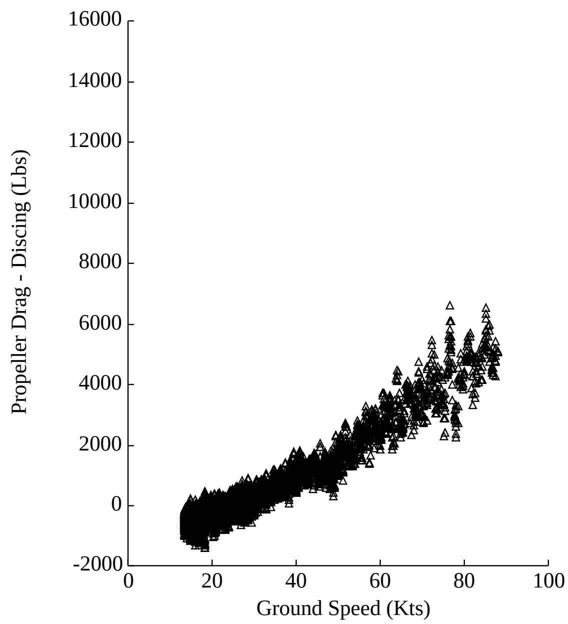
Flight 2001/02, Run Number 14

Configuration: Flaps 15, Flight Idle, No Braking



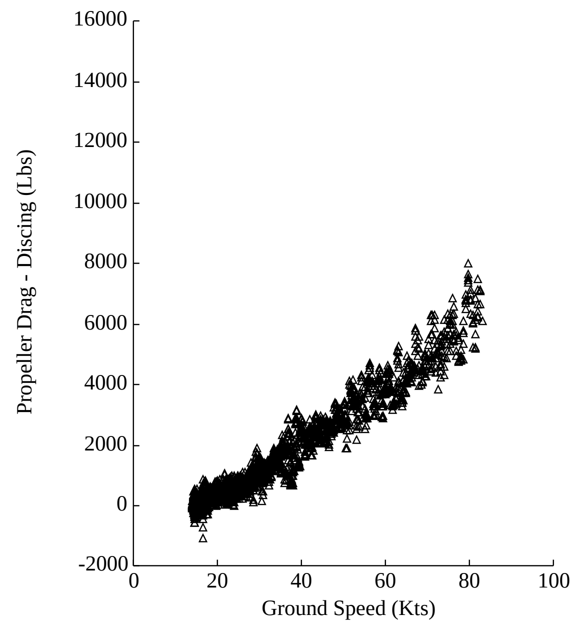
Flight 2001/02, Run Number 15

Configuration: Flaps 15, Discing, No Braking



Flight 2001/02, Run Number 17

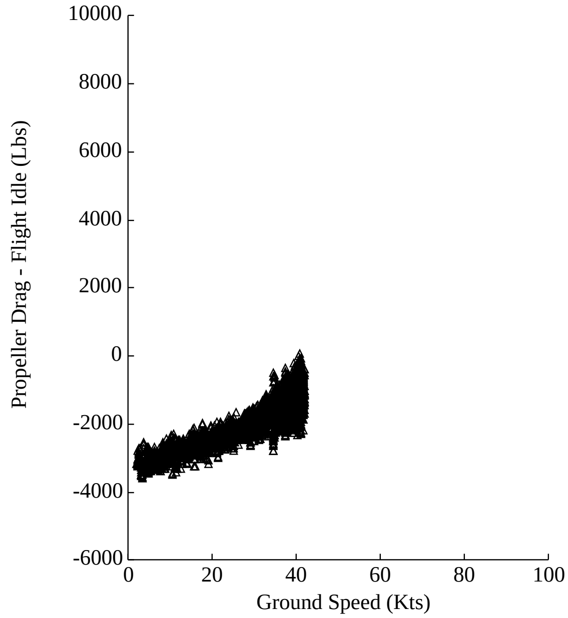
Configuration: Flaps 15, Discing, No Braking



Surface: 100% Bare and Dry

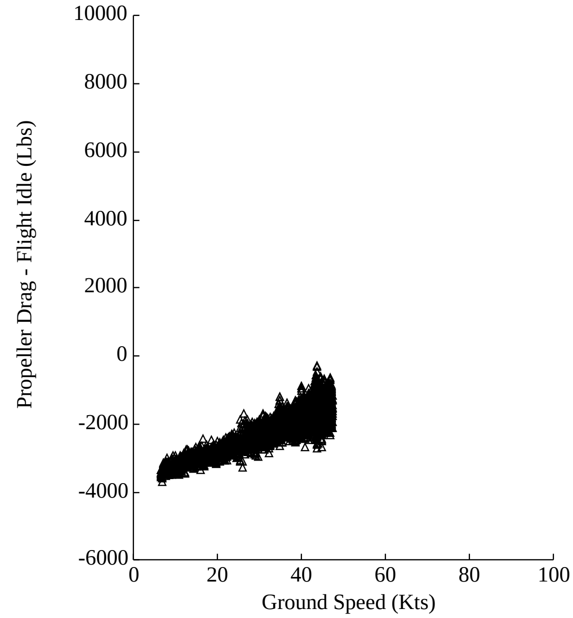
Flight 2001/05, Run Number 6

Configuration: Flaps 15, Flight Idle, No Braking



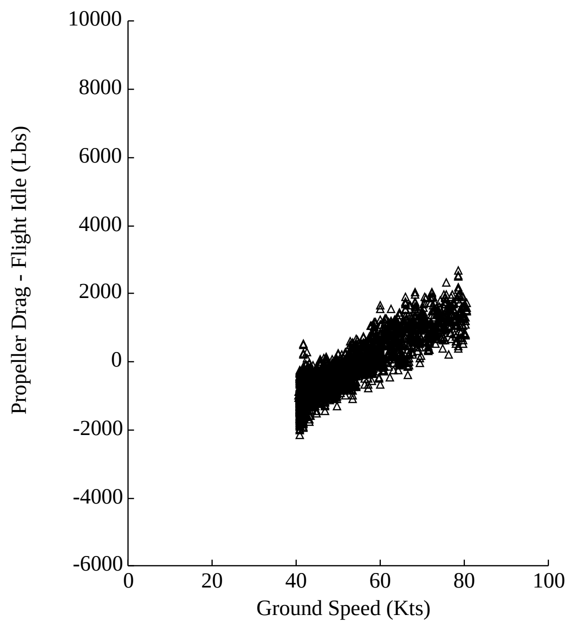
Flight 2001/05, Run Number 7

Configuration: Flaps 15, Flight Idle, No Braking



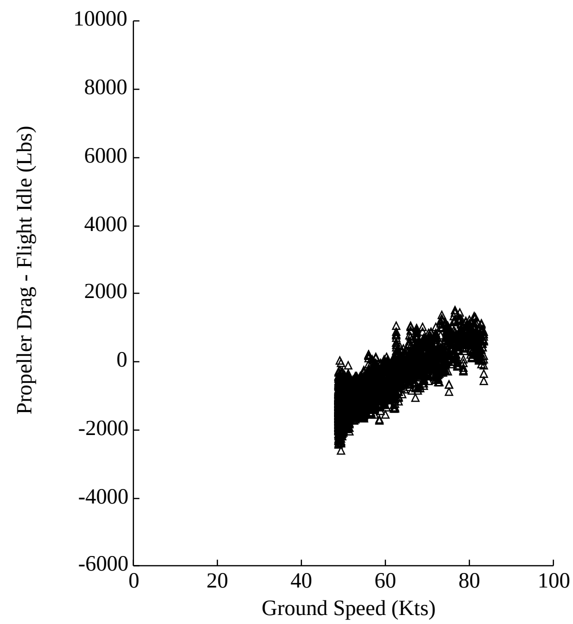
Flight 2001/05, Run Number 8

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/05, Run Number 9

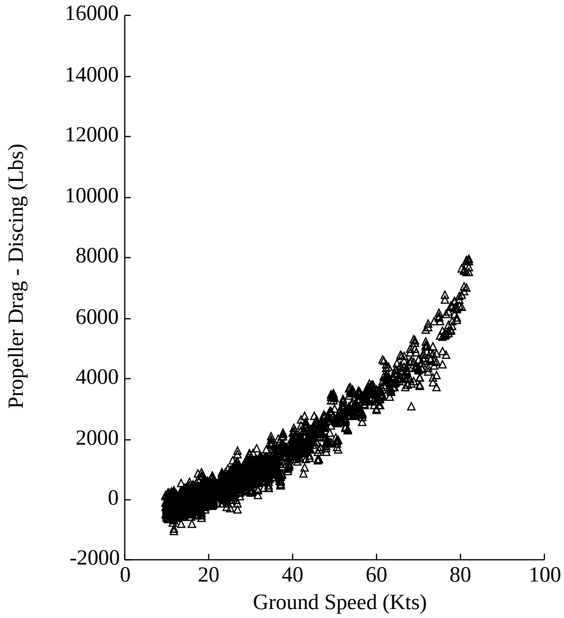
Configuration: Flaps 15, Flight Idle, No Braking



Surface: 100% Bare and Dry

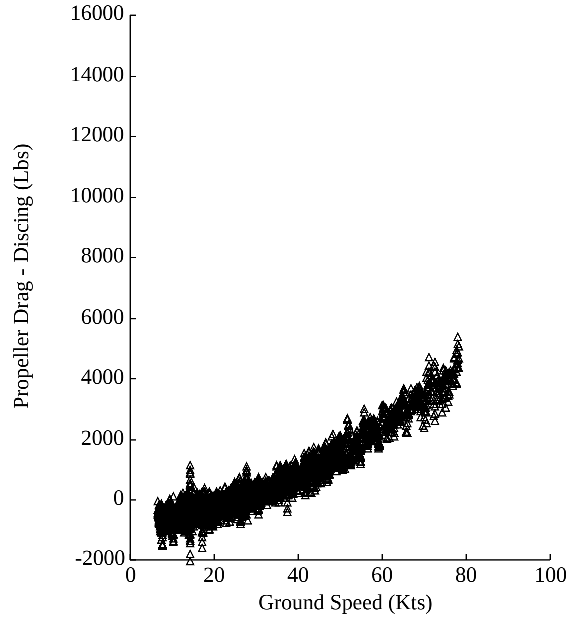
Flight 2001/05, Run Number 10

Configuration: Flaps 15, Discing, No Braking



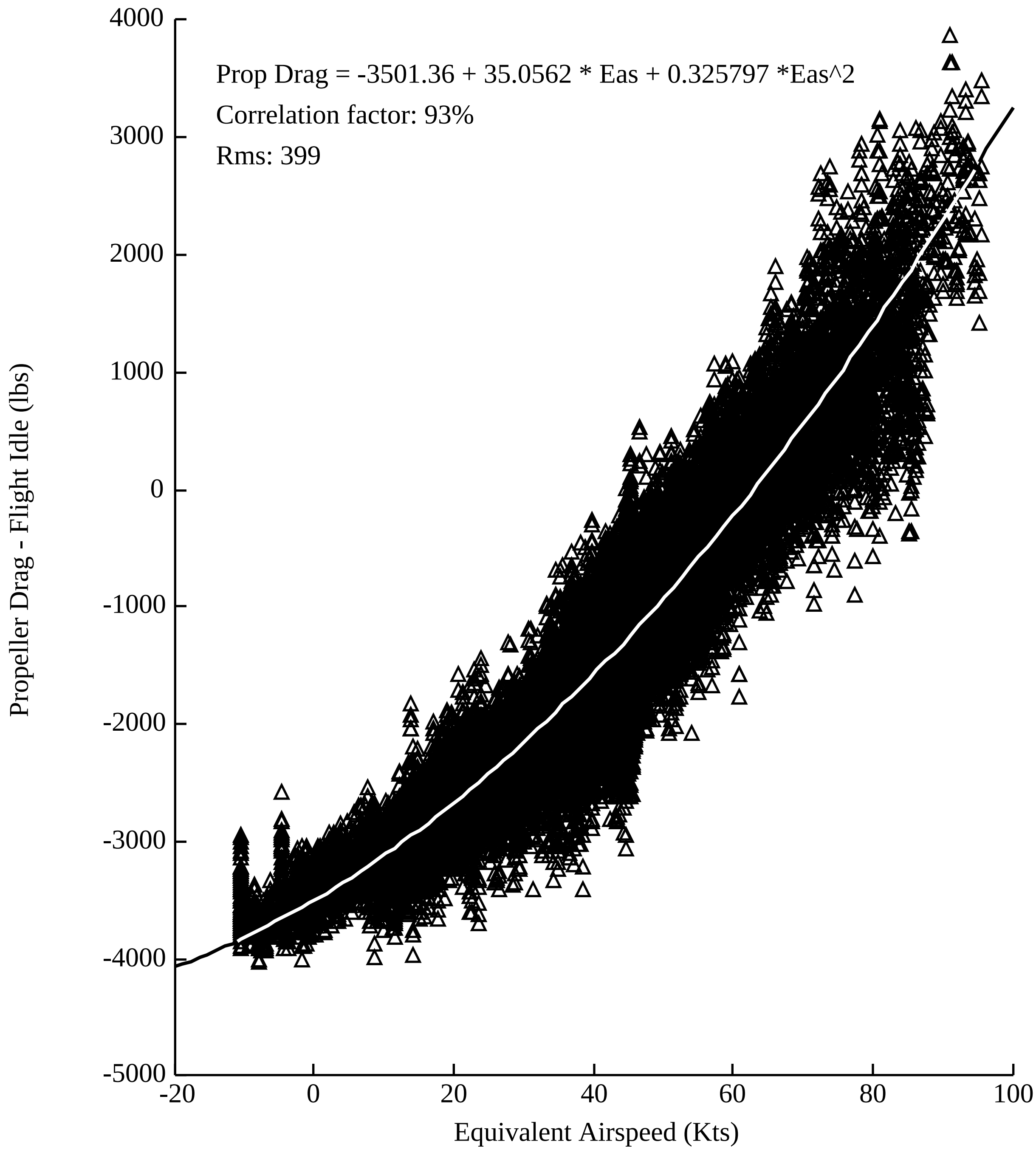
Flight 2001/05, Run Number 11

Configuration: Flaps 15, Discing, No Braking



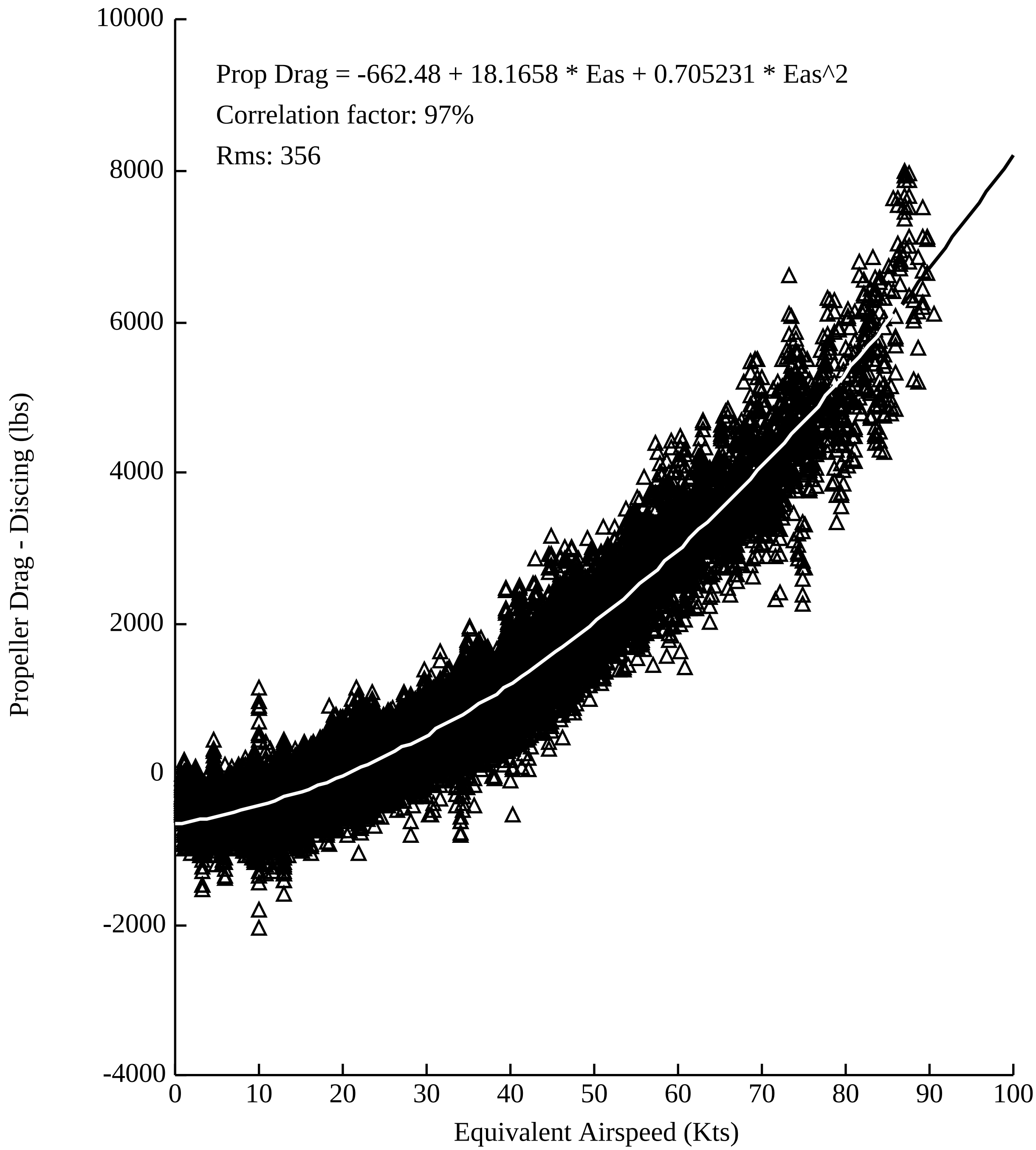
Flight Idle Propeller Drag - Total Drag for Both Propellers

Flights 1, 2 & 5



Discing Propeller Drag - Total Drag for Both Propellers

Flights 1, 2 & 5



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

The following table shows the test runs used to determine the anti-skid braking wheel slip ratio ($_S$). Pages C3 to C48 show time histories of all the brake related data. The series of graphs down the left-hand side of the page show the ground speed and the left-hand: inner and outer wheel speeds, inner and outer brake pressures, left and right brake pressures, and the inner and outer wheel slip ratios. The series of graphs down the right-hand side of the page, show similar data both for the right-hand side of the aircraft. The average run value of ground speed and $_S$ for each wheel is shown in the table and on Page C49.

FLT/ Date	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK	WEIGHT (LB)	MEAN SPEED (KTGS)	MEAN SLIP RATIO S see note **			
							LO	LI	RO	RI
2001/01 29/01/01	8 15:42	26	RTO	15/IDLE/B	31150	51	0.139	0.139	0.108	0.108
	9 15:53	26	LAND	15/IDLE/B	31050	54	0.142	0.141	0.123	0.120
2001/02 31/01/01	5 14:45	31TS	RTO	15/IDLE/B	32240	21	0.102	0.103	0.099	0.103
	6 15:03	31TS	RTO	15/IDLE/B	32060	27	0.093	0.097	0.091	0.103
	7 15:13	31TS	RTO	15/IDLE/B	31960	37	0.061	0.064	0.056	0.058
	8 15:20	31TS	RTO	15/IDLE/B	31890	54	0.063	0.065	0.051	0.050
	9 15:32	31TS	RTO	15/DISC/B	31770	41	0.067	0.066	0.050	0.056
	10 15:38	31TS	RTO	15/DISC/B	31710	44	0.066	0.064	0.053	0.056
	11 15:43	31TS	RTO	15/DISC/B	31660	49	0.072	0.070	0.057	0.052
	13 16:04	08TS	RTO	15/IDLE/B	31450	48	0.084	0.082	0.094	0.086
	16 16:25	08TS	RTO	15/DISC/B	31240	35	0.120	0.120	0.094	0.084
	18 16:39	08TS	RTO	15/IDLE/B	31100	41	0.083	0.084	0.100	0.084
2001/03 01/02/01	1 10:47	36N	RTO	15/IDLE/B	30700	28	0.087	0.087	0.112	0.117
	2 10:52	36N	RTO	15/IDLE/B	30650	26	0.100	0.101	0.076	0.090
	3 11:02	36N	RTO	15/IDLE/B	30560	46	0.071	0.071	0.058	0.059
	4 11:09	36N	RTO	15/DISC/B	30500	37	0.103	0.104	0.092	0.089
	5 11:52	31TS	RTO	15/IDLE/B	30150	26	0.113	0.115	0.096	0.131
	6 11:58	31TS	RTO	15/IDLE/B	30090	49	0.070	0.072	0.062	0.064
	7 12:04	31TS	RTO	15/IDLE/B	30030	61	0.080	0.081	0.055	0.055
	8 12:15	31TS	LAND	15/IDLE/B	29880	51	0.075	0.076	0.057	0.061
	9 12:22	31TS	LAND	15/DISC/B	29780	52	0.075	0.076	0.066	0.064
	10	31TS	LAND	15/DISC/B	29720	52	0.075	0.075	0.063	0.063

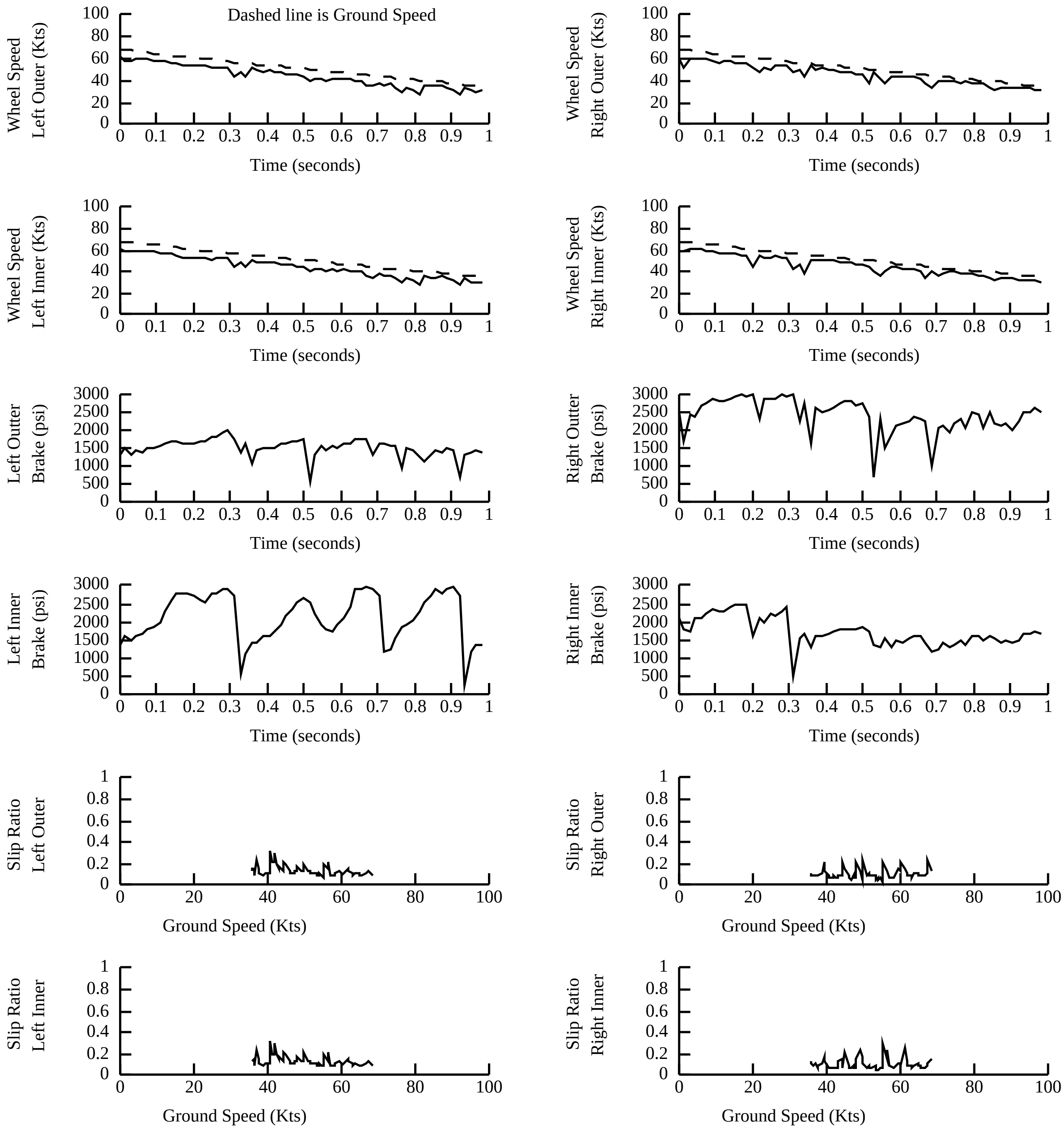
FLT/ Date	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK	WEIGHT (LB)	MEAN SPEED (KTGS)	MEAN SLIP RATIO S see note **			
	12:26									
	11 12:31	31TS	LAND	15/DISC/B	29650	31	0.131	0.130	0.150	0.108
2001/04 01/02/01	1 14:46	31TS	RTO	15/IDLE/B	30730	25	0.160	0.161	0.164	0.163
	2 14:50	31TS	RTO	15/IDLE/B	30700	40	0.104	0.104	0.083	0.087
	3 14:54	31TS	RTO	15/IDLE/B	30660	60	0.096	0.096	0.081	0.080
	4 15:02	31TS	LAND	15/IDLE/B	30520	40	0.103	0.103	0.093	0.092
	5 15:08	31TS	LAND	15/DISC/B	30440	38	0.097	0.097	0.093	0.099
	6 15:15	31TS	LAND	15/DISC/B	30350	40	0.123	0.123	0.101	0.115
2001/05 21/03/01	1 14:11	31N	RTO	15/IDLE/B	31210	23	0.151	0.154	0.142	0.146
	2 14:24	31N	RTO	15/IDLE/B	31100	27	0.145	0.140	0.110	0.107
	3 14:35	31N	RTO	15/IDLE/B	31000	53	0.060	0.059	0.059	0.073
	4 14:42	31N	RTO	15/IDLE/B	30940	28	0.115	0.113	0.103	0.101
2001/06 22/03/01	1 07:25	31N	RTO	15/DISC/B	30450	12	1.000	1.000	1.000	1.000
	2 07:30	31N	RTO	15/DISC/B	30410	16	1.000	1.000	1.000	1.000
	3 07:40	31N	RTO	15/DISC/B	30330	24	0.130	0.132	0.132	0.156
	4 07:45	31N	RTO	15/DISC/B	30290	25	0.112	0.114	0.140	0.131
	5 07:55	31N	RTO	15/IDLE/B	30210	33	0.107	0.109	0.117	0.120
	6 08:00	31N	RTO	15/IDLE/B	30170	33	0.091	0.093	0.106	0.114
	7 08:13	31N	RTO	15/IDLE/B	30060	36	0.096	0.099	0.090	0.099
	8 08:17	31N	RTO	15/IDLE/B	30030	38	0.100	0.102	0.088	0.098
2001/07 22/03/01	1 10:08	31N	RTO	15/IDLE/B	29810	34	0.099	0.099	0.094	0.112
	2 10:12	31N	RTO	15/IDLE/B	29780	50	0.085	0.086	0.089	0.077
2001/08 23/03/01	1 11:28	31TS	RTO	15/IDLE/B	29300	38	0.097	0.098	0.087	0.091
	2 11:32	31TS	RTO	15/IDLE/B	29270	35	0.128	0.129	0.104	0.118
	3 12:02	31TS	RTO	15/IDLE/B	29030	45	0.087	0.087	0.079	0.080

Surface: 100% Bare and Dry

Flight 2001/01, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.67

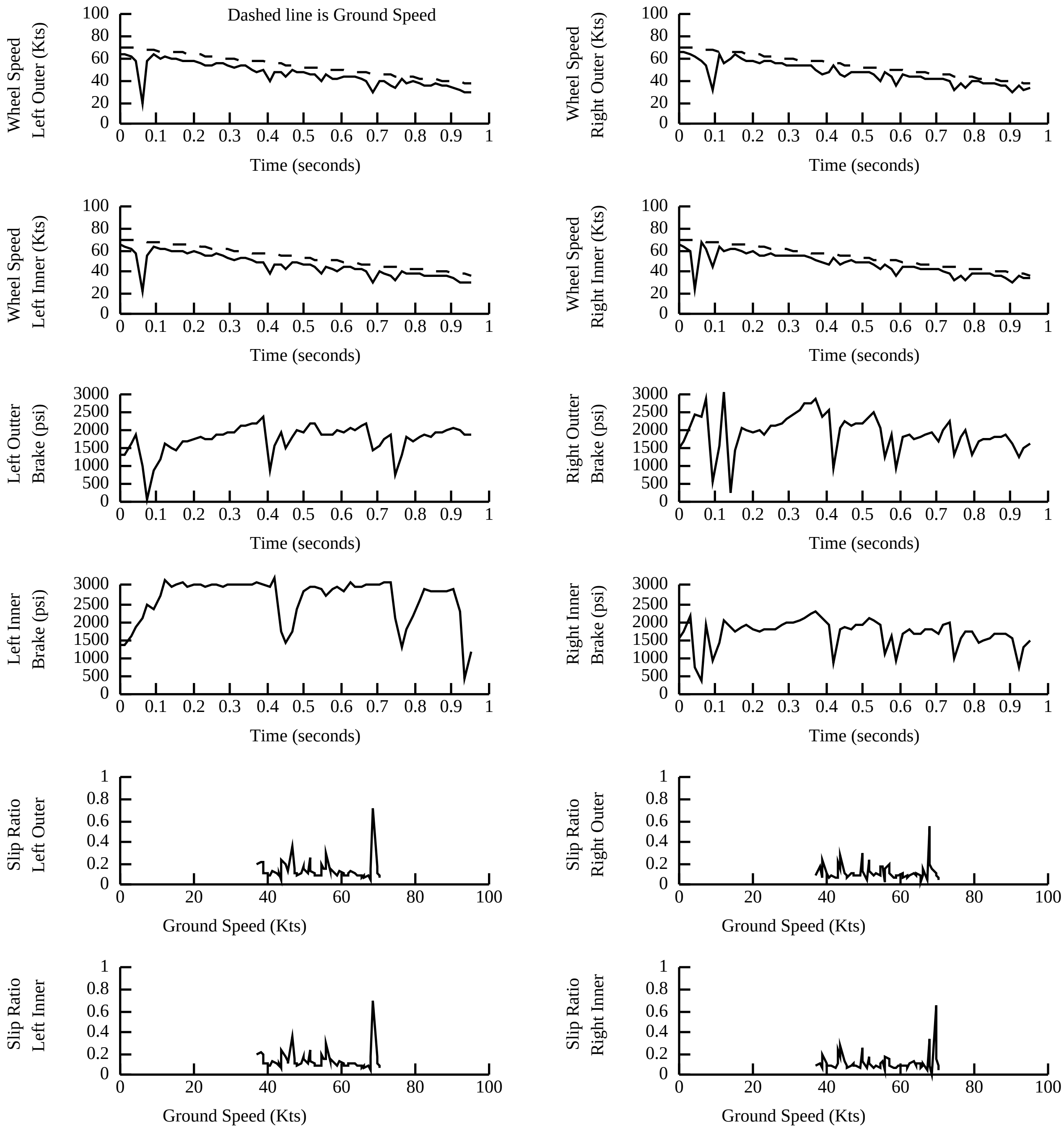


Surface: 100% Bare and Dry

Flight 2001/01, Run Number 9

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.67

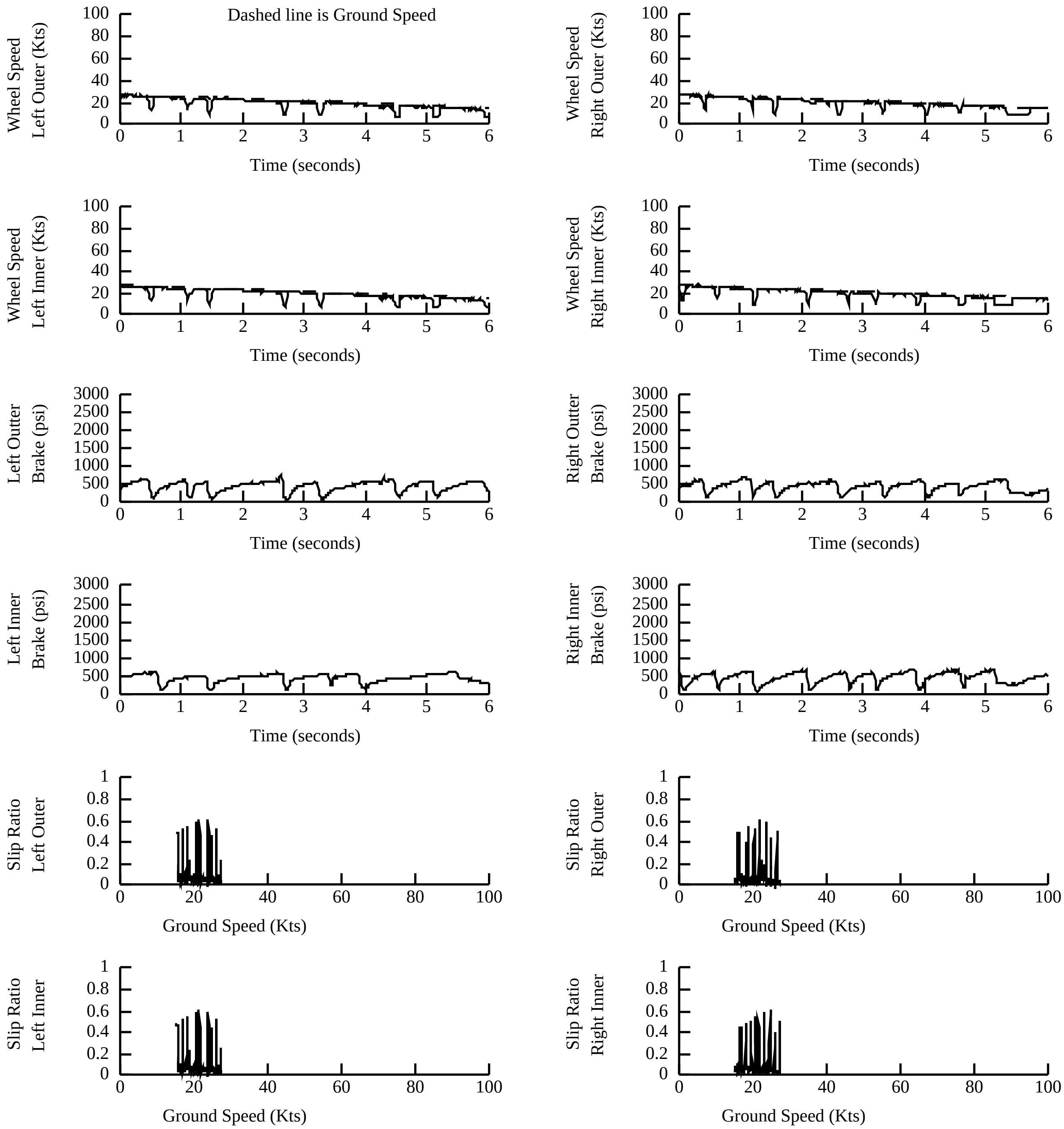


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.28

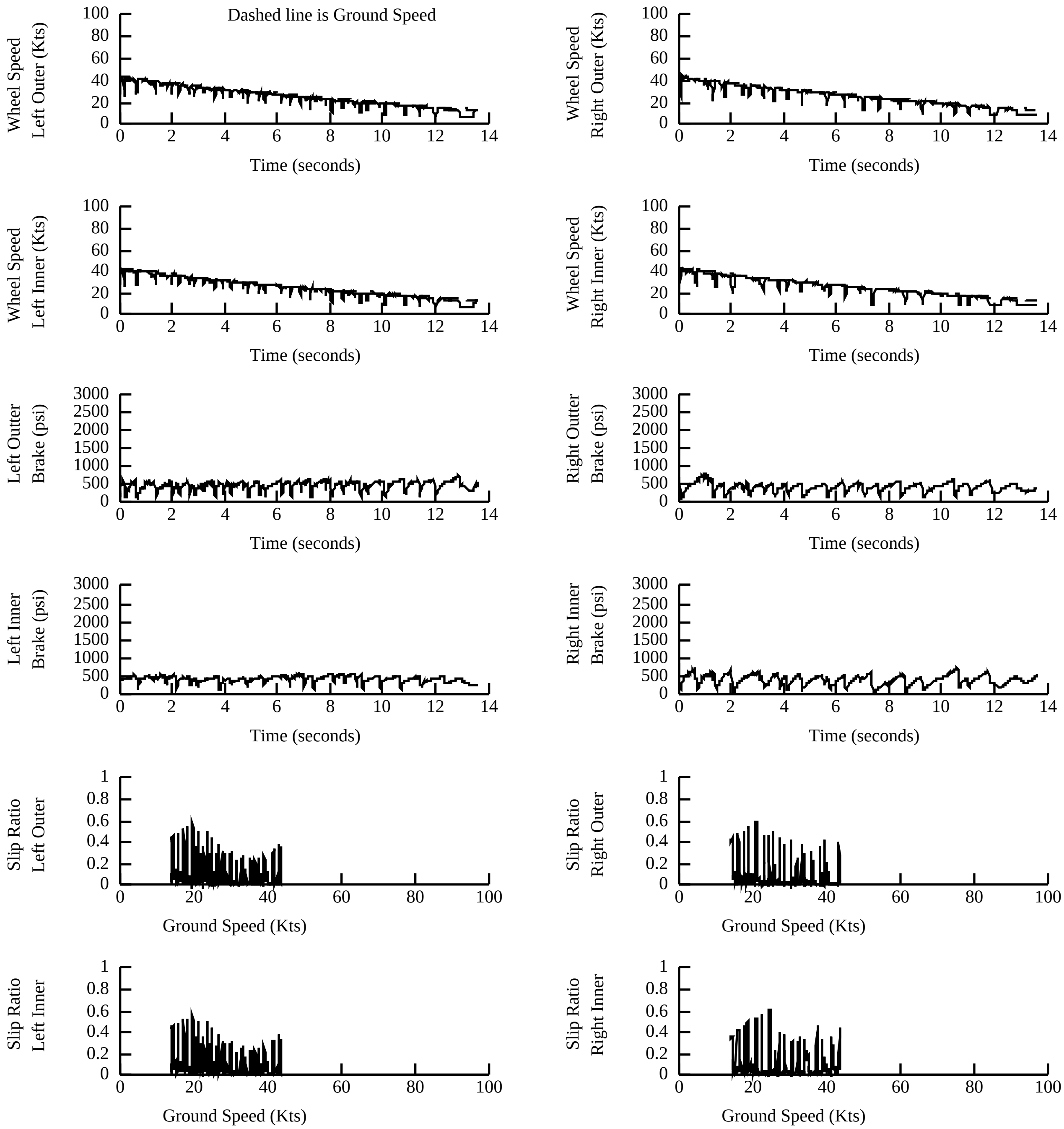


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.28

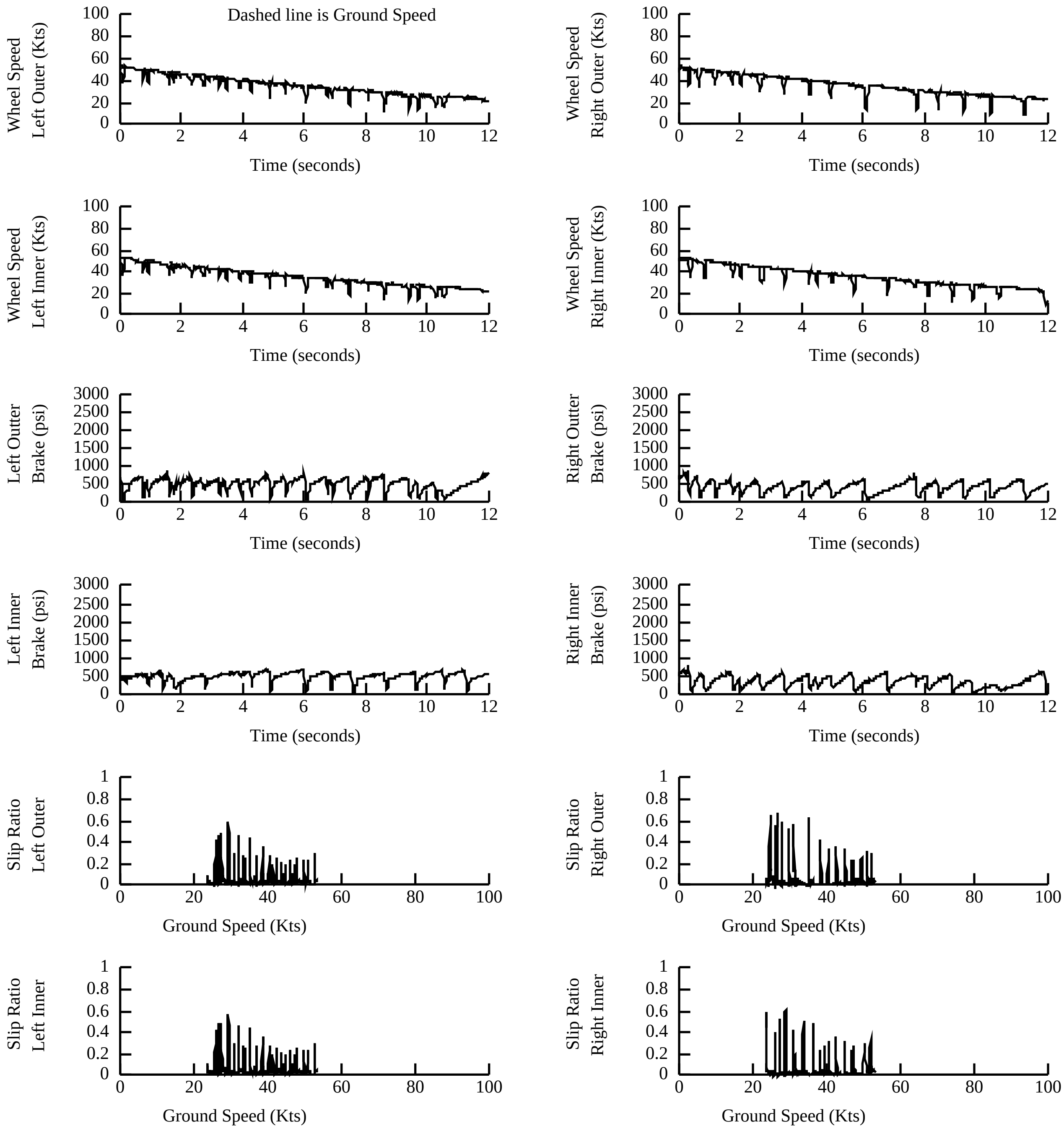


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.27

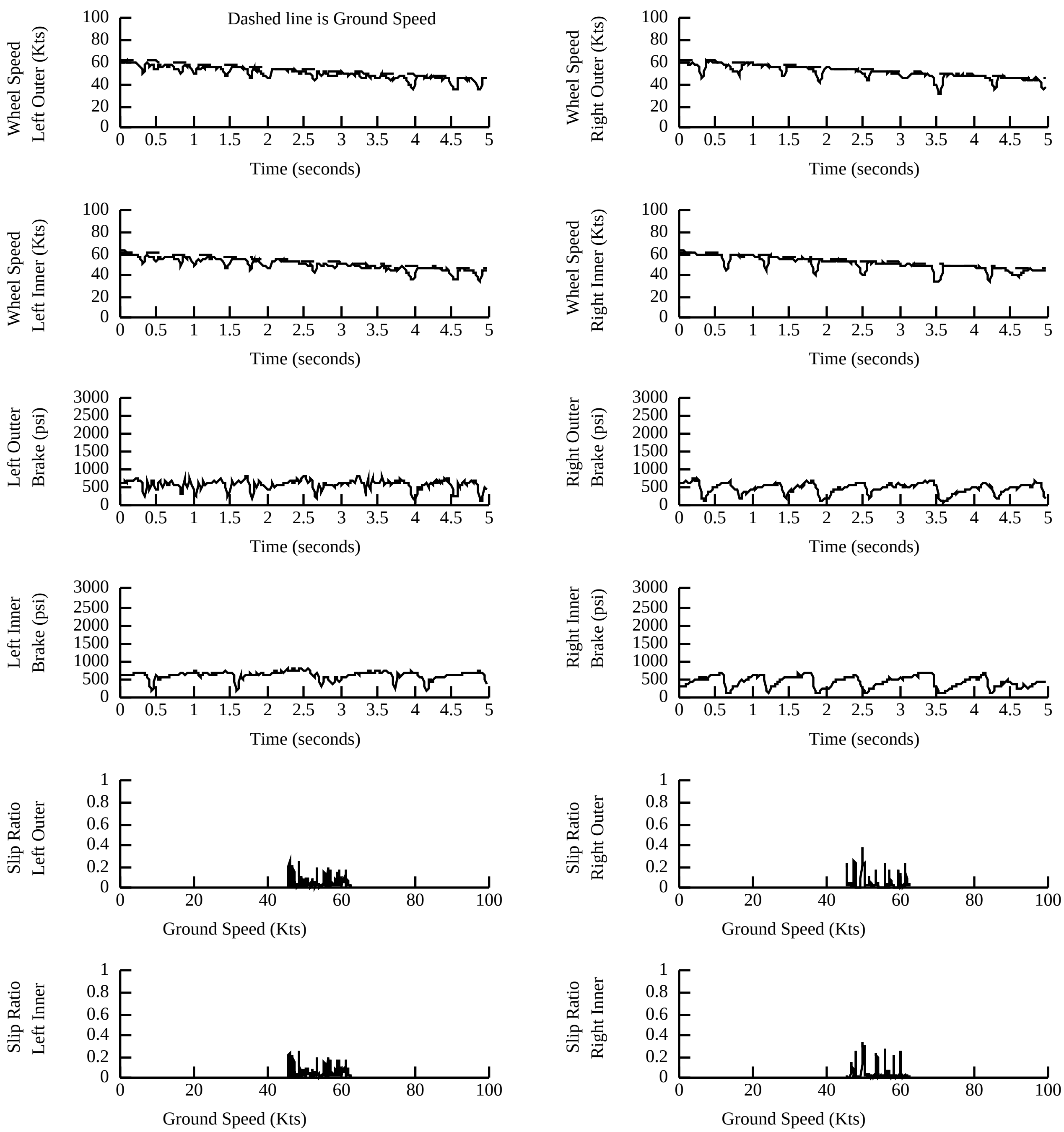


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.27

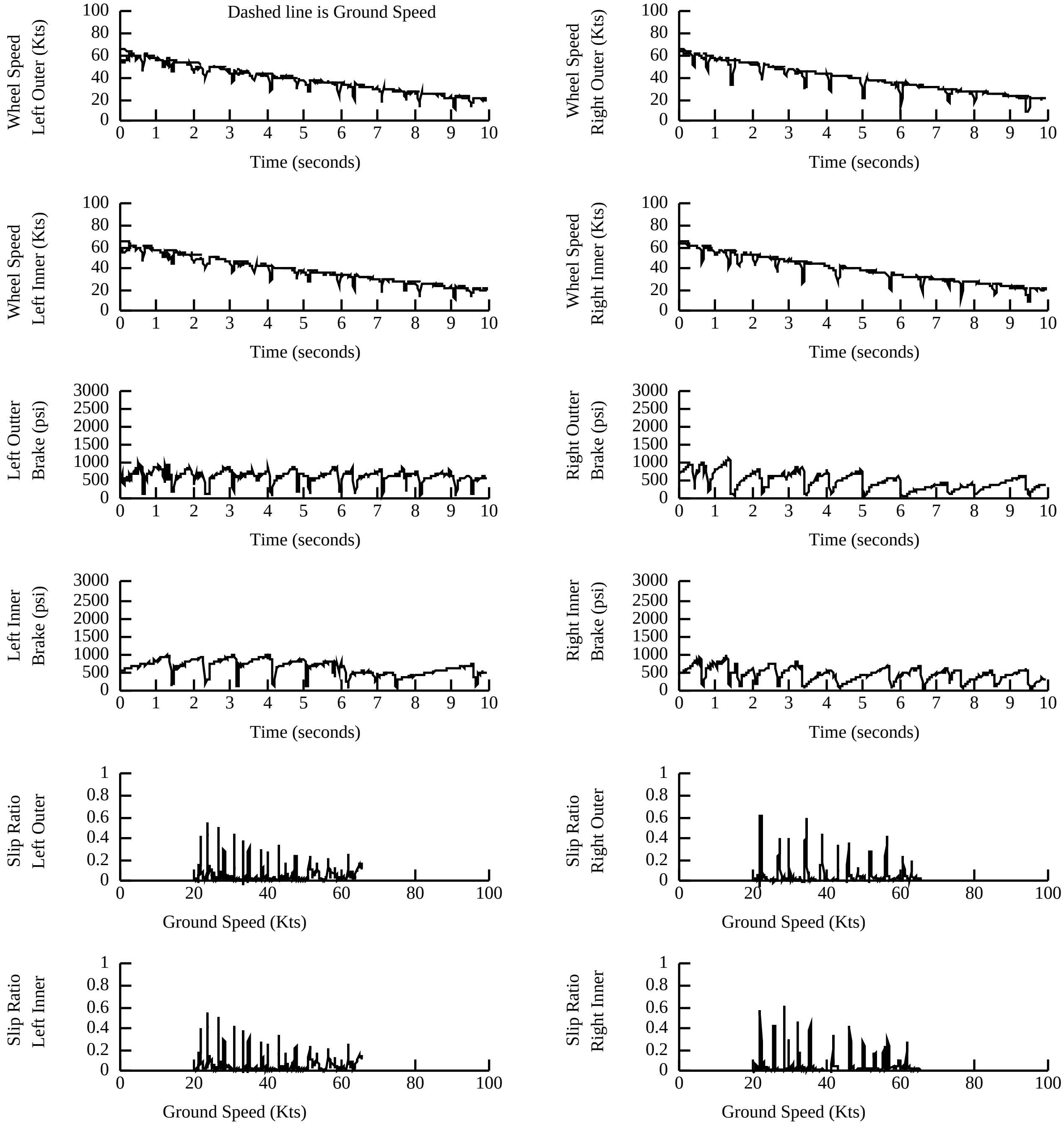


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 9

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.26

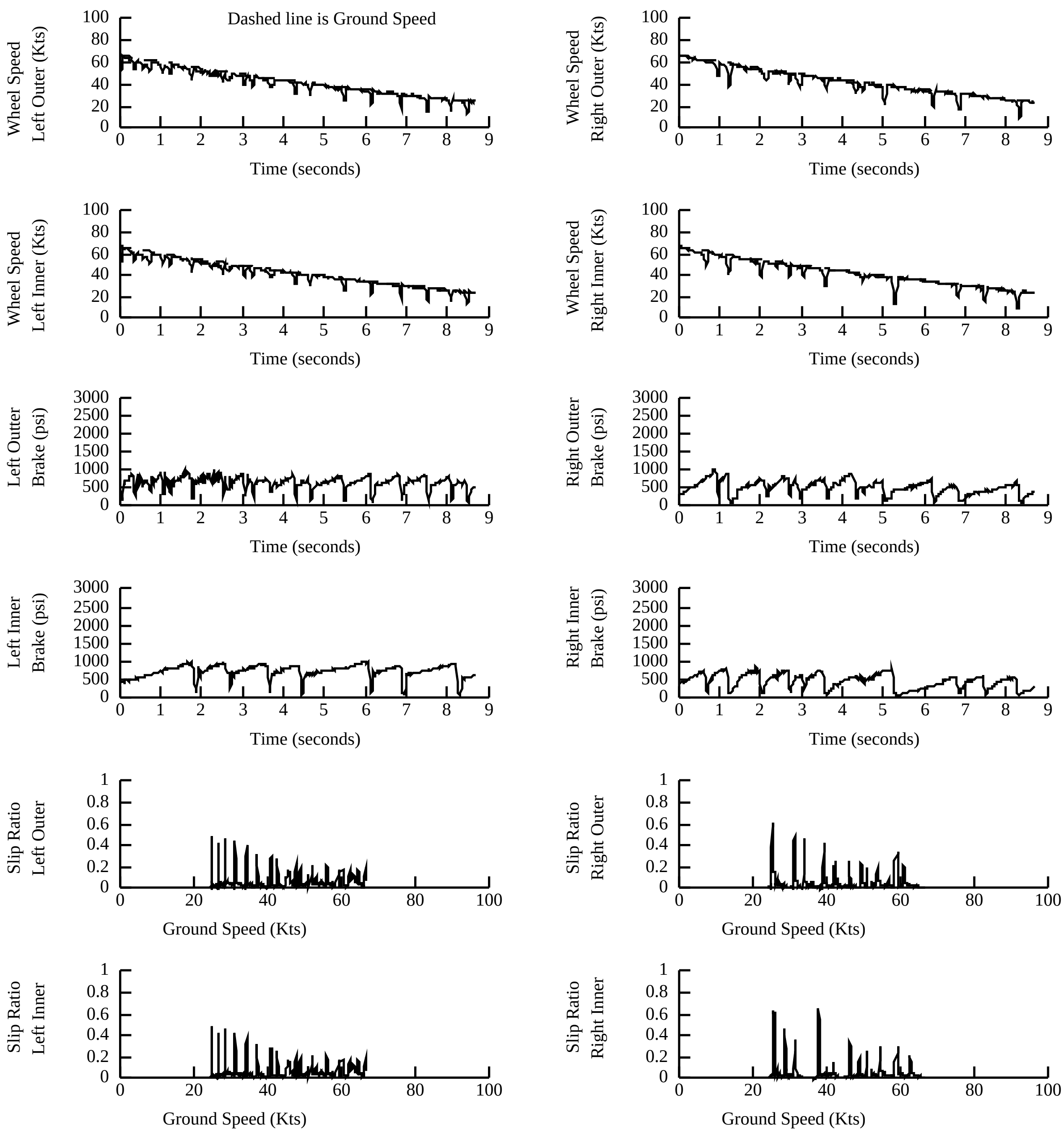


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 10

Configuration: Flaps 15, Discing, Max Reverse

CRFI Average 0.25

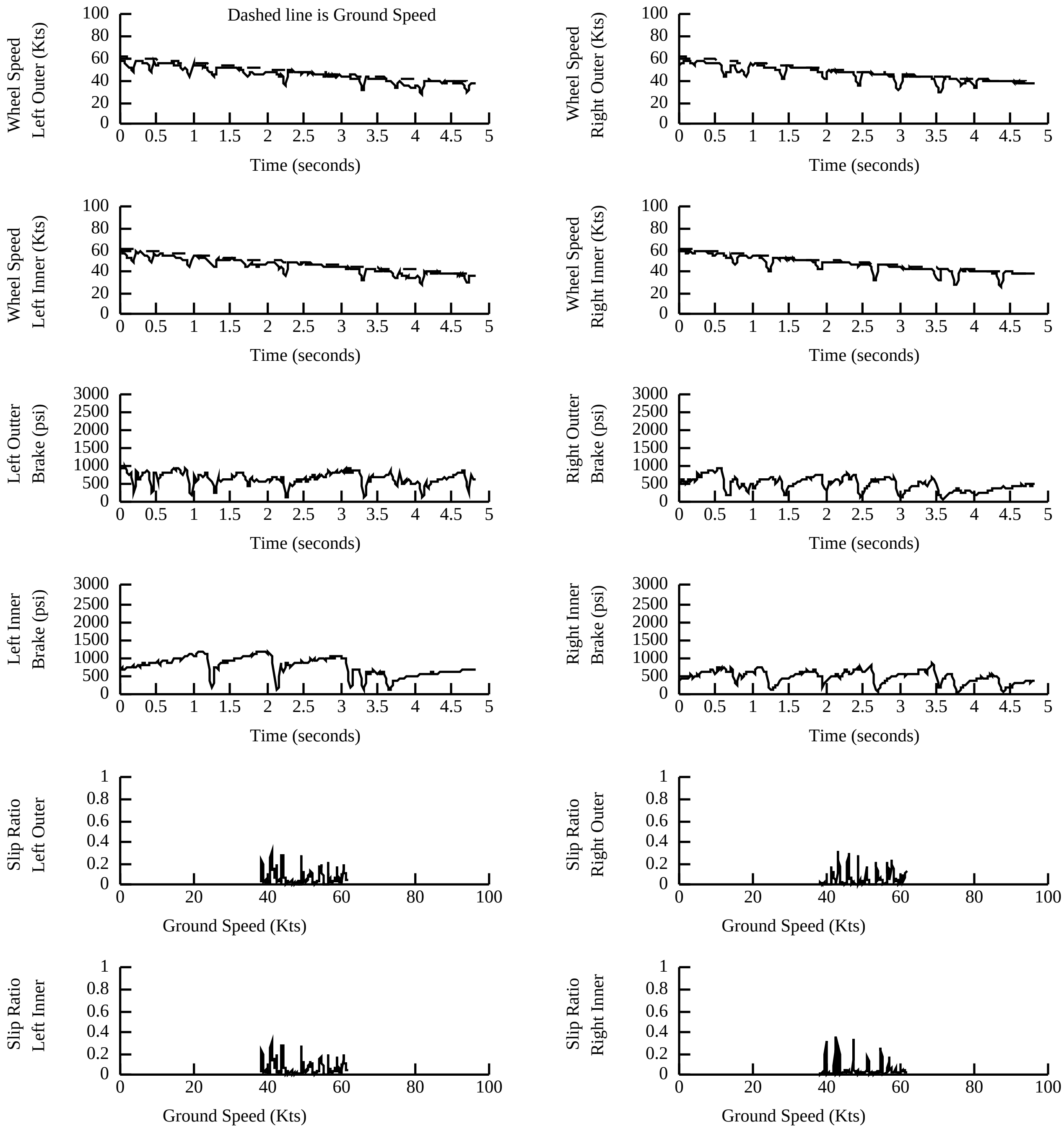


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 11

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.24

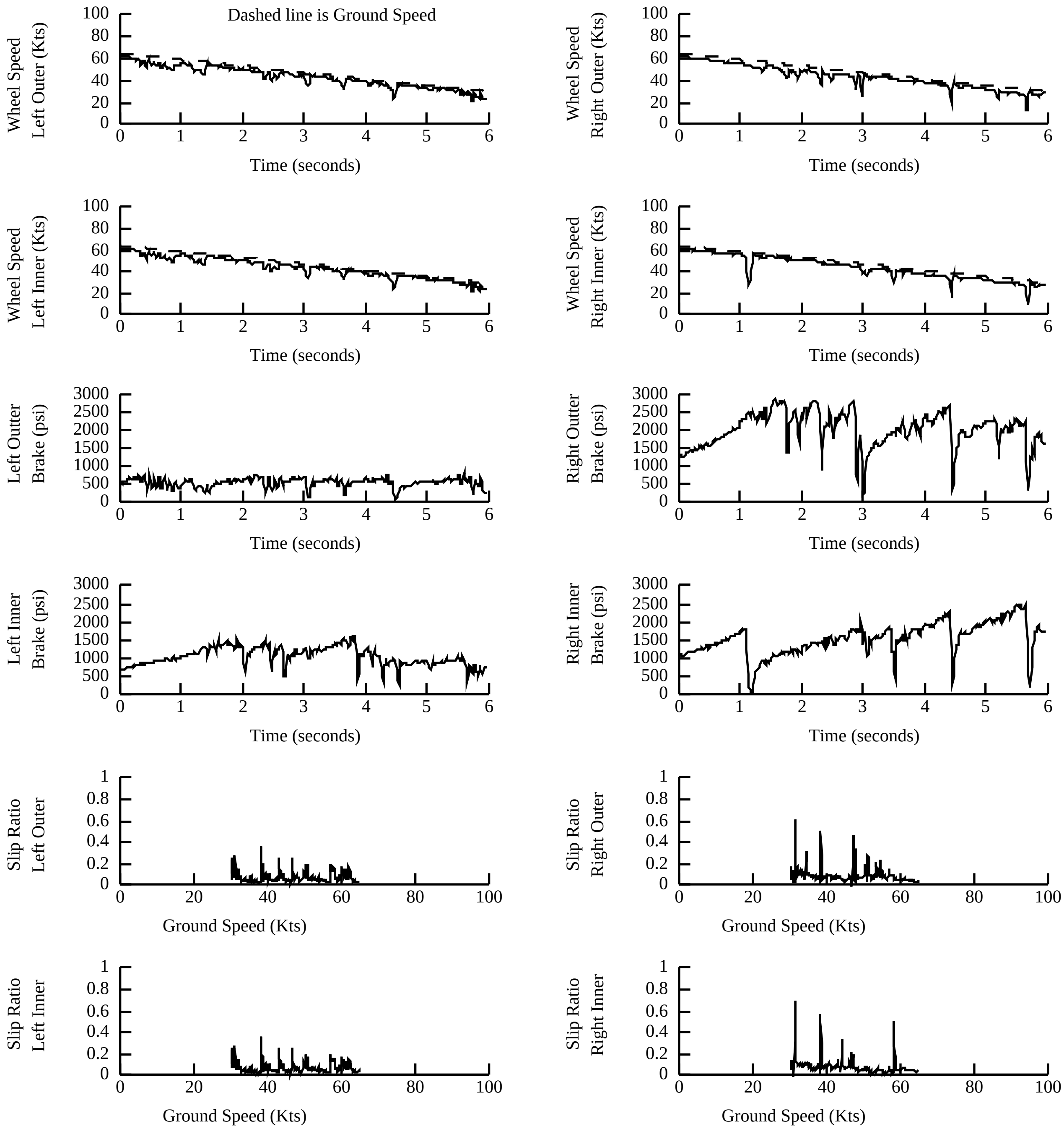


Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 13

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.31

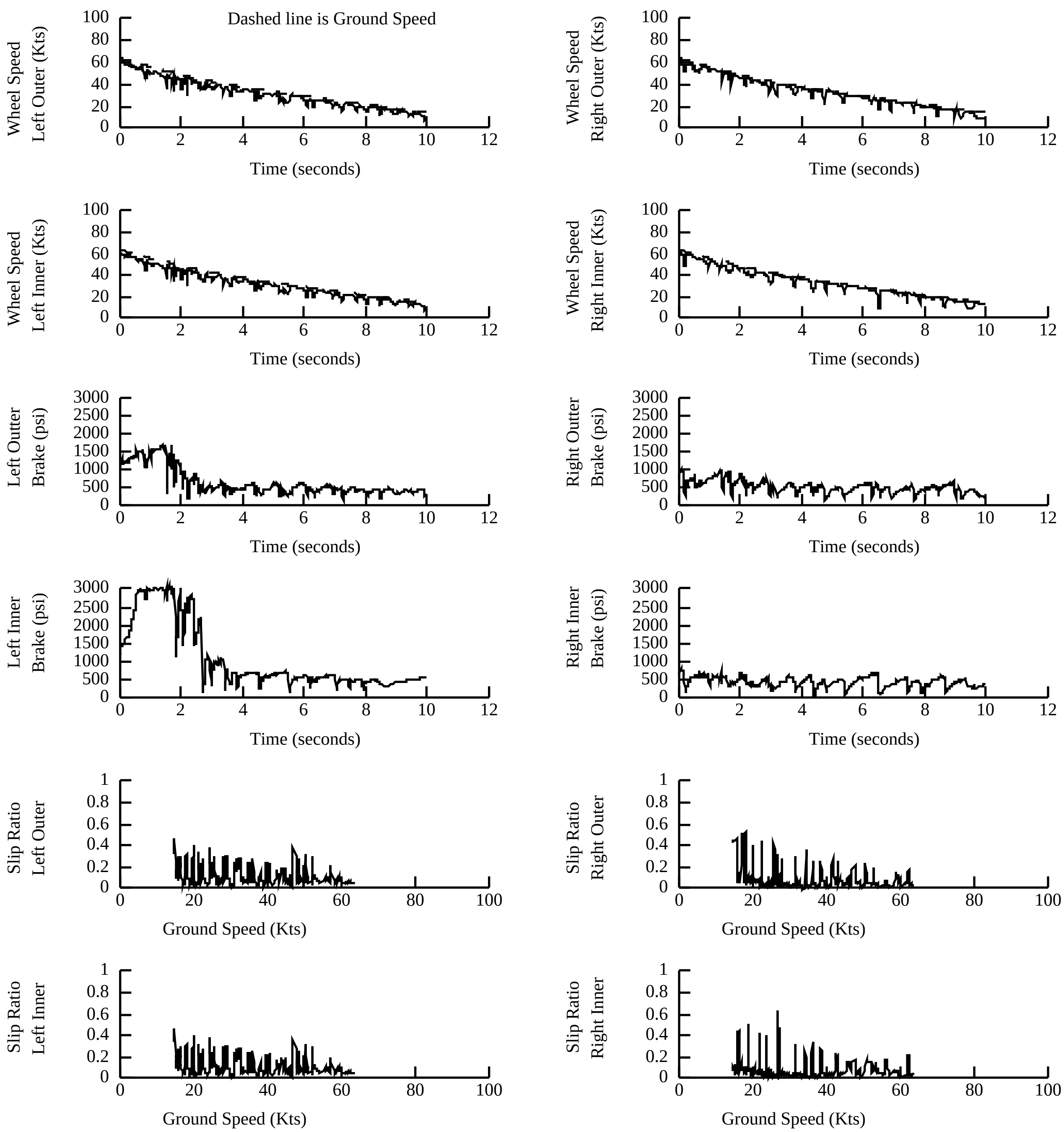


Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 16

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.31

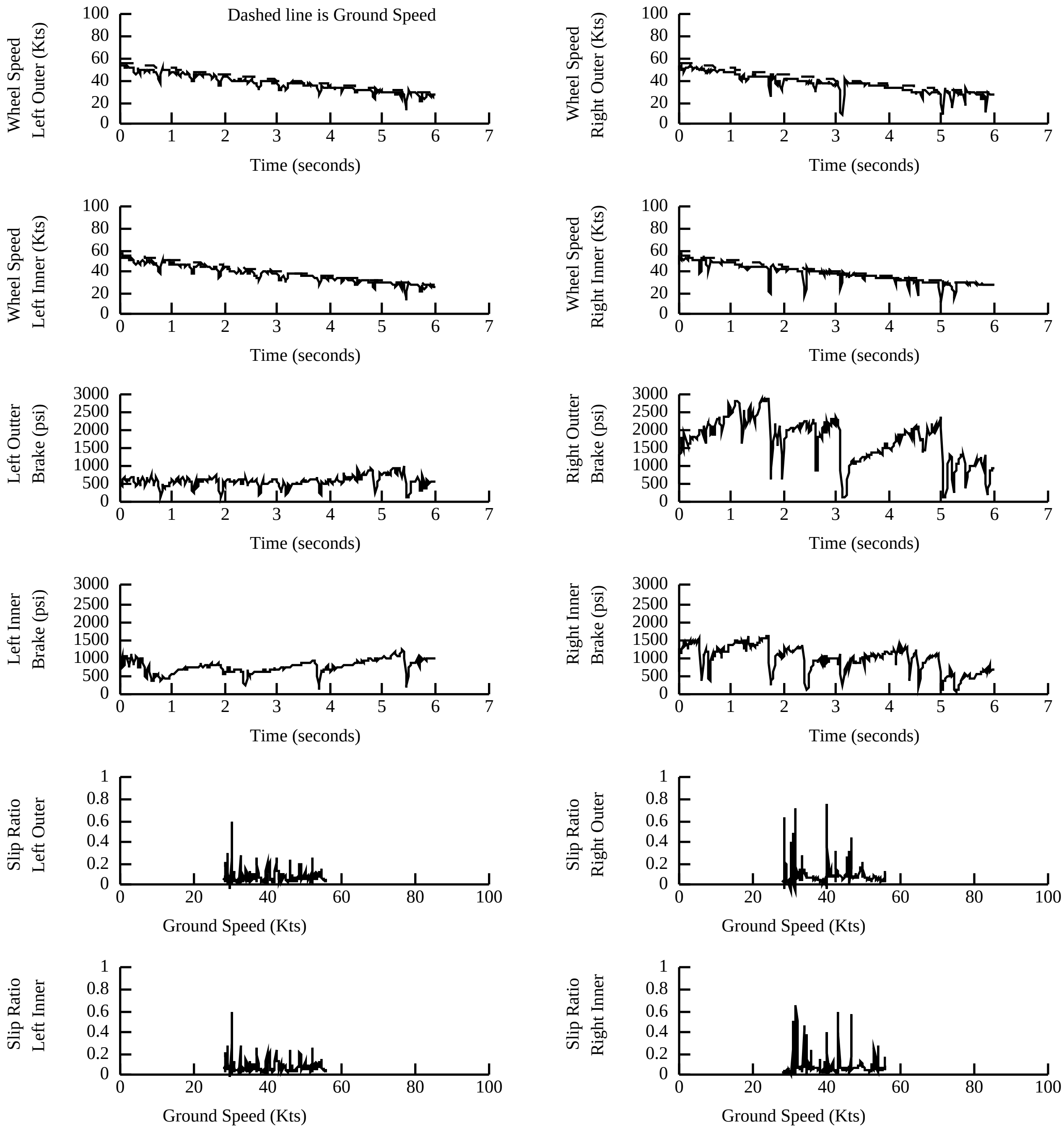


Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 18

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.32

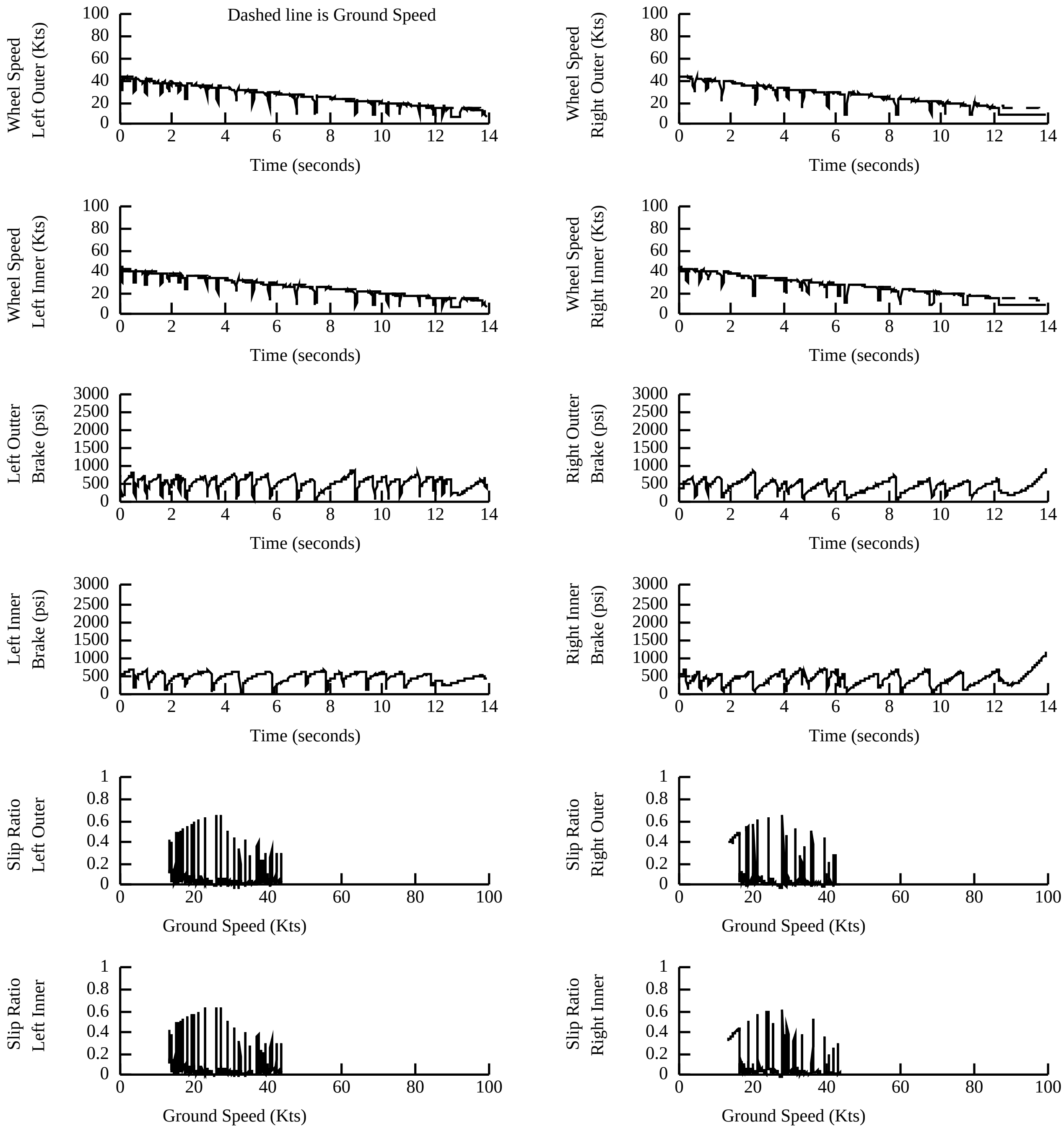


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.27

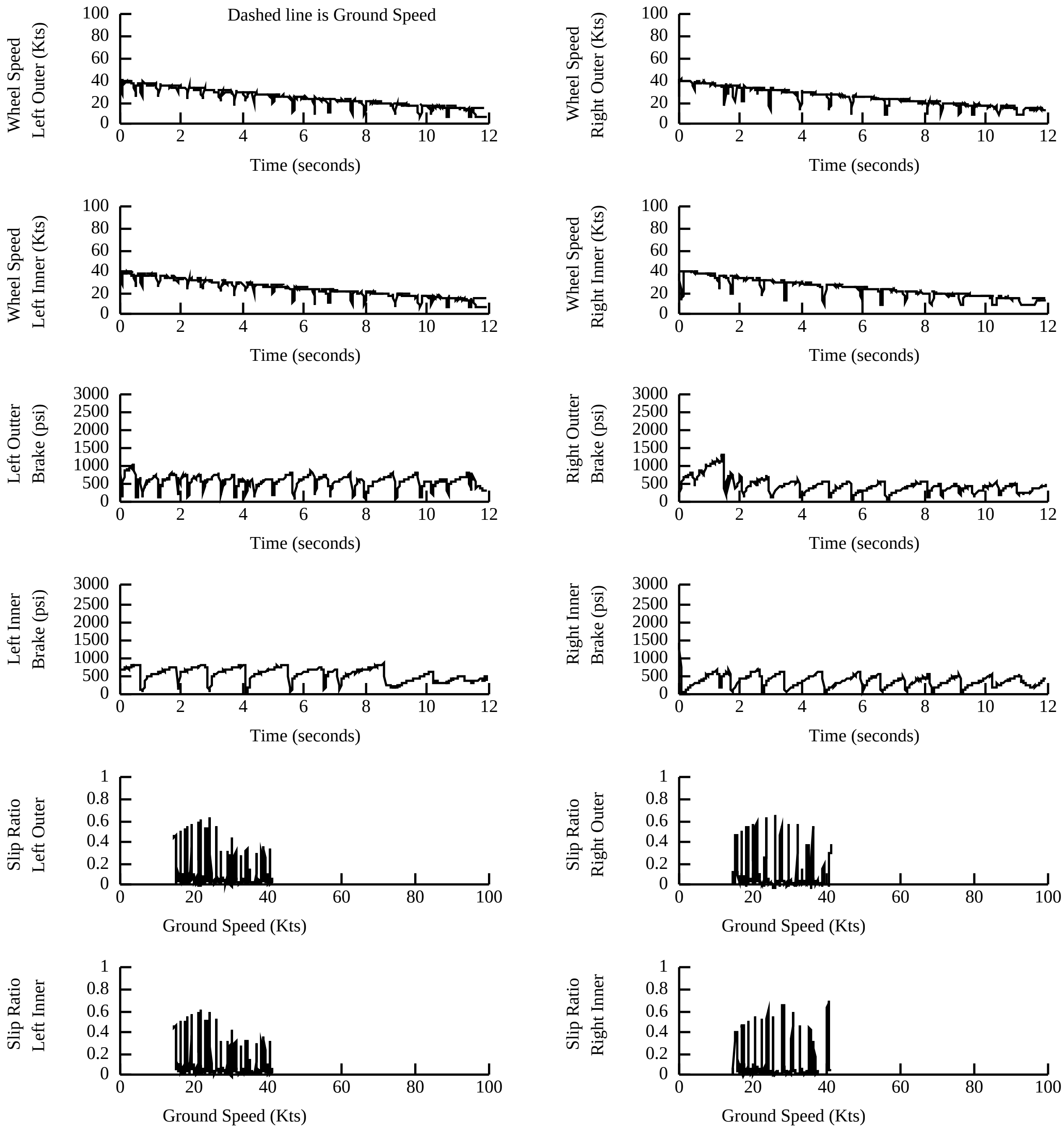


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.26

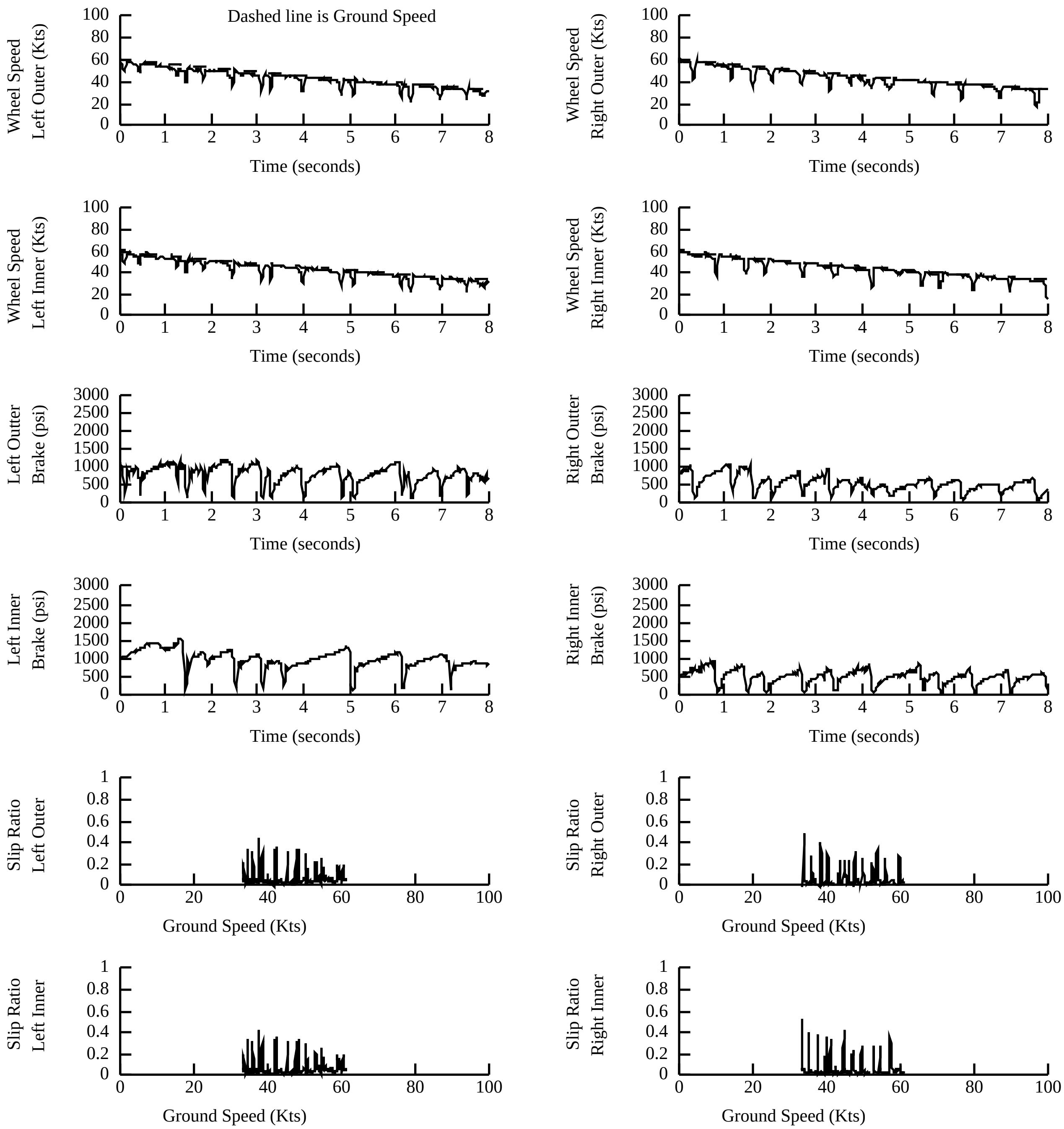


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.25

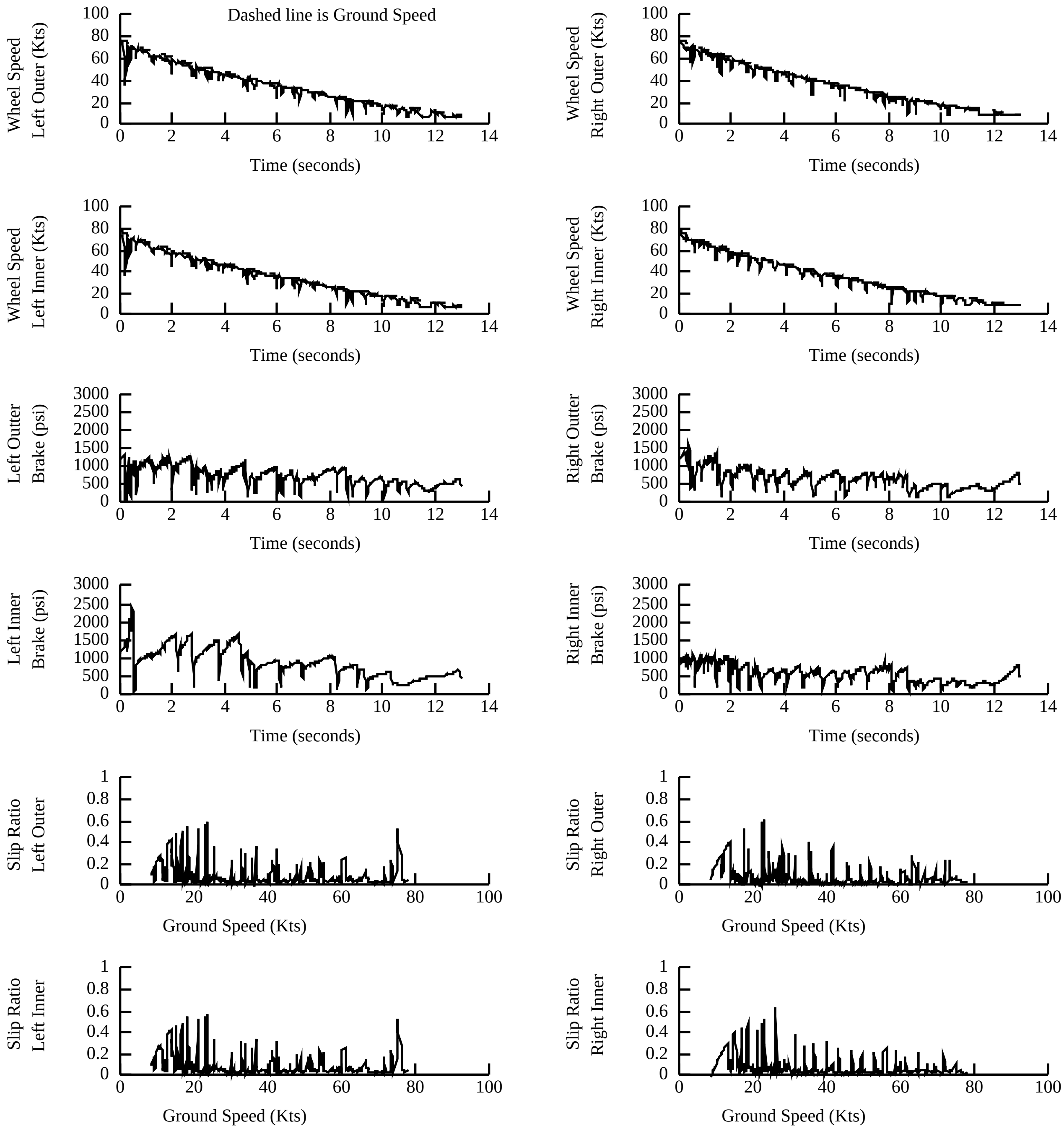


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 4

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

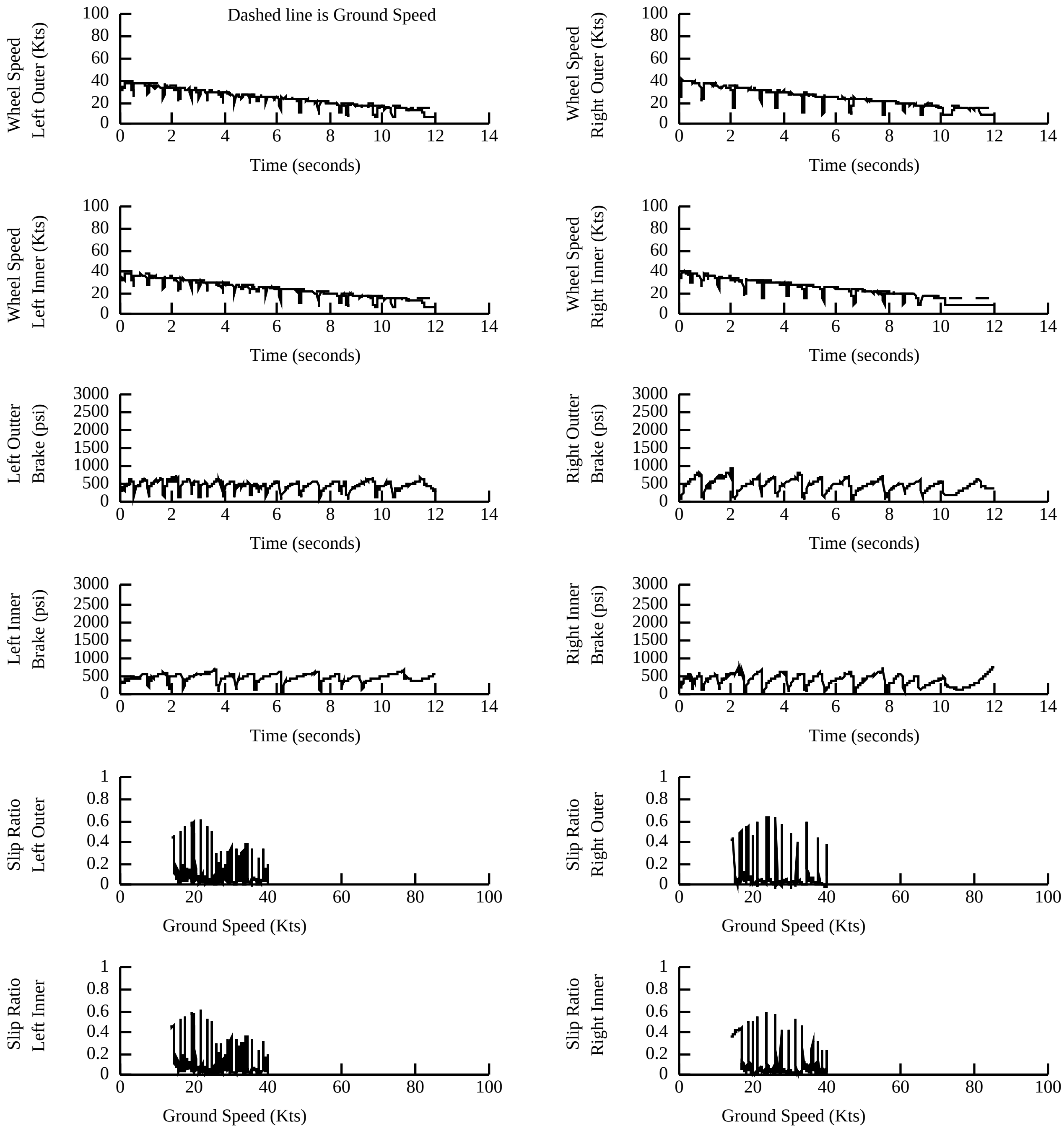


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.24

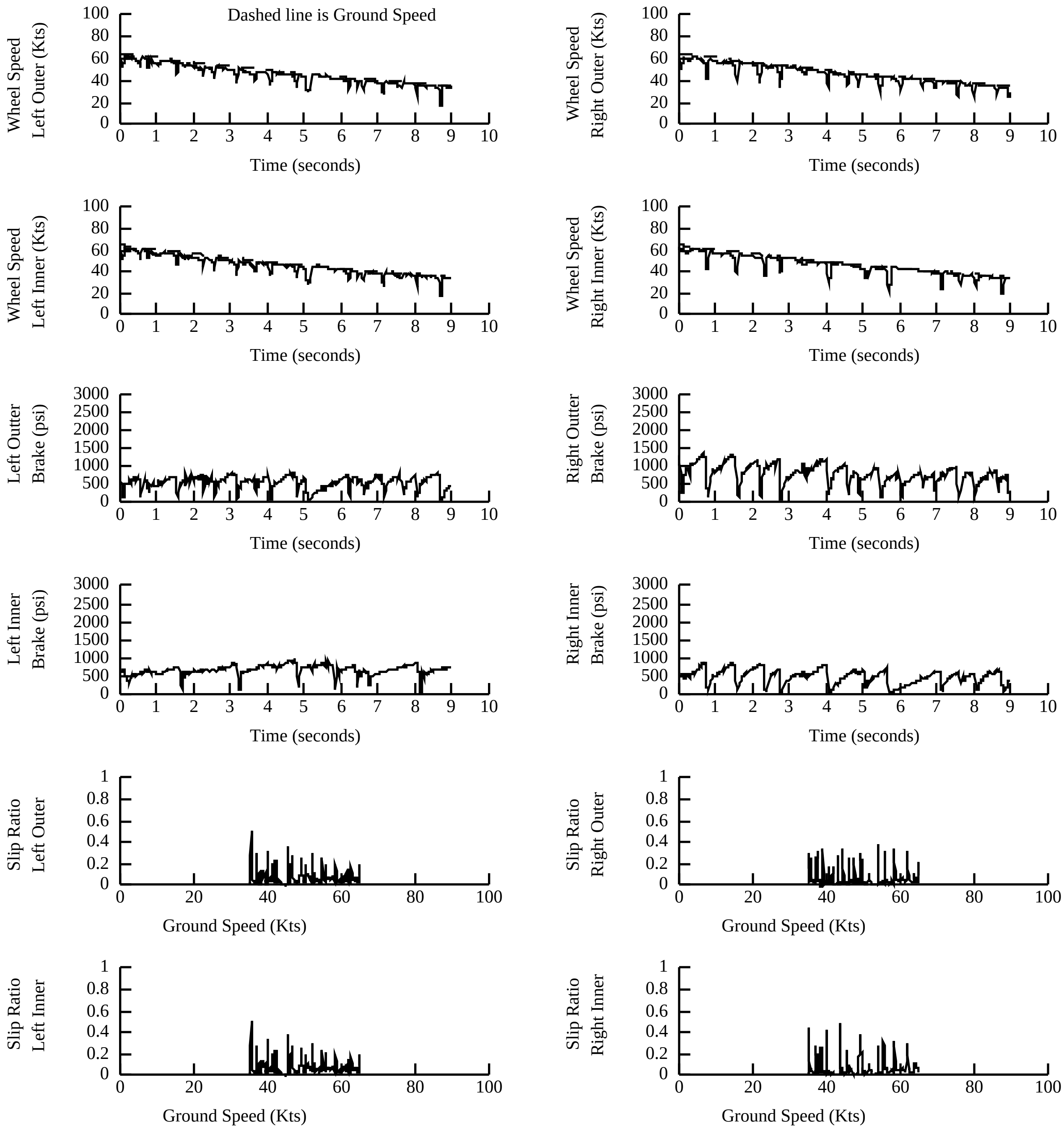


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.25

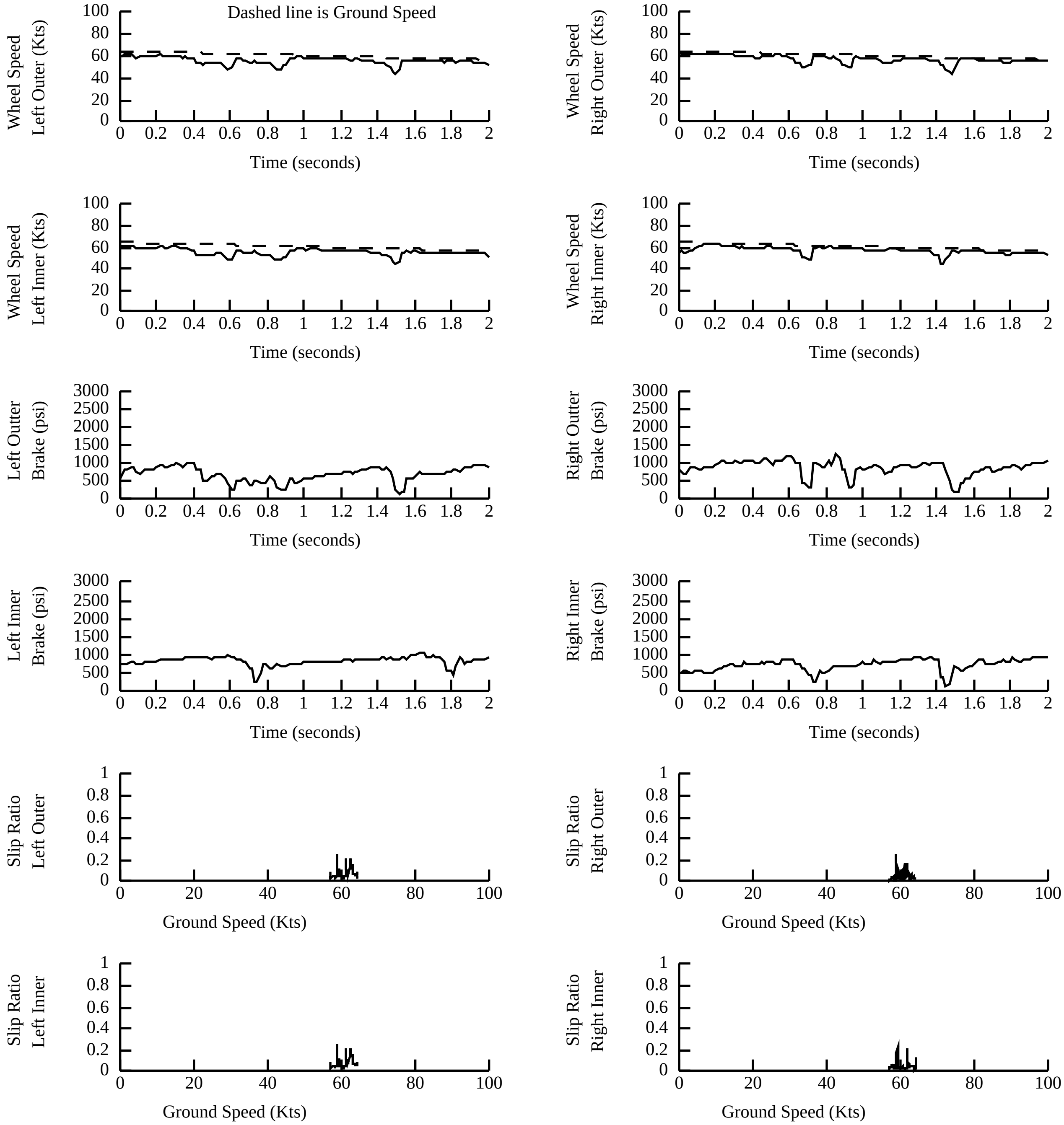


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.26

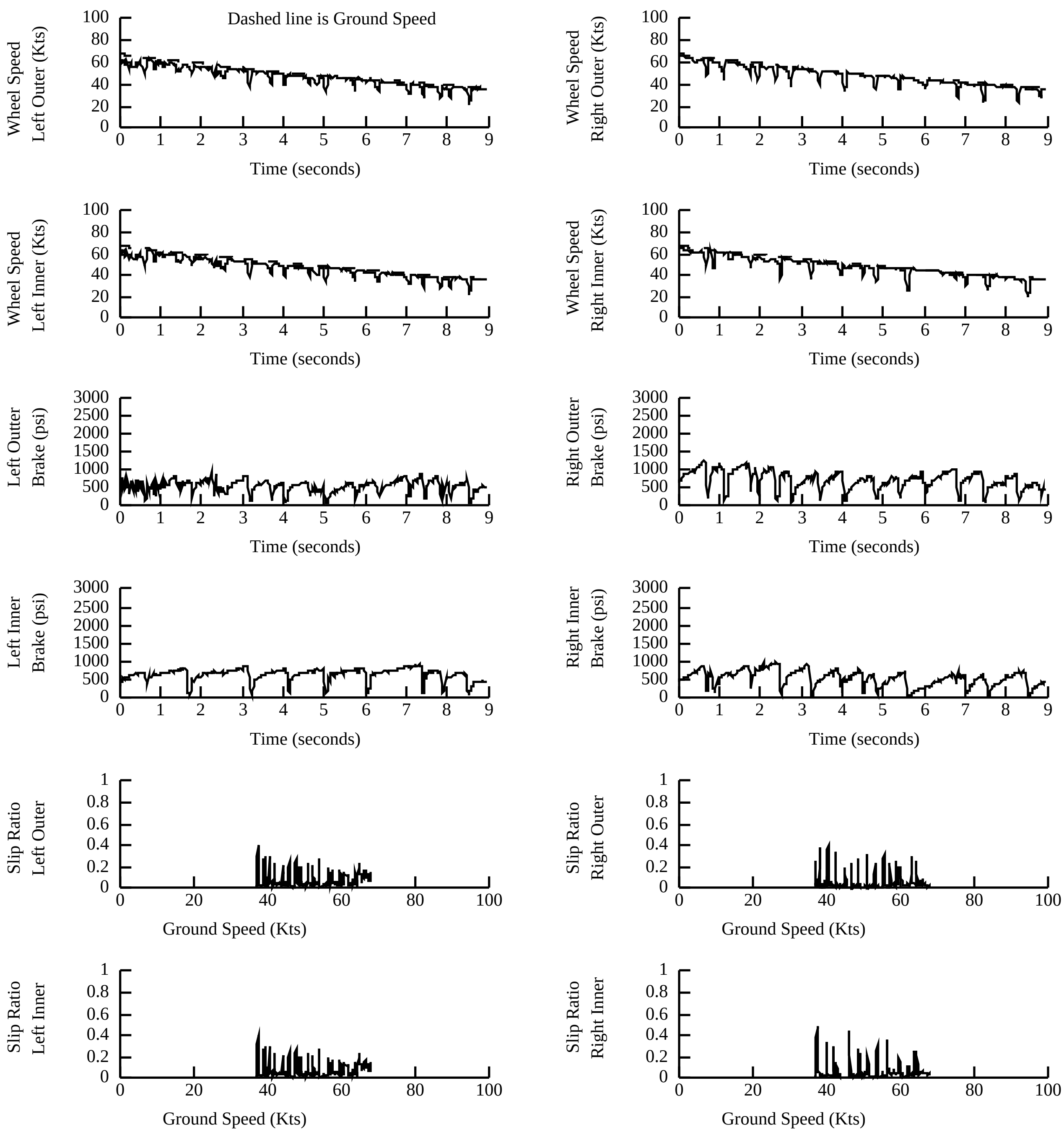


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.26

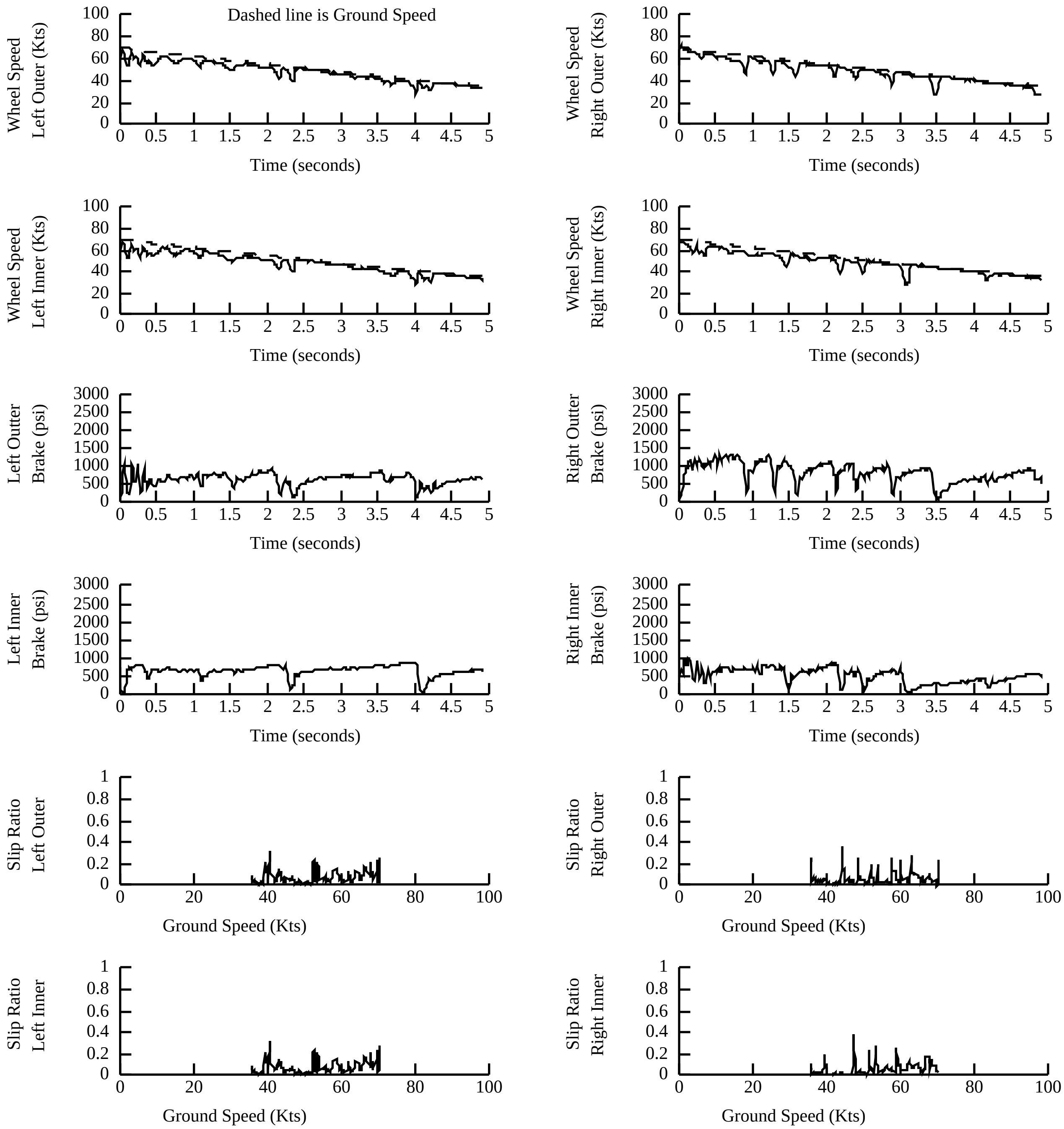


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 9

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

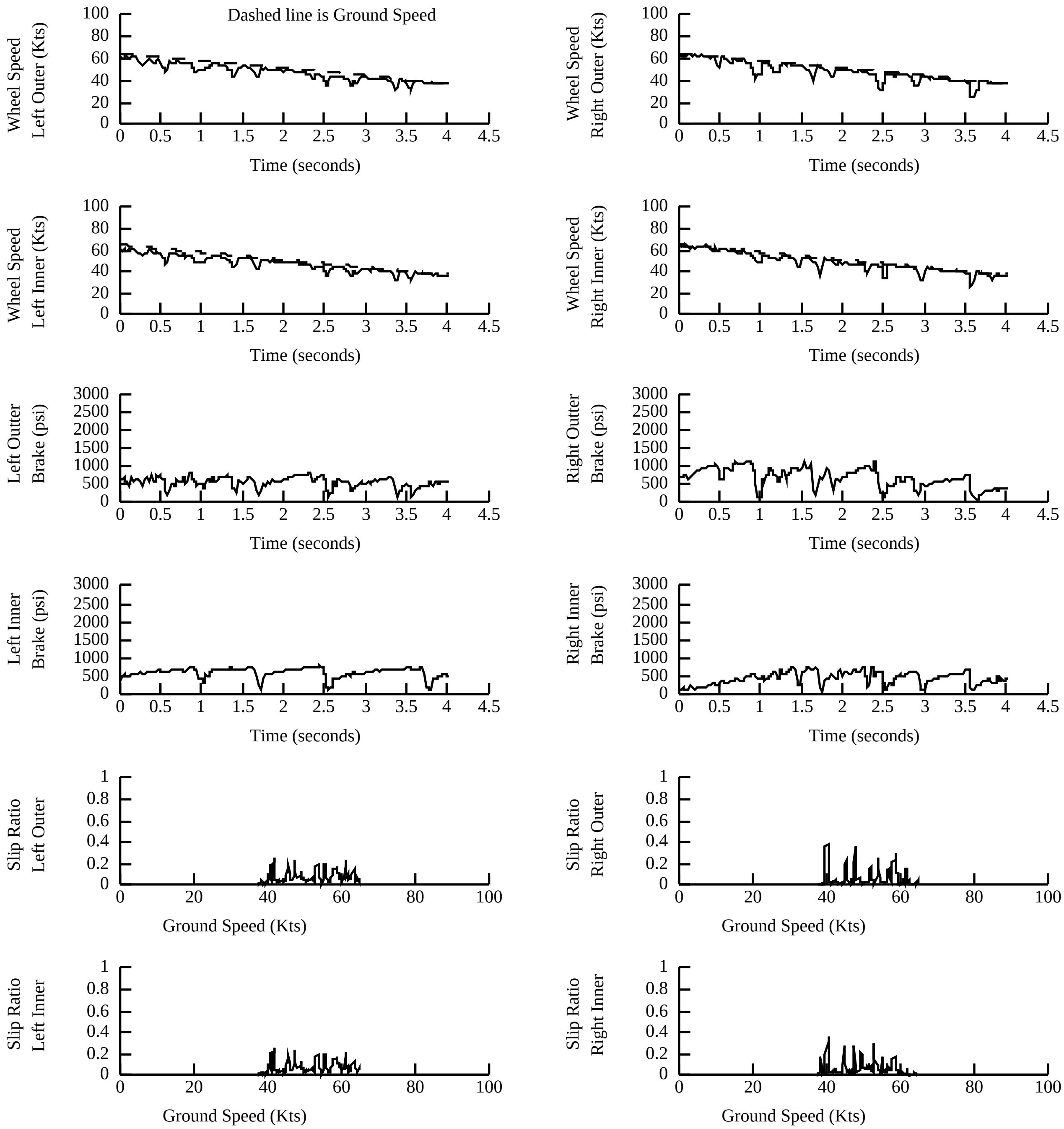


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 10

Configuration: Flaps 15, Discing, Max Reverse

CRFI Average 0.27

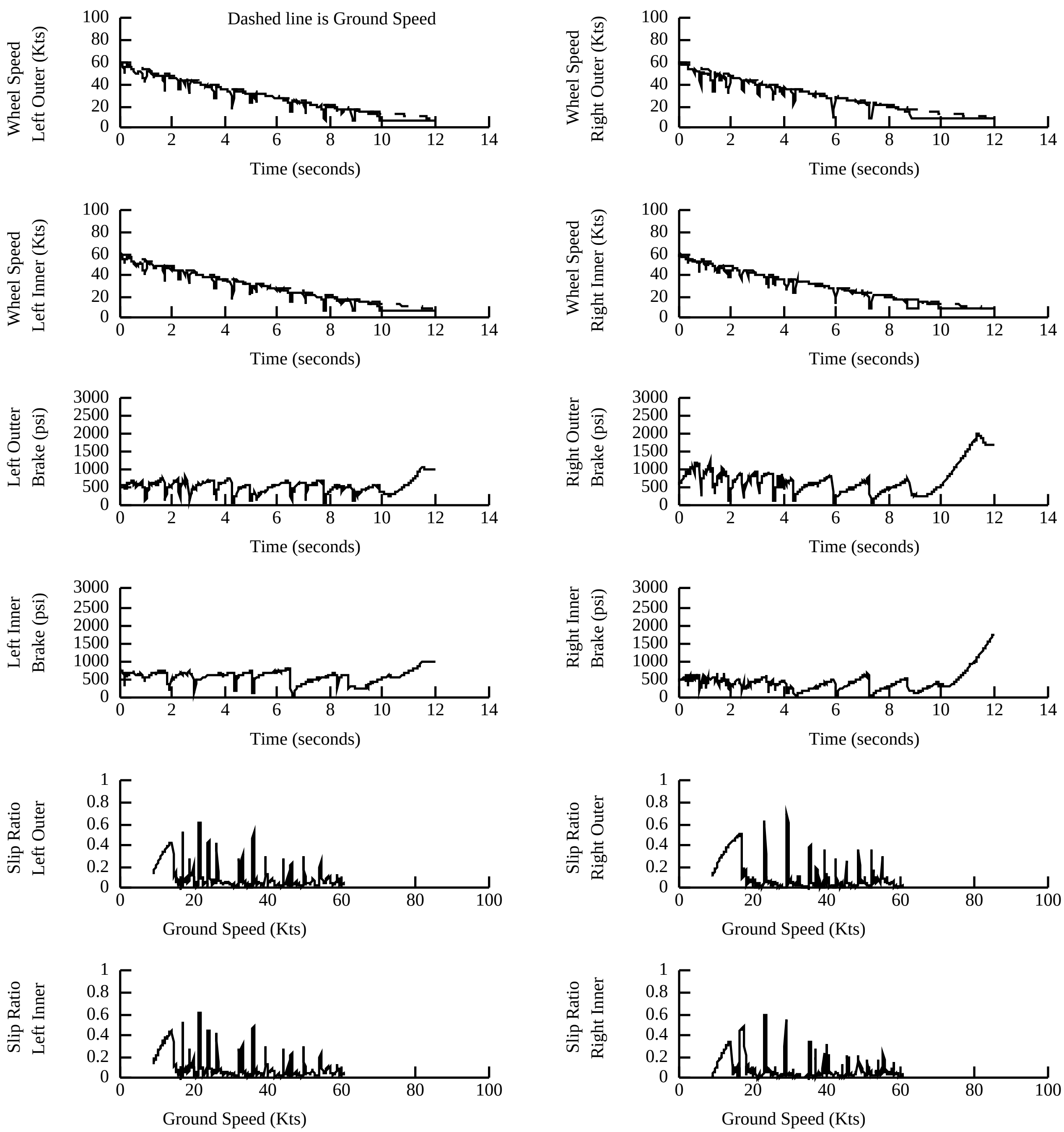


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 11

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

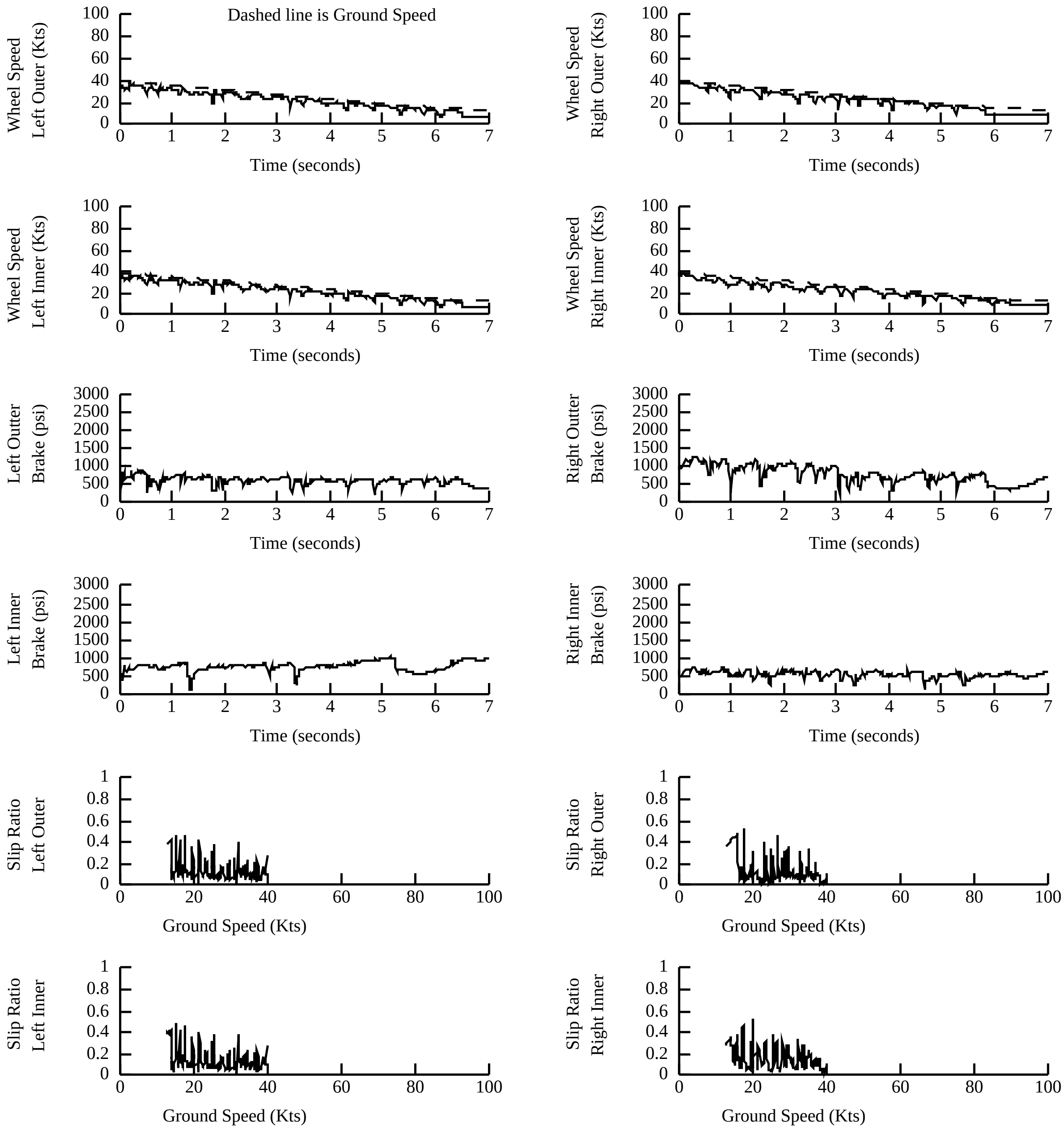


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.40

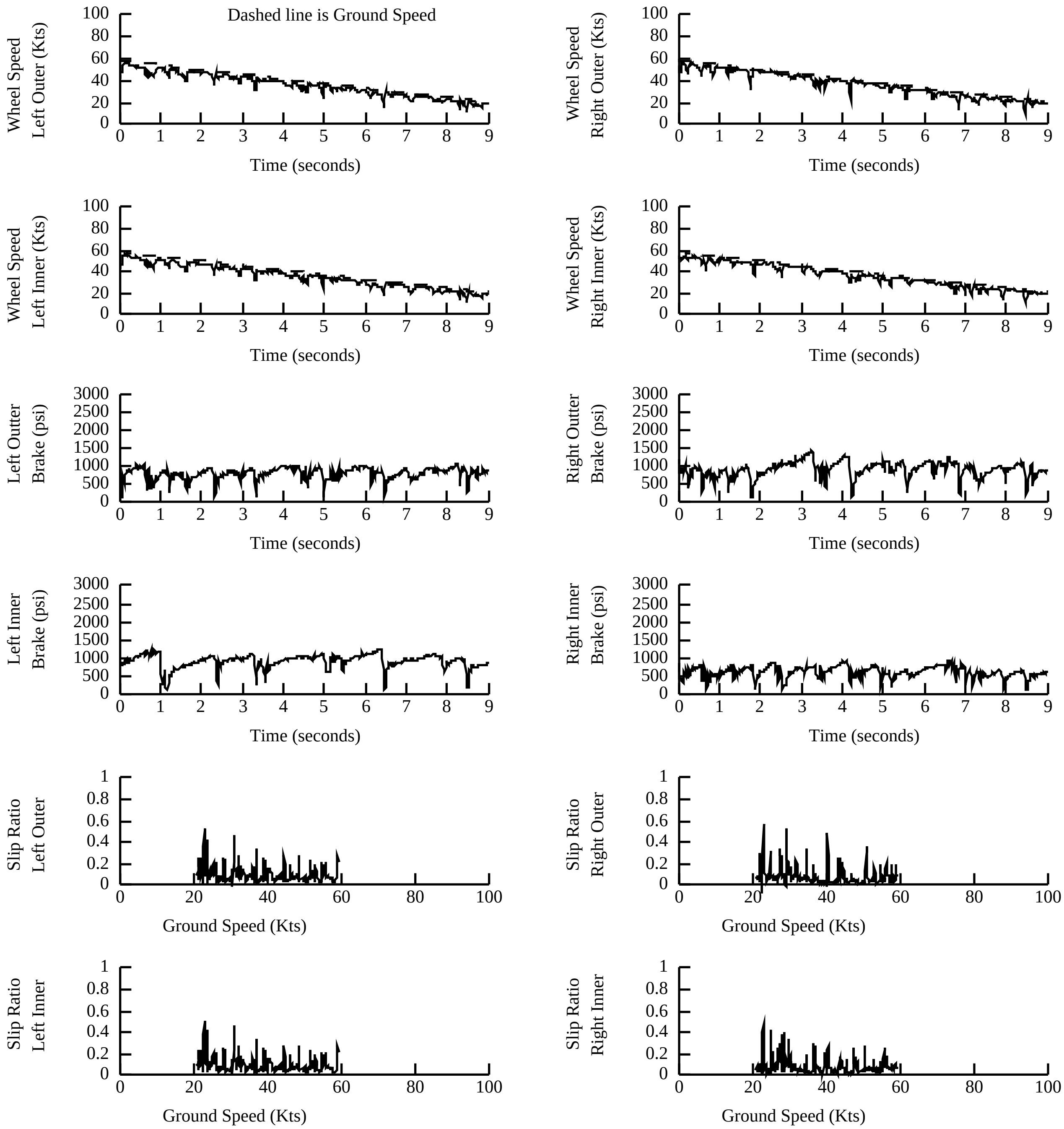


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.38

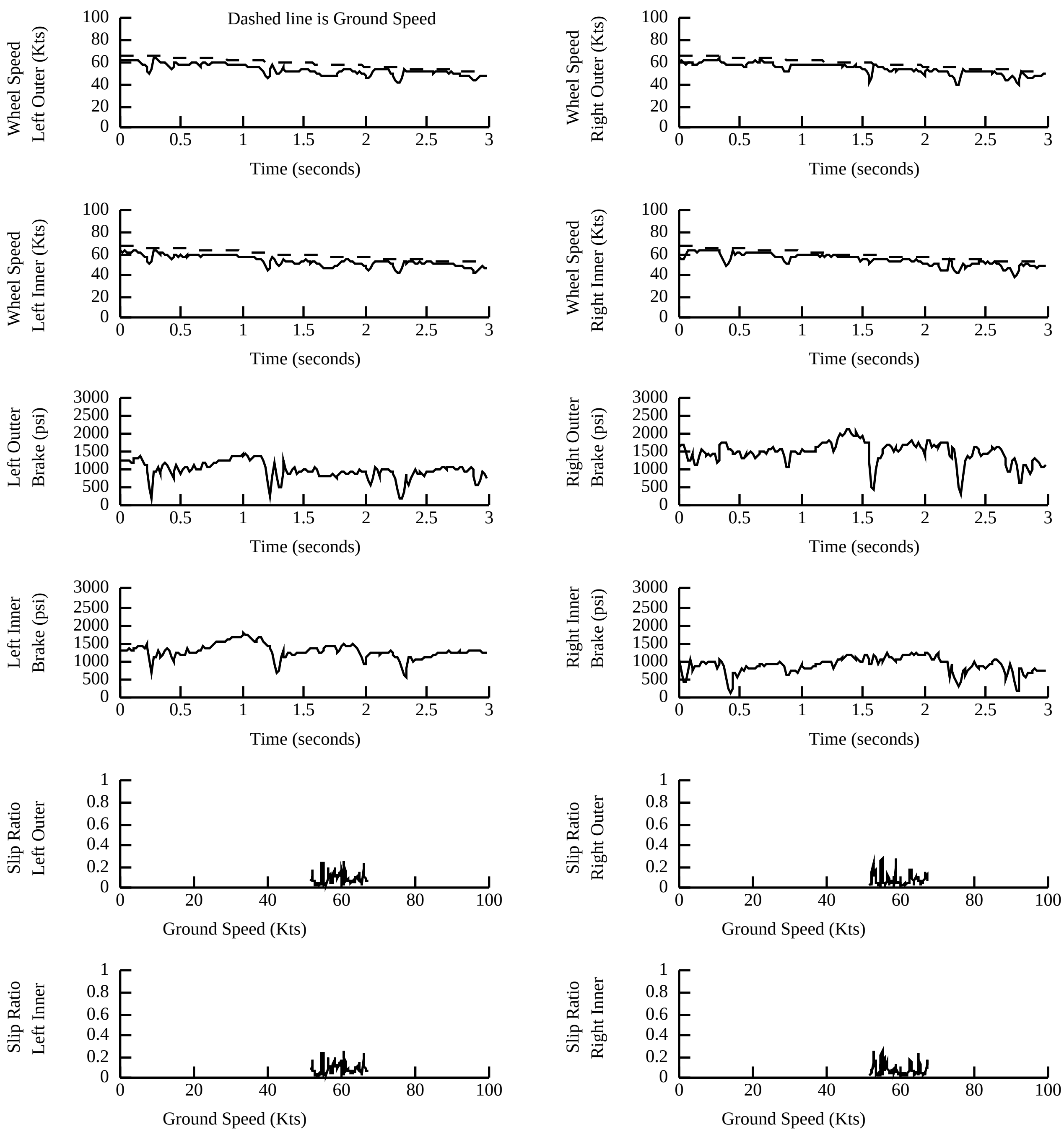


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.36

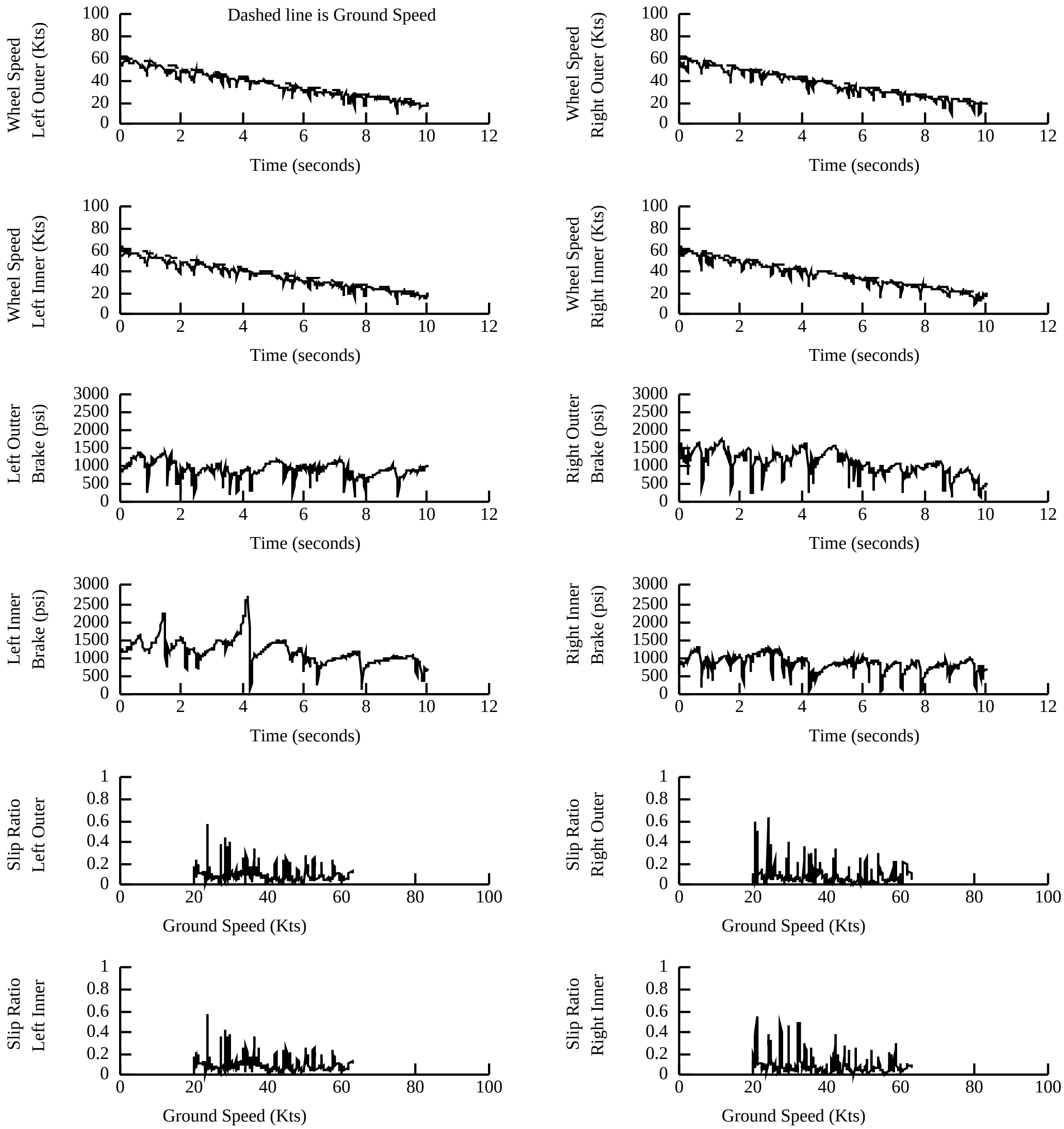


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 4

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.36

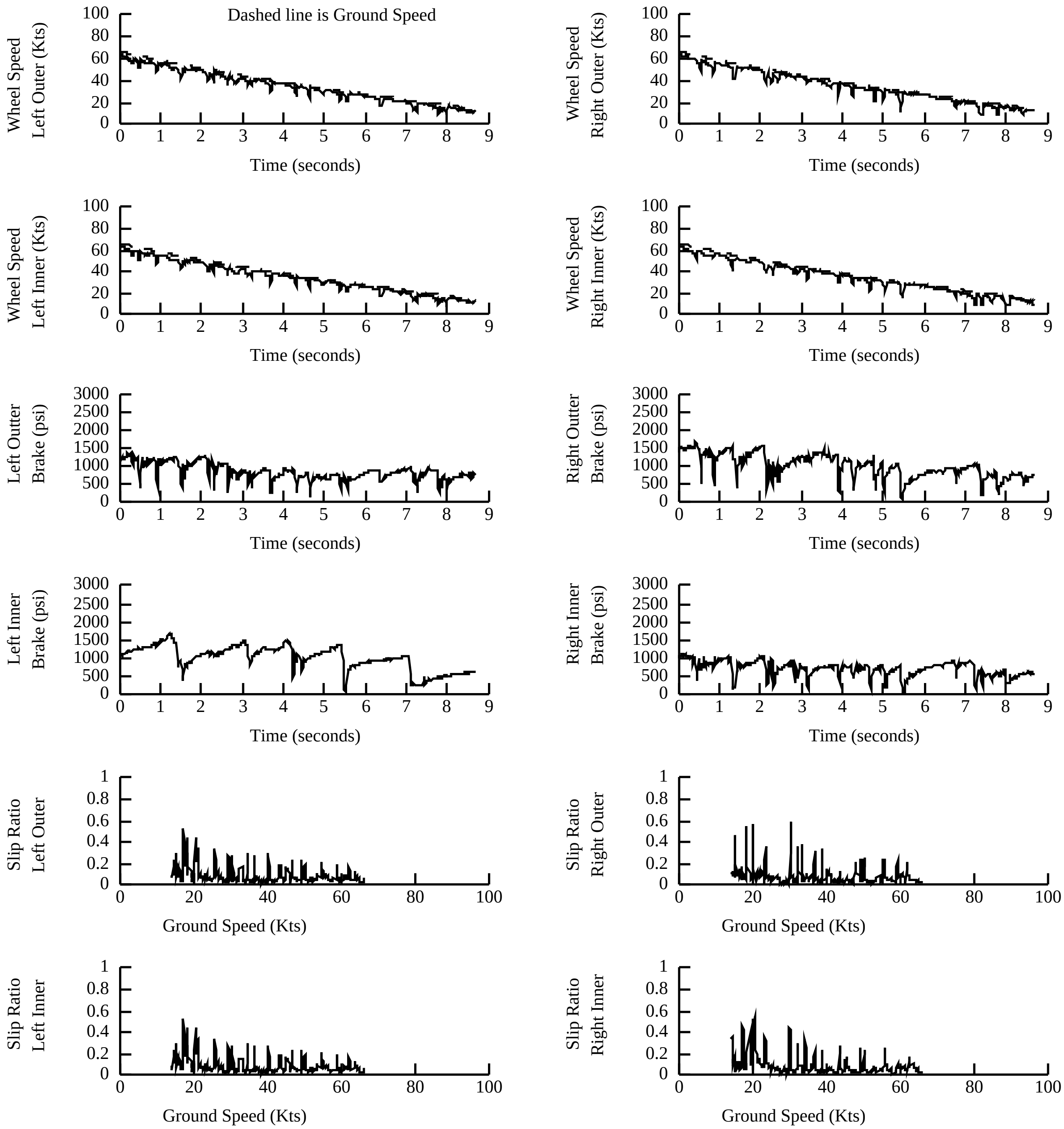


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 5

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.36

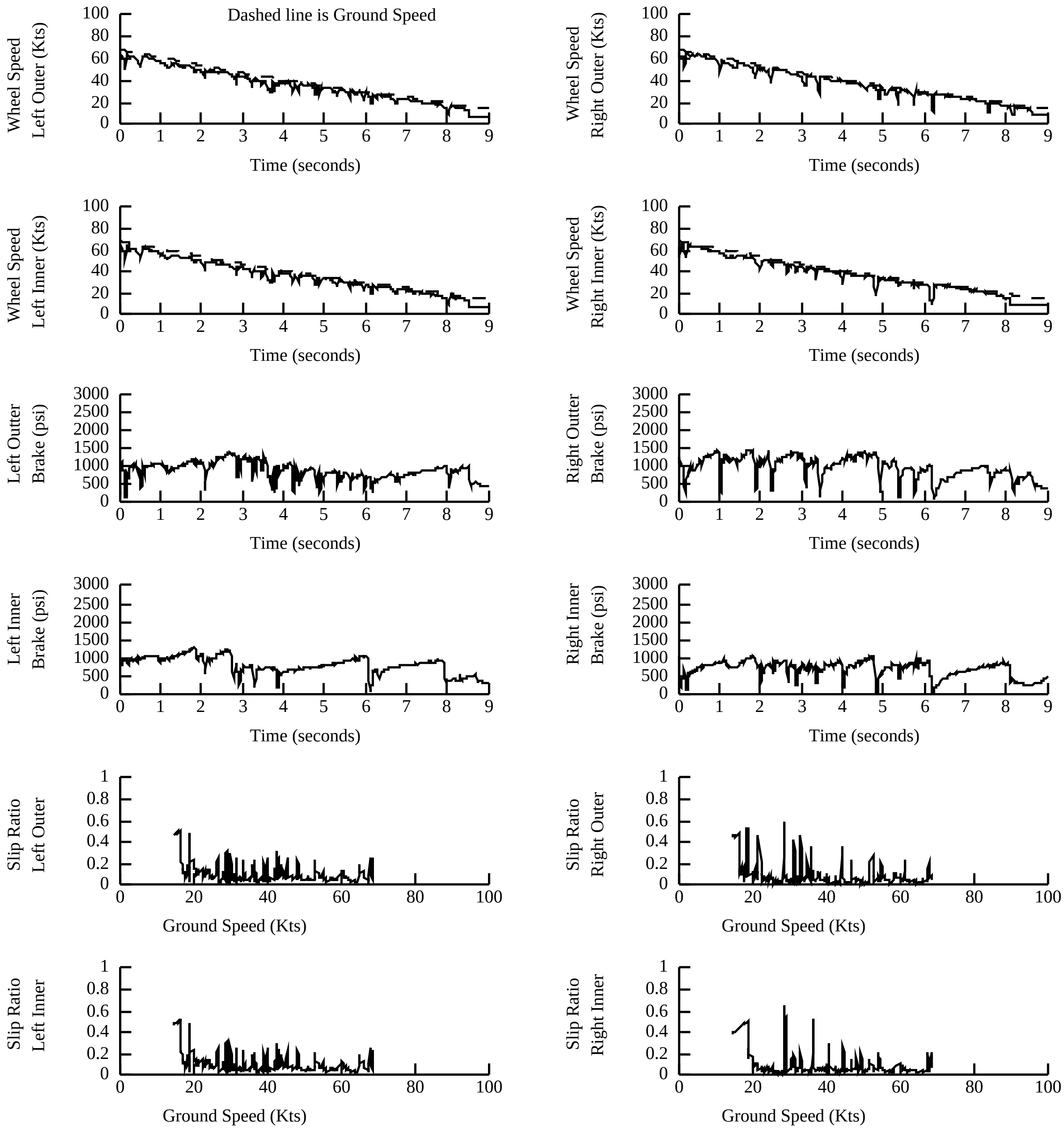


Surface: 100% sanded of 60% compacted snow
over ice, 40% ice patches

Flight 2001/04, Run Number 6

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.36

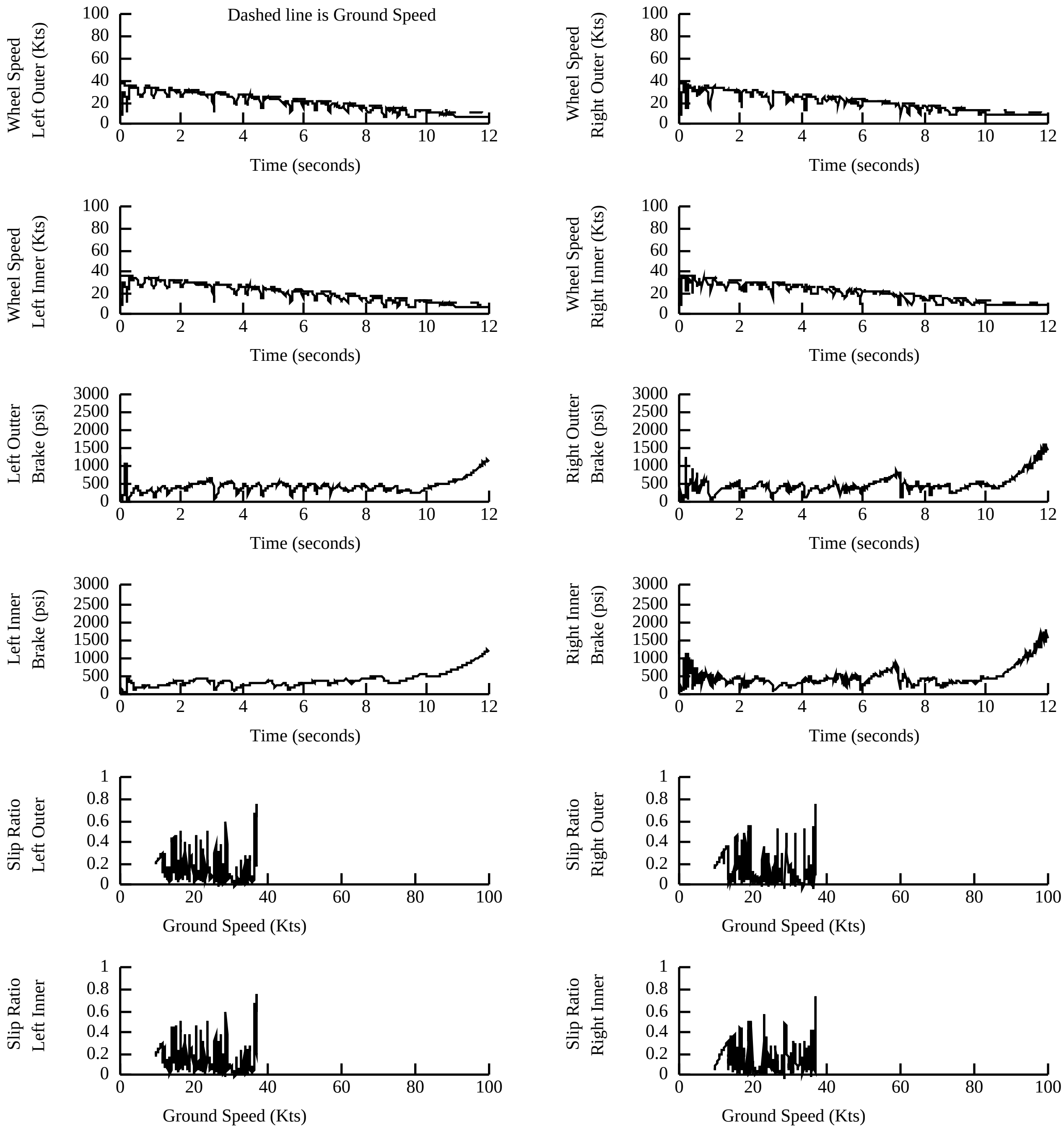


Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.32

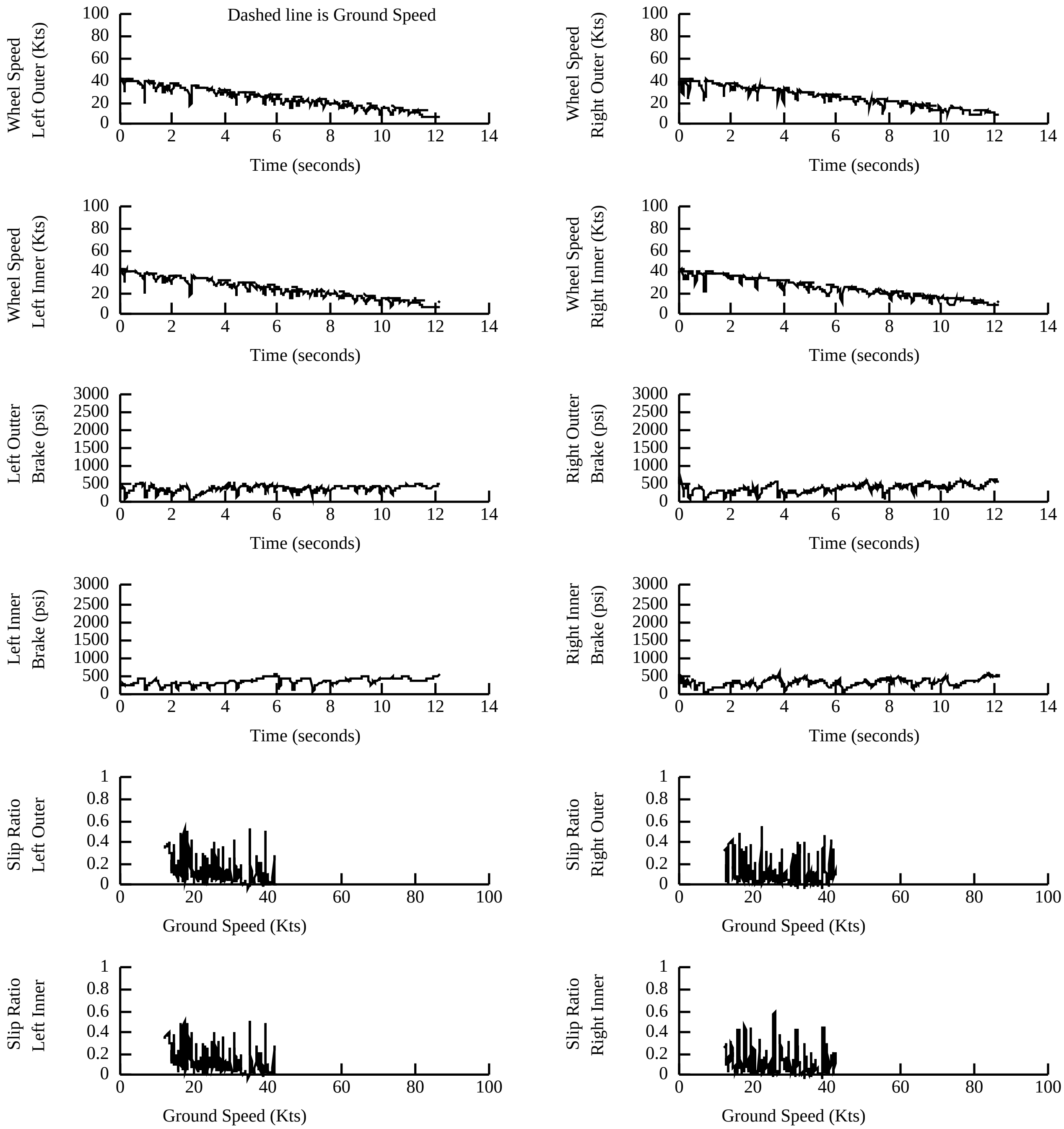


Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.30

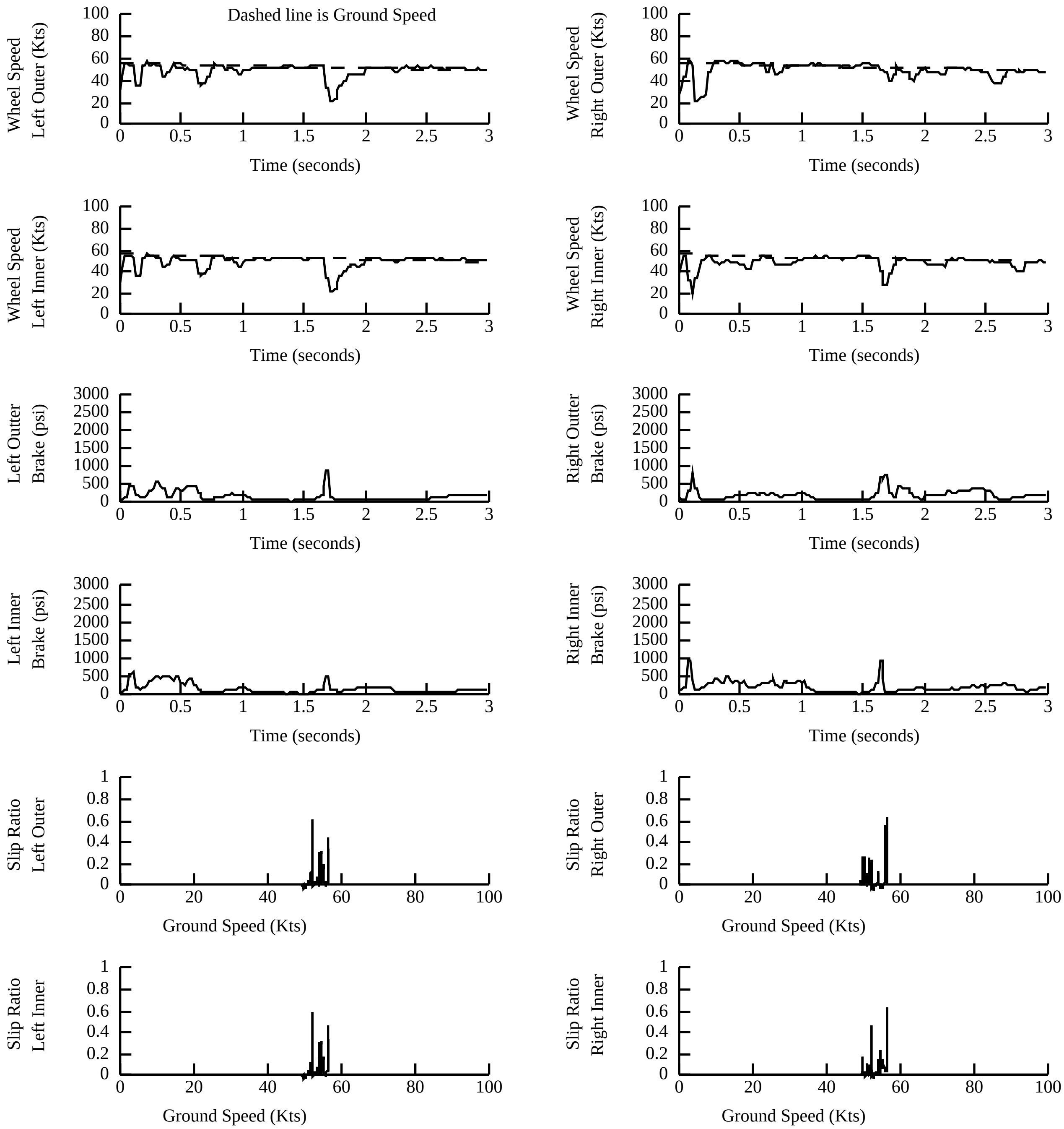


Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.30

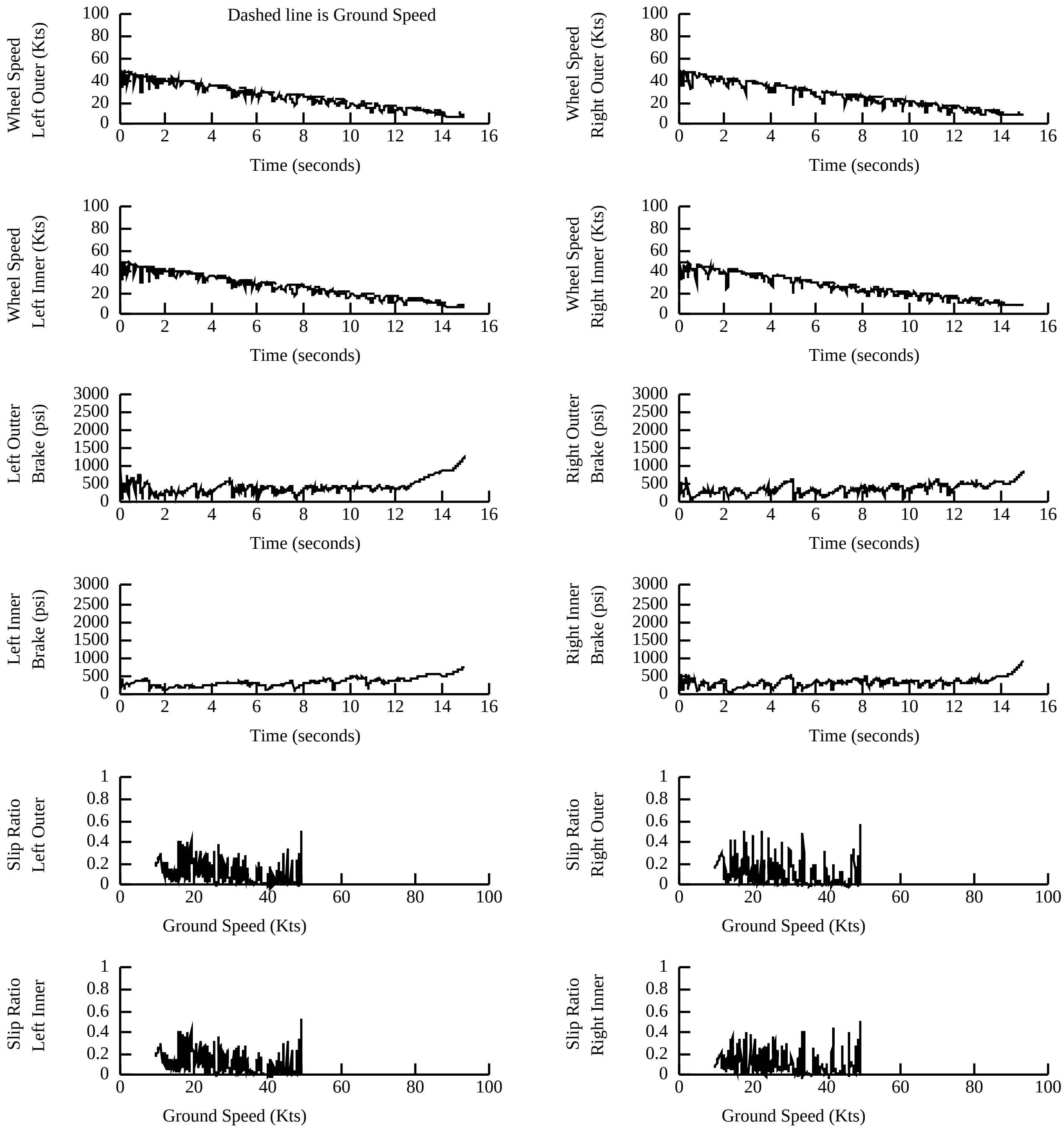


Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 4

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.29

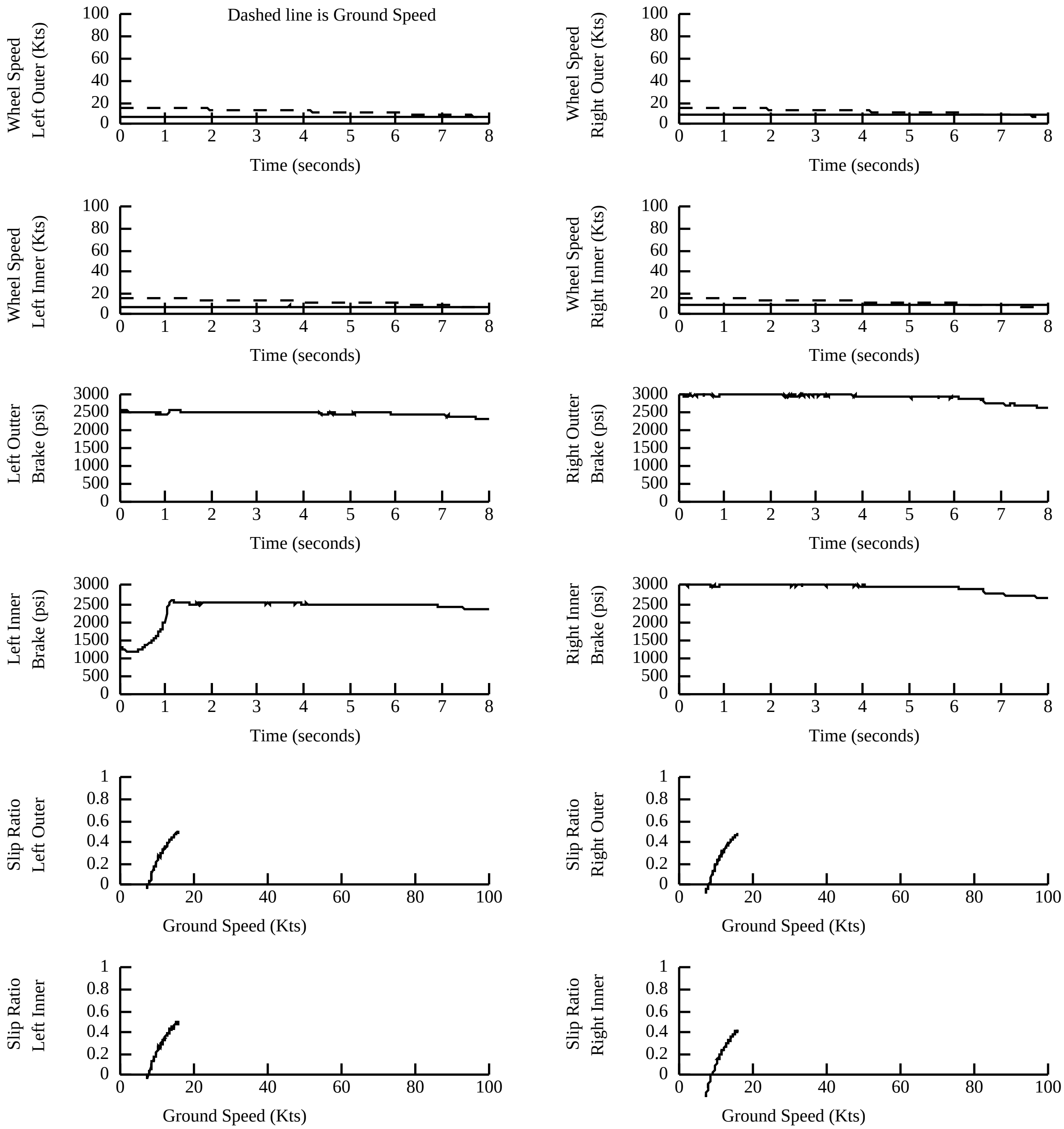


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 1

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.10

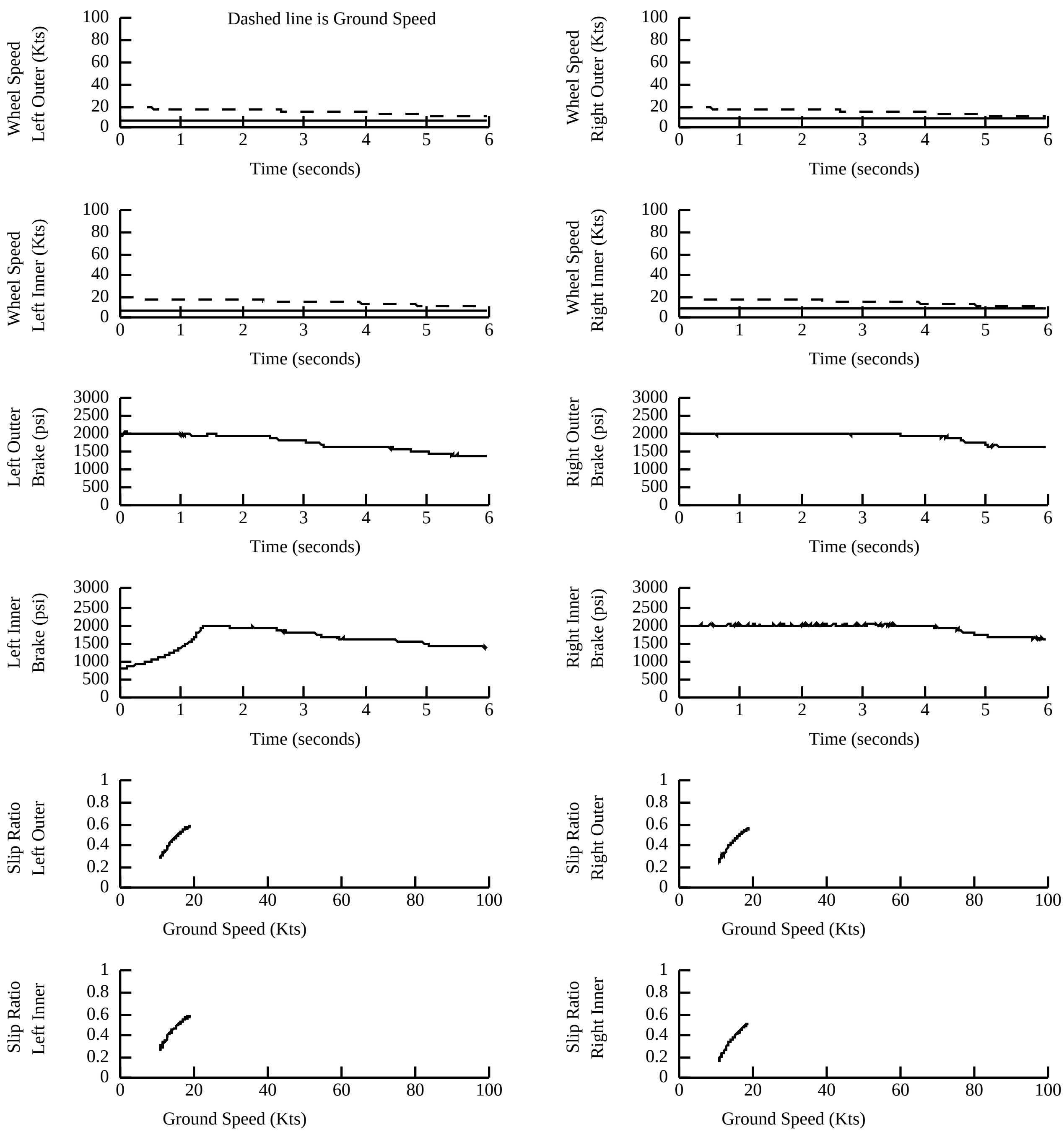


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 2

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.11

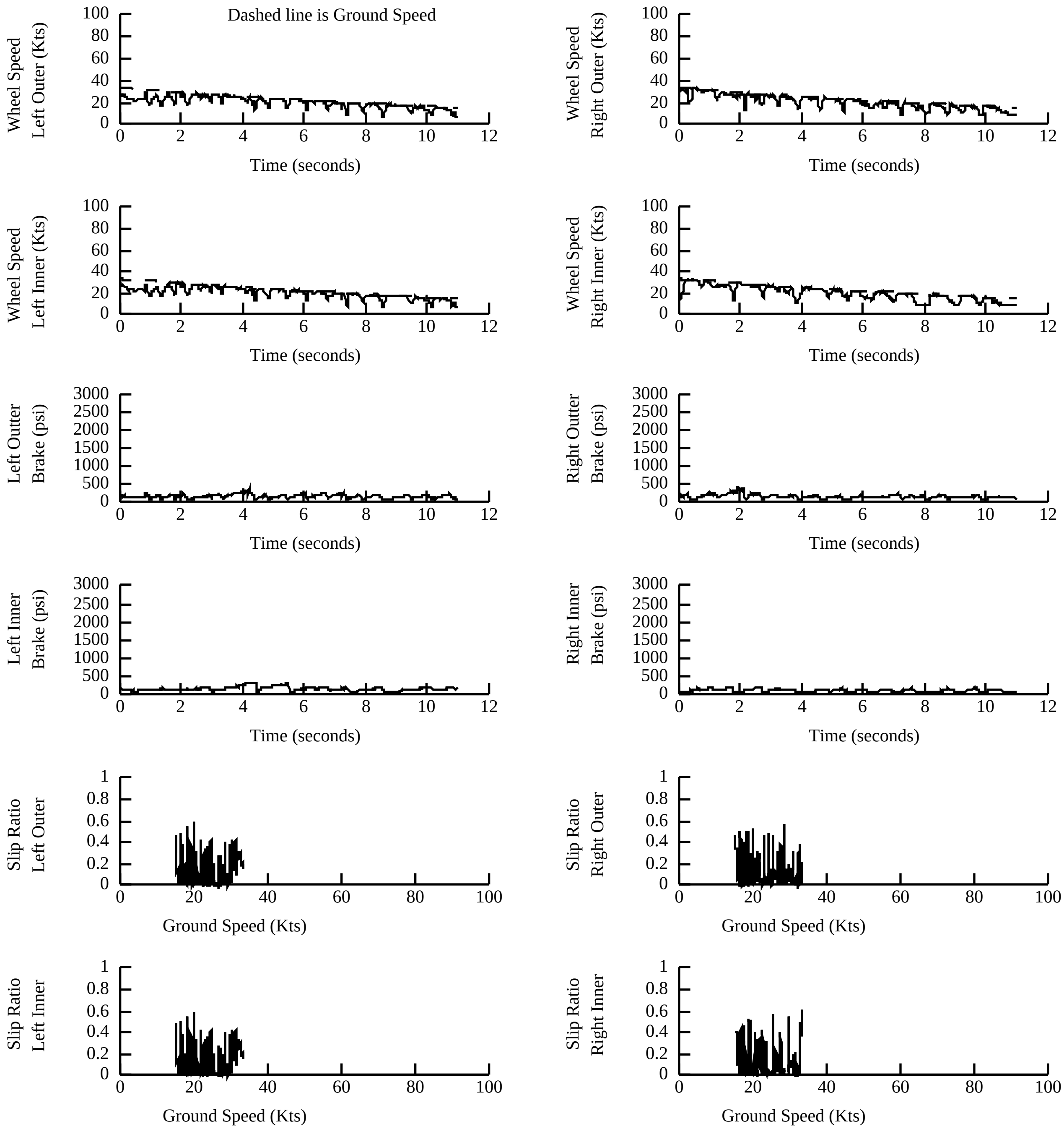


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 3

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.11

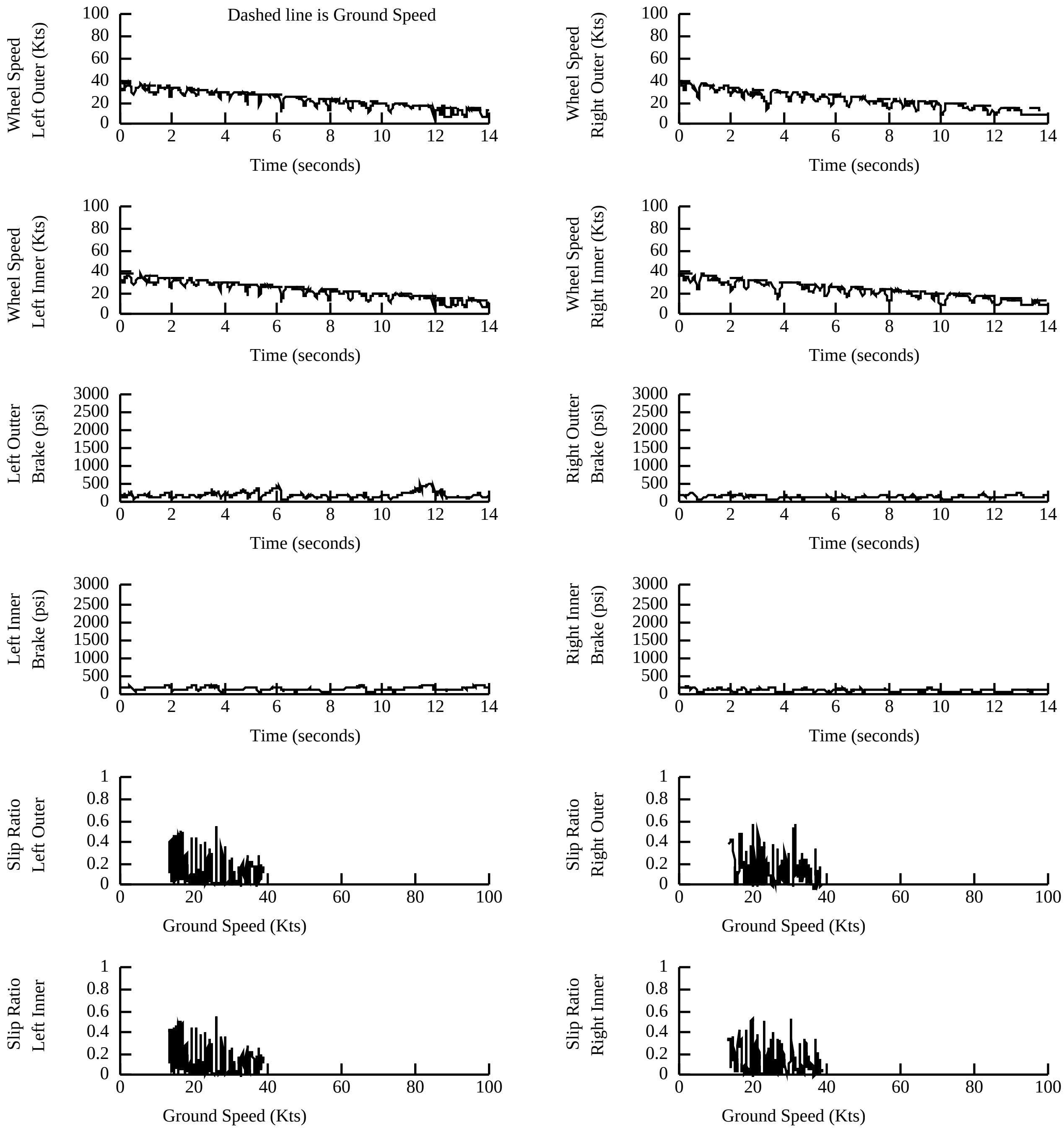


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 4

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.11

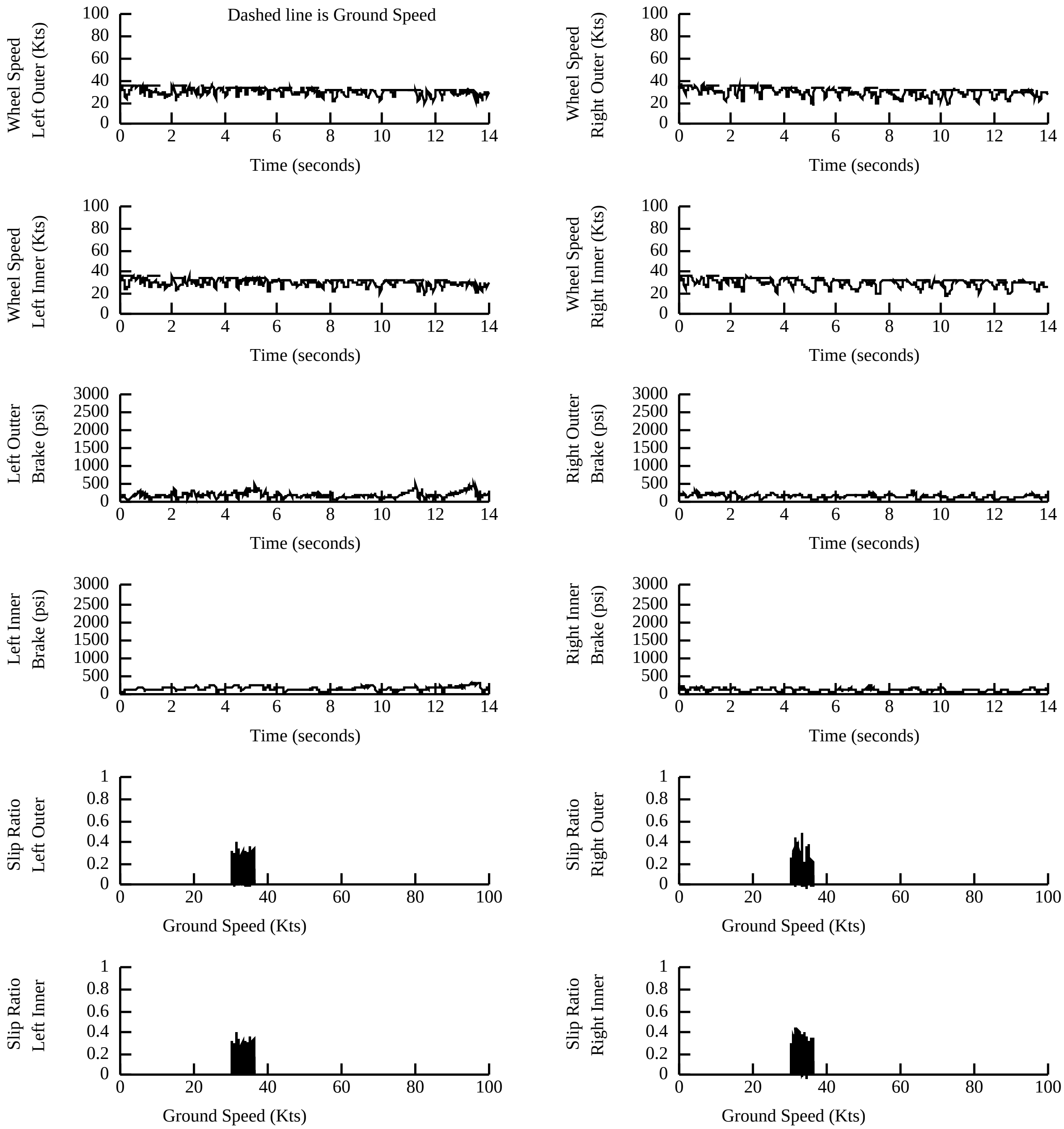


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.11

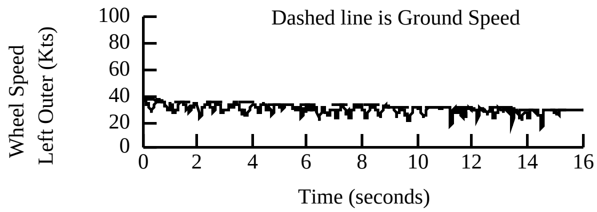


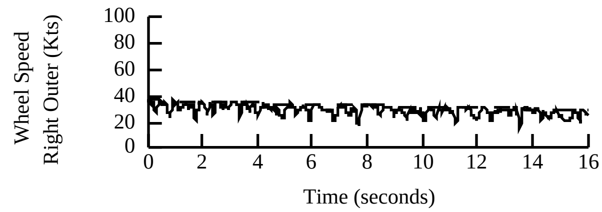
Surface: 100% smooth dry ice

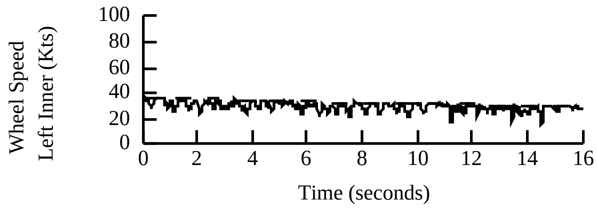
Flight 2001/06, Run Number 6

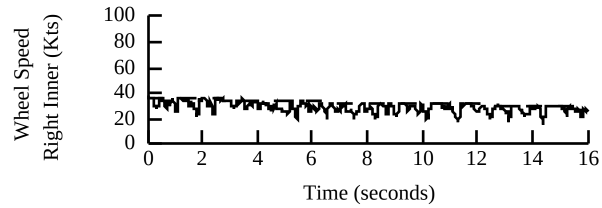
Configuration: Flaps 15, Flight Idle, Max Braking

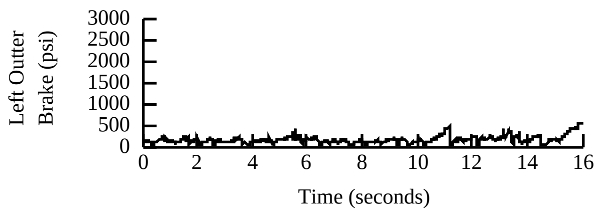
CRFI Average 0.12

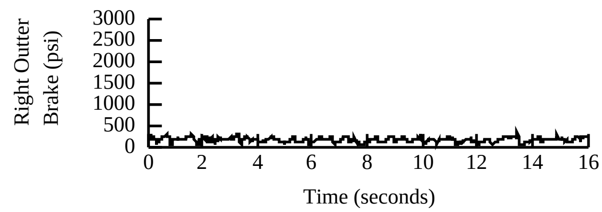


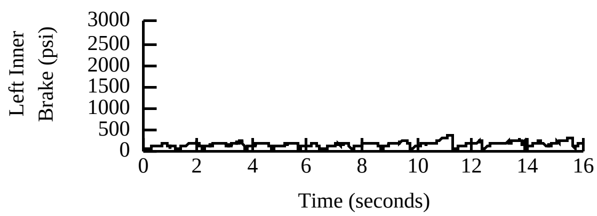


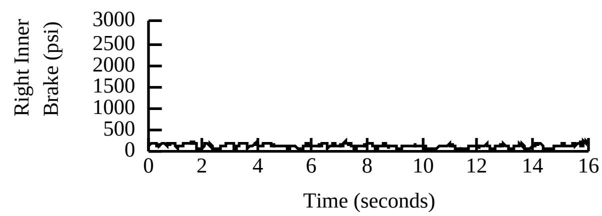


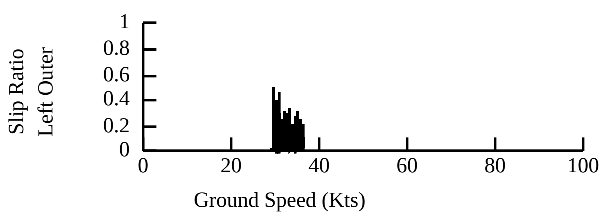


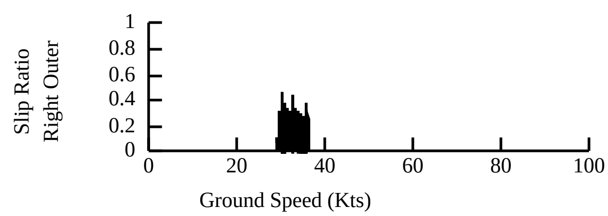


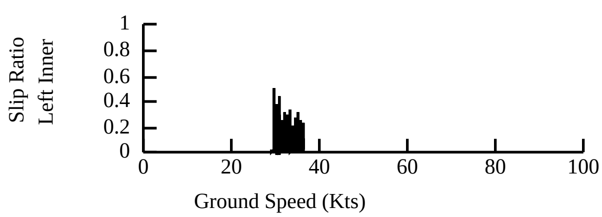


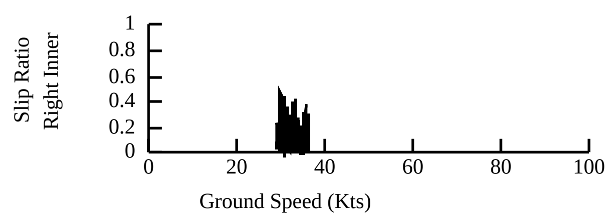










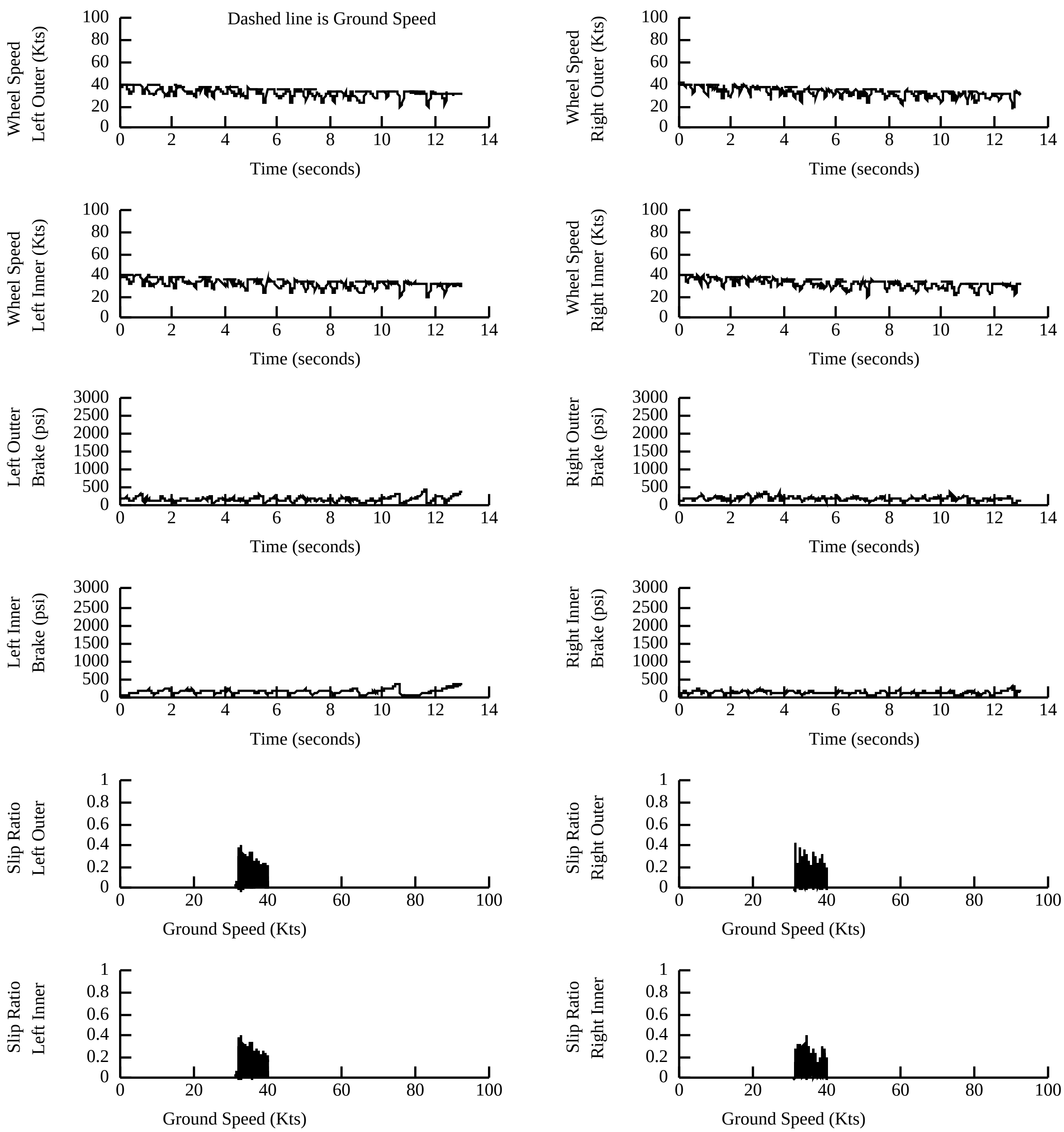


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.11

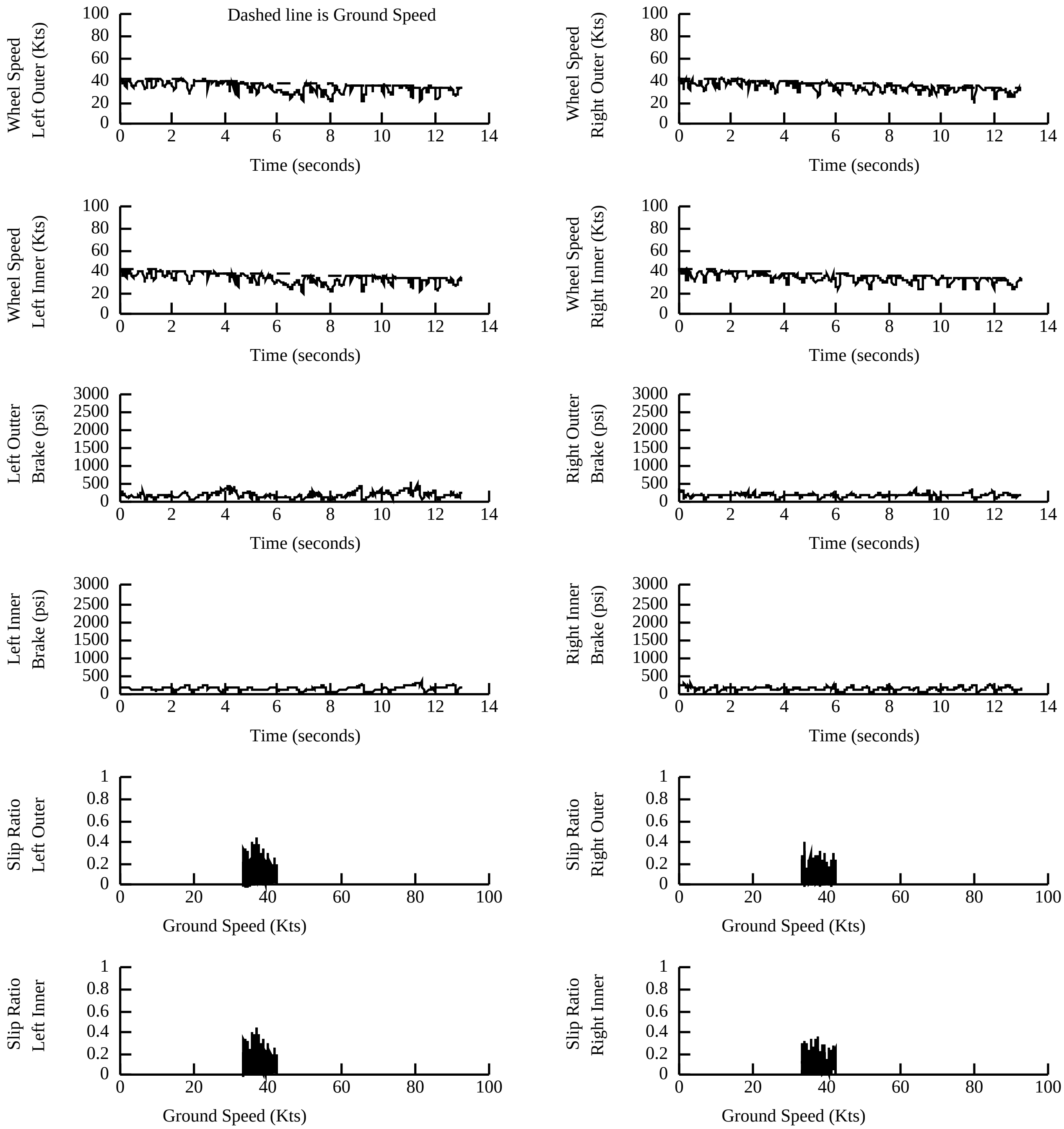


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.11

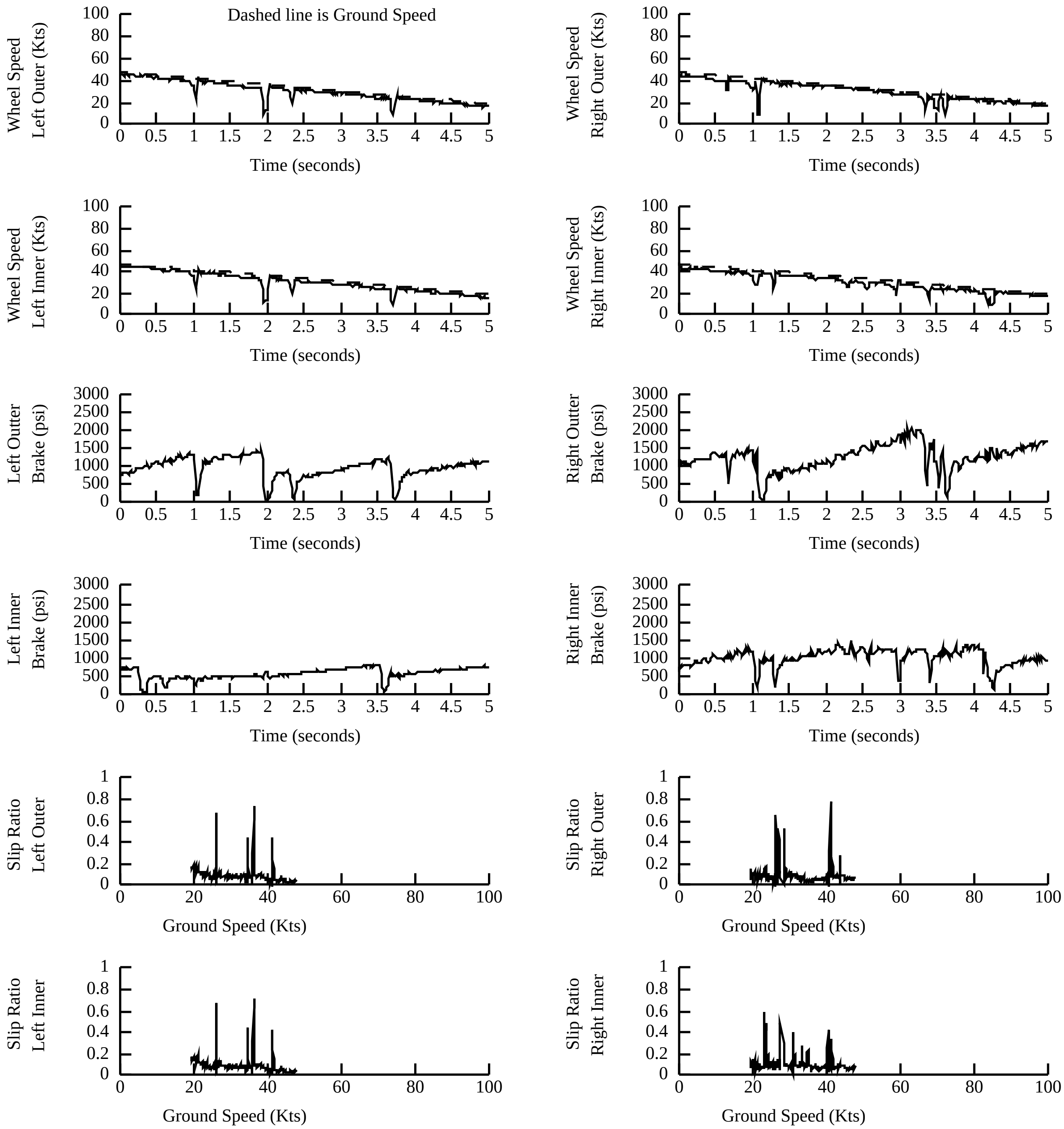


Surface: 20% bare and dry, 80% bare and damp
with patches of standing water

Flight 2001/07, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.54

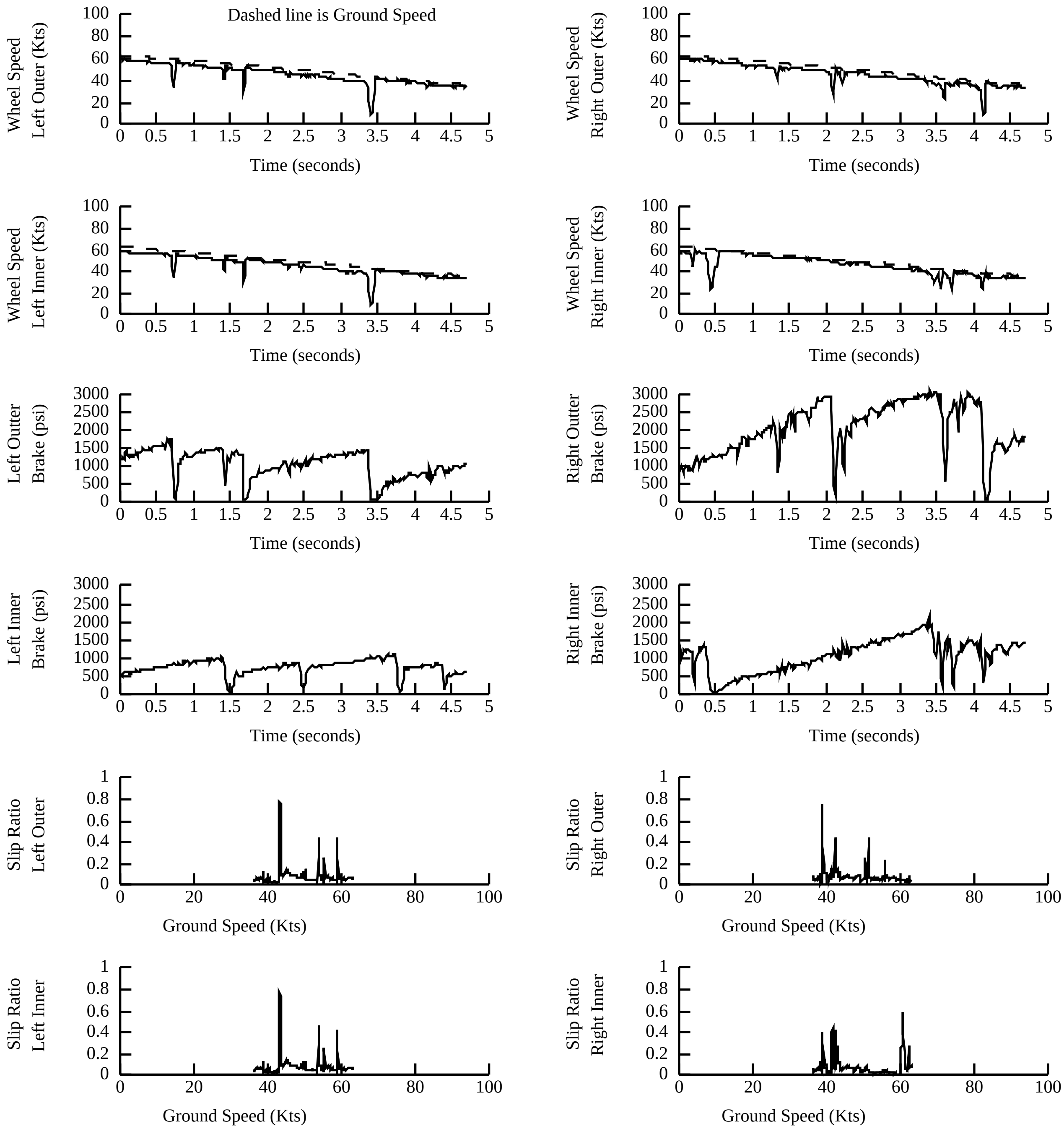


Surface: 20% bare and dry, 80% bare and damp
with patches of standing water

Flight 2001/07, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.60

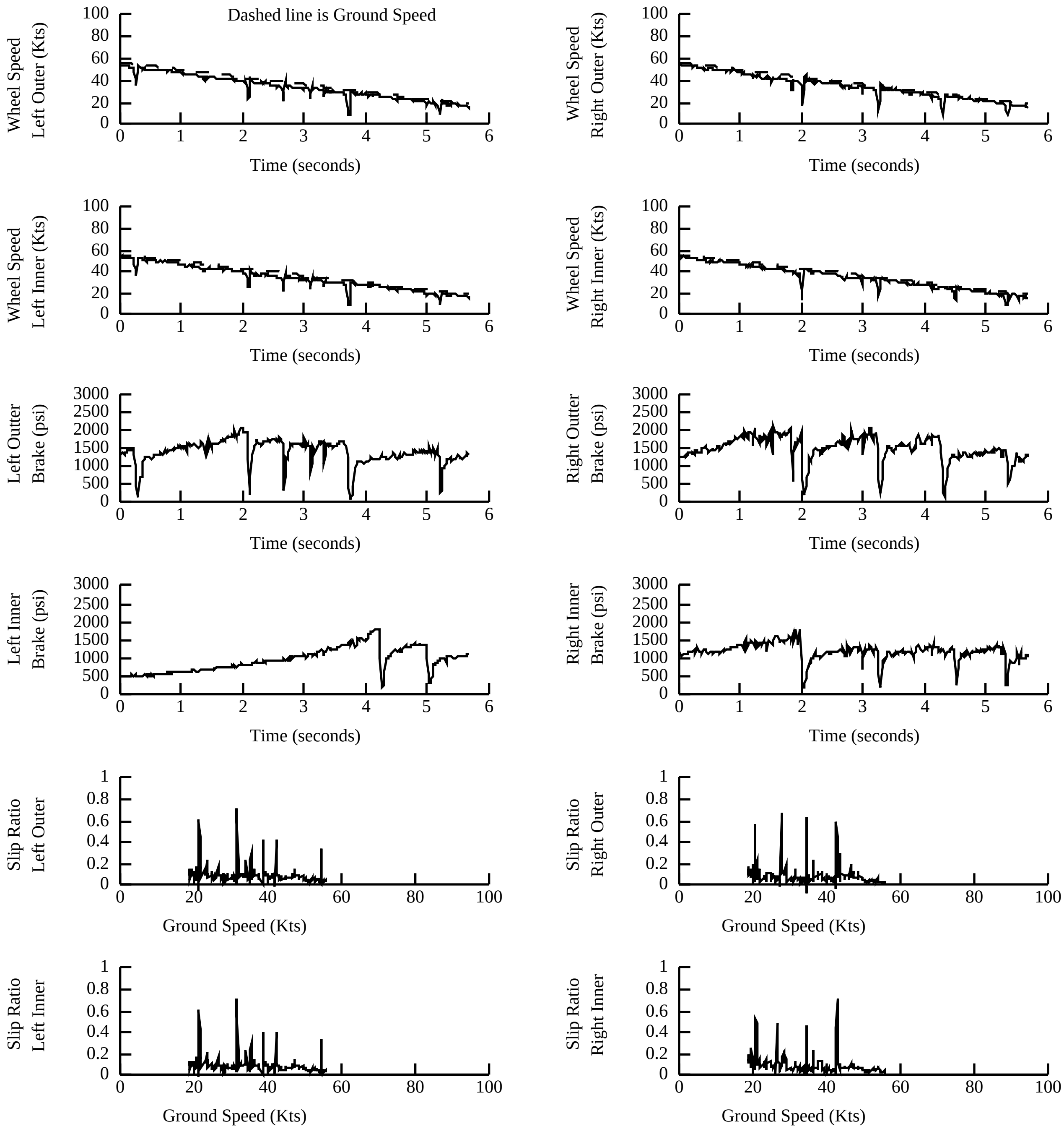


Surface: 100% bare and damp with 10-20% standing water

Flight 2001/08, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.74

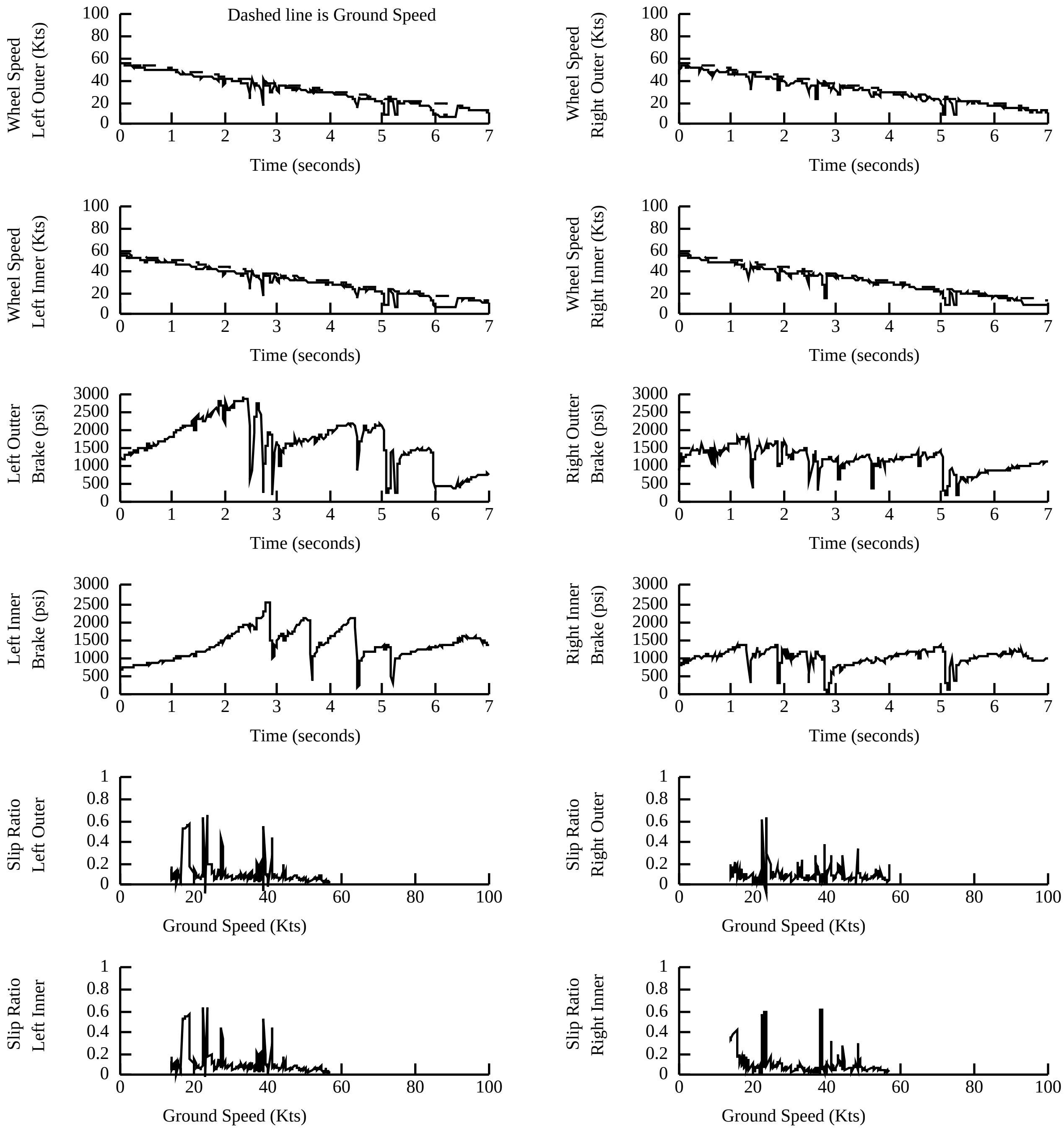


Surface: 100% bare and damp with 10-20% standing water

Flight 2001/08, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.72

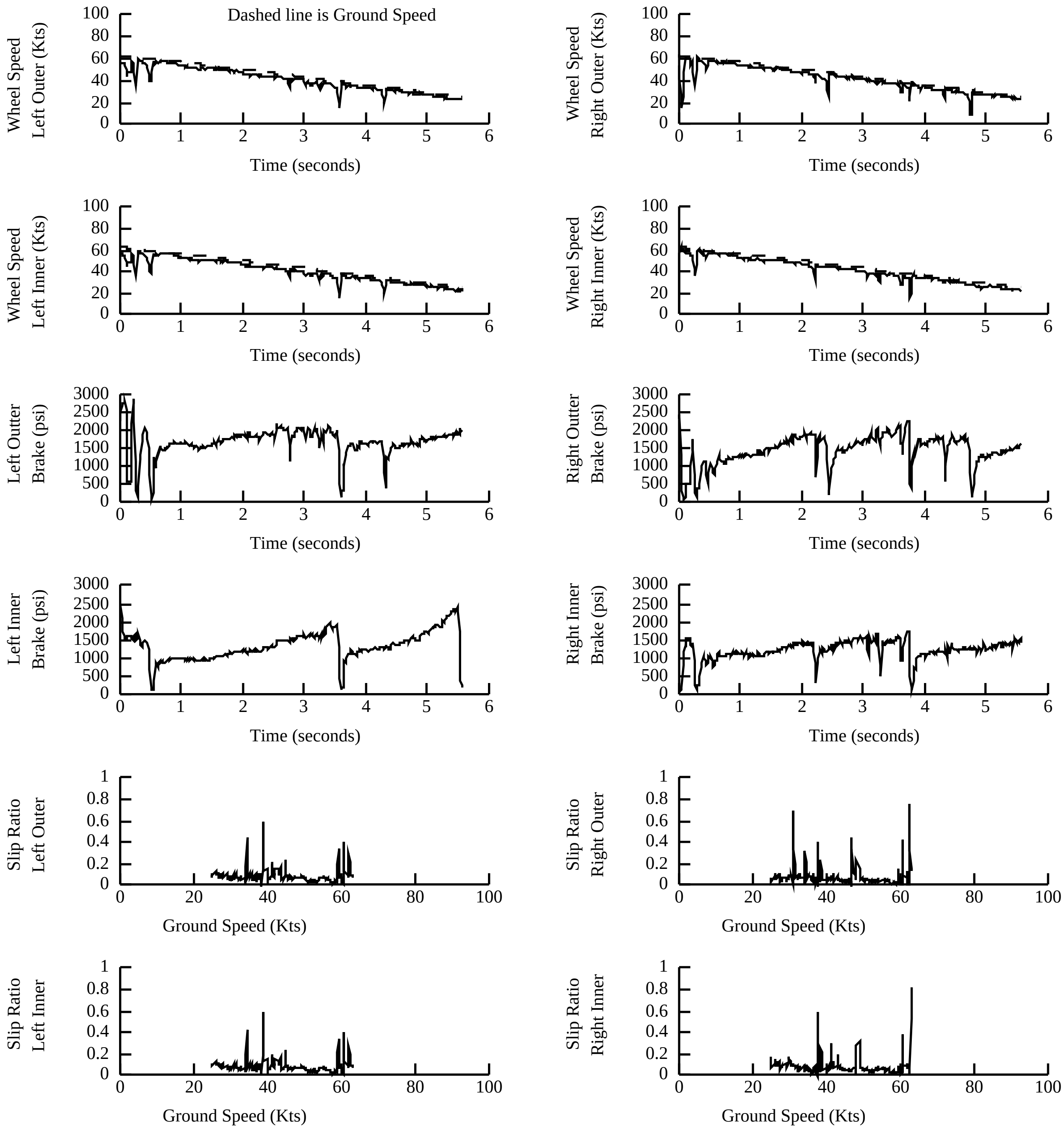


Surface: 100% bare and damp with 20-40% standing water

Flight 2001/08, Run Number 3

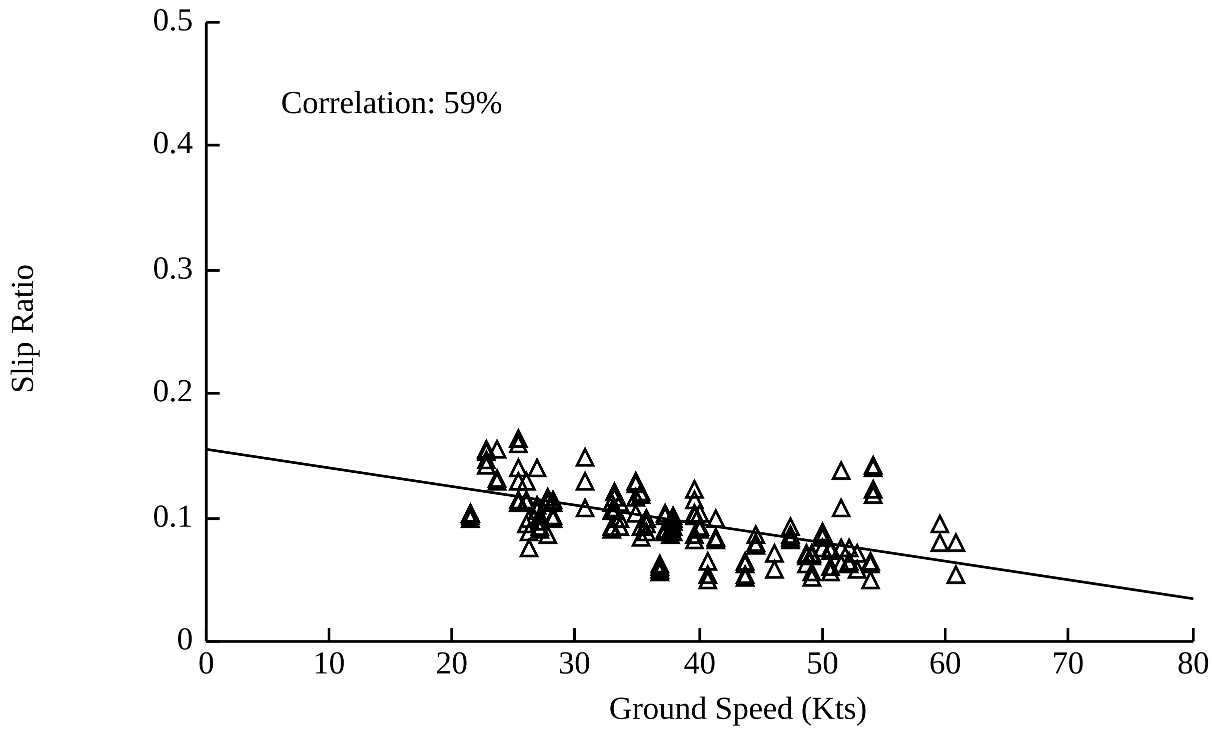
Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.72



Slip Ratio versus Ground Speed

Slip Ratio = 0.155 - 0.0015 * Ground Speed



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

The following table shows the test runs used to determine the aircraft braking coefficient ($_B$) on runway surfaces with no or negligible contamination drag. Pages D3 to D15 show the variation of $_B$ with ground speed for each run. The mean ground speed and mean $_B$ for each run are shown in the table and on Page D16 to D18 for each runway surface condition. Page D19 shows the mean $_B$ plotted against the mean CRFI value for each run, together with the results obtained from previous tests. Page D20 shows the mean $_B$ plotted against the mean IRFI values for each run, together with the results obtained from the previous test.

FLT/ Date	**RUN/ Time**	**RW**	**TAXI/ RTO/ LAND**	**FLAP/PWR BRK**	**Weight (LB)**	**MEAN CRFI**	**MEAN IRFI**	**MEAN SPEED (KTGS)**	**MEAN B**
2001/01 29/01/01	8 15:42	26	RTO	15/IDLE/B	31150	0.67	0.87	51	0.407
	9 15:53	26	LAND	15/IDLE/B	31050	0.67	0.87	54	0.429
2001/02 31/01/01	5 14:45	31TS	RTO	15/IDLE/B	32240	0.28	0.19	21	0.174
	6 15:03	31TS	RTO	15/IDLE/B	32060	0.28	0.20	27	0.178
	7 15:13	31TS	RTO	15/IDLE/B	31960	0.27	0.21	37	0.170
	8 15:20	31TS	RTO	15/IDLE/B	31890	0.27	0.22	54	0.178
	9 15:32	31TS	RTO	15/DISC/B	31770	0.26	0.22	40	0.179
	10 15:38	31TS	RTO	15/DISC/B	31710	0.25	0.21	44	0.186
	11 15:43	31TS	RTO	15/DISC/B	31660	0.24	0.20	49	0.174
	13 16:04	08TS	RTO	15/IDLE/B	31450	0.31	0.38	48	0.306
	16 16:25	08TS	RTO	15/DISC/B	31240	0.31	0.38	35	0.188
	18 16:39	08TS	RTO	15/IDLE/B	31100	0.32	0.37	41	0.265
2001/03 01/02/01	1 10:47	36N	RTO	15/IDLE/B	30700	0.27	0.18	28	0.177
	2 10:52	36N	RTO	15/IDLE/B	30650	0.26	0.20	26	0.176
	3 11:02	36N	RTO	15/IDLE/B	30560	0.25	0.21	46	0.184
	4 11:09	36N	RTO	15/DISC/B	30500	0.27	0.21	37	0.205
	5 11:52	31TS	RTO	15/IDLE/B	30150	0.24	0.19	26	0.181
	6 11:58	31TS	RTO	15/IDLE/B	30090	0.25	0.19	49	0.174
	7 12:04	31TS	RTO	15/IDLE/B	30030	0.26	0.20	61	0.167
	8 12:15	31TS	LAND	15/IDLE/B	29880	0.26	0.20	51	0.177
	9 12:22	31TS	LAND	15/DISC/B	29780	0.27	0.20	52	0.259
	10 12:26	31TS	LAND	15/DISC/B	29720	0.27	0.20	51	0.253
	11 12:31	31TS	LAND	15/DISC/B	29650	0.27	0.20	30	0.183

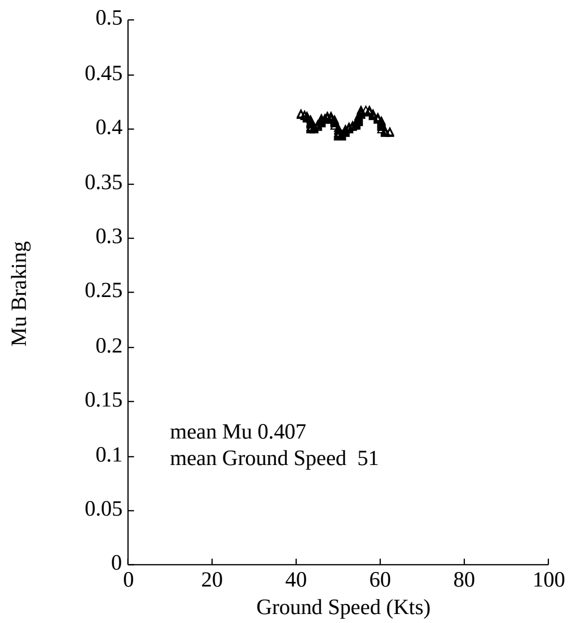
FLT/ Date	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK	Weight (LB)	MEAN CRFI	MEAN IRFI	MEAN SPEED (KTGS)	MEAN B
2001/04 01/02/01	1 14:46	31TS	RTO	15/IDLE/B	30730	0.40	0.35	25	0.270
	2 14:50	31TS	RTO	15/IDLE/B	30700	0.38	0.35	40	0.251
	3 14:54	31TS	RTO	15/IDLE/B	30660	0.36	0.36	59	0.240
	4 15:02	31TS	LAND	15/IDLE/B	30520	0.36	0.36	40	0.248
	5 15:08	31TS	LAND	15/DISC/B	30440	0.36	0.36	37	0.250
	6 15:15	31TS	LAND	15/DISC/B	30350	0.36	0.35	39	0.247
2001/06 22/03/01	1 07:25	31N	RTO	15/DISC/B	30450	0.10	0.16	12	0.069
	2 07:30	31N	RTO	15/DISC/B	30410	0.11	0.15	16	0.086
	3 07:40	31N	RTO	15/DISC/B	30330	0.11	0.14	23	0.086
	4 07:45	31N	RTO	15/DISC/B	30290	0.11	0.13	25	0.089
	5 07:55	31N	RTO	15/IDLE/B	30210	0.11	0.14	33	0.086
	6 08:00	31N	RTO	15/IDLE/B	30170	0.12	0.15	33	0.085
	7 08:13	31N	RTO	15/IDLE/B	30060	0.11	0.15	36	0.088
	8 08:17	31N	RTO	15/IDLE/B	30030	0.11	0.15	38	0.087
2001/07 22/03/01	1 10:08	31N	RTO	15/IDLE/B	29810	0.54	0.59	34	0.363
	2 10:12	31N	RTO	15/IDLE/B	29780	0.60	0.72	50	0.321
2001/08 23/03/01	1 11:28	31TS	RTO	15/IDLE/B	29300	0.74	0.72	38	0.387
	2 11:32	31TS	RTO	15/IDLE/B	29270	0.72	0.74	35	0.392
	3 12:02	31TS	RTO	15/IDLE/B	29030	0.72	0.73	45	0.360

Surface: 100% Bare and Dry

Flight 2001/01, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

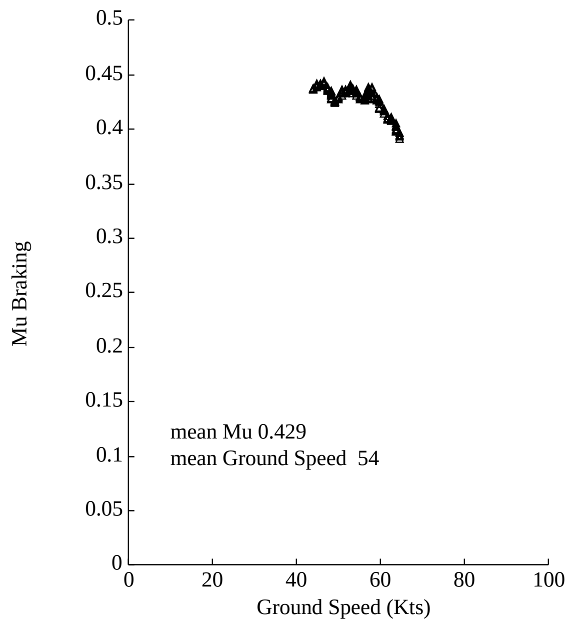
CRFI Average 0.67



Flight 2001/01, Run Number 9

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.67

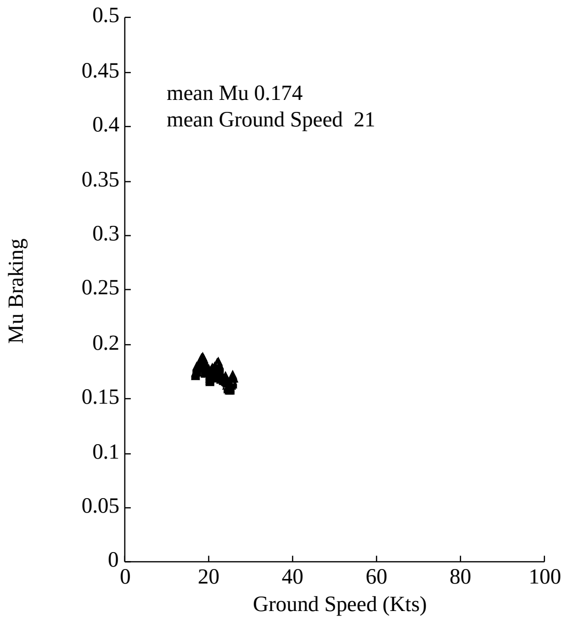


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

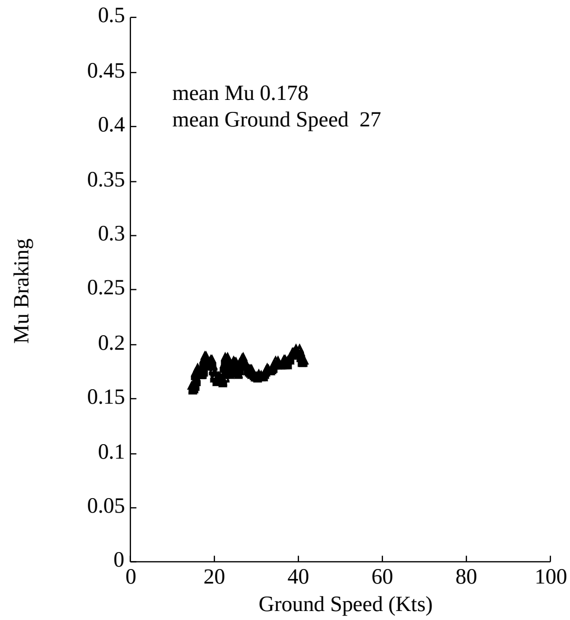
CRFI Average 0.28



Flight 2001/02, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

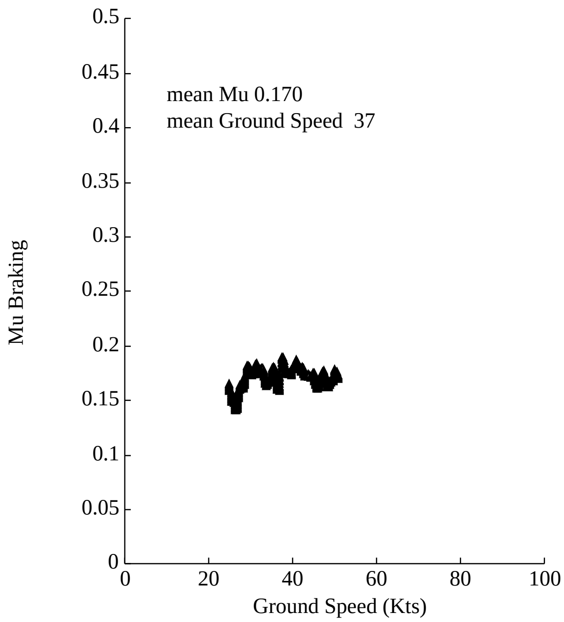
CRFI Average 0.28



Flight 2001/02, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

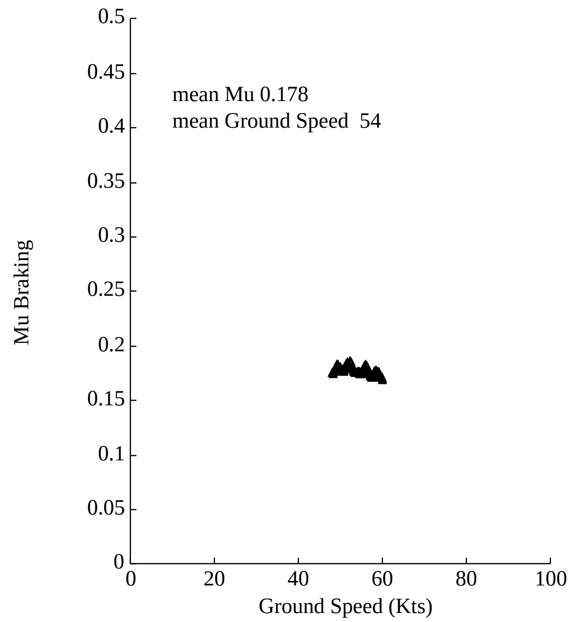
CRFI Average 0.27



Flight 2001/02, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.27

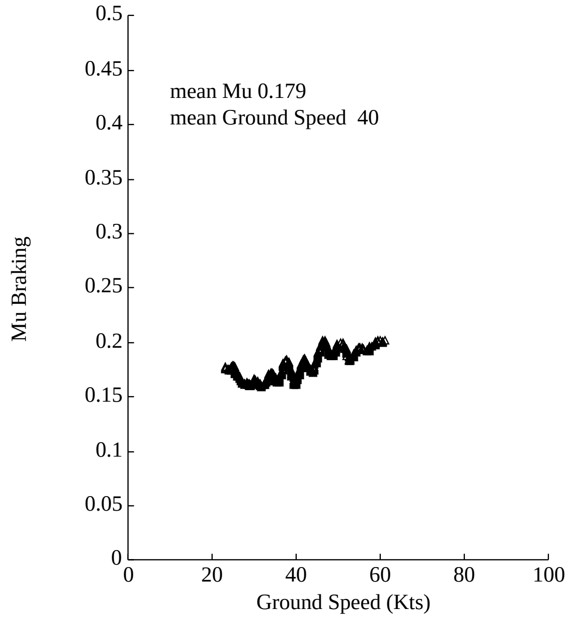


Surface: 60% compacted snow over ice,
40% ice patches.

Flight 2001/02, Run Number 9

Configuration: Flaps 15, Discing, Max Braking

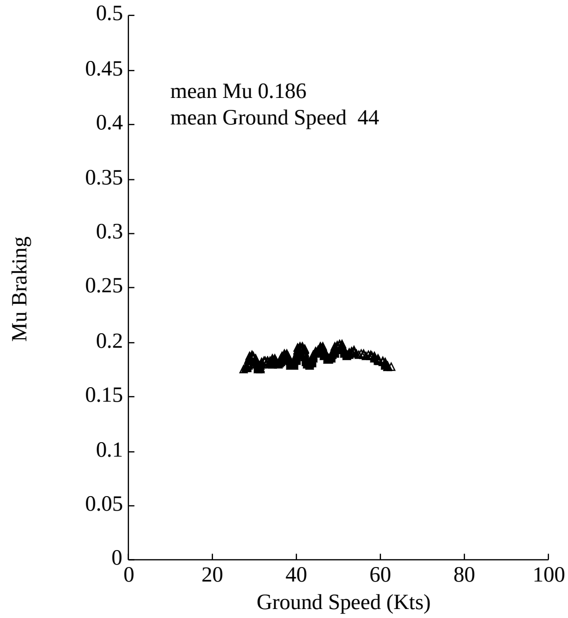
CRFI Average 0.26



Flight 2001/02, Run Number 10

Configuration: Flaps 15, Discing, Max Reverse

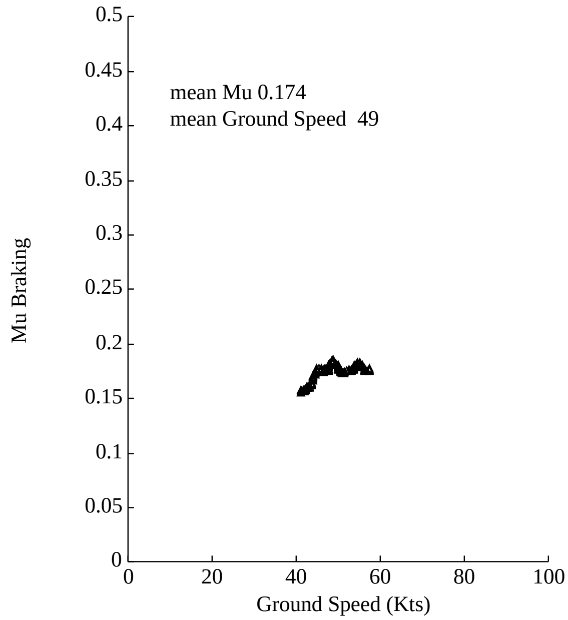
CRFI Average 0.25



Flight 2001/02, Run Number 11

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.24

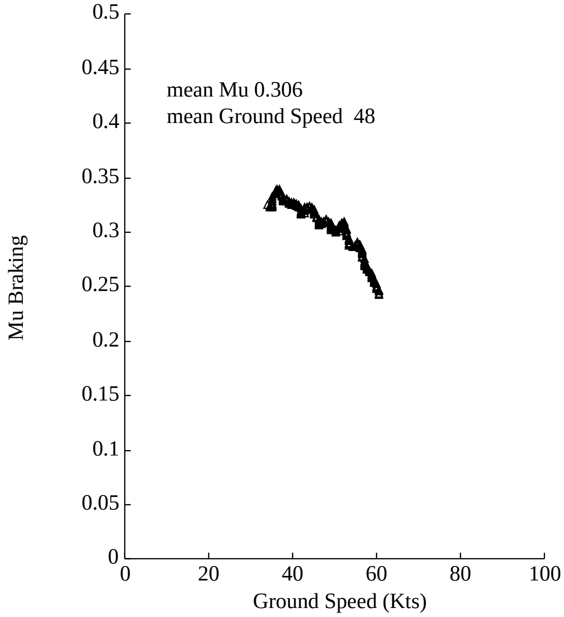


Surface: 60% loose snow over ice, 40% ice patches.

Flight 2001/02, Run Number 13

Configuration: Flaps 15, Flight Idle, Max Braking

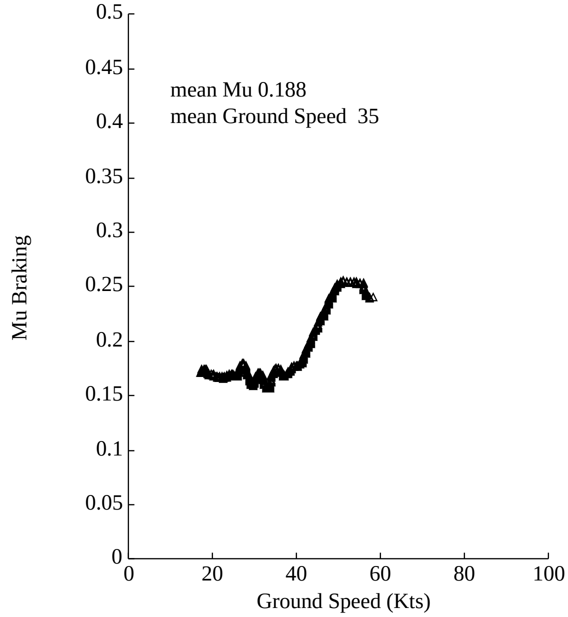
CRFI Average 0.31



Flight 2001/02, Run Number 16

Configuration: Flaps 15, Discing, Max Braking

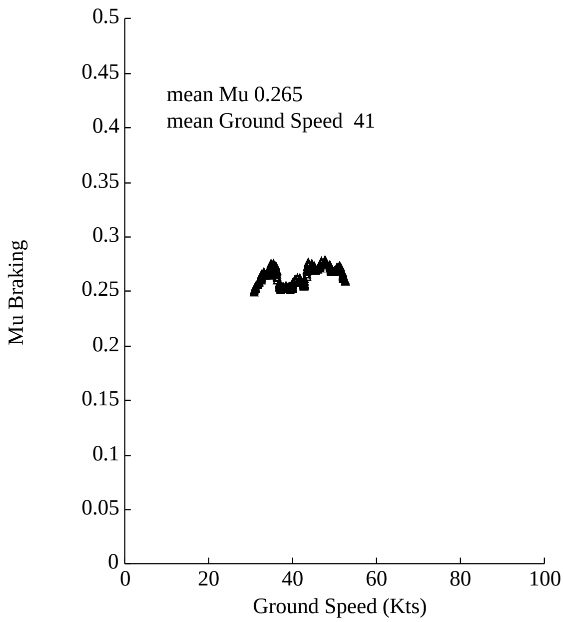
CRFI Average 0.31



Flight 2001/02, Run Number 18

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.32

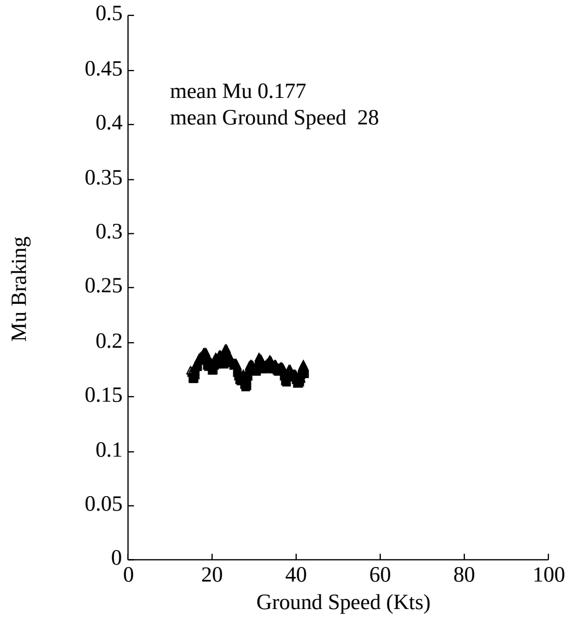


Surface: 1/4 inch loose snow over bare and dry

Flight 2001/03, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

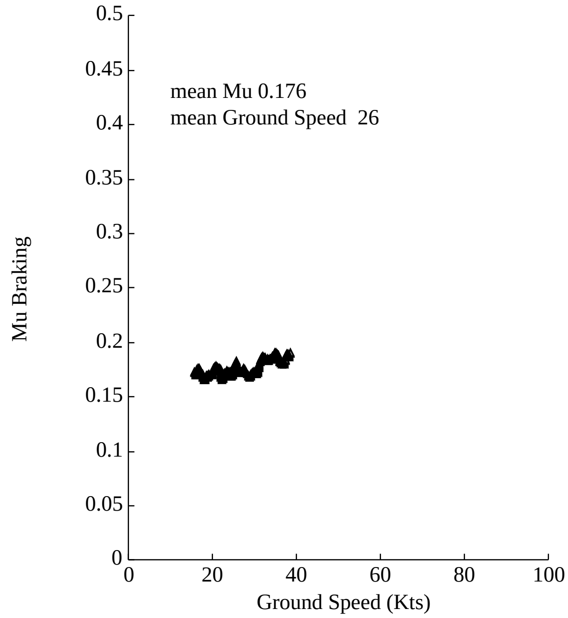
CRFI Average 0.27



Flight 2001/03, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

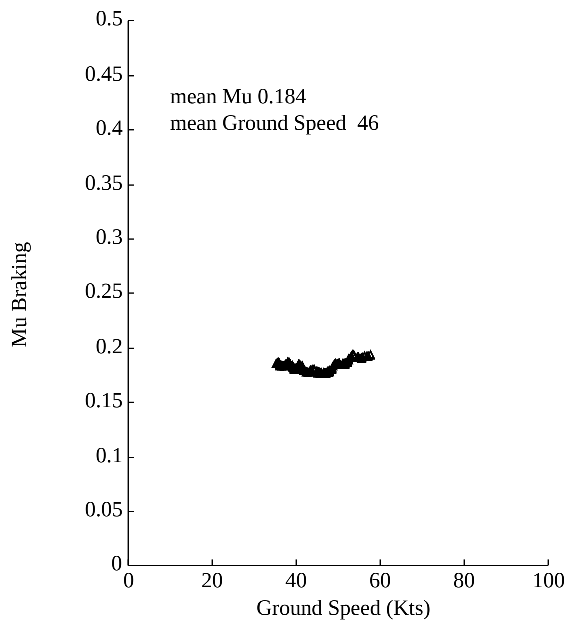
CRFI Average 0.26



Flight 2001/03, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

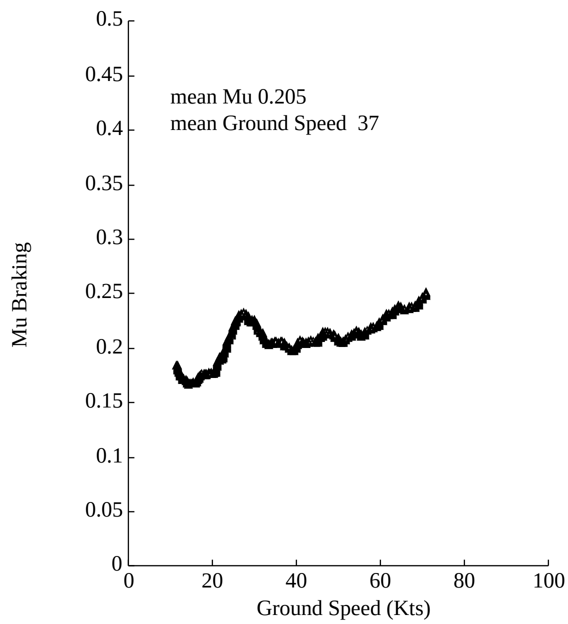
CRFI Average 0.25



Flight 2001/03, Run Number 4

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

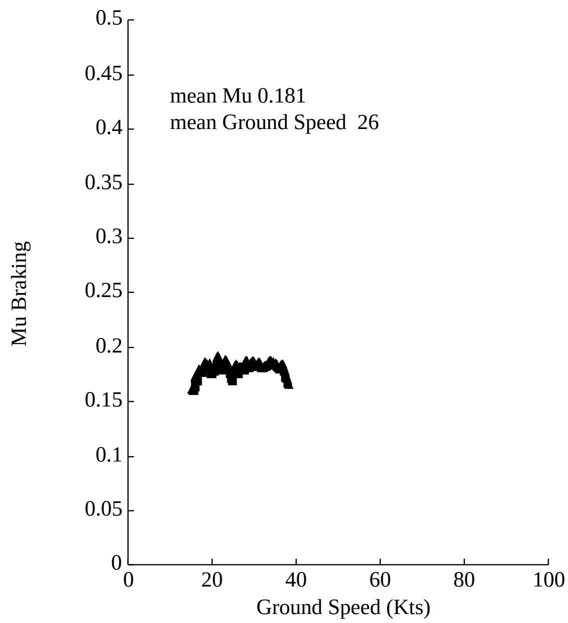


Surface: 1/4 inch loose snow over 60% compacted snow over ice, 40% ice patches

Flight 2001/03, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

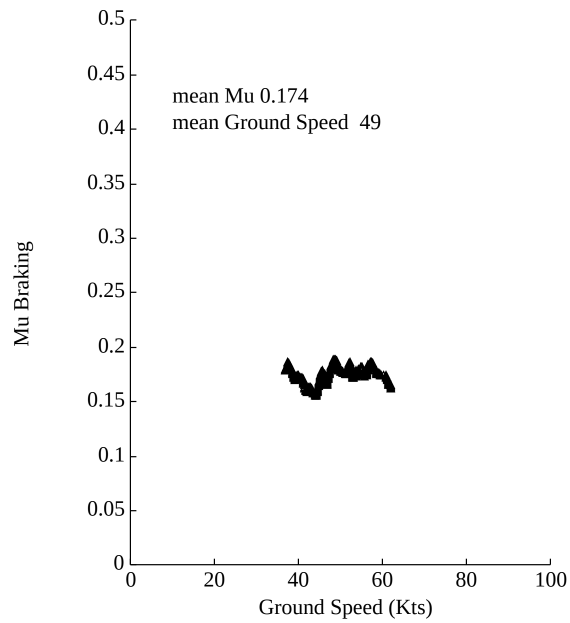
CRFI Average 0.24



Flight 2001/03, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

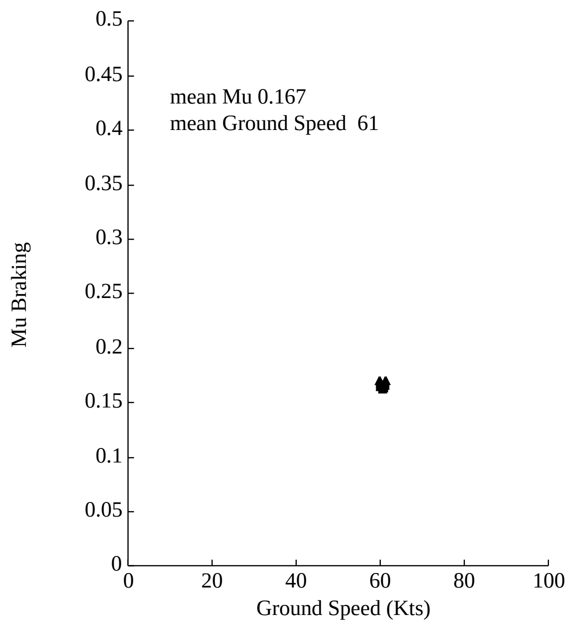
CRFI Average 0.25



Flight 2001/03, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

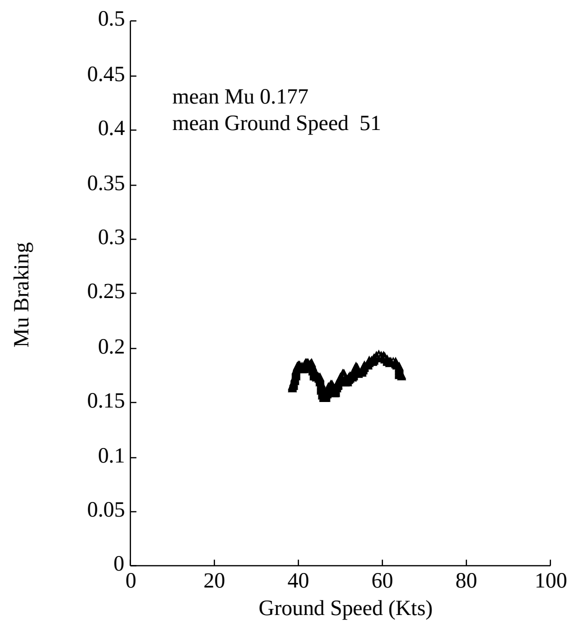
CRFI Average 0.26



Flight 2001/03, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.26

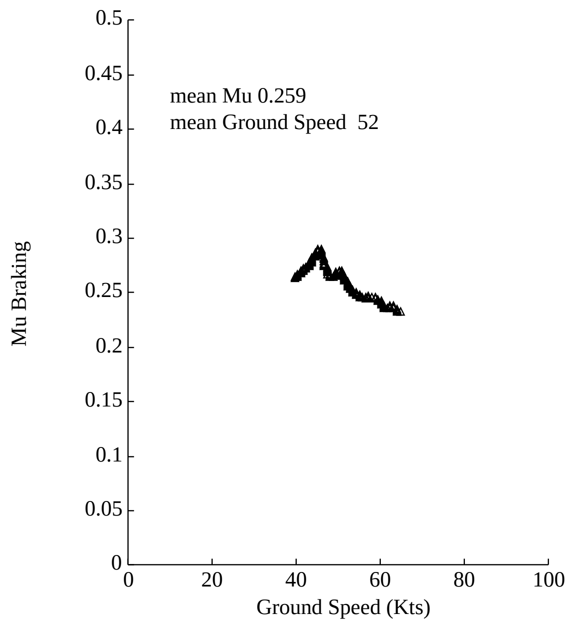


Surface: 1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches

Flight 2001/03, Run Number 9

Configuration: Flaps 15, Discing, Max Braking

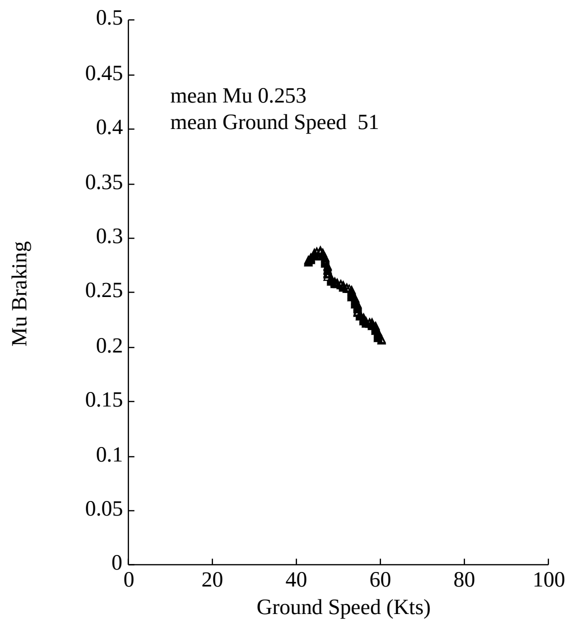
CRFI Average 0.27



Flight 2001/03, Run Number 10

Configuration: Flaps 15, Discing, Max Reverse

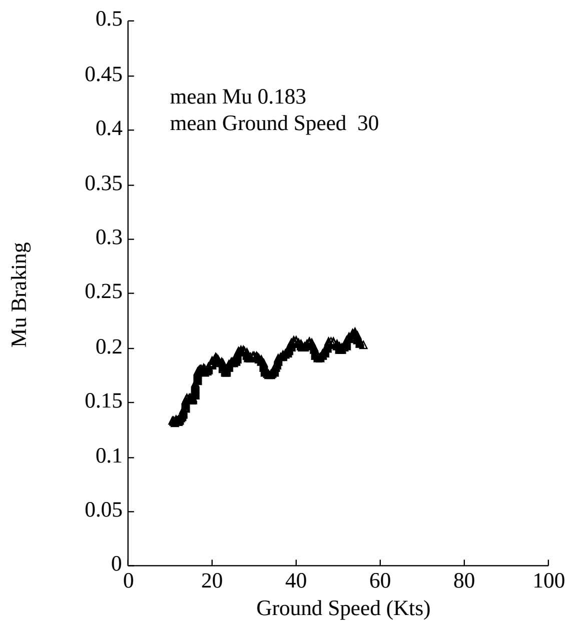
CRFI Average 0.27



Flight 2001/03, Run Number 11

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.27

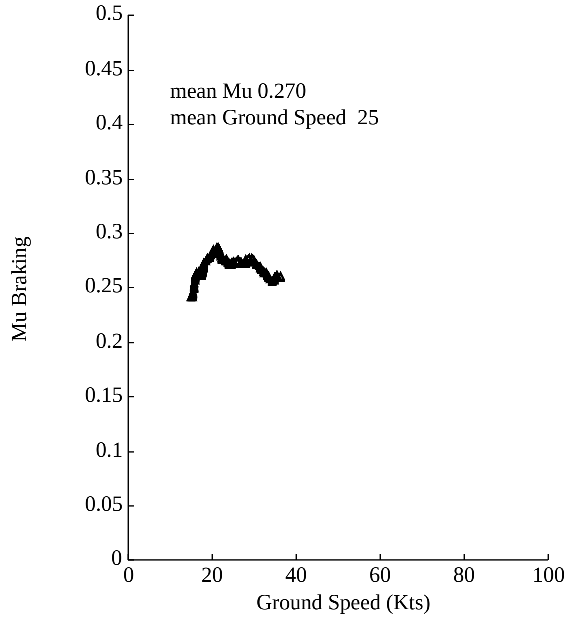


Surface: 100% sanded of 60% compacted snow over ice, 40% ice patches

Flight 2001/04, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

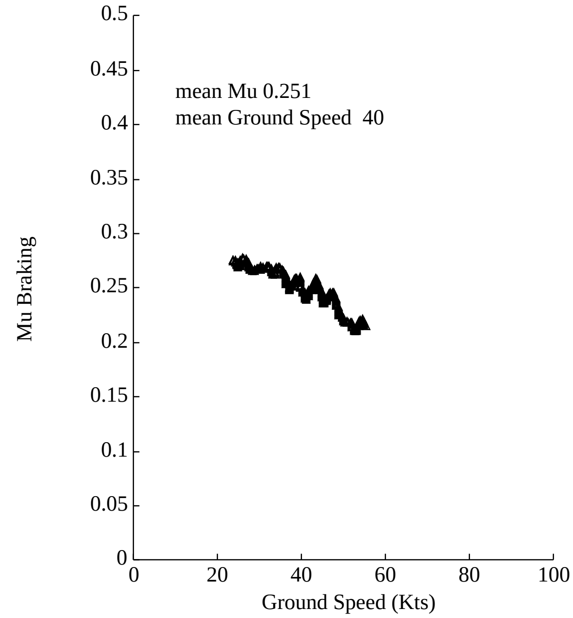
CRFI Average 0.40



Flight 2001/04, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

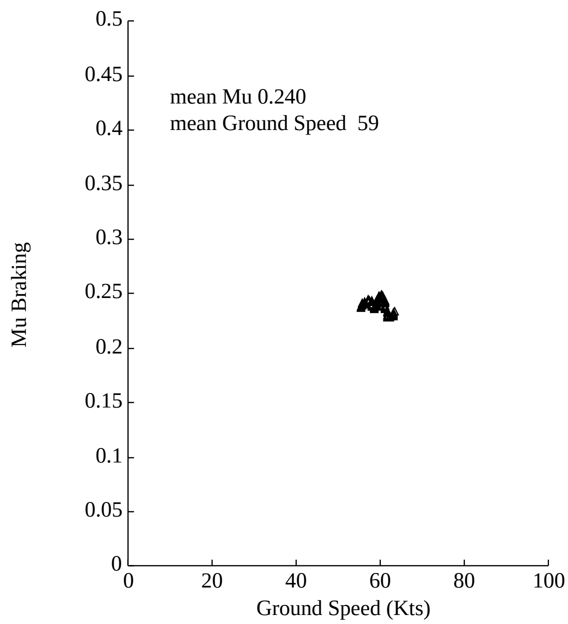
CRFI Average 0.38



Flight 2001/04, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

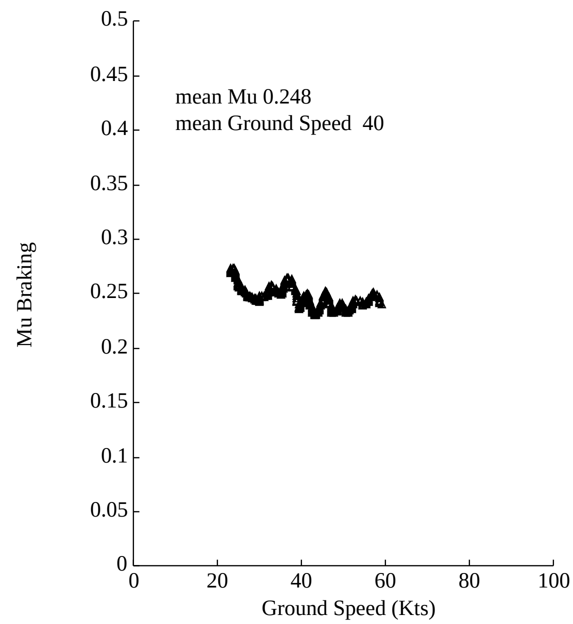
CRFI Average 0.36



Flight 2001/04, Run Number 4

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.36

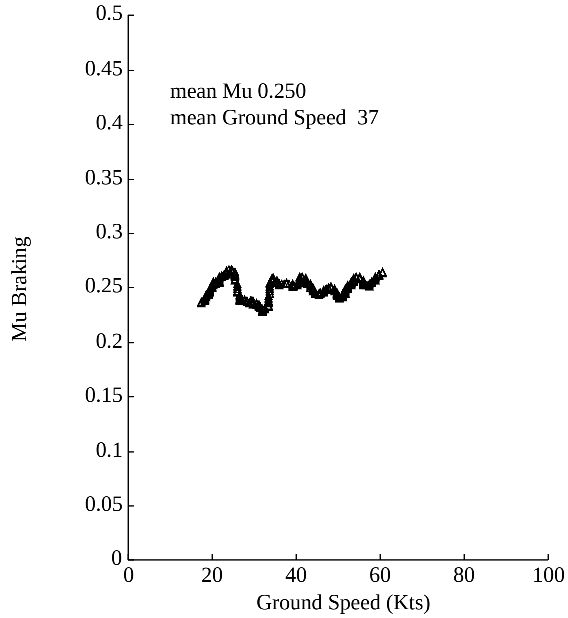


Surface: 100% sanded of 60% compacted snow over ice, 40% ice patches

Flight 2001/04, Run Number 5

Configuration: Flaps 15, Discing, Max Braking

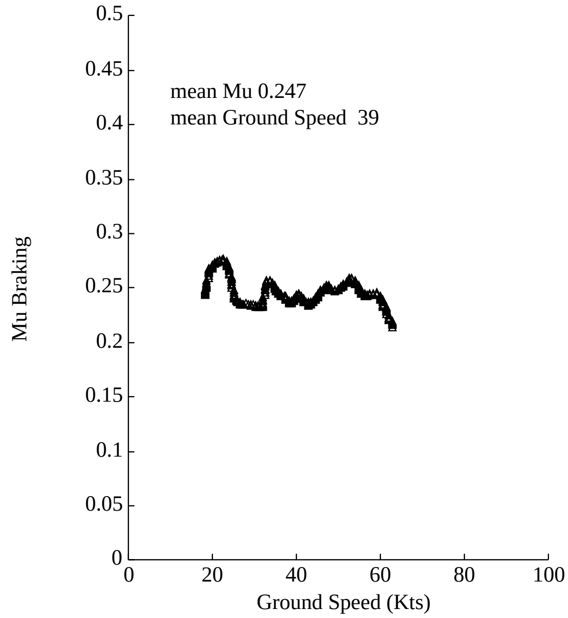
CRFI Average 0.36



Flight 2001/04, Run Number 6

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.36

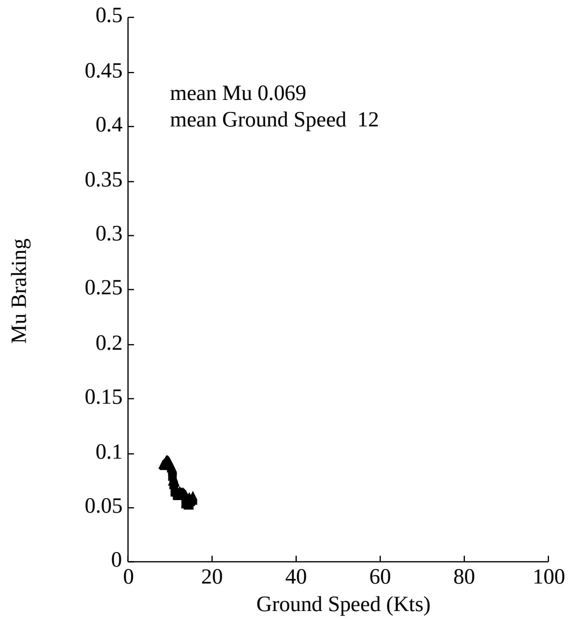


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 1

Configuration: Flaps 15, Discing, Max Braking

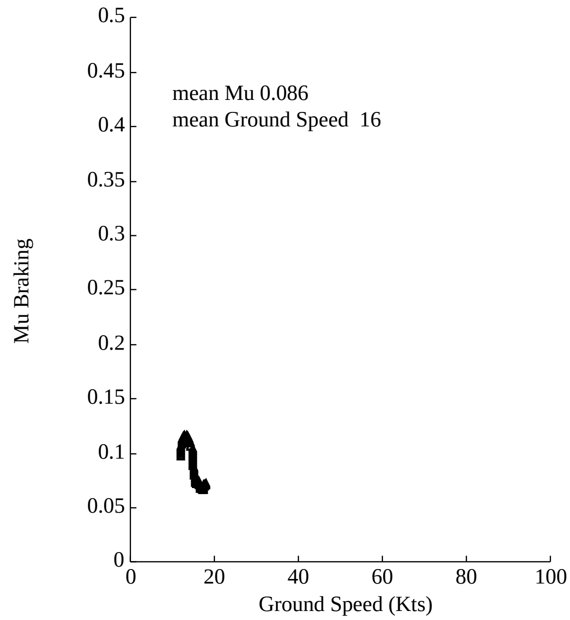
CRFI Average 0.10



Flight 2001/06, Run Number 2

Configuration: Flaps 15, Discing, Max Braking

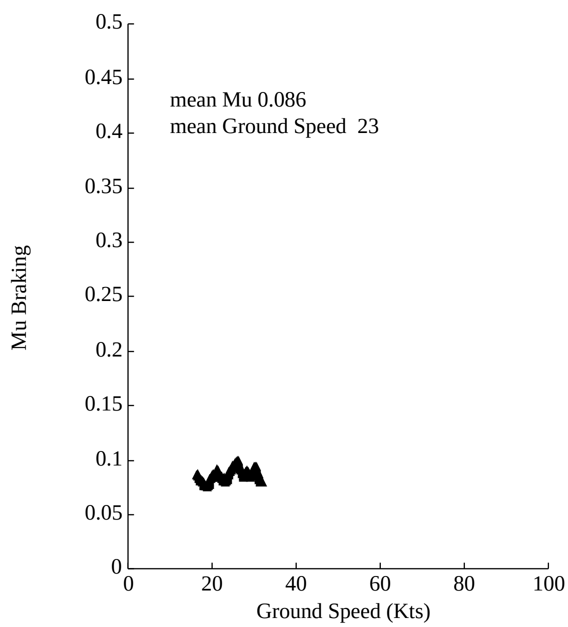
CRFI Average 0.11



Flight 2001/06, Run Number 3

Configuration: Flaps 15, Discing, Max Braking

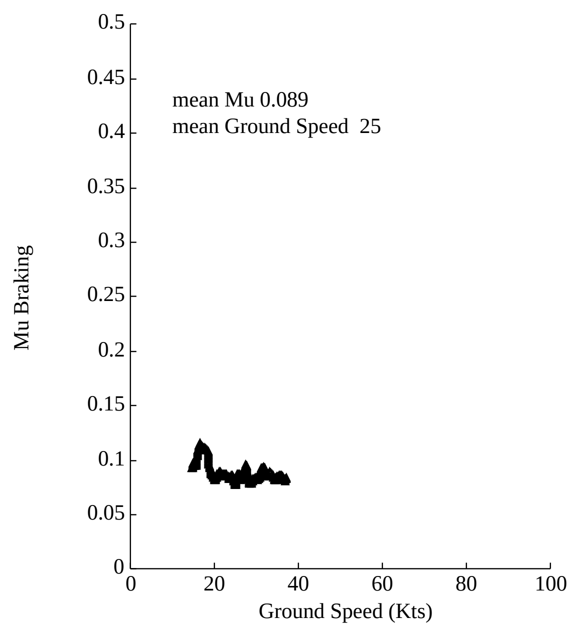
CRFI Average 0.11



Flight 2001/06, Run Number 4

Configuration: Flaps 15, Discing, Max Braking

CRFI Average 0.11

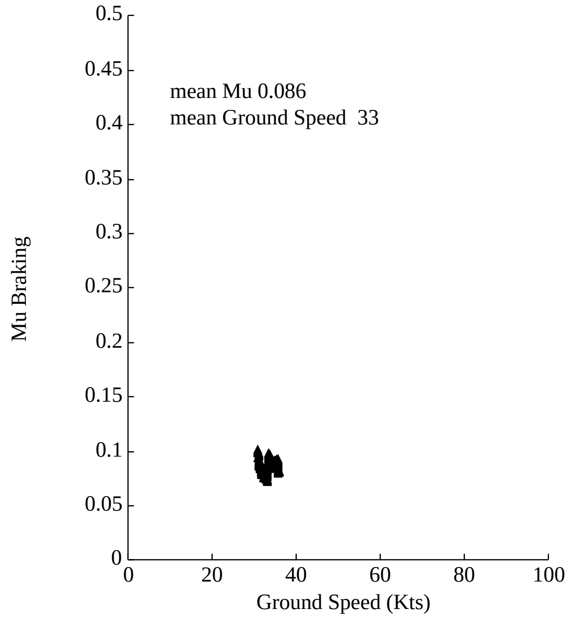


Surface: 100% smooth dry ice

Flight 2001/06, Run Number 5

Configuration: Flaps 15, Flight Idle, Max Braking

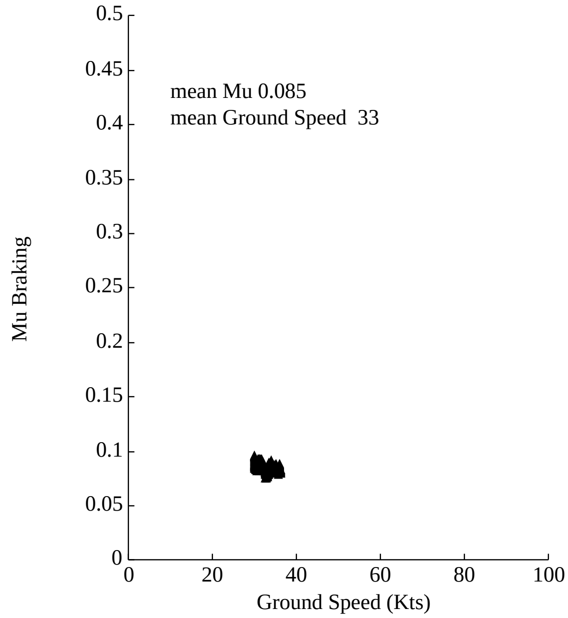
CRFI Average 0.11



Flight 2001/06, Run Number 6

Configuration: Flaps 15, Flight Idle, Max Braking

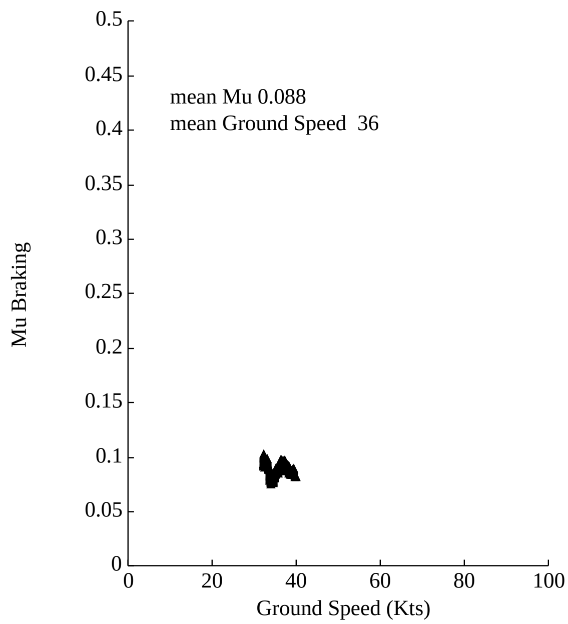
CRFI Average 0.12



Flight 2001/06, Run Number 7

Configuration: Flaps 15, Flight Idle, Max Braking

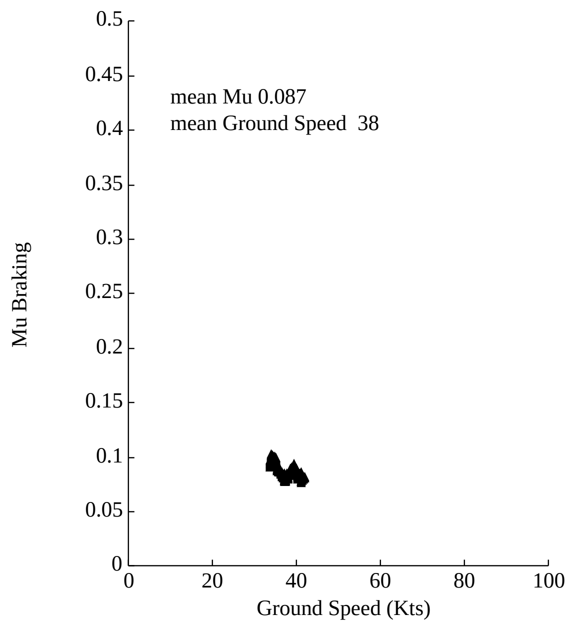
CRFI Average 0.11



Flight 2001/06, Run Number 8

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.11

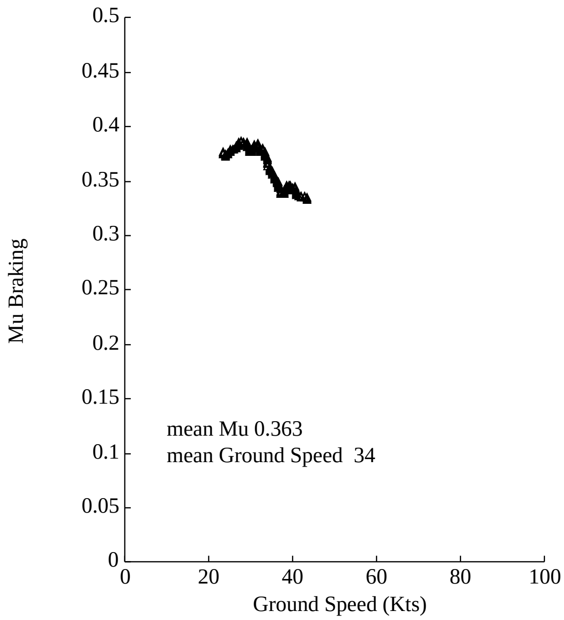


Surface: 20% bare and dry, 80% bare and damp
with patches of standing water

Flight 2001/07, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

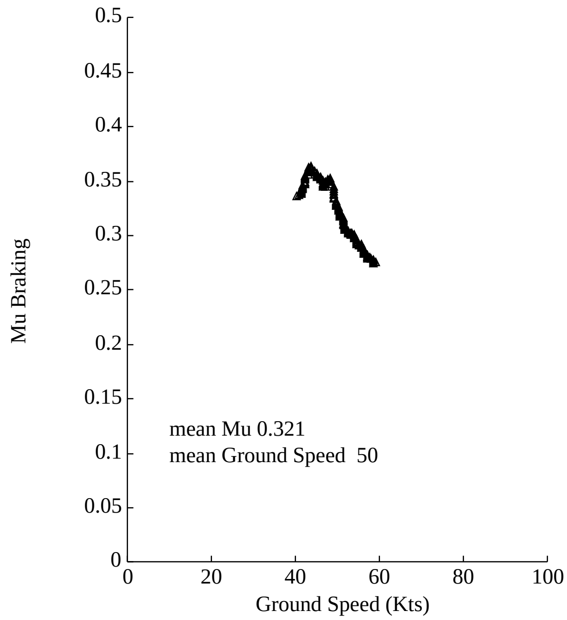
CRFI Average 0.54



Flight 2001/07, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

CRFI Average 0.60

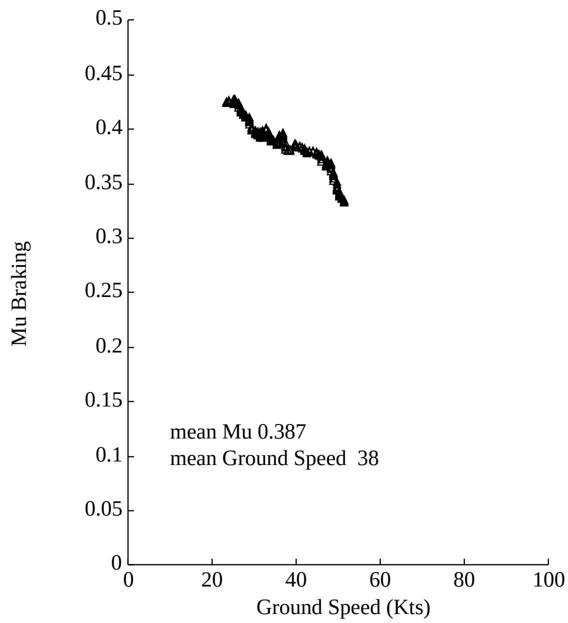


Surface: 100% bare and damp with 10-20% standing water

Flight 2001/08, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

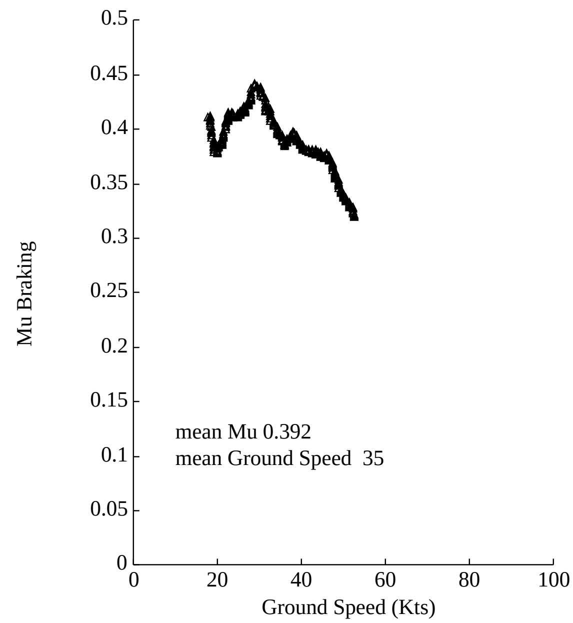
CRFI Average 0.74



Flight 2001/08, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

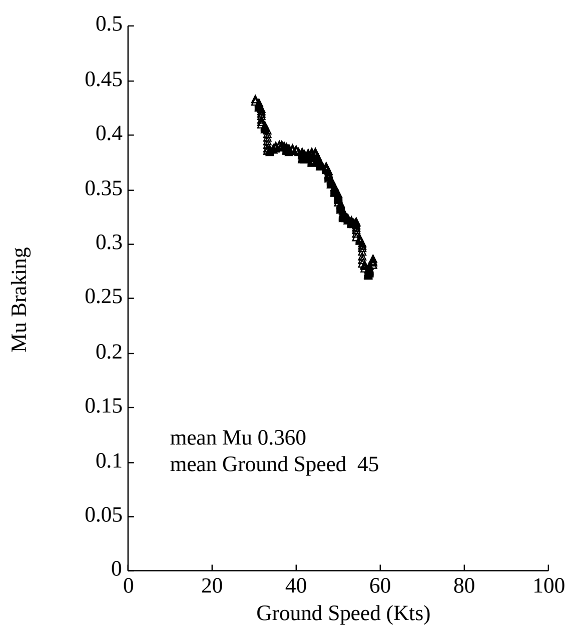
CRFI Average 0.72



Flight 2001/08, Run Number 3

Configuration: Flaps 15, Flight Idle, Max Braking

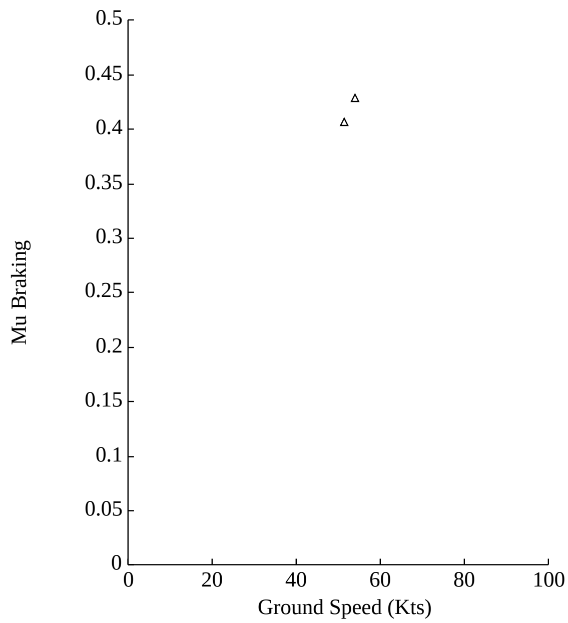
CRFI Average 0.72



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

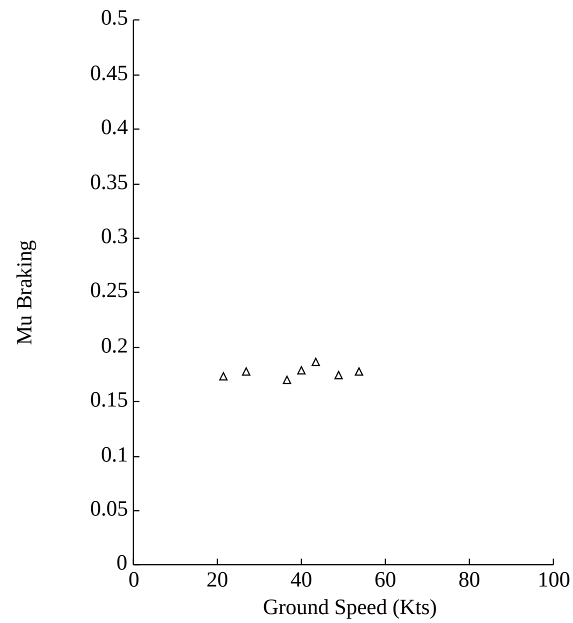
Flight 2001/01, Run Numbers 8 and 9

100% Bare and Dry



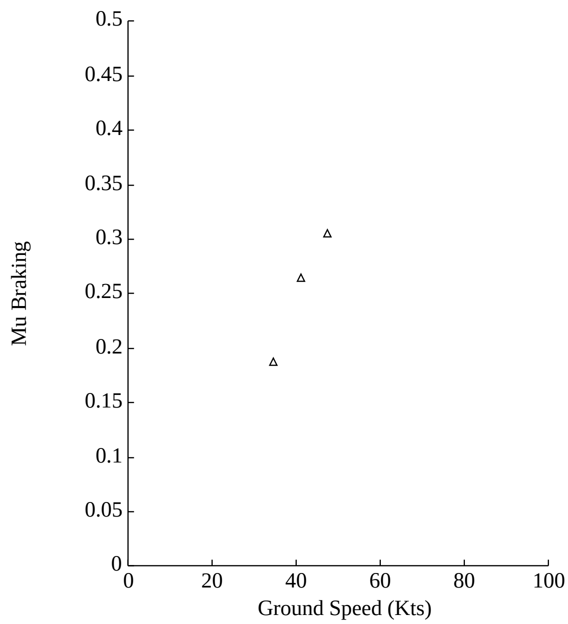
Flight 2001/02, Run Numbers 5 through 11

60% compacted snow over ice,
40% ice patches.



Flight 2001/02, Run Numbers 13, 16 and 18

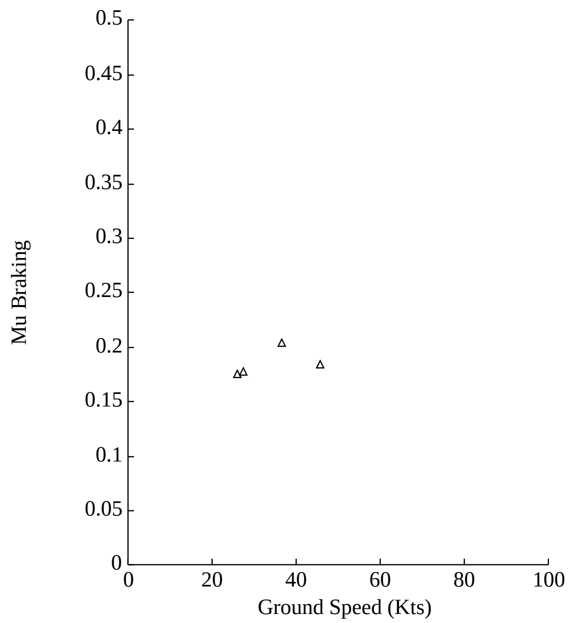
60% loose snow over ice, 40% ice patches.



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

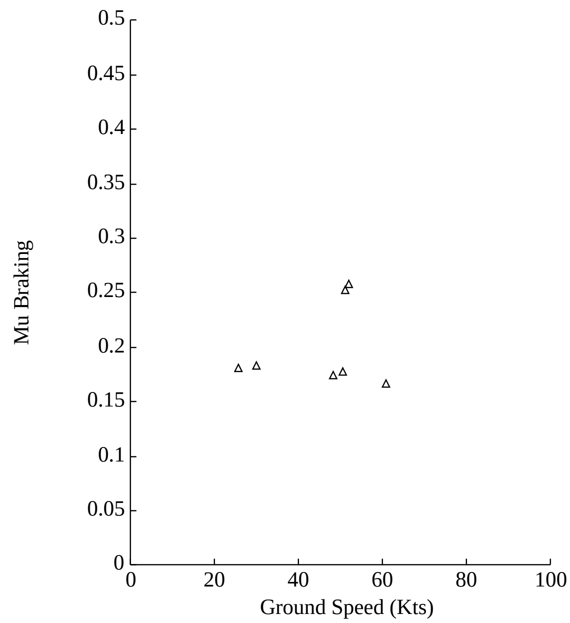
Flight 2001/03, Run Numbers 1 through 4

1/4 inch loose snow over bare and dry



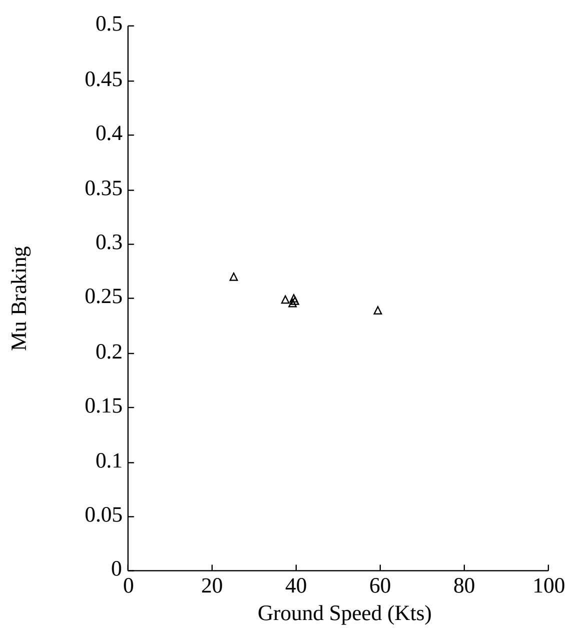
Flight 2001/03, Run Numbers 5 through 11

1/4 inch loose snow over 60% compacted
snow over ice, 40% ice patches



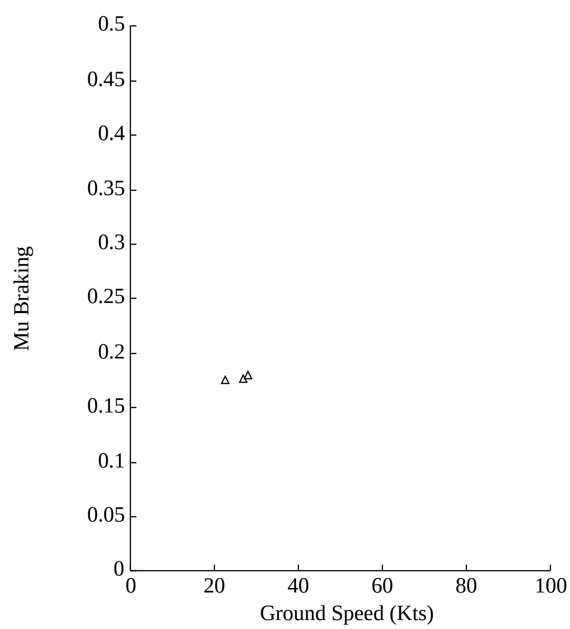
Flight 2001/04, Run Numbers 1 through 6

100% sanded of 60% compacted snow
over ice, 40% ice patches



Flight 2001/05, Run Numbers 1, 2 and 4

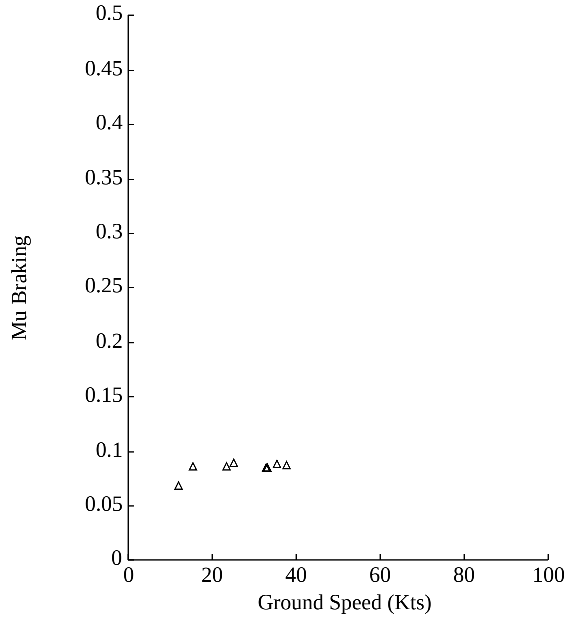
Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep



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

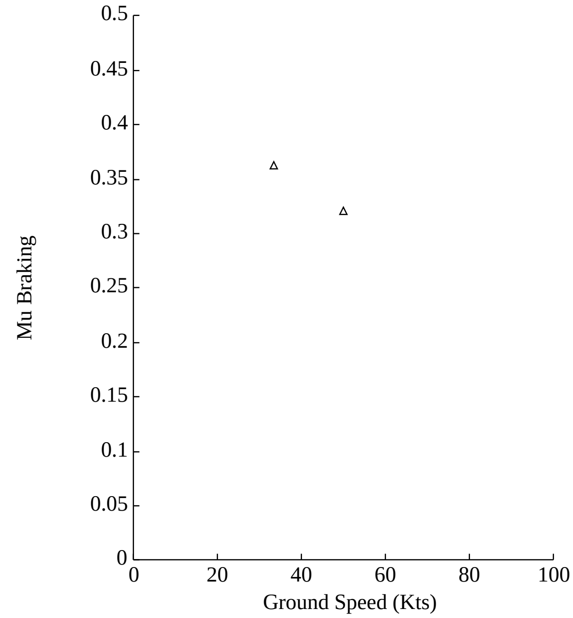
Flight 2001/06, Run Numbers 1 through 8

100% smooth dry ice



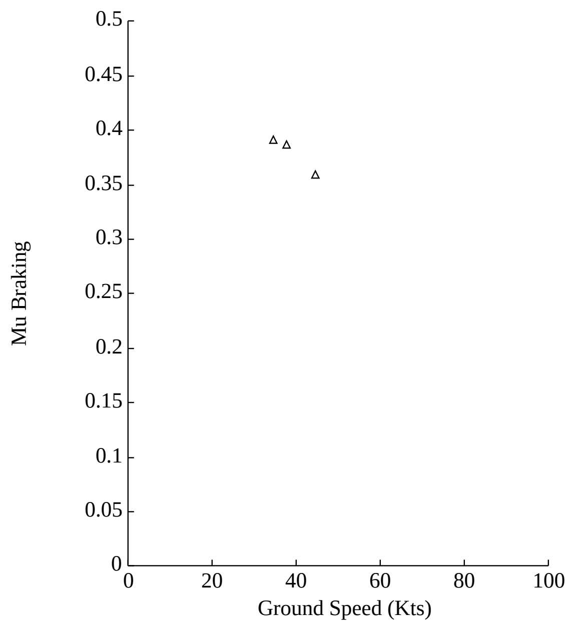
Flight 2001/07, Run Numbers 1 and 2

20% bare and dry, 80% bare and damp
with patches of standing water



Flight 2001/08, Run Numbers 1 through 3

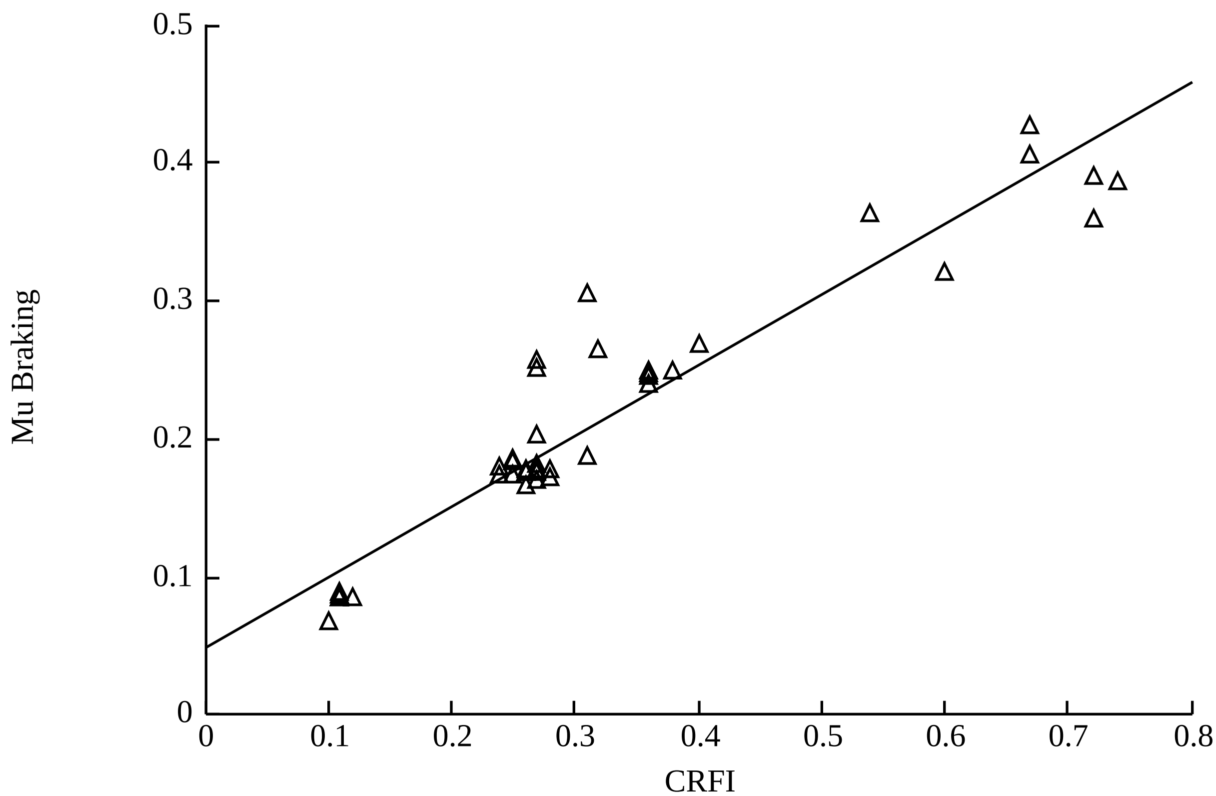
100% bare and damp with 10-20% standing water



Mean Mu Braking versus CRFI

Surfaces with No or Negligible Contamination Drag

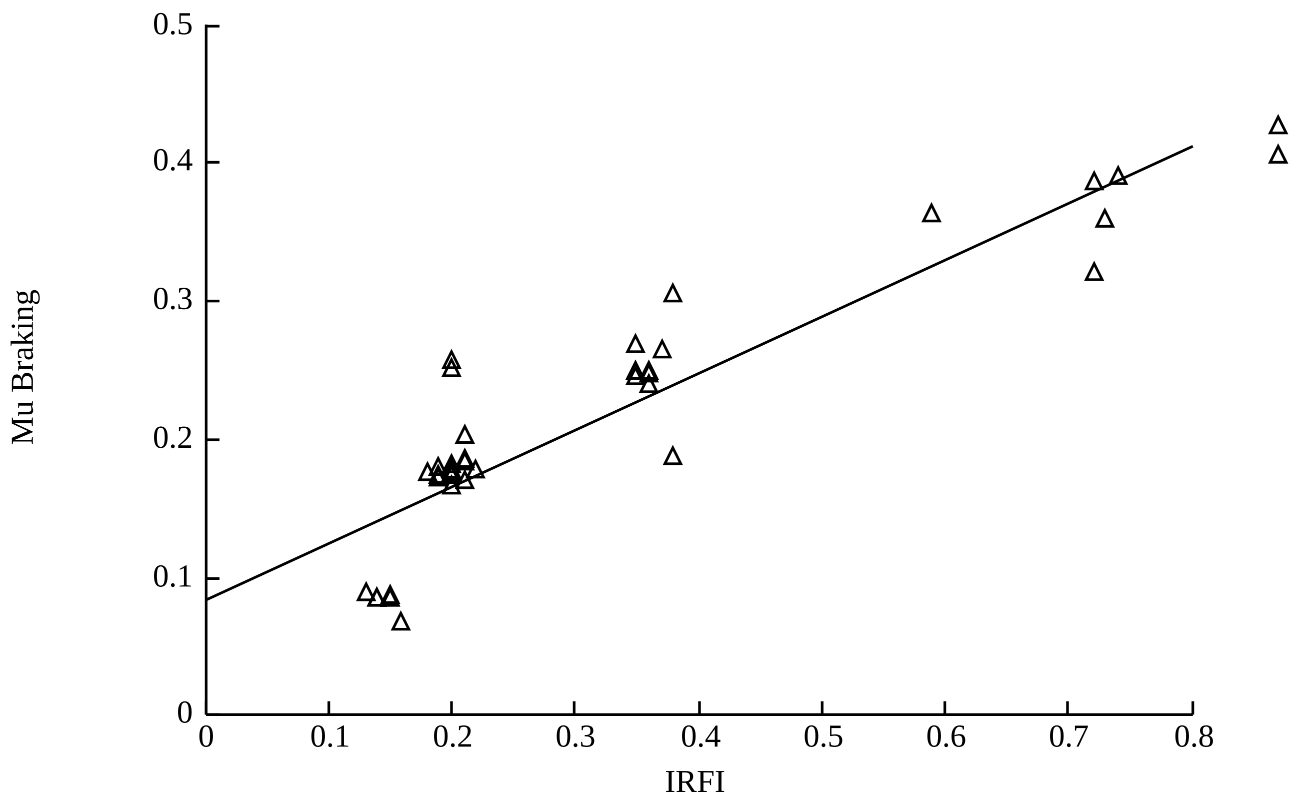
Mu Braking = 0.05021 + 0.5116 * CRFI
Correlation factor: 95%
Rms: 0.0302



Mean Mu Braking versus IRFI

Surfaces with No or Negligible Contamination Drag

Mu Braking = 0.08372 + 0.4104 * IRFI
Correlation factor: 91%
Rms: 0.0397



APPENDIX E - TEST RUNS FOR CONTAMINATION DRAG

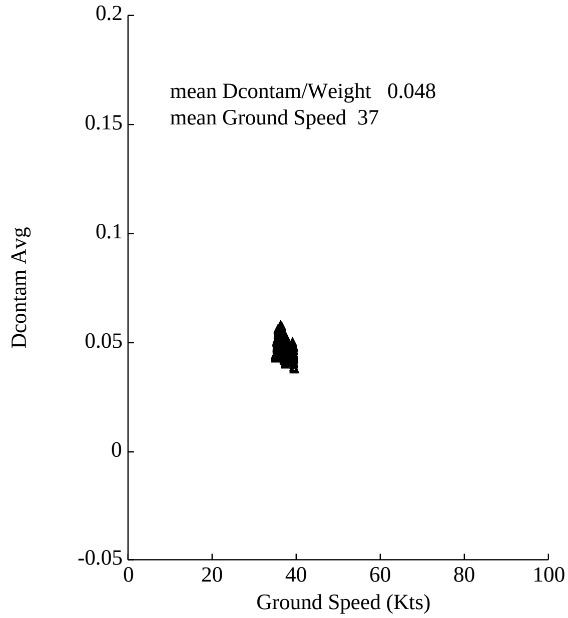
The following table shows the test runs used to determine the contamination drag. Pages E2 and E3 show the variation of D_{CONTAM}/W with ground speed for each run. The mean ground speed and mean D_{CONTAM}/W for each run are shown in the table and on Page E4.

FLT/ Date	RUN/ Time	RW	TAXI/ RTO/ LAND	FLAP/PWR BRK	WEIGHT (LB)	MEAN DEPTH (INCH)	MEAN SG	MEAN SPEED (KTGS)	MEAN D_{CONTAM} /W	MEAN D_{CONTAM} (LB)
2001/02 31/01/01	1 14:19	31N	RTO	15/IDLE/NO	32500	4.0	0.15	37	0.048	585
	2 14:27	31N	RTO	15/IDLE/NO	32420	4.0	0.15	33	0.077	1556
	3 14:34	31N	RTO	15/IDLE/NO	32350	4.0	0.15	44	0.071	1068
	4 14:40	31N	RTO	15/IDLE/NO	32290	4.0	0.15	44	0.129	2842
2001/05 21/03/01	5 14:57	31N	RTO	15/IDLE/NO	30810	2.0	Not Available	35	0.062	1017

Surface: 4 inches of loose snow
Sg of snow 0.15

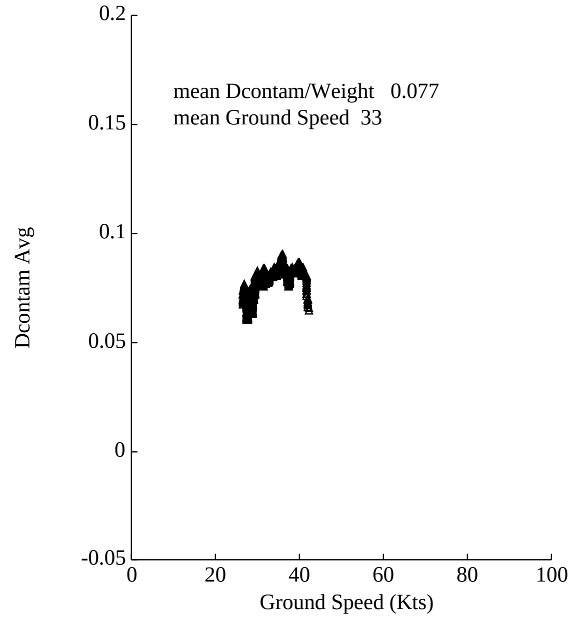
Flight 2001/02, Run Number 1

Configuration: Flaps 15, Flight Idle, No Braking



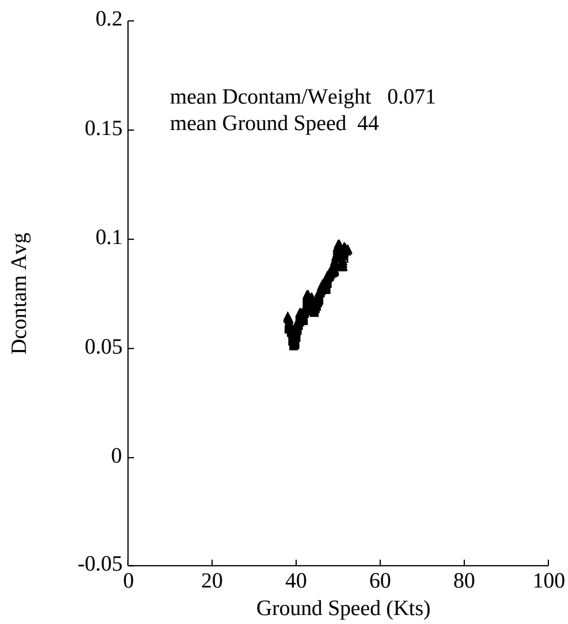
Flight 2001/02, Run Number 2

Configuration: Flaps 15, Flight Idle, No Braking



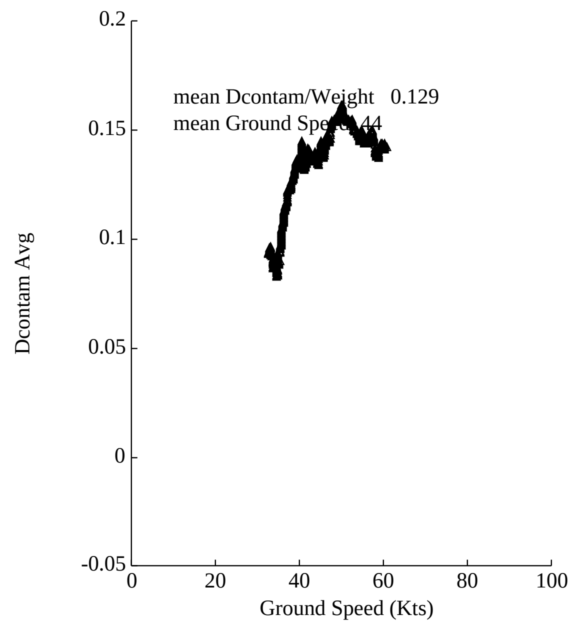
Flight 2001/02, Run Number 3

Configuration: Flaps 15, Flight Idle, No Braking



Flight 2001/02, Run Number 4

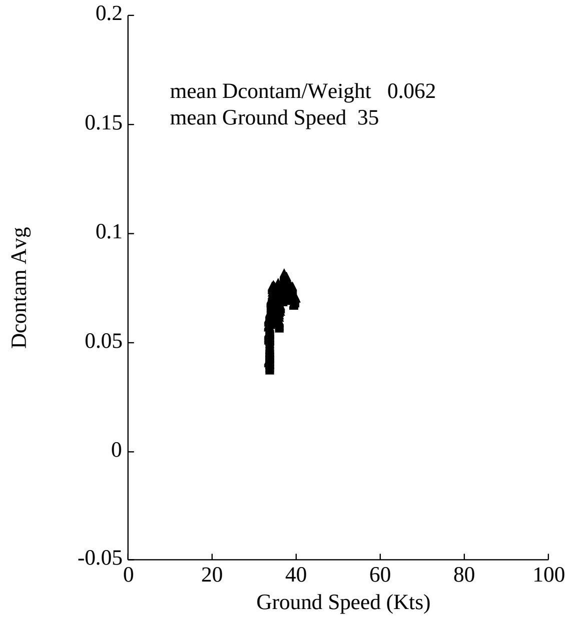
Configuration: Flaps 15, Flight Idle, No Braking



Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 5

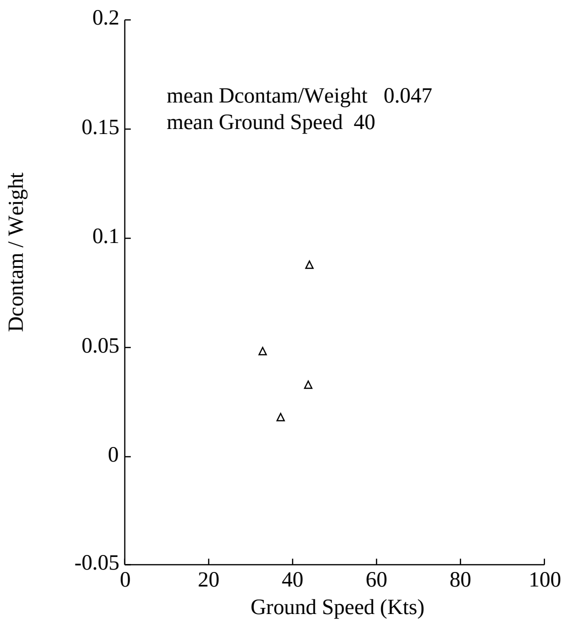
Configuration: Flaps 15, Flight Idle, No Braking



Summary of Aircraft Contamination Drag

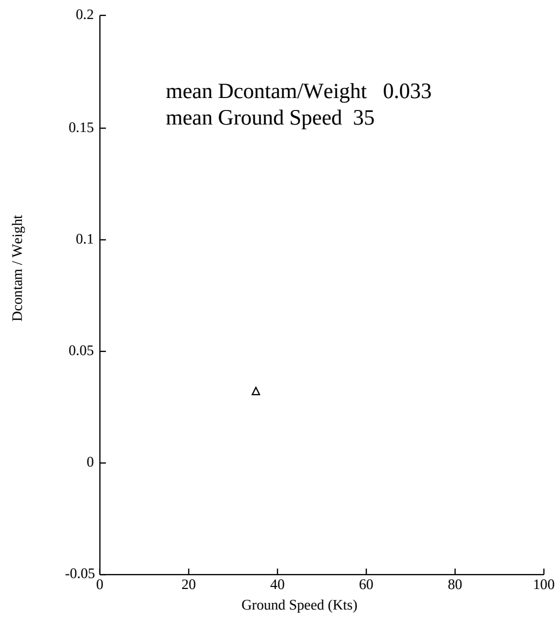
Flight 2000/02, Run Numbers 1 through 4

4 inches of loose snow



Flight 2000/05, Run Number 5

Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep



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

The following table shows the test runs used to determine the aircraft braking coefficient ($_B$) on runway surfaces with contamination drag. Page F2 shows the variation of $_B$ with ground speed for each run. The mean ground speed and mean $_B$ for each run are shown in the table. Page F3 shows the mean $_B$ plotted against the mean CRFI. Page F4 shows the mean $_B$ plotted against the mean IRFI.

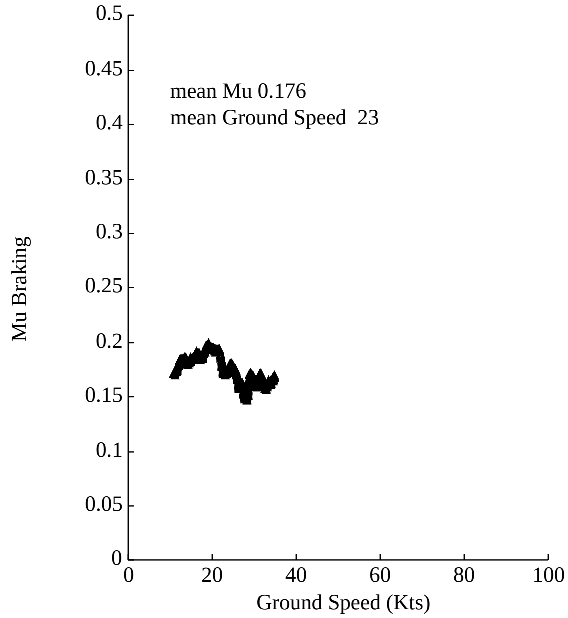
FLT Date	**RUN/ Time**	**RW**	**TAXI/ RTO/ LAND**	**FLAP/PWR BRK**	**WEIGHT (LB)**	**MEAN D_{CONTAM}/ W**	**MEAN CRFI**	**MEAN IRFI**	**MEAN SPEED (KTGS)**	**MEAN $_B$**
2001/05 21/03/01	1 14:11	31N	RTO	15/IDLE/B	31210	0.033	0.32	0.36	23	0.176
	2 14:24	31N	RTO	15/IDLE/B	31100	0.033	0.30	0.39	27	0.177
	4 14:42	31N	RTO	15/IDLE/B	30940	0.033	0.29	0.39	28	0.180

Surface: Wet snow and slush over ice patches and bare pavement
20-40% water puddles 1.5-2.5" deep

Flight 2001/05, Run Number 1

Configuration: Flaps 15, Flight Idle, Max Braking

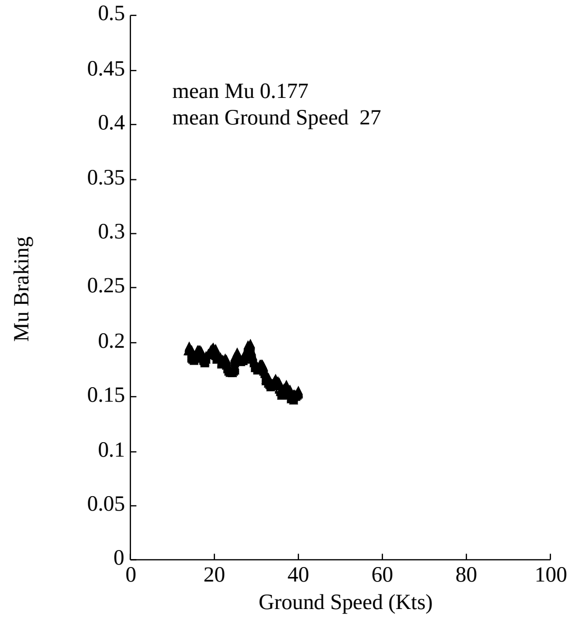
CRFI Average 0.32



Flight 2001/05, Run Number 2

Configuration: Flaps 15, Flight Idle, Max Braking

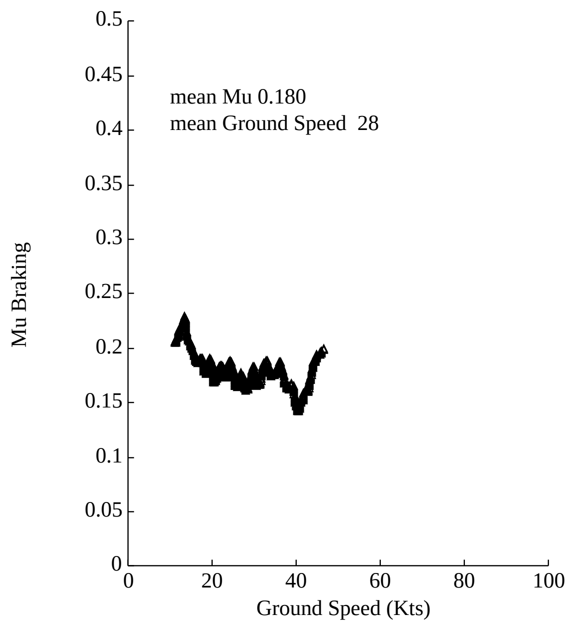
CRFI Average 0.30



Flight 2001/05, Run Number 4

Configuration: Flaps 15, Flight Idle, Max Braking

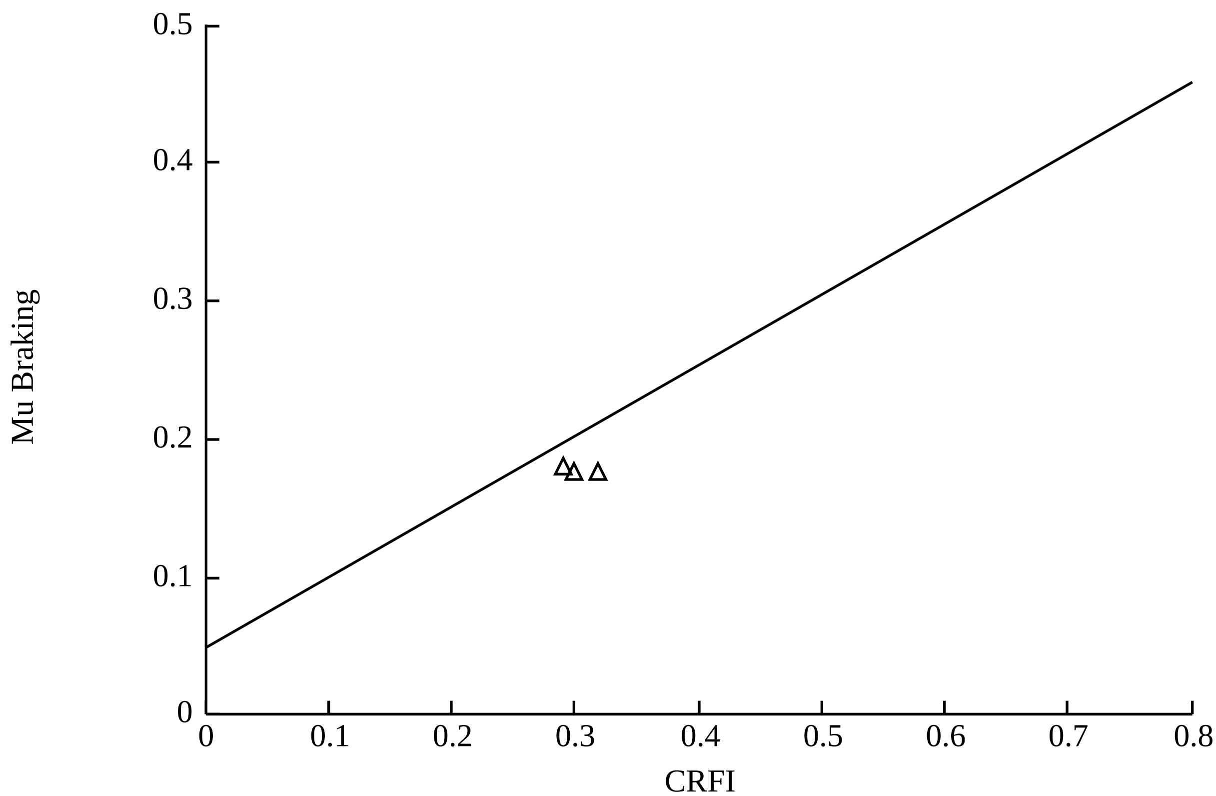
CRFI Average 0.29



Mean Mu Braking versus CRFI

Surfaces with Appreciable Contamination Drag

Mu Braking = 0.02902 + 0.4652 * CRFI
From Appendix D Page D20



Mean Mu Braking versus IRFI

Surfaces with Appreciable Contamination Drag

Mu Braking = 0.05921 + 0.3676 * IRFI
From Appendix D Page D21