TP 12866E

Evaluation of Ground Test Friction Measuring Equipment on Runways and Taxiways under Winter Conditions

Prepared by
CDRM Inc.
State College, Pennsylvania, USA

for
Norsemeter
and
Transport Canada, Airports
Safety and Technical Services

Under the Auspices
of the
1996 Joint Transport Canada/Norsemeter
Winter Runway Friction Testing Program

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16. Abstract

Tests with four ground friction measuring devices - an electronic recording decelerometer, a GripTester, a runway analyser and recorder, and a SAAB friction tester - were conducted on a variety of runway and taxiway winter-contaminated surfaces at Jack Garland Airport, North Bay, Ontario. These tests were part of a joint Transport Canada/Norsemeter winter runway friction program aimed at comparing, measuring, and understanding the effects of winter conditions on ground friction. Conditions included bare and dry from +2°C to -24°C, bare and wet, slush, smooth and rough ice, loose snow, medium-packed snow, and hard-packed snow at variable temperatures as recorded. For a given contaminant, one to five loops were run by each of the four devices. Correlations between the equipment are given for the various speeds, tires, and ambient temperatures, as well as for the various contaminants.

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16. Résumé

Quatre appareils pour la mesure de la glissance au sol - décéléromètre électronique (ERD), GripTester, analyseur de profil (RUNAR) et appareil SAAB (SFT) - ont été utilisés pour mesurer la glissance des chaussées aéronautiques et des voies de circulation de l'aéroport Jack Garland à North Bay (Ontario) soumises à diverses précipitations. Ces tests s'inscrivaient dans le cadre d'un programme mené conjointement par Transports Canada et Norsemeter, dont l'objectif principal était de mesurer, de comparer et d'approfondir le phénomène de glissance dans des conditions de contamination hivernale variées. Ces conditions étaient les suivantes : surfaces dégagées et sèches entre 2^{o} C et - 24^{o} C, surfaces dégagées et mouillées, neige fondante, glace lisse et rugueuse, neige folle, neige tassée densité moyenne et neige gelée dur à des températures variées. Les appareils de mesure ont effectué entre un et cinq circuits chacun par forme de contaminant. Des corrélations ont été établies entre les appareils de mesure en faisant varier les paramètres de vitesses, de pneus, de températures ambiantes et de forme de contamination.

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Dr. James C. Wambold of CDRM Inc. was invited to be the program supervisor and principal investigator due to his extensive experience in field testing with ground friction devices. He is professor emeritus in Mechanical Engineering at Pennsylvania State University. Dr. Wambold is also a certified aircraft mechanic and a pilot. We thank him for his diverse contributions to the program, from experimental design, planning, and test run management through final analysis and reporting.

For the data analysis we thank Dr. Charles Antle, a statistician and professor emeritus at Pennsylvania State University and Dr. Zoltán Radó of Norsemeter. Dr. Radó applied his promising new unified friction model to the data with great success.

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SUMMARY

Tests with four ground friction measuring devices - an electronic recording decelerometer (ERD), a GripTester, a runway analyser and recorder (RUNAR), and a SAAB friction tester (SFT) - were conducted on a variety of runway and taxiway winter-contaminated surfaces at Jack Garland Airport in North Bay, Ontario. These tests were part of a joint Transport Canada/Norsemeter winter runway friction program. The main objectives were to evaluate the effectiveness of RUNAR and other ground friction measuring devices for use on various winter contaminated surfaces and to establish correlations between them based on the data collected. Conditions included bare and dry from +2°C to -24°C, bare and wet, slush, smooth and rough ice, loose snow, and medium-packed and hard-packed snow at variable temperatures as recorded. For a given contaminant, one to five loops were run by each of the four devices. An instrumented Falcon 20 Jet was also included and ground equipment typically made runs before and after the Falcon made its tests. In total the ground equipment made 935 runs (313 by GT, 314 by SFT, 265 by RR, and 43 by ERD) and the Falcon made 22 landings. Deceleration versus ground speed and James brake index was measured. Table S1 summarizes the runs made on each test site.

Table S1
Number of test runs

Taxiway Lima	**30 km/h**	**65 km/h**	**90 km/h**	**others**
GripTester	44	76	62	1
SAAB Tester	44	76	62	2
RUNAR	30	56	44	1
ERD				20
Runway 10/31				
GripTester	6	33	20	1
SAAB Tester	6	33	20	1
RUNAR	8	35	22	3
ERD				18
Falcon 20				18
Runway 08/26				
GripTester	12	28	28	2
SAAB Tester	12	28	28	2
RUNAR	12	26	26	2
ERD				5
Falcon 20				4

The ground friction measuring devices were correlated against each other; the best correlations occurred when the bare and contaminated surfaces were included. Table S2 summarizes the correlations with all of the data and Table S3 lists correlations for tests on snow and ice only. In the report correlations are also made separately for the different speeds for each case.

A review of the data indicated that they formed two groups, one for bare and dry or wet surfaces and one for ice- and snow-covered surfaces. Furthermore, analysis of icy surfaces only or one snow condition only showed that the data for one condition were insufficient to make a correlation. A parallel report on the North Bay tests by G. Argue et al. also correlates the ground friction measuring equipment. It gives two correlations, one for bare and ice surfaces only and one for all surfaces. The authors demonstrate that bare and icy surfaces seem to go together and can be separated out from other surfaces. However, an analysis of ice-covered and snow-covered conditions indicates that statistically the data all belong to the same group, thus they are not separated in the correlations presented here. When additional data become available, it is recommended that these issues be re-examined.

Table S2
Correlation R^2 between devices on all surfaces at all speeds

	SFT	GT	RR15	RR18	RRpeak	RRF60
ERD	0.75	0.85	0.79	0.85	0.82	0.78
SFT	n.a.	0.74	0.48	0.48	0.64	0.72
GT	0.74	n.a.	0.81	0.83	0.70	0.69

Table S3
Correlation R^2 between devices on snow and ice at all speeds

	SFT	GT	RR15	RR18	RRpeak	RRF60
ERD	0.002	0.09	0.42	0.51	0.35	0.44
SFT	n.a.	0.35	0.38	0.24	0.13	0.14
GT	0.35	n.a.	0.58	0.49	0.59	0.33

Another set of reduced data related to the distribution of the percent slip (or slip ratio), at which the peak friction occurred. The data show that the percent slip at the peak occurred in the 10 to 24 percent slip range, with an average of 16 to 18 percent for bare pavement. They also show that the range on ice and snow was from 18 to 40 percent, with the mean at 31 percent. Normal behaviour on bare and wet pavement is for the peak friction to decrease with speed and for the percent slip for these peak friction values to increase with speed, which it did here as well on the bare pavement tests. On ice and snow the percent slip where peak friction is reached also increases with increased speed, but the peak friction either increased slightly or was nearly flat with increased vehicle speed above the peak value.

Special tests were performed to evaluate the effects of temperature and speed on American Society for Testing and Materials (ASTM) tires, as opposed to natural rubber tires. In the case of the SAAB friction tester the natural tire measures considerably below the ASTM tire. In the case of the GripTester the natural tire still measures lower, but only about half that of the SAAB friction tester. The effect of temperature on the two tires of the SAAB friction tester and GripTester showed that, in the case of the SAAB friction tester, the ASTM tire read about the same value throughout the temperature range. However, for the GripTester, both tires gave about the same values.

The distribution of slip ratios at which peak friction occurs indicates that ice- and snow-covered runways behave differently from the classic wet runway. For wet runways peak friction occurs at slip ratios in the range of 10 to 26 percent. Peak friction is observed to decrease with vehicle speed and the slip at which peak friction occurs increases with speed. This is not the case with ice and snow. First the slip ratio varies from 22 to 40 percent on ice and snow and the average slip ratio is about double, near 32 percent rather than the 15 percent on wet runways. This means the present fixed slip devices are measuring well before the peak and not at any constant ratio to the peak slip ratio. Once the peak friction is reached on ice and snow, the friction levels off with increased speed, rather than dropping off as it does on wet pavements. This supports the suggestion in the NASA/FAA study (Yager et al.) that the low shear strength of ice and snow determine the friction-speed characteristics, rather than the tire. Yager et al.

further assumed that frictional variations from speed, tire size, vertical load, and inflation pressure are insignificant for ice and compacted snow. These assumptions should be further evaluated in the follow-ons to this study, but they do seem reasonable, based on the results of this study, if the speed effect is taken at or above the peak slip speed.

Ground friction measurement equipment was evaluated in parallel with another program conducted by TC's Transportation Development Centre. Transport Canada's Airworthiness Group and the NRC Flight Research Laboratory provided the test data obtained from operating the National Research Council (NRC) instrumented Falcon 20 jet on the contaminated test surfaces. Ten different surface conditions were tested in January, and the data recorded. Note that the deceleration of the Falcon decreases with decreased speed. This is contrary to tire pavement friction, where friction increases with decreased speed; however, the results included aerodynamic drag, which causes an increase with speed. The Falcon 20 is equipped with a Mark II anti-skid system and the efficiency of the Mark II also affects the average deceleration on ice and snow. Correlations were made between the Falcon and the ground test equipment. Typically, all other ground measurements (except the ERD) show improved correlations with Falcon at decreased speeds. As with ground vehicles, there may be a different correlation for snow and ice surfaces versus bare surfaces. Table S4 gives a summary of the correlations.

Table S4
Correlation Value R^2 between the Falcon jet and the ground friction devices

	ERD	RR15	SFT	RR18	GT	RRpeak
Falcon Jet	0.84	0.76	0.77	0.79	0.80	0.80

Additional test data and tests with other aircraft and brake systems will show whether these relations hold up. The data so far are not sufficient to draw any such conclusions.

These tests have led to the following conclusions:

- ice- and snow-contaminated pavements behave differently from wet pavements;
- the average slip ratio at peak friction on ice and snow is at 32 percent slip or about double that for wet pavements;
- correlations of ground vehicles on wet pavements do not apply to vehicles on surfaces covered by ice and snow;
- the Rado Friction Model is useful and generally correlates well with equipment run at fixed percent slip, when the same slip ratio is calculated;
- the temperature effect on the ASTM and natural tires on the SAAB friction tester and the GripTester is inconclusive; however, the natural rubber tires measure lower frictional values than the ASTM tire at all slip speeds;

- a speed of 90 km/h is not safe on ice and deep snow and therefore routine measurements at 90 km/h are not recommended on these types of contaminated surfaces;

- additional tests under winter runway conditions are recommended to further define the influence of temperature and tire heating, and to determine the frictional correlations for ground vehicles.

SOMMAIRE

Quatre appareils pour la mesure de l’adhérence au sol - décéléromètre électronique (ERD), GripTester, analyseur de profil (RUNAR) et appareil SAAB (SFT) - ont été utilisés pour mesurer la glissance des chaussées aéronautiques et des voies de circulation de l’aéroport Jack Garland à North Bay (Ontario) soumises à diverses précipitations. Ces tests s’inscrivaient dans le cadre d’un programme mené conjointement par Transports Canada et Norsemeter, dont l’objectif principal était d’évaluer l’efficacité de mesure de ces appareils dans des conditions de contamination hivernale variées, et d’établir des corrélations les uns par rapport aux autres à la lumière des résultats de mesure. Ces conditions étaient les suivantes : surfaces dégagées et sèches entre 2° C et - 24° C, surfaces dégagées et mouillées, neige fondante, glace lisse et rugueuse, neige folle, neige tassée densité moyenne et neige gelée dur à des températures variées. Les appareils de mesure ont effectué entre un et cinq circuits chacun par forme de contaminant. Un avion à réaction Falcon 20 instrumenté a également été utilisé, dont chacun des atterrissages avaient été précédés et suivis d’un circuit effectué par les appareils au sol. Ceux-ci ont effectué en tout 935 circuits (GT : 313, SFT : 314, RR : 265, ERD : 43) et le Falcon a effectué 22 atterrissages. Des courbes de décélération en fonction de la vitesse sol et le coefficient de freinage James ont également été calculés. Le tableau S1 montre le nombre de circuits effectués sur les diverses pistes utilisées.

Tableau S1
Nombre de circuits

Piste Lima	**30 km/h**	**65 km/h**	**90 km/h**	**autres**
GripTester	44	76	62	1
SAAB Tester	44	76	62	2
RUNAR	30	56	44	1
ERD				20
Piste 10/31				
GripTester	6	33	20	1
SAAB Tester	6	33	20	1
RUNAR	8	35	22	3
ERD				18
Falcon 20				18
Piste 08/26				
GripTester	12	28	28	2
SAAB Tester	12	28	28	2
RUNAR	12	26	26	2
ERD				5
Falcon 20				4

Les appareils de mesure de l’adhérence ont été corrélés les uns par rapport aux autres; les meilleures corrélations ont été obtenues lorsqu’on a tenu compte des surfaces dégagées et contaminées. Le tableau S2 récapitule ces corrélations toutes surfaces confondues et le tableau S3, les corrélations des surfaces enneigées et glacées seulement. Le rapport donne en outre les corrélations en fonction de la vitesse.

Tableau S2
Corrélations R^2 toutes surfaces et toutes vitesses confondues

	SFT	**GT**	**RR15**	**RR18**	**RRmax**	**RRF60**
ERD	0,75	0,85	0,79	0,85	0,82	0,78
SFT	s.o.	0.,74	0,48	0,48	0,64	0,72
GT	0,74	s.o.	0,81	0,83	0,70	0,69

Tableau S3
Corrélations R^2 surfaces enneigées et glacées seulement et toutes vitesses confondues

	SFT	**GT**	**RR15**	**RR18**	**RRmax**	**RRF60**
ERD	0,002	0,09	0,42	0,51	0,35	0,44
SFT	s.o.	0,35	0,38	0,24	0,13	0,14
GT	0,35	s.o.	0,58	0,49	0,59	0,33

L’examen des résultats montre que ces derniers forment deux groupes distincts : un groupe rassemblant les surfaces dégagées, sèches ou mouillées, et un groupe, les surfaces enneigées et glacées. De plus, l’analyse des surfaces glacées seulement ou d’une seule surface enneigée seulement montre l’impossibilité d’établir une corrélation à partir des données relatives à un seul état de surface. Dans un rapport parallèle sur les tests effectués à North Bay et rédigé par G. Argue et al., des corrélations sont faites entre les appareils de mesure de l’adhérence. Elles sont au nombre de deux : une pour les surfaces dégagées et glacées seulement et une toutes surfaces confondues. Les auteurs montrent que les premières semblent aller de pair et se distinguer des autres surfaces. Cependant, l’analyse des données propres aux surfaces glacées et enneigées montre qu’elles appartiennent au même groupe statistique et que, par conséquent, il n’y a pas eu lieu de les analyser séparément. Il est recommandé d’approfondir cet aspect des choses lorsqu’on aura obtenu un plus grand nombre de données.

Le dépouillement des données a permis d’établir la distribution des valeurs d’adhérence (ou de glissance) en fonction des valeurs de frottement maximales (μ_{max}). On constate que les valeurs de glissance à μ_{max} s’inscrivent dans l’intervalle de 10 à 24 p. 100, la moyenne sur surface dégagée allant de 16 à 18 p. 100. On constate également que les valeurs sur surfaces enneigées ou glacées s’établissent entre 18 et 40 p. 100, avec une moyenne de 31 p. 100. Sur surfaces dégagées mouillées, il est normal que μ_{max} diminue lorsque la vitesse augmente, mais que les valeurs de glissance correspondantes augmentent, elles, avec la vitesse. Cela s’est vérifié non seulement pour les surfaces dégagées mouillées, mais également pour les surfaces dégagées sèches. Sur surfaces enneigées ou glacées, les valeurs de glissance augmentent avec la vitesse jusqu’au point μ_{max} mais, au-delà de ce point, les valeurs de μ_{max} augmentent peu ou n’augmentent presque plus avec la vitesse.

Des tests particuliers ont été menés pour connaître l’effet de la vitesse et de la température sur les pneus normalisés ASTM (American Society for Testing and Materials) et sur les pneus faits de caoutchouc naturel. Du point de vue de la vitesse, l’appareil SFT de SAAB équipé d’un pneu en caoutchouc naturel donne des valeurs de glissance dans une gamme bien au-dessous de celle des pneus ASTM. Il en est de même avec le GripTester, sauf que, avec celui-ci, les valeurs obtenues sont d’environ de moitié celles du SFT. Du point de vue de la température, les valeurs obtenues du SFT équipé d’un pneu ASTM montrent peu de variations dans tout l’intervalle des températures mesurées, alors que dans le cas du GripTester, les valeurs obtenues avec le pneu ASTM et le pneu en caoutchouc naturel ont été à peu près égales.

La distribution des valeurs de glissance à μ_{max} montre un comportement sur surfaces enneigées ou glacées différent de celui sur surfaces mouillées. Dans ce dernier cas, μ_{max} correspond à des valeurs de glissance dans l'intervalle de 10 à 26 p. 100, donnant une moyenne de 15 p. 100. Il a été observé que μ_{max} diminue à mesure qu'augmente la vitesse de traction et que la glissance correspondante augmente, elle, avec la vitesse. Sur surfaces enneigées ou glacées, les choses se passent différemment. D'abord, la glissance varie entre 22 et 40 p. 100, donnant une moyenne de 32 p. 100, soit à peu près le double de celle sur surfaces mouillées. Il s'ensuit que, avec les appareils à glissance constante, les valeurs de glissance s'inscrivent dans une gamme bien au-dessous de la valeur correspondant au point de μ_{max} , et que ces valeurs sont sans rapport fixe avec cette dernière. De plus, sur surfaces enneigées ou glacées, une fois dépassé le point de μ_{max} , la courbe de frottement s'aplatit avec l'augmentation de la vitesse, au lieu de fléchir, comme c'est le cas sur surfaces mouillées. Cette constatation vient renforcer l'hypothèse formulée dans une étude de la NASA/FAA (Yager et al.) voulant que la courbe adhérence en fonction de la vitesse est conditionnée par la faible résistance en cisaillement de la glace et de la neige plutôt que par les caractéristiques du pneu. Poussant leur raisonnement plus loin, Yager et al. tiennent pour acquis que les variations de l'adhérence en fonction de la vitesse, de la taille du pneu, de la charge verticale et de la pression de gonflage sont négligeables lorsqu'il s'agit de glace ou de neige tassée. Ces hypothèses mériteraient d'être approfondies par des recherches plus poussées, et les résultats de la présente étude semblent les vérifier sous réserve que les valeurs de vitesse dont il s'agit soient égales ou supérieures à la valeur correspondant à μ_{max} .

Le programme de mesure de la glissance par des appareils au sol s'est déroulé parallèlement à un autre programme mené par le Centre de développement des transports de Transports Canada. Le Groupe Navigabilité aérienne de Transports Canada et le Laboratoire de recherche en vol du Conseil national de recherches ont fourni les résultats d'expérimentations menées avec un Falcon 20 instrumenté du CNR atterrissant sur des chaussées présentant des états de surface différents. Dix de ces états de surface ont été mis en oeuvre en janvier. Il a été constaté que, avec le Falcon 20, les décélérations diminuent à mesure que diminue la vitesse. Ce qui est l'inverse de ce qui se passe avec les appareils au sol, où le frottement augmente à mesure que la vitesse diminue. Il y a lieu cependant de préciser que les résultats des expérimentations avec le Falcon 20 tiennent compte de la traînée aérodynamique qui augmente avec la vitesse. Le Falcon 20 est équipé d'un système antipatinage Mark II qui produit un effet sur les valeurs moyennes de décélération sur surfaces enneigées ou glacées. Des corrélations ont été établies entre le Falcon 20 et les appareils de mesure au sol. De façon générale, tous les appareils de mesure au sol montrent que, aux vitesses correspondant aux vitesses de 60 et de 20 noeuds de l'avion, les corrélations sont meilleures qu'à 100 noeuds, la meilleure corrélation s'établissant par rapport à la vitesse avion de 60 noeuds. À l'exception du ERD, tous les appareils de mesure au sol ont eu des corrélations améliorées dès lors que l'on utilise la valeur moyenne de μ du Falcon, toutes vitesses confondues. À l'instar des appareils de mesure au sol, il semble que les corrélations surfaces enneigées ou glacées par rapport aux surface dégagées soient différentes. Les corrélations sont récapitulées dans le tableau S4.

Il serait intéressant de voir dans quelle mesure ces corrélations se vérifient une fois que des expérimentations auront eu lieu avec d'autres types d'avions équipés d'autres systèmes de frein. Les données actuelles ne permettent pas de tirer des conclusions définitives.

Tableau S4

Corrélations R^2 entre le Falcon (valeur moyenne de μ) et les appareils de mesure au sol

	ERD	RR15	SFT	RR18	GT	RRmax
Falcon Jet	0,84	0,76	0,77	0,79	0,80	0,80

Ces tests ont mené aux conclusions suivantes :

- Le comportement des surfaces enneigées ou glacées est différent de celui des surfaces mouillées;

- La valeur moyenne de glissance de 32 p. 100 est à peu près le double de celle sur surfaces mouillées;

- Les corrélations des valeurs obtenues des appareils de mesure au sol sur surfaces mouillées ne sont pas valables pour les surfaces enneigées ou glacées;

- Le modèle de calcul Rado s’est révélé très utile, car les corrélations sont bonnes avec les appareils à glissance constante et comparable;

- Les expérimentations sur l’effet de la température sur l’appareil SFT de la SAAB et sur le GripTester, équipés d’un pneu ASTM ou en caoutchouc naturel ne sont pas concluantes, mais il a été observé que le pneu en caoutchouc naturel donne des valeurs de frottement moindres que le pneu ASTM quelle que soit la glissance;

- Il est dangereux de rouler à 90 km/h sur des surfaces glacées ou très enneigées et il n’est pas recommandé d’effectuer des tests sur de telles surfaces à cette vitesse;

- Il est recommandé de procéder à d’autres tests dans des conditions de contamination hivernale afin de pouvoir définir avec plus de précision l’effet de la température, de l’échauffement des pneus et des corrélations des valeurs de glissance obtenus des appareils de mesure au sol.

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SYMBOLS

A	intercept value of dependent variable
B	slope of linear regression equation
F(60)	friction value at slip speed of 60 km/h, one of two values of IFI
g	acceleration (1 g=32.2 ft/sec^2)
IFI	International Friction Index
p	tire pressure, psi
S	tire slip speed, km/h
S_p	speed gradient, one of two values of IFI
S_{peak}	slip speed where peak friction occurs
V	vehicle speed, km/h
T_{peak}	peak friction

Note that slip ratio or percent slip is (S/V)x100 and the slip ratio at peak friction is (S_{peak}/v)x100

ABBREVIATIONS

A/C	aircraft
BD	bare and dry
BW	bare and wet
cg	centre of gravity
CREL	Army Cold Regions Laboratory
DOT	day of test
ERD	Electronic Recording Decelerometer
FAA	Federal Aviation Administration, USA
flt	flight
GMT	Greenwich mean time
GT	GripTester
HPS	hard-packed snow
LS	loose snow
MIX	mixed conditions
MPS	medium-packed snow
N/A	not applicable
NB	North Bay Airport
RI	rough ice
RIHP	rough ice on hard-packed snow
RR	RUNAR
R/W	runway
SFT	SAAB Friction Tester
SI	smooth ice
SL	slush
SN	snow
TEMP	temperature, degrees Celsius
WSI	wet smooth ice
826	runway 08/26
1331	runway 13/31

1. INTRODUCTION

The measurement and reporting of runway friction under winter conditions is recognized by worldwide governmental regulatory authorities, airport operators, and airlines as an essential component in the provision of a safe air transportation system (1-8). The availability of meaningful, consistent, and timely information on runway surface conditions is a significant factor in reducing the number of aircraft running off the end of a runway or veering onto the shoulder area during a landing or aborted takeoff run. Research directed at obtaining a better understanding of aircraft performance under winter surface conditions has been actively pursued by worldwide aviation authorities such as Transport Canada, the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the Army Cold Regions Laboratory (CREL), and the United Kingdom's Ministry of Transportation (9-14). Over the years, manufacturers of friction testing equipment have also been enthusiastic participants in research activities and programs aimed at assessing and improving the measurement reliability of the many devices currently available.

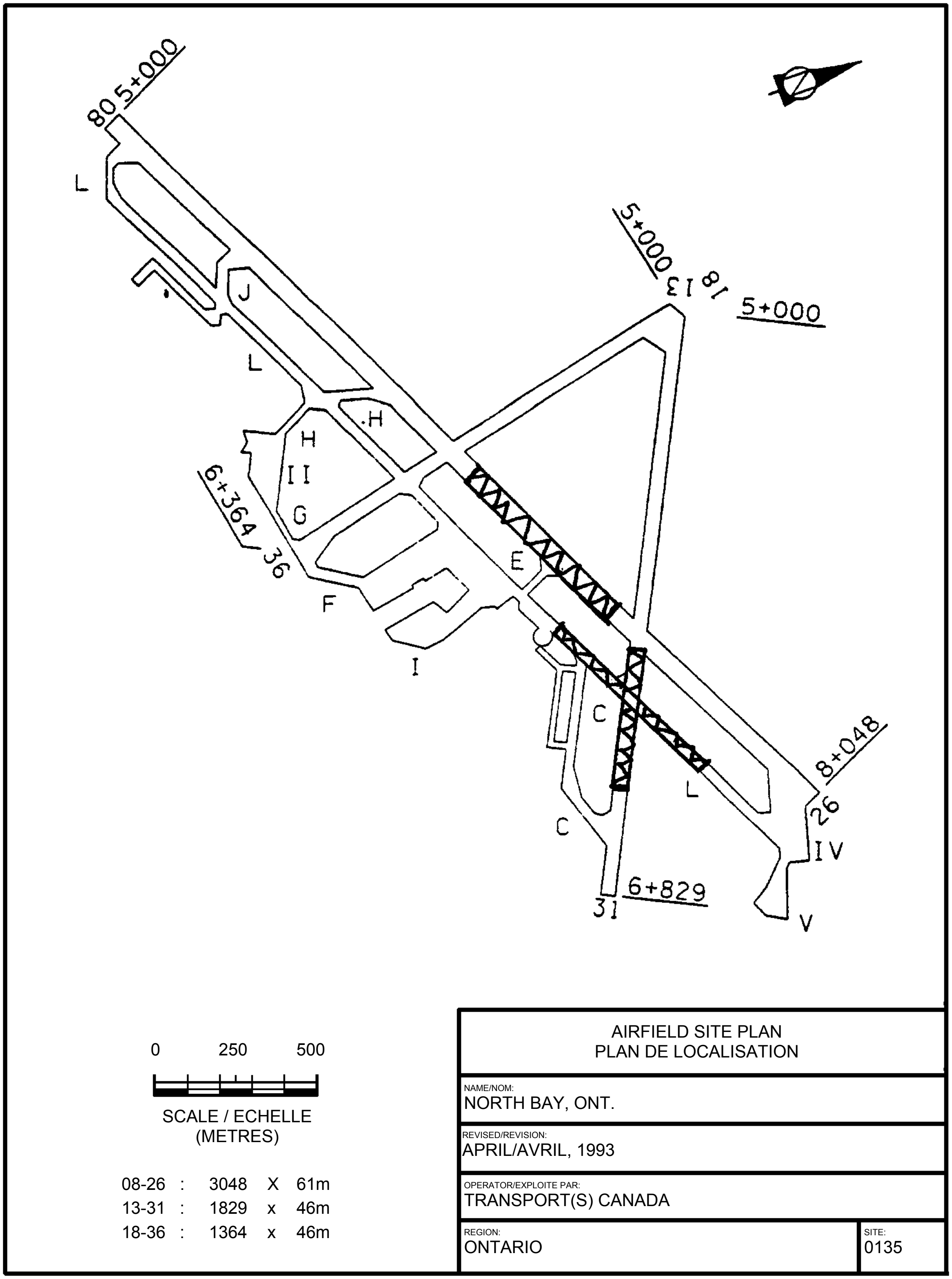
This report contains the results of a joint Transport Canada and Norsemeter project (undertaken during January 1996) to evaluate and correlate results obtained using ground-based friction measuring vehicles under a variety of winter surface conditions. Approximately 500 test runs were made with four ground friction measuring devices - the electronic recording decelerometer (ERD), GripTester, runway analyser and recorder (RUNAR), and SAAB friction tester (SFT). North Bay Airport in Ontario was selected as a suitable test site based on its varied range of precipitation and temperature conditions during the winter months. Two main test sections were established on Runway 13/31 and Taxiway Lima; in addition, a supplemental test section on the main Runway 08/26 was used, with its availability subject to operational restrictions imposed by site air traffic. Friction tests were carried out on various surfaces: bare and dry, bare and wet, smooth ice, rough ice, slush, loose snow, medium-packed snow and hard-packed snow. The effect of sand and urea applications on friction levels was also tested.

The main objectives of the joint project were to evaluate the effectiveness of RUNAR and other ground friction measuring devices for use on various winter contaminated surfaces and to establish correlations between them based on the data collected. In both the field and the analytical studies, the effects of several other test variables known to influence friction readings were also investigated, namely vehicle test speed, the rubber composition (synthetic or natural) of the tire itself, and test wheel slip ratios and their relation to peak friction values. Ultimately, future studies will lead to the correlation of ground friction measurements to aircraft braking performance under different winter surface conditions. Ten landings were made with an instrumented Falcon 20 jet aircraft and ground equipment measurements were made before, after, or before and after each landing. Preliminary correlations between the Falcon and ground equipment are made and reported here.

2. TEST SITE

The Jack Garland Airport in North Bay, Ontario, was selected as the winter test site. North Bay is about 200 miles north of Toronto and about 200 miles west of Ottawa. This airport was selected because its northern location provides a variety of natural winter conditions. The airport is operated by Transport Canada. Thus, it provided excellent personnel support and was very well suited for the tests, with space available for an office, meeting rooms, and an analysis room. Hangar space was also available to house all the ground test vehicles, as well as the aircraft to be used in this study and future tests.

The three-runway layout at North Bay Airport is shown in Figure 1. The three runways are: 08/26 - 10 000 ft (3 050 m) long by 200 feet (61 m) wide; 13/31 - 6 000 ft (1 830 m) long by 150 feet (46 m) wide; and 18/36 - 4 474 ft (1 365 m) long by 150 feet (46 m) wide. In the winter, runway 13/31 is not normally used, so it was made available to the project for testing and was used to test both ground vehicles and aircraft. In addition, the east end of taxiway Lima was made available as a test site for the ground vehicles, and runway 08/26 was also used as a test site for ground vehicles and aircraft when natural conditions and traffic allowed. The area used on taxiway Lima (L) was 600 m long; it is marked on Figure 1. The test site on runway 13/31 was generally 400 m long, but as much as 800 m were used at times. Similarly, the test site on runway 08/26 was generally 600 m long, but 1 800 or even 2 400 m were used for some tests.



08-26 : 3048 X 61m
13-31 : 1829 x 46m
18-36 : 1364 x 46m

AIRFIELD SITE PLAN
PLAN DE LOCALISATION

NAME/NOM:
NORTH BAY, ONT.

REVISED/REVISION:
APRIL/AVRIL, 1993

OPERATOR/EXPLOITE PAR:
TRANSPORT(S) CANADA

REGION:
ONTARIO

SITE:
0135

Figure 1. North Bay Airport layout

3. TEST APPARATUS

In this section each device, as well as the support equipment, is described. Appendix A contains photographs of the devices, the operators, the support equipment, and key personnel.

3.1 Ground Friction Equipment

The following ground friction measuring devices were assessed:

- Electronic recording decelerometer (ERD)
- GripTester (GT)
- Norsemeter runway analyser and recorder (RUNAR)
- SAAB friction tester (SFT)

3.1.1 Electronic Recording Decelerometer

A decelerometer type mounted at the approximate centre of gravity of a host vehicle. The host vehicle used was a 1.5 t pick-up truck with rear-wheel drive. The host vehicle is brought up to measuring speed and its wheels are braked to a fully locked state. During this braking action, the deceleration is measured every few milliseconds and recorded. The measured deceleration value is converted by a digital computer to a peak friction coefficient average for the four wheels. The measuring procedure is non-continuous, and is repeated five to six times. The computer calculates an average value of the friction value for a number of vehicle brake tests. Commercial tires are fitted onto the vehicle wheels.

3.1.2 The GripTester

A continuous fixed slip type designed as a three-wheel trailer towed by a host vehicle. The trailer wheels are fitted to a rotating axle with the test wheel suspended behind the midpoint. The test wheel is driven at a slower rotational speed than the driving wheels of the rotating axle. The geared ratio between the driving and the driven wheel was found to be 18 percent and is accomplished by a roller chain and sprockets. The braking torque of the test wheel is sensed by a force transducer sensitive to the tension in the test wheel suspension. A vertical load of 206 N (46 lb) is applied on the test wheel, which has a suspension with springs. The device uses a test tire with a tread of ASTM E-1551 rubber compound and an operating inflation pressure of 137.9 kPa (20 psi). The instrumentation provides for acquisition of force acting on the test wheel converted to friction coefficient in a digital computer and the rotational speed of trailer wheels converted to distance traveled per unit time. The computer is programmed to calculate the average friction value of a preselected distance and the average speed over the same distance. The measured values are stored in the computer and output as a printout on a strip chart and data files on diskette.

3.1.3 Runway Analyser & Recorder

A continuous measuring type with a variable slip test wheel. It is mounted on a two-wheel trailer and towed by a host vehicle. The test wheel is directly mounted on the axle of a hydraulic wheel slip controller programmed to perform a desired braking action on the test wheel. One braking action is a linearly decreasing rotational wheel speed from free rolling to locked wheel. During this action the torque on the wheel axle is measured and converted to a friction coefficient by the digital computer of the device. A vertical static load of 1.5kN (337 lb) is applied on the test wheel, which has a four-bar suspension with no spring and no shock absorber.

The American Society for Testing and Materials (ASTM) E-1551 was used as the test tire with inflation pressure 207 kPa (30 psi). The instrumentation provides for acquisition of the torque acting on the test wheel, which is converted to friction coefficients in a digital computer, and the rotational speed of the test wheel is converted to a distance and distance travelled per unit time. The computer is programmed to calculate several friction process parameters, including peak friction coefficient, the slip speed at which the peak friction occurred, and the slope of the friction coefficient curve as a variable of slip speed. The computer program uses the Rado Friction Model to derive these parameters. Friction coefficients for all slip speeds can be estimated from each braking action, including friction at lower slip ratios, such as 15 or 18 percent, and for travelling speeds other than the one tested. The measured values are stored in the computer and output as a printout on a strip chart and data files on diskette.

3.1.4 SAAB Friction Tester

The SAAB friction tester is equipped with front-wheel drive and a hydraulically retractable friction-measuring wheel installed behind the rear axle. The SFT measuring device is a continuous fixed slip type integrated into the host vehicle. The host vehicle is a front-wheel drive compact class automobile. The specially designed rear axle has the test wheel suspended behind its midpoint. The test wheel is driven at a slower rotational speed than the driving wheels of the rear axle. The geared ratio between the driving and driven wheel is accomplished by a roller chain. The braking torque of the test wheel is sensed by a force sensor sensitive to the tension in the roller chain. A vertical load of 1.38 kN (310 lb) is applied on the test wheel which has a suspension with a spring and shock absorber. The ASTM E-1551 was used as the test tire with inflation pressure 207 kPa (30 psi). The instrumentation provides for acquisition of torque acting on the test wheel converted to a friction coefficient in a digital computer and the rotational speed of a host vehicle wheel converted to distance travelled per unit time. The computer is programmed to calculate the average friction value of a preselected distance and the average speed over the same distance. The measured values are stored in the computer and output as a printout on a strip chart only.

3.2 Support Equipment

The support equipment used during the experiment included:

- Ice and snow condition measuring equipment:
  - Smithers ice and snow compaction gauge (see photo 9 in Appendix A)
  - Snow and ice depth gauge (see photo 9 in Appendix A)
  - Snow density measuring equipment (see photo 8 in Appendix A)

- Runway markers
  - Measuring wheel to place markers (see photo 7 in Appendix A)
  - Start and end of test section markers (see photo 7 and 10 in Appendix A)

- Snow removal and preparation equipment
  - Snow blowing equipment (see photos 11 and 12 in Appendix A)

- Grader (see photo 13 in Appendix A)
- Rollers (see photo 14 in Appendix A)
- Sweepers, both brush and steel, for ice removal
- Snow plows
- Watering truck (see photo 16 in Appendix A)

All the equipment for snow removal and preparation was provided by the airport. The watering truck was furnished by the fire department. The rest of the equipment was supplied by either Transport Canada or Norsemeter.

4. TEST PROCEDURES

The complete proposed test plan is given in Appendix B. This plan was modified as needed to accommodate actual conditions, time, and safety. For each test condition the ground equipment made five loops (one run out and one run back) at speeds of 30, 65, and 90 km/h; the data later showed that the two runs were almost always within 0.01 and thus there was no need to consider the two runs of a loop as different sites. Data were obtained on ten runs at each speed. Repeatability was evaluated and confidence levels established at 95 percent. Later, because of the amount of data, only three loops were run at the 30 km/h speed to cut back on the time required to run the test sequence; this still provided 6 runs.

Exceptions to this procedure occurred mostly where sand was applied on one side and urea (or a different condition) was on the other side of centre line. The two runs of a loop were then tested as separate sites and the loops referred to as split runs. The other exception was before aircraft runs where only one loop of 65 km/h and one loop of 90 km/h were run.

The surface conditions planned for testing were:

- Bare
  - Bare and dry
  - Bare and damp

Friction tests on all runways and taxiways to be tested were run under bare and dry or bare and damp conditions to provide baseline measurements from which to compare surface contaminants.

- Loose snow
  - Loose snow - dusting
  - Loose snow - ½ to 1 inch
  - Loose snow - 1 to 1 ½ inch
  - Loose snow - 2 or more inches

The loose snow was obtained by blowing uncontaminated snow from the runway infields onto the test sections. Snow depth was controlled using graders and groomers. When natural conditions occurred they were groomed as needed to obtain uniform depth.

- Compacted snow - medium packed

Lightly rolled snow of a depth sufficient to prevent wheels from breaking through to the surface. Uniformity was controlled using graders.

- Compacted snow - hard packed

Heavy snow rolled and/or packed down with trucks. While compaction was obtained, the cold granular snow would not remain hard packed during testing. A wetter snow should be used in the future to obtain hard-packed snow.

- Loose snow on hard-packed snow

Snow was to be blown on to hard-packed snow. Since true hard-packed snow was not obtained, this condition was never met.

- Sand on packed snow

Sand was applied on packed snow and tested. This was followed with a second application and retested.

- Chemicals on packed snow

Urea was applied to compacted snow and tested right after the application and again after about one hour. During one of these sets of tests, slush was present as the chemicals were working and tests were run during the slush phase.

- Rough ice

Rough ice was to be made by placing water on top of hard-packed snow; however, natural rough ice was available at different times and thus natural rough ice was tested.

- Rough ice with sand

Sand was applied on top of the rough ice and tested, followed by a second application of sand and a retest.

- Smooth ice

Smooth ice was created by spraying water onto a bare cold surface. In addition, natural wet smooth ice was available during the test period.

- Smooth ice with sand

Sand was applied twice, as before.

- Slush

Slush was present when urea was applied to loose-packed snow and on a day when rain fell on snow, producing slush naturally.

In addition to the tests on the contaminated surfaces noted above, several special tests that were planned, should conditions allow, were run: one set with the GripTester and SAAB tester to determine the effect of slip speed on the ASTM and natural rubber tires for these two testers (speeds from 20 to 120 km/h were run); another set tested the effect of temperatures from 3 to - 20°C on the same two tires; and RUNAR tested two different ASTM tires at various speeds to determine whether consistent results were obtained with the two tires.

5. TEST DATA

A summary of the daily tests is given in Table 1. The complete daily test program and records are given in Appendix C. In total 935 runs where made with the ground test equipment and 10 landings with data for the Falcon Jet.

Table 1
North Bay Tests (16-25 January 1996)

Date	Day	Test	Section Length (metres)	Site	Speeds (km/h)	Time	Temp (°C)	Conditions
1/16	1	1	600	Lima	30/65/90	1217 1522	-17 -14	Loose snow, variable depth, 1" to 2"
	1	2	600	Lima	30/65/90	1558 1614	-14 -12	Bare-dry with ice patches
	1	3	2 400	0826	90	1620 1626	-12 -11	Bare-dry, 1/3" average, last 3rd had ice
1/17	2	1	600	0826	30/65/90	0956 1157	0 0	Wet smooth ice, 3/16"
	2	2	900	0826	Falcon Flight 04	1200 1445	0 1	Bare-wet
	2	3	900	0826	65/90	1443 1454	-3 -4	Bare-wet, post aircraft
	2	4	600	Lima	30/65/90	1505 1606	-4 -4	Rough ice on HP
	2	5	600	Lima	30/65/90	1624 1640	-4 -3	Rough ice on HP + sand 1st application
	2	6	600	Lima	30/65/90	1620 1636	-4 -4	Rough ice on HP + urea
	2	7	600	Lima	30/65/90	1705 1722	-3 -3	Rough ice on HP + sand 2nd application
	2	8	600	Lima	30/65/90	1700 1719	-3 -3	Rough ice on HP + urea + 40 minutes
	2	9	600	Lima	65	1729 1730	-3 -3	Rough ice on HP, post tests on untreated surface
1/18	3	1	600	Lima	30/65/80	1015 1048	7 6	Slush
	3	2	600	Lima	30 & 65	1100 1132	6 7	50% bare-wet, 50% ice & sand
	3	3	600	Lima	30	1136 1159	7 7	50% bare-wet 50% scattered ice
	3	4	300	1331	30 & 65	1150	7	Compacted snow, scattered bare and ice
	3	5	1 800	0826	65/90/120	1449 1508	8 9	Bare-wet with puddles & sand
	3	6	800	1331	65 & 90	1523 1528	9 9	Bare-wet, low last 3rd
1/19	4	1	100	Lima	20-110	920	2	Speed tests, two tires
	4	2	100-300	Lima	65	0920	2 to -20	Temp tests, two tires

Table 1
North Bay Tests (16-25 January 1996) (cont.)

Date	Day	Test	Section Length (metres)	Site	Speeds (km/h)	Time	Temp (°C)	Conditions
	4	3	600	Lima	30/65/90	1625	-11	Bare-dry, baseline
	4	4	600	Lima	45/55/65	1000 1014	0 -1	RUNAR tire 1
	4	5	600	Lima	45/55/65	1120 1138	-1 -2	RUNAR tire 2
1/20	5	1	400	1331	65 & 90	1355 1358	-14 -14	Loose snow, 1/2", pre aircraft
	5	2	400	1331	Falcon Flight 07			Loose snow, 1/2"
	5	3	400	1331	65 & 90	1614 1617	-13 -13	Loose snow, 1/2", post aircraft
	5	4	300	Lima	30/65/90	1447 1610	-13 -11	Wet ice
	5	5	300	Lima	30/65/90	1623 1654	-10 -11	Wet ice + sand 1
	5	6	300	Lima	30/65/90	1704 1725	-14 -14	Wet ice + sand 2
	5	7	600	0826	65	1604 1605	-13 -13	Bare-dry, pre aircraft
	5	8	600	0828	Falcon Flight 07			Bare-dry
1/21	6	1	400	1331	65 & 90	1104 1559	-10 -9	Loose snow 1", pre aircraft
	6	2	400	1331	Falcon Flight 08			Loose snow 1"
	6	3	400	1331	65 & 90	1736 1738	-8 -8	Loose snow 1", post aircraft
	6	4	400	1331	50 (ERD only)	1739	-7	Graded snow 1 3/4", pre aircraft
	6	5	400	1331	Falcon Flight 09			Graded snow 1 3/4"
	6	6	400	1331	65 & 90	1725	-6	Graded snow 1 3/4", post aircraft
	6	7	400	1331	40/65/90	1754 1759	-6 -6	RUNAR only, loose snow
1/24	9	1	600	0826	30/65/90	0903 1021	-13 -13	1/2" loose snow, 200 m bare
	9	2	600	0826	65 & 90	1130 1134	-12 -13	Loose snow, pre aircraft
	9	3	600	0826	Falcon Flight 11			Loose snow
	9	4	600	0826	65 & 90	1230 1231	-13 -13	Loose snow, post aircraft
	9	5	300	1331	30/65/90	1427 1455	-12 -12	Medium-packed snow

Table 1
North Bay Tests (16-25 January 1996) (cont.)

Date	**Day**	**Test**	**Section Length** (metres)	**Site**	**Speeds** (km/h)	**Time**	**Temp** (°C)	**Conditions**
	9	6	400	1331	50	1650	-12	ERD, pre aircraft
	9	7	400	1331	Falcon Flight 12			Medium-packed snow
	9	8	400	1331	30 & 65	1653 1657	-12 -12	Medium-packed snow, post aircraft
1/25	10	1	400	1331	65 & 90	0856 0926	-25 -23	1/2" to 1" hard-packed snow, pre aircraft
	10	2	400	1331	Falcon Flight 13			1/2" to 1" hard-packed snow
	10	3	400	1331	65 & 90	1130 1133	-20 -19	1/2" to 1" hard-packed snow, post aircraft
	10	4	400	1331	65 & 90	1454 1456	-16 -15	Mixed ice & ice on snow, 1 appl. sand, pre aircraft
	10	5	400	1331	Falcon Flight 14			Mixed ice & ice on snow, 1 appl. sand
	10	6	400	1331	65 & 90	1651 1657	-15 -15	Mixed ice & ice on snow, 1 appl. sand, post aircraft
	10	7	400	1331	50 (ERD only)	1703	-21	Mixed ice & ice on snow, 2nd appl. sand, pre aircraft
	10	8	400	1331	Falcon Flight 14			Mixed ice & ice on snow, 2nd appl. sand

5.1 Ground Friction Equipment

Each ground test vehicle operator was responsible for checking and tabulating the friction readings for each run. The data for each device were reported in raw form and in summary form. These values were turned in each day to the Transport Canada data collector who then compiled the data for each test day. Only the summary form is reported here. Appendix C gives a test-by-test breakdown of the data compiled by Transport Canada. The data from each device give the friction average per a total run. Note that Transport Canada compiled a 100 m average and only in one case was the difference of any significance. Thus the run average was used in all but one case (where one third of that run was excluded). Table 2 lists the data where the runs of each test condition and speed have been averaged to provide the average of all the loops run at a given time and speed. An expanded spread sheet giving the average of every run was also compiled, as well as even more detailled data for every 100 m. These data, as well as the original raw data, are on computer disk only and can be provided on request by Transport Canada or Norsemeter.

5.2 Weather and Surface Conditions

The table in Appendix D is a spread sheet giving the weather and surface conditions. The weather is taken from the hourly reported conditions by the flight service centre at North Bay Airport. The spread sheet merges the flight service reports with the surface temperature measured by the infrared equipment and the surface conditions measured by Transport Canada before each test sequence. This table is the merged combination of all data, hour-by-hour. During the test period the air temperatures varied from a high of +9°C to a low of -23°C. The ground temperature varied from a high of 5°C to a low of -28°C. The weather varied from snow to rain, and from cloudy days to bright sunny days - a good mix of conditions.

Table 2
Average test data

DOT	TEST	LENG	SITE	COND	TEMP	TIME	SPEED	LOOP	RUN	C2	Speak	Rpk	R15	SAAB	R18	GT	Sp	F60	ERD	COMMENTS
1	1	600	Lima	LS	-11	1246	30		Ave					0.17		0.24			0.31	LS w drifts
1	1	600	Lima	LS	-10		65		Ave					0.14		0.25			0.31	LS w drifts
1	1	600	Lima	LS	-10		90		Ave					0.12		0.28			0.31	LS w drifts
1	2	600	Lima	BD			30		Ave					0.91		0.96			0.73	Baseline
1	2	600	Lima	BD			65		Ave					0.91		0.96			0.73	Baseline
1	2	600	Lima	BD			90		Ave					0.87		0.91			0.73	Baseline
1	3	2 400	826	BD			90		Ave					0.9		0.92				Less last 3rd
2	1	600	826	WSI	0		30		Ave	4.73		0.3	0.27	0.25	0.28	0.31	125	0.1	0.2	Wet smooth ice
2	1	600	826	WSI			65		Ave	2.71		0.36	0.31	0.23	0.33	0.29	136	0.18	0.2	Wet smooth ice
2	1	600	826	WSI			90		Ave			0.42	0.3	0.18	0.38	0.29			0.2	Wet smooth ice
2	2	800	826	BW			AIR 04													Falcon 20 tests
2	3	900	826	BW	1		65		Ave					0.68		0.58			0.56	Post aircraft
2	3	900	826	BW	1		90		Ave					0.71		0.6			0.56	Post aircraft
2	4	600	Lima	RIHP	1		30		Ave					0.28		0.32			0.28	Untreated
2	4	600	Lima	RIHP			65		Ave					0.29		0.33			0.28	Untreated
2	4	600	Lima	RIHP					Ave					0.28		0.34			0.28	Untreated
2	5	600	Lima	SAND	1	1624	30	0.5	2					0.33		0.34			0.32	Split runs, 1st app.
2	5	600	Lima	SAND	1	1633	65	0.5	2					0.32		0.35			0.32	Split runs, 1st app.
2	5	600	Lima	SAND	1	1640	90	0.5	2					0.32		0.35			0.32	Split runs, 1st app.
2	6	600	Lima	UREA	1	1620	30	0.5	1					0.33		0.35			0.34	Split runs, 1st app.
2	6	600	Lima	UREA	1	1630	65	0.5	1					0.32		0.35			0.34	Split runs, 1st app.
2	6	600	Lima	UREA	1	1636	90	0.5	1					0.32		0.37			0.34	Split runs, 1st app.
2	7	600	Lima	SAND2		1705	30	0.5	2					0.32		0.33			0.37	Split runs, 2nd app.
2	7	600	Lima	SAND2		1715	65	0.5	2					0.33		0.35			0.37	Split runs, 2nd app.
2	7	600	Lima	SAND2		1722	90	0.5	2					0.32		0.36			0.37	Split runs, 2nd app.
2	8	600	Lima	UREA		1700	30	0.5	1					0.31		0.33			0.35	Split runs, +40 min.
2	8	600	Lima	UREA		1712	65	0.5	1					0.3		0.34			0.35	Split runs, +40 min.
2	8	600	Lima	UREA		1719	90	0.5	1					0.3		0.35			0.35	Split runs, +40 min.
2	9	600	Lima	SN			65		Ave					0.28		0.36				No sand/urea
3	1	600	Lima	SH			30		Ave	10.4	12	0.49	0.43	0.27	0.47	0.31	159	0.31	0.51	Bare patches
3	1	600	Lima	SH	4		65		Ave	8.51	23	0.66	0.57	0.27	0.63	0.38	243	0.51	0.51	Bare patches
3	1	600	Lima	SH	4		90		Ave	16.3	21	0.89	0.79	0.37	0.89		271	0.68	0.51	Puddles
3	2	600	Lima	MIX	5		30		Ave	7.13	12	0.64	0.53	0.45	0.59	0.42	119	0.33	0.3	50% BW, 50% ice/sand
3	2	600	Lima	MIX	6		65		Ave	11.5	23	0.7	0.59	0.44	0.67	0.41	362	0.5	0.3	50% BW, 50% ice/sand
3	3	180	Lima	I	6	1150	30		Ave	2.56	10	0.66	0.41	0.28	0.59	0.35	34	0.22	0.35	Bare with flooding

DOT - day of test
LENG - length m
COND - condition
TEMP - temperature °C
SPEED - km/h

C2 - RUNAR factor
S_{peak} - peak slip speed
Rpk - peak friction
R15 - RUNAR 15%
SAAB - Friction Test SAAB

R18 - RUNAR 18%
GT - GripTester
Sp - IFI gradient
F60 - IFI friction average
ERD - Electronic Recording Decelerometer

Table 2
Average test data

DOT	TEST	LENG	SITE	COND	TEMP	TIME	SPEED	LOOP	RUN	C2	Speak	Rpk	R15	SAAB	R18	GT	Sp	F60	ERD	COMMENTS
3	4	300	1331	I	7		30		Ave			0.72		0.33		0.43				ice/rain/bare
3	4	300	1331	I	6		65		Ave	2	21	0.9	0.28	0.28	0.77	0.43	44	0.35		ice/rain/bare
3	4	300	1331	I	6		75		Ave	30.1	17	0.76	0.7		0.76		254	0.22		ice/rain/bare
3	5	1 800	826	BW	10		65		Ave	7.5	21	1	0.92	0.75	0.96	0.61	445	0.75	0.58	Puddles/sand
3	5	1800	826	BW	8		90		Ave	15.3	28	1.06	0.99	0.74	1.05	0.62	570	0.82	0.58	Puddles/sand
3	5	1800	826	BW	8		120		Ave	3.6	35	1.07	0.85	0.73	1.02	0.63	323	0.86	0.58	Puddles/sand
3	6	800	1331	BW	7		65		Ave	4.6	20	1.12	0.98	0.9	1.06	0.82	108	0.81	0.73	Damp, low last third
3	6	800	1331	BW	7		90		Ave	4.5	27	1.12	1.05	0.86	1.07	0.79	242	0.87	0.73	Damp, low last third
4	3	600	Lima	BD	-10		30		Ave	23.6	10	1	0.99	0.96	0.99	0.97	293	0.72	0.75	Baseline at -10
4	3	600	Lima	BD	-10		60		Ave	10.3	22	1.02	0.94	0.92	0.64	0.96	277	0.96	0.75	Baseline at -10
4	3	600	Lima	BD	-10		90		Ave	56.1	24	1.03	1.02	0.9	1.03	0.96	246	1.04	0.75	Baseline at -10
5	1	400	1331	LS	-14	1355	65	0.5	1	3.9	17	0.41	0.38	0.26	0.4	0.3	215	0.37	0.36	Blown 0.5"
5	1	400	1331	LS	-14	1358	90	0.5	1	1.8	27	0.52	0.42	0.29	0.45	0.34	227	0.45	0.36	Blown 0.5"
5	2	400	1331	LS	-14		Air 07													Falcon 20 tests
5	3	400	1331	LS	-13	1614	65	0.5	1	2.7	21	0.53		0.31	0.47	0.33	440	0.41	0.37	Post aircraft
5	3	400	1331	LS	-13	1617	90	0.5	1	3.01	22	0.49		0.35	0.48	0.34	844	0.31	0.37	Post aircraft, spikes
5	4	300	Lima	WI	-13		30		Ave	6.5	8	0.2		0.16	0.2	0.25	136	0.1	0.12	Before treatment
5	4	300	Lima	WI	-12		65		Ave	2.08	20	0.33	0.24	0.16	0.29	0.24	278	0.16	0.12	Before treatment
5	4	300	Lima	WI	-11		90		Ave	0.54	31	0.48	0.11	0.17	0.24	0.25	180	0.15	0.12	Before treatment
5	5	300	Lima	WIS	-10		30		Ave	6.1	11	0.39		0.33	0.36	0.34	148	0.22	0.2	1st appl. sand
5	5	300	Lima	WIS	-10		65		Ave	6.1	17	0.41	0.39	0.24	0.4	0.37	431	0.29	0.2	1st appl. sand
5	5	300	Lima	WIS	-11		90		Ave	3.25	25	0.44	0.45	0.31	0.42	0.37	210	0.33	0.2	1st appl. sand
5	6	300	Lima	WIS	-10		30		Ave	5.44	12	0.44	0.38	0.29	0.4	0.3	165	0.24	0.22	2nd appl. sand
5	6	300	Lima	WIS	-11		65		Ave	6.7	16	0.46	0.44	0.34	0.45	0.34	320	0.31	0.22	2nd appl. sand
5	6	300	Lima	WIS	-12		90		Ave	3.2	20	0.51	0.47	0.35	0.5	0.32	220	0.29	0.22	2nd appl. sand
5	7	600	826	BD	-10		65		Ave	4.06	18	1.12	1.03	0.96	1.08	0.93	178	0.67	0.74	pre aircraft, tire rubber
5	8	600	826	BD	-1		Air 07													Falcon 20 tests
6	1	400	1331	LS	-10		65		Ave	4.99	20	0.36	0.32	0.14	0.34	0.27	316	0.26	0.35	Pre aircraft, 1"
6	1	400	1331	LS	-10		90		Ave	3.6	28	0.42	0.31	0.12	0.39	0.3	330	0.34	0.35	Pre aircraft, 1"
6	2	400	1331	LS			Air 08													Falcon 20 tests
6	3	400	1331	LS	-8	1736	65	0.5	1	2.9	23	0.38	0.31	0.12	0.33	0.26	476	0.28	0.36	1 to 2" snow, pre
6	3	400	1331	LS	-8	1738	90	0.5	1	1.74	27	0.42	0.28	0.08	0.37	0.3	914	0.24	0.36	1 to 2" snow, pre
6	4	400	1331				50												0.39	ERD only
6	5	400	1331				Air 09													Falcon 20 tests
6	6	400	1331	LS	-10		65	1	1	2.87	19	0.36	0.32	0.04	0.33	0.32	1294	0.25	0.37	Post aircraft

DOT - day of test
LENG - length m
COND - condition
TEMP - temperature °C
SPEED - km/h

C2 - RUNAR factor
S_{peak} - peak slip speed
Rpk - peak friction
R15 - RUNAR 15%
SAAB - Friction Test SAAB

R18 - RUNAR 18%
GT - GripTester
Sp - IFI gradient
F60 - IFI friction average
ERD - Electronic Recording Decelerometer

Table 2
Average test data

DOT	TEST	LENG	SITE	COND	TEMP	TIME	SPEED	LOOP	RUN	C2	Speak	Rpk	R15	SAAB	R18	GT	Sp	F60	ERD	COMMENTS
6	6	400	1331	LS	-10		90	1	1	3.83	21	0.41	0.38	0.07	0.4	0.37	711	0.42	0.37	Post aircraft
9	1	400	826	LS	-13		30		Ave	11.5	12	0.33	0.3	0.31	0.31	0.3	394	0.19		0.5" snow, 200 m bare
9	1	400	826	LS	-10		65		Ave	2.67	20	0.38	0.3	0.2	0.34	0.29	177	0.19		0.5" snow, 200 m bare
9	1	400	826	LS	-10		90		Ave	1.14	28	0.52	0.28	0.26	0.42	0.37	251	0.25		0.5" snow, 200 m bare
9	2	400	826	LS	-12	1130	65	0.5	1	2.85	17	1.09	0.98	0.92	1.05	0.92	72	0.55	0.57	Pre aircraft
9	2	400	826	LS	12	1134	90	0.5	1	2.75	25	1.06	0.92	0.88	1	0.92	279	0.73	0.57	Pre aircraft
9	3	400	826	LS			Air 11													Falcon 20 tests
9	4	600	826	LS	-12	1230	65	0.5	1	4.03	17	1.12	1.04	0.96	1.09	0.95	90	0.58	0.57	Post aircraft
9	4	600	826	LS	-12	1231	90	0.5	1	4.56	22	1.1	1.05	0.89	1.08	0.86	269	0.8	0.57	Post aircraft
9	5	300	1331	MPS	-13		30		Ave	3	11	0.77	0.6	0.75	0.66	0.78	55	0.18	0.63	Pre aircraft, 1-1.25"
9	5	300	1331	MPS	-13		65		Ave	3.02	19	1	0.84	0.75	0.93	0.84	140	0.54	0.63	Pre aircraft, 1-1.25"
9	5	300	1331	MPS	-13		90		Ave	4.33	22	1.07	0.93	0.79	1.05	0.83	123	0.59	0.63	Pre aircraft, 1-1.25"
9	6	400	1331	MPS	-13	1650	50												0.25	ERD only
9	7	400	1331	MPS			Air 12													Falcon 20 tests
9	8	400	1331	MPS		1653	65	0.5	1	2.31	21	0.37	0.2	0.03	0.32	0.31	203	0.4	0.29	Post aircraft
9	8	400	1331	MPS		1657	90	0.5	1	1.13	24	0.42	0.3	0.06	0.37	0.43		0.2	0.29	Post aircraft
10	1	400	1331	HPS	-25		30		Ave	2.96	10	0.3	0.25	0.26	0.27	0.3	112	0.08	0.28	0.5 to 1" snow
10	1	400	1331	HPS	-23		65		Ave	2.74	20	0.36	0.29	0.21	0.33	0.34	869	0.18	0.28	0.5 to 1" snow
10	2	400	1331	HPS			Air 13													Falcon 20 tests
10	3	400	1331	HPS	-21	1131	65	0.5	1	1.43	23	0.31	0.16	0.17	0.23	0.32	271	0.14	0.28	Post aircraft
10	3	400	1331	HPS	-21	1133	90	0.5	1	0.72	31	0.46	0.14	0.14	0.27	0.34	177	0.16	0.28	Post aircraft
10	4	400	1331	MIX	-21	1459	65	0.5	1	3.23	25	0.38	0.31	0.2	0.32	0.31		0.14	0.2	1/2 ice, 1/2 ice on snow
10	4	400	1331	MIX	-21	1456	90	0.5	1	2.74	22	0.42	0.38	0.29	0.41	0.3	385	0.24	0.2	1/2 ice, 1/2 ice on snow
10	5	400	1331	MIX	-21		Air 14													Falcon 20 tests
10	6	400	1331	MIX	-15	1651	65	0.5	1	3.52	23	0.44	0.36	0.27	0.39	0.29	977	0.3	0.24	1/2 ice, 1/2 ice on snow, 1st sand
10	6	400	1331	MIX	-15	1657	90	0.5	1	4.08	21	0.52	0.49	0.28	0.51	0.31	225	0.29	0.25	1/2 ice, 1/2 ice on snow, 1st sand
10	7	400	1331	IS															0.26	Ice, 2nd sand, ERD only, pre
10	8	400	1331	IS			Air 14													Falcon 20 tests

DOT - day of test
LENG - length m
COND - condition
TEMP - temperature °C
SPEED - km/h

C2 - RUNAR factor
S_{peak} - peak slip speed
Rpk - peak friction
R15 - RUNAR 15%
SAAB - Friction Test SAAB

R18 - RUNAR 18%
GT - GripTester
Sp - IFI gradient
F60 - IFI friction average
ERD - Electronic Recording Decelerometer

6. DATA REDUCTION AND ANALYSIS

The data presented in this report have been analysed in various ways to support the discussions and conclusions. Correlations amongst the devices were carried out for all the data at all speeds and for 65 km/h and 90 km/h runs. This was then repeated for the contaminated surfaces alone. A review of the data indicated that there were two groups of data, those for bare and dry or wet surfaces, and those for ice- and snow-covered surfaces. Correlations of just ice or just one snow condition showed that the data were insufficient to make a correlation. A parallel report on the North Bay tests by G. Argue et al. (15), also correlated the ground friction measuring equipment results. It gives two correlations, one for bare and ice surfaces only and one for all surfaces. It indicates that bare and ice surfaces seem to go together and can be separated out from the other surfaces. However, an analysis of the ice- and snow-covered conditions shows that statistically the data all belong to the same group. Thus they are not separated in the correlations presented here. It is recommended that these issues be re-examined when additional data become available.

Figure 2 was developed from typical RUNAR data and shows the frictional values for different contaminants as a function of percent slip. Note that not only do the overall values of friction change with the different contaminants, but the percentage of slip at the peak and the slope after the peak also change. These changes produce signatures that appear to allow RUNAR to determine the type of contaminant (see Appendix E for more details on variable slip). Note that on the bare (dry and wet) surfaces the differences between slips below the peak and at the peak are much greater that on ice and snow because of the greater rise of the curve before the peak. Thus, as the peak slip varies on bare surfaces, the fixed slip devices could show greater error, depending on how far they are in front of the peak slip value. On ice and snow the slope

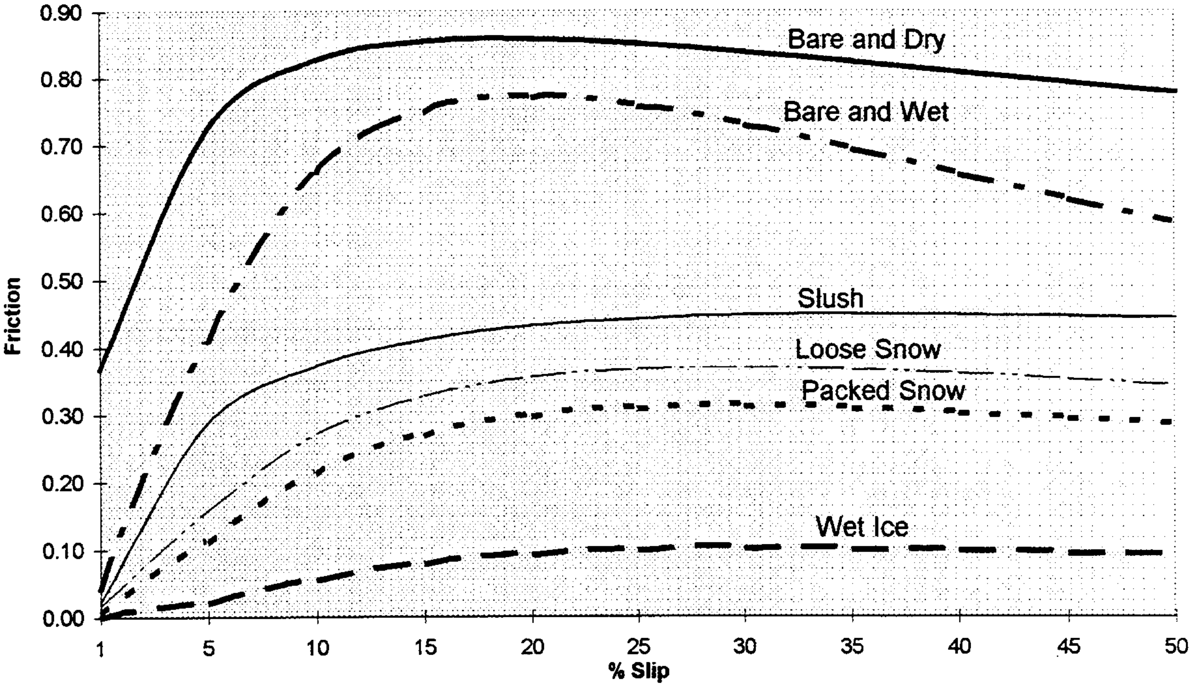


Figure 2. Friction versus percent slip for different contaminated runways

before the peak is not as great; however, the fixed slip devices are further from the peak and could still show some differences. The differences are not as great because the overall friction levels are much smaller.

Tables 3 and 4 give the R^2 values of the correlations between the various devices. Table 3 gives values for all surfaces and Table 4 deals with surfaces contaminated with ice and snow. In the case of RUNAR, the measured parameters - peak friction (RRpeak), slip speed at the peak (S_{peak}), and the shape factor (C) - were used to calculate the friction at 15 percent slip and 18 percent slip. The IFI values, friction at a slip speed of 60 km/h, and S_p, the speed gradient, are calculated directly from the raw data. The two tables give the correlation value between each of the following measures:

ERD
GripTester- GT
RUNAR- RRpeak
RUNAR- RR15
RUNAR- RR18
RUNAR- RRF60
SAAB friction tester - SFT

In the case of the contaminated surfaces, a split run on loose snow and a test set on medium-packed snow were not included, since the friction values were in the high range of .9 to over 1.0. These high values were reached because the tires went through the contamination to bare pavement. Plots of the correlations given in Tables 3 and 4 are presented in Appendix G.

Table 3
Correlation R^2 between devices on all surfaces

			All Runs			Runs Averaged		
			all Speeds	65 km/h	90 km/h	all Speeds	65 km/h	90 km/h
ERD	vs	GT	.82	.80	.85	.85	.83	.92
		RRpeak	.80	.81	.80	.82	.83	.91
		RR15	.77	.79	.83	.79	.82	.92
		RR18	.82	.81	.88	.85	.84.85	.95
		RRF60	.78	.78	.88	.78	.78	.92
		SFT	.73	.74	.74	.75	.74	.82
GT	vs	RRpeak	.70	.88	.91	.88	.91	.93
		RR15	.81	.83	.81	.86	.89	.91
		RR18	.83	.86	.83	.86	.90	.87
		RRF60	.69	.65	.83	.67	.72	.88
		SFT	.74	.86	.89	.92	.93	.92
SFT	vs	RRpeak	.64	.80	.87	.83	.78	.91
		RR15	.48	.84	.86	.90	.92	.88
		RR18	.84	.85	.84	.87	.90	.83
		RRF60	.72	.70	.82	.72	.78	.78

Another set of reduced data was used to examine the distribution of the percentage of slip (or slip ratio), at which the peak friction occurred. The slip ratio is calculated by dividing the slip speed at the peak friction value by the actual vehicle speed. Figure 3 shows that the slip ratio at the peak occurred in the 10 to 24 percentage slip range with an average of 16 to 18 percent for bare pavement. The figure further shows that the range on ice and snow was from 18 to 40 percent, with the mean at 31 percent. The distribution of the ice and snow slip ratio at the peak friction suggests three peaks. Figure 4 shows that the three peaks come from each of the three vehicle speeds used. Normal behaviour on bare and wet pavement is for the peak friction to decrease with speed and for the percentage of slip for these peak friction values to increase with speed, which it did here, as well on the bare pavement tests. On ice and snow the percentage of slip where peak friction is reached also increases with increased speed, but the peak friction either increased slightly or was nearly flat with increased vehicle speed above the peak value.

Table 4
Correlation R^2 between devices on just ice and snow

			All Runs			Runs Averaged		
			all Speeds	**65 km/h**	**90 km/h**	**all Speeds**	**65 km/h**	**90 km/h**
ERD	vs	GT	.14	.06	.37	.09	.10	.004
		RRpeak	.32	.20	.45	.35	.34	.73
		RR15	.38	.21	.57	.42	.35	.76
		RR18	.47	.26	.70	.51	.41	.86
		RRF60	.43	.26	.74	.44	.42	.86
		SFT	.004	.02	.10	.002	.03	.04
GT	vs	RRpeak	.39	.47	.23	.59	.68	.30
		RR15	.33	.50	.20	.58	.75	.49
		RR18	.39	.53	.23	.49	.70	.10
		RRF60	.34	.54	.26	.33	.66	.0007
		SFT	.29	.51	.14	.35	.62	.13
SFT	vs	RRpeak	.12	.22	.11	.13	.18	.26
		RR15	.38	.39	.42	.38	.43	.49
		RR18	.29	.36	.25	.24	.34	.16
		RRF60	.23	.35	.20	.14	.31	.10

Applications of sand and of urea were also studied. Table 5 gives the data measured for the test where urea was applied onto rough ice - friction being measured before application, immediately after application, and about one hour after application. Table 5 also gives the frictional values on wet smooth ice and rough ice before application of sand and after one and then two applications of sand. Figure 5 shows the measurements related to the urea application. Both the SFT and the GripTester show an increase after application; however, the SFT shows a return to the baseline value after one hour, whereas the GripTester shows only half the drop. Note that the SFT shows a .03 change and the GripTester shows a .02 change. Figure 6 gives the measurements for the application of sand. Note that the values for sand are the same as those for urea, except that the friction value remains the same after two applications of sand. Thus it appears that urea acts like sand before melting. In future tests, a time longer than one hour should be monitored to study the effects of urea.

Figure 7 relates to the application of sand on wet smooth ice. It includes measurements for the RUNAR and the ERD, as well as for the SFT and the GripTester. On wet smooth ice, the improvement is much greater than on the rough ice in all cases except for the GripTester, where a very modest improvement is shown with the second application of sand. The average increase is about .1 after the first application and .03 after the second.

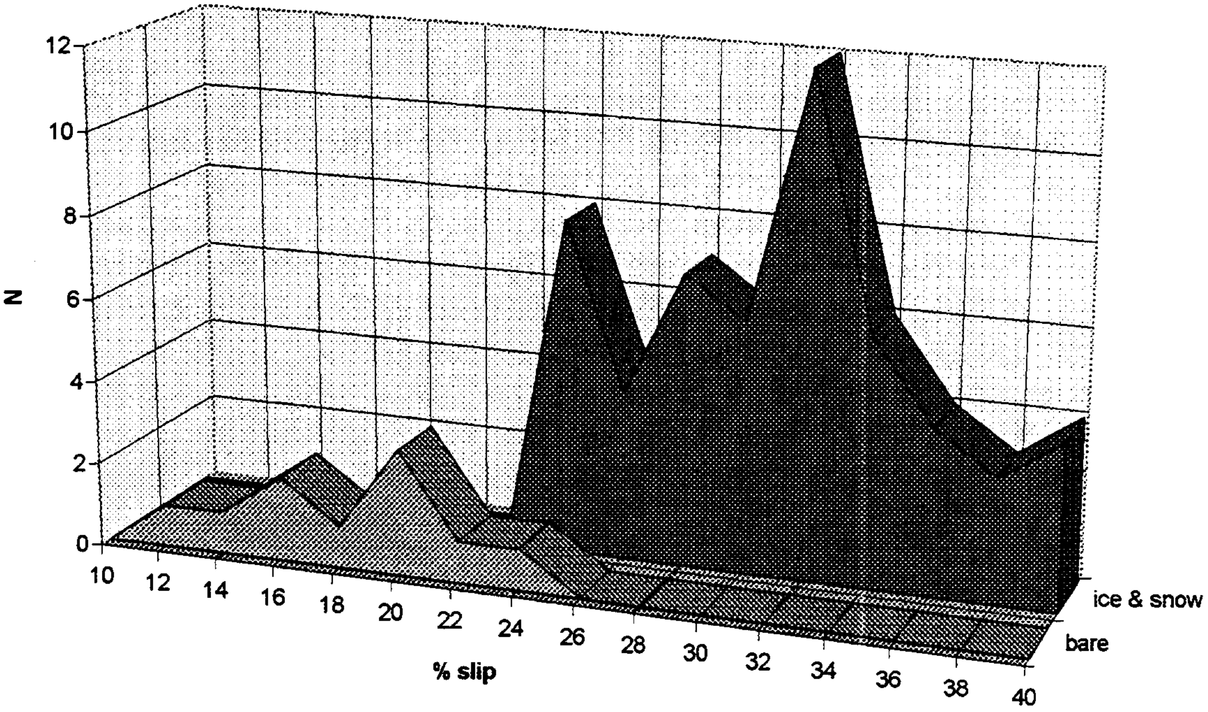


Figure 3. Distribution of peak percent slip of bare runways versus ice and snow covered runways

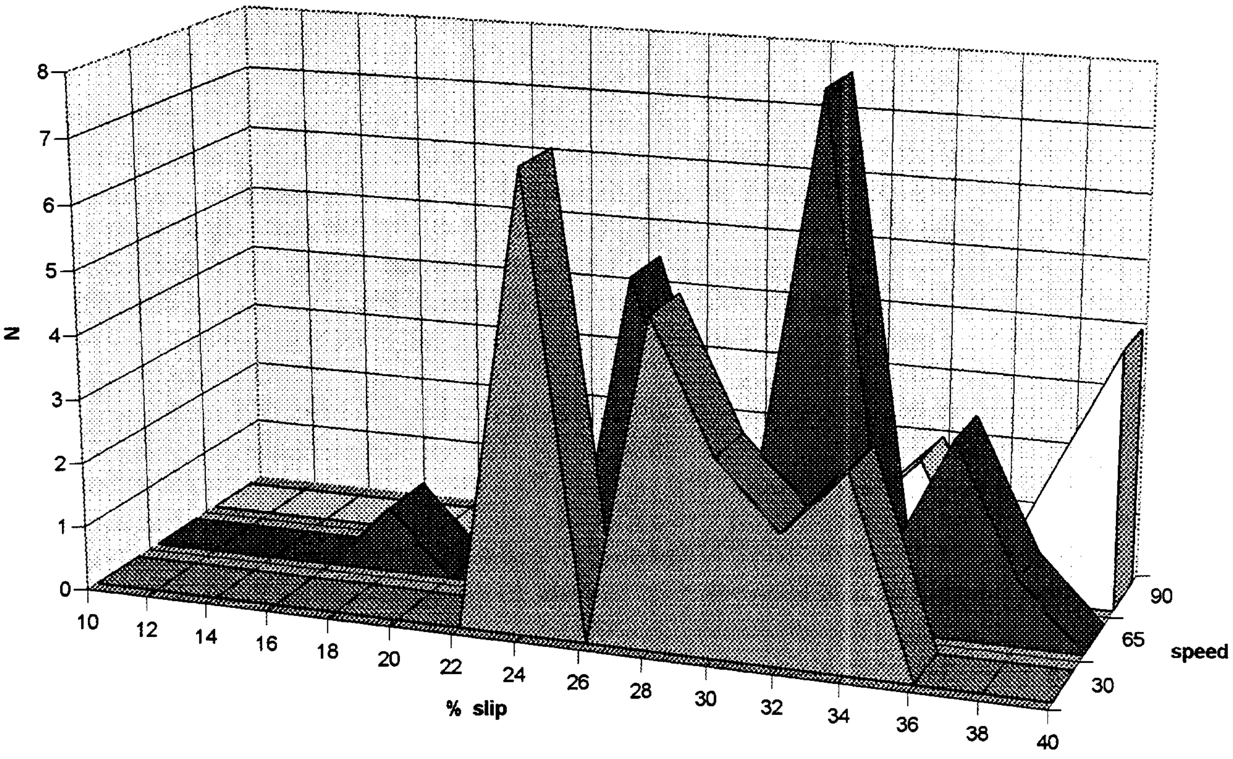


Figure 4 Distribution of the peak percent slip on ice and snow at vehicle speeds of 30, 65 and 90 km/h

Table 5
Test with applications of urea and sand

Test	Baseline			Urea + 5			Urea + 40		
Speed	SAAB	GT	ERD	SAAB	GT	ERD	SAAB	GT	ERD
30	0.28	0.32		0.33	0.35		0.29	0.33	
65	0.29	0.33		0.33	0.35		0.29	0.34	
90	0.28	0.34		0.32	0.37		0.29	0.35	
50			0.28			0.34			

Test	Baseline			Sand-1			Sand-2		
Speed	SAAB	GT	ERD	SAAB	GT	ERD	SAAB	GT	ERD
30	0.28	0.32		0.33	0.34		0.32	0.33	
65	0.29	0.33		0.32	0.35		0.32	0.35	
90	0.28	0.34		0.32	0.35		0.33	0.36	
50			0.28			0.34			

Test	Baseline					Sand-1					Sand-2				
Speed	S	Peak	SAAB	GT	ERD	S	Peak	SAAB	GT	ERD	S	Peak	SAAB	GT	ERD
30	27	0.27	0.15	0.25		37	0.39	0.34	0.34		40	0.45	0.3	0.3	
65	31	0.36	0.16	0.24		26	0.41	0.3	0.37		35	0.49	0.34	0.34	
90	34	0.5	0.17	0.25		28	0.55	0.3	0.37		23	0.51	0.36	0.32	
50					0.12					0.2					0.22

A set of special tests evaluated the effects of temperature and speed on the ASTM tires, as opposed to natural rubber tires. Figure 8 shows the speed effect on the SFT tires and Figure 9 shows the effect on the GripTester tires. Both plots show the effects related to vehicle speed and slip speed. Note that at a vehicle speed of about 60 km/h both of the natural rubber tires show a jump in the frictional value. In the case of the SFT, the natural tire measures considerably below the ASTM tire. In the case of the GripTester, the natural tire still measures lower, but only about half as low as the SFT.

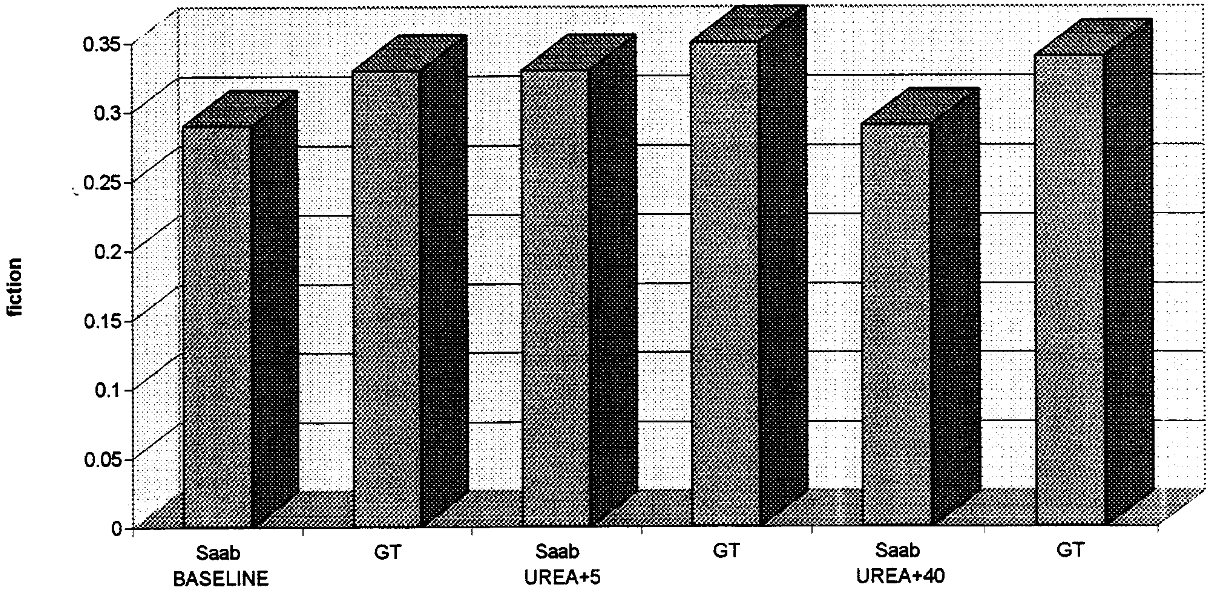


Figure 5. Applications of urea on rough ice

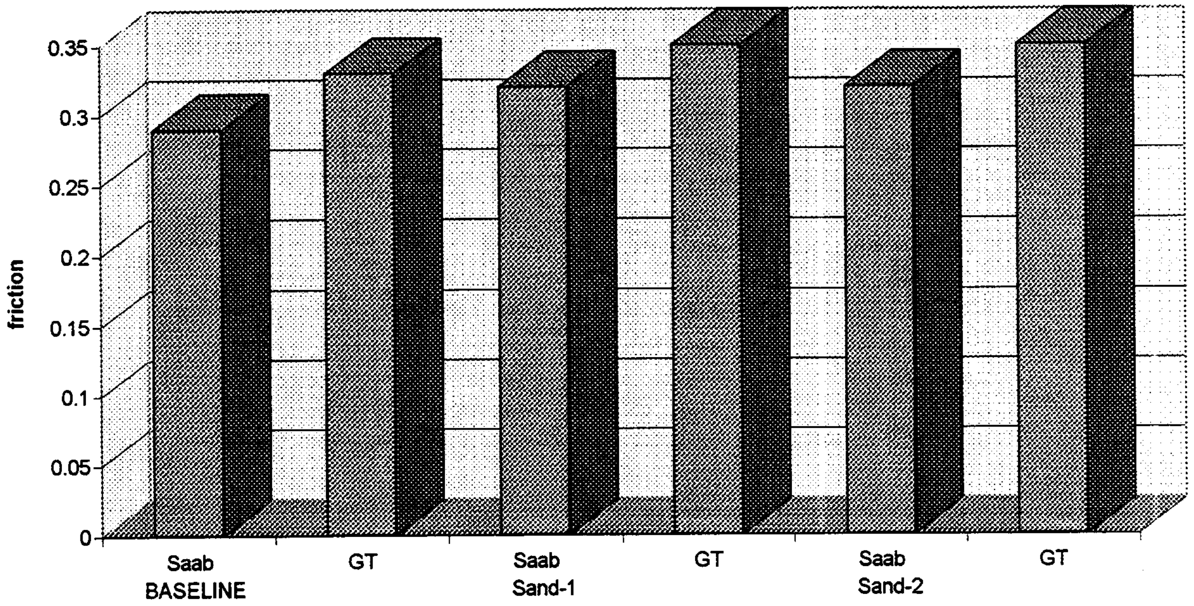


Figure 6. Applications of sand on rough ice

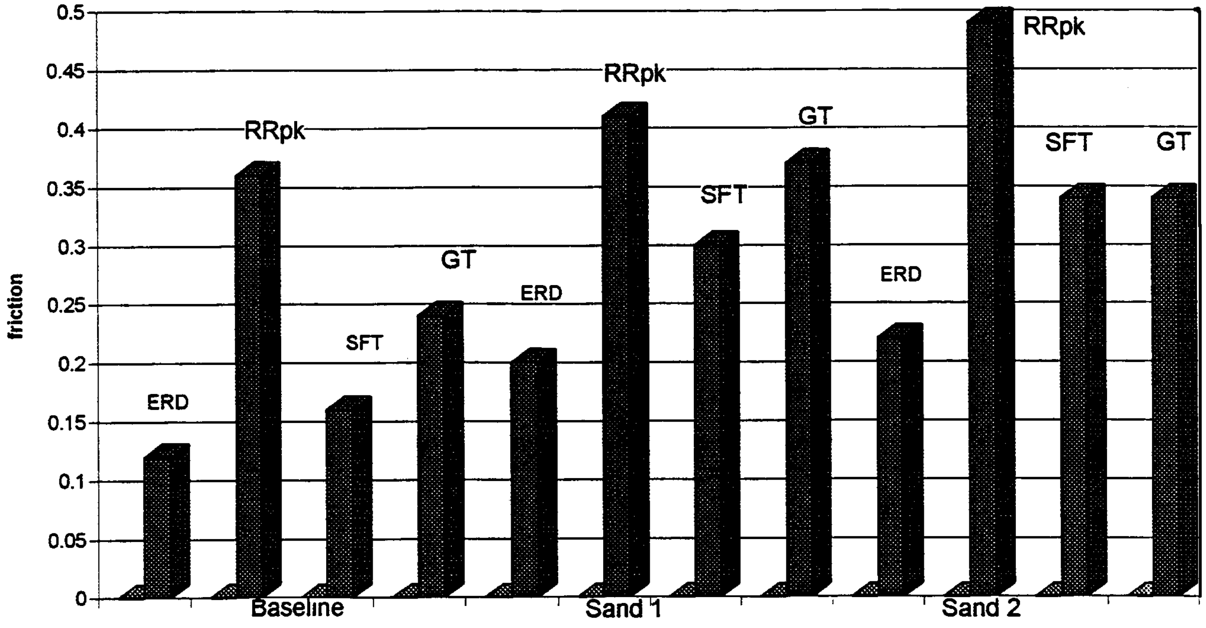


Figure 7. Applications of sand on wet smooth ice

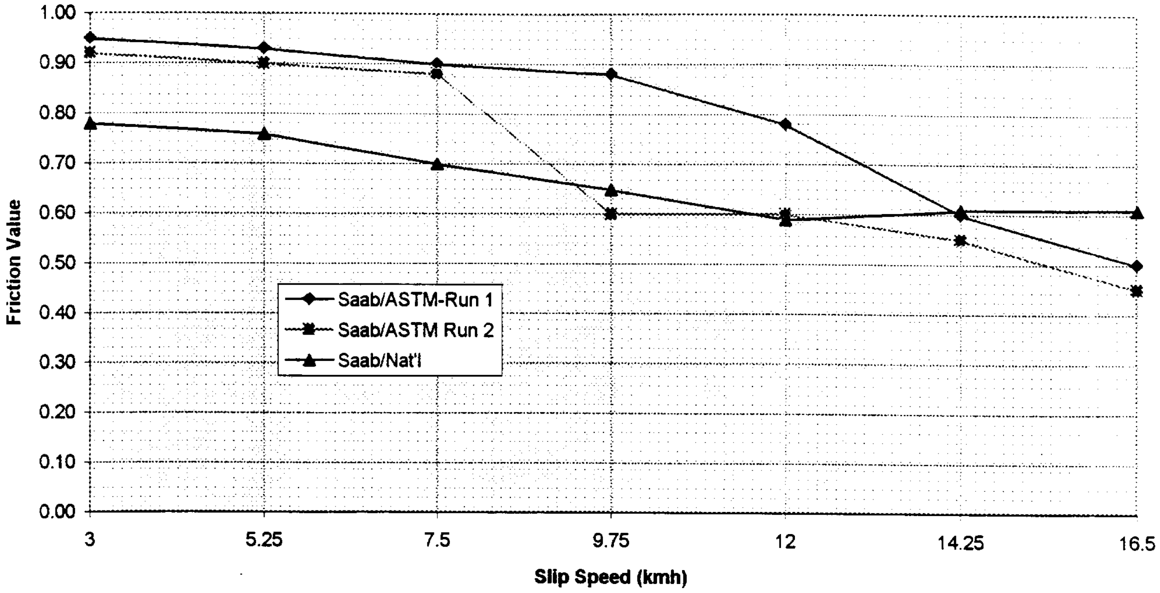


Figure 8. Slip speed effects on SFT's tires

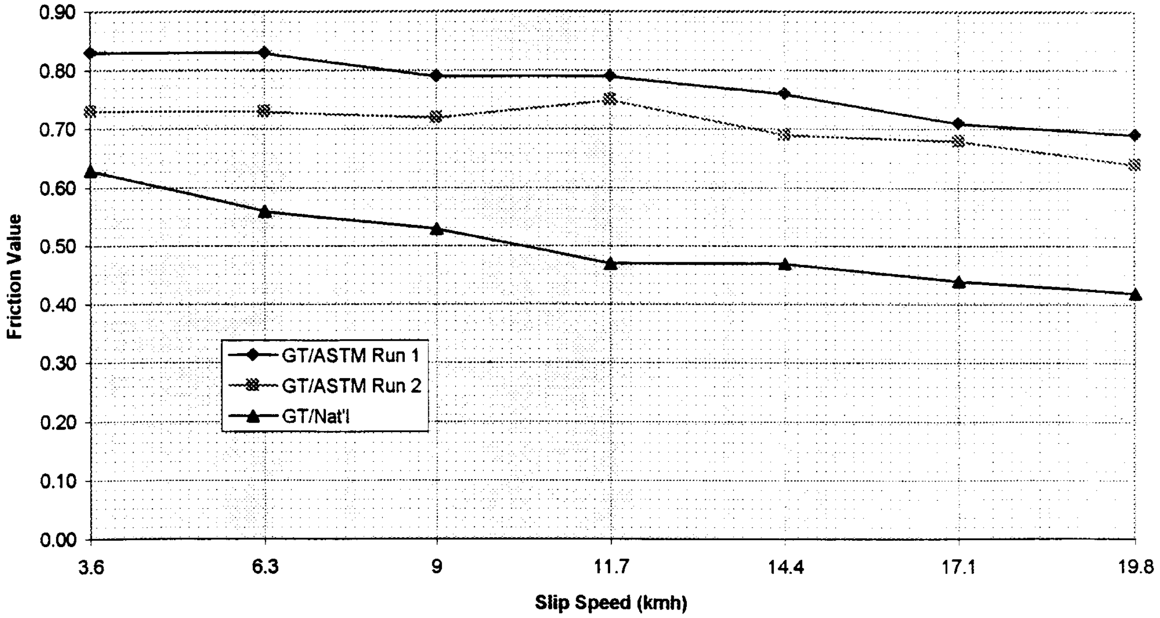


Figure 9. Slip speed effects on GripTester's tires

Figures 10 and 11 show the effects of temperature on the tires of the SFT and the GripTester. In the case of the SFT, the ASTM tire reads about the same value throughout the temperature range. The natural rubber tire behaves in the classical way, in that it drops significantly just below 0°C and then recovers to about 85 percent of the original reading. Figure 11, however, shows that on the GripTester both tires dip and then recover to near the original value. The SFT tires behaved as expected. Further tests should be conducted with the GripTester to verify these results and to determine whether the difference is caused by the tires or by the device. This study indicates that the GripTester may have a problem with its tires at low temperatures.

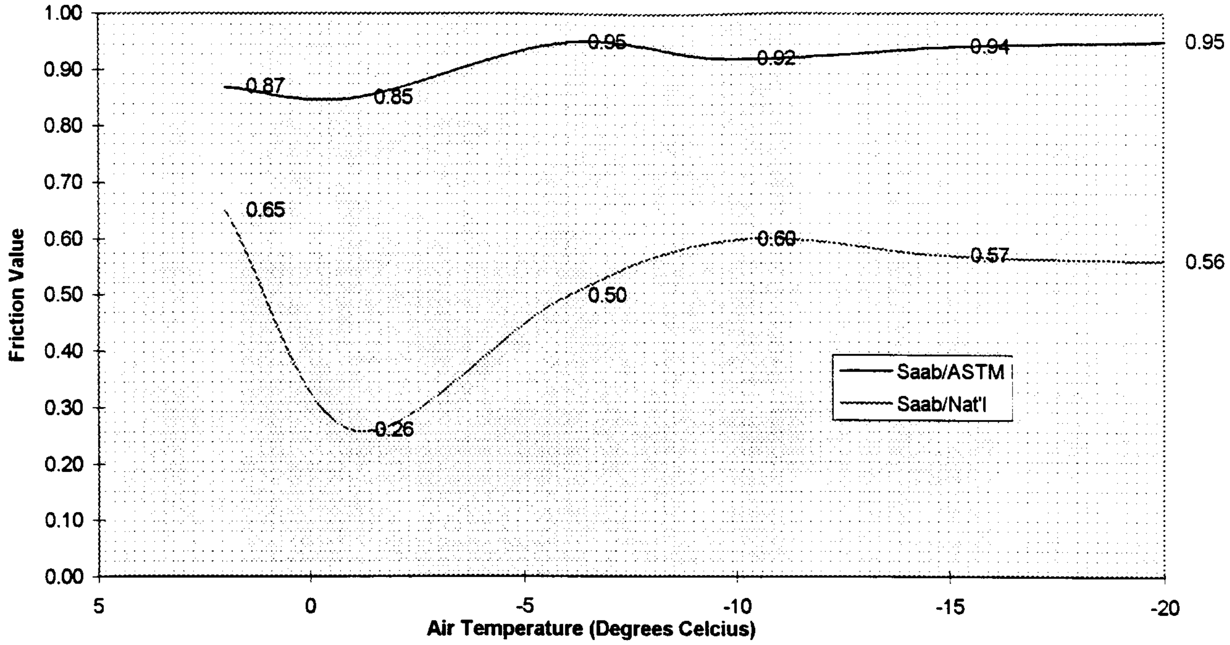


Figure 10. Temperature effects on SFT's tires

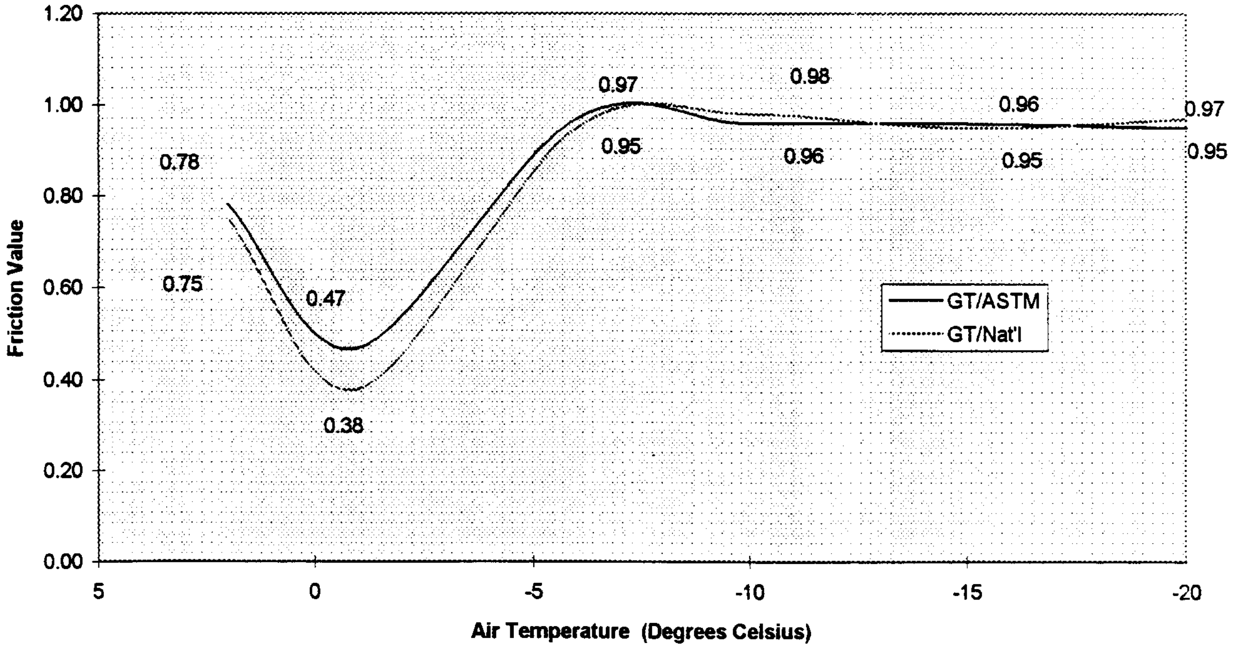


Figure 11. Temperature effects on GripTester's tires

7. RESULTS AND DISCUSSION

On covered surfaces, the distribution of slip ratios at which peak friction occurs indicates that ice and snow have different effects from those of the classic wet runway. For wet runways, peak friction occurs at slip ratios in the range of 10 to 26 percent, thus the 15 to 18 percent slip is near the average and the friction measured at these slip ratios should be around the peak friction. While this is true on the average, large differences can occur in any one test because of the steep slope on the front side of the friction-slip ratio relationship (see Figure 2). Furthermore, peak friction is observed to decrease with vehicle speed and the slip ratio where the peak friction occurs increases with speed. However, this is not the case with ice and snow. First, the slip ratio varies from 22 to 40 percent on ice and snow and the average slip ratio is about double, near 32 percent rather than the 15 percent on wet runways. This means that the present fixed slip devices are measuring well before the peak and not at any constant ratio to the peak slip ratio. Once peak friction is reached on ice and snow, the friction seems to level off with increased speed, rather than dropping off as on wet pavements. In many cases the friction actually increases. This is suspected to be due to the drag of the snow plowing rather than to the friction. This supports the suggestion in the NASA/FAA study (13) that the low shear strength of ice and snow, rather than the tire, determines the friction-speed characteristics. Yager et al. (13) further assumed that frictional variations from speed, tire size, vertical load, and inflation pressure are insignificant for ice and compacted snow. These assumptions should be further evaluated, but they do seem reasonable, based on the results of this study, if the speed effect is taken at or above the peak slip speed.

In evaluating the correlations of device to device the following rating is used:

R^2	RATING
>0.9	Excellent
0.8-0.9	Very good
0.65-0.8	Good
0.5-0.65	Fair
0.36-0.5	Poor
<0.36	Very poor

In general much better correlations were obtained when all surfaces were used, as opposed to just ice and snow. This is to be expected in view of the distribution of peak slip; the low percent slip of 15 percent works well for bare and wet surfaces but measures low on ice and snow. Furthermore, on ice and snow the variations in how far the 15 percent slip is from the actual peak percent slip are very much greater, typically from 5 percent to 25 percent, with an average of 17 percent; this as compared to 5 percent with an average of about ± 2 percent for wet pavement.

Tables 3 and 4 show that the correlations are generally better at a vehicle speed of 65 km/h than they are at all speeds or at 90 km/h. Note that better correlations are obtained by averaging runs first and then doing the correlations. This is a better statistical method, because the noise of the devices is reduced, thus improving the correlation of device to device. The difference between the two methods is actually a measure of the variability of one or both devices. A large difference indicates a larger variability.

Referring to the averaged correlations for just ice and snow (Table 4), we see that the best correlations of the ERD are with RR18 and RRF60. The poorest are to the GripTester and the SFT, all being below 0.1.

ERD to: RR18 (R^2 =.51) and RRF60 (R^2 = .44) at all speeds
RR18 (R^2 =.86) and RRF60 (R^2 = .86) at 90 km/h

The GripTester has the best correlation with RR15 and RR18. The correlations being poorest with the ERD and fair to good with the SFT.

GT to: RR15 (R^2 =.58) and RR18 (R^2 = .49) at all speeds
RR15 (R^2 =.75) and RR18 (R^2 = .70) at 65 km/h

The SFT had the best correlations with RR15 and the poorest with the ERD.

SFT to: RR15 (R^2=0.38) at all speeds and R^2=0.49 at 90 km/h

Correlations to RRpeak were best for the GripTester (in fact this was the best correlation of any two ground devices), followed by the ERD. The correlations with the SFT were the worst. Of all the RUNAR measures, the correlation of RR15 with the GripTester (0.58) was best. However, this is closely followed by RR18 and the ERD (0.51).

When all surfaces are included, much better correlations are obtained, especially between the GripTester and the ERD and SFT. The best correlations of each device are:

ERD to RR18 at any speed (R^2=0.85 to 0.95)
GT to RR15 and RRpeak (R^2=0.86 to 0.93)
SFT to RR15 (R^2= 0.88 to 0.92)

A series of correlations of the ERD with different percentages of slip (see Figure 12), and with slip speed (see Figure 13), show that the best ERD correlations are at 31 percent slip and a slip speed of 35 km/h. With percentage of slip, the correlations are good below the 31 percent point,

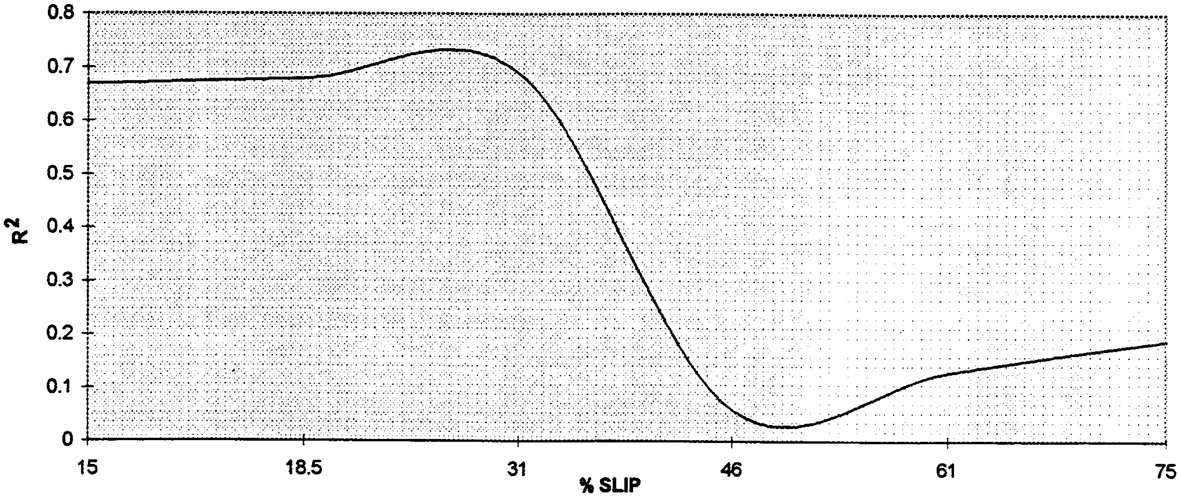


Figure 12. Correlation of the ERD with peak percent slip

where the best occurs. Above this point, the correlations become very poor. In the case of the slip speed, the correlation improves up to the maximum at 35 km/h and then falls off.

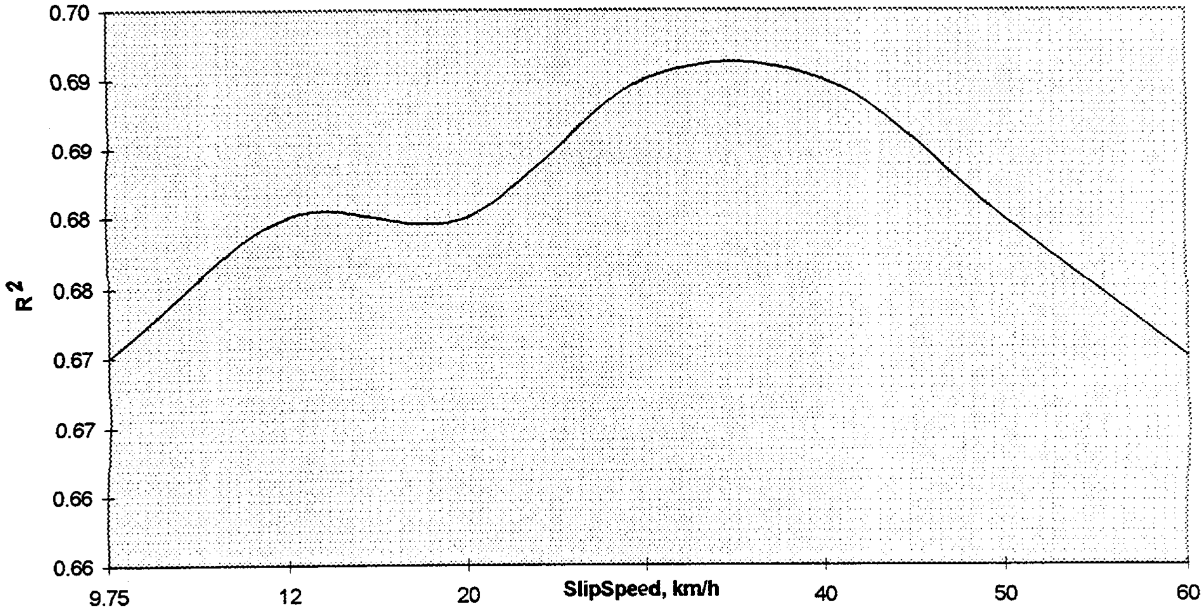


Figure 13. Correlation of the ERD with peak slip speed

7.1. Variation and Means

Table 6 gives the coefficient of variation (CV - standard deviation divided by the mean times 100) for each of the ground devices for snow, ice, sand, mixed conditions, and bare surfaces. Table 7 gives the means for the same conditions. The ERD generally has the lowest CV, but it also has low samples and includes data from a single speed. The bare condition is most likely the best estimate of the CV for the devices and the higher values for the rest of the conditions are mostly a measure of the variability of the condition. In addition, the increase may also be a measure of the increased bounce of the vehicles, especially at higher speeds. All devices have similar CVs, except that the SFT appears to be much more influenced by snow.

Generally, the means of the ERD, GT, SFT and F60 are close, with the peak being higher but ranging up or down with the rest. The one exception is the SFT on snow, where it is high (the CV is also very large here).

Table 6
Coefficient of variation

Device	Snow		Ice		Sand		Mix		Bare	
	N	CV	N	CV	N	CV	N	CV	N	CV
ERD	11	8.50	6	18.70	4	13.20	3	15.80	6	9.30
SFT	76	60.74	41	32.47	47	15.35	7	8.92	19	6.97
GT	74	35.49	39	18.63	46	12.00	7	3.17	19	9.70
PK	57	40.16	14	27.38	32	8.64	5	12.35	8	3.22
F60	56	40.35	18	33.59	32	14.81	7	11.90	9	9.99

Table 7
Means

Device	Snow		Ice		Sand		Mix		Bare	
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
ERD	11	0.34	6	0.20	4	0.27	3	0.39	6	0.70
SFT	76	0.65	41	0.21	47	0.28	7	0.38	19	0.86
GT	74	0.37	39	0.30	46	0.32	7	0.38	19	0.82
PK	57	0.57	22	0.40	34	0.49	6	0.71	8	1.25
F60	56	0.37	18	0.18	32	0.25	7	0.38	9	0.82

8. FALCON 20 CORRELATIONS

The evaluation of ground friction measurement equipment was carried out in parallel with another program conducted by the Transportation Development Centre. Transport Canada's Airworthiness Group and the Flight Research Laboratory provided the test data obtained from operating the National Research Council instrumented Falcon 20 jet on the contaminated test surfaces. Twenty-two landings on ten test surfaces were made during the January test period. These landings were made in between the tests of ground friction measurement equipment. Typically ground measurements were made before and after landings; however, they were sometimes made only before or only after landings. The Falcon reported decelerations at 100, 60, and 20 knots ground speed. Table 8 is a list of the data for both the aircraft and the ground equipment. In the table the aircraft ground speeds are given in km/h rather than in knots (185, 111, and 37 km/h). Note particularly that the decelerations of the Falcon decrease with decreased speed. This is contrary to tire pavement friction, where friction increases with decreased speed; however, these results included air drag, which accounts for the increase with ground speed. The Falcon 20 is equipped with a Mark II anti-skid system and the efficiency of the Mark II may also contribute to friction increasing with speed. It will be interesting to see if any improvement is made with the Mark III system in the NASA 737 tests conducted in March. The mean effective friction (see "mT mean" column in Table 8) was obtained by making a log linear fit to the three speeds and then integrating the distance and speed (16). The mean effective friction is the constant friction or deceleration level that will stop the aircraft in the same distance.

Table 9 gives the correlation value R^2 between the ground vehicles (at all speeds and where the ground vehicles ran at 65 km/h) versus the Falcon deceleration rates for the mean and each of the three speeds where decelerations were reported. Plots of some of these correlations are given in Appendix G. As in the case of just the ground vehicles, there may be a different correlation for the snow and ice versus the bare; however, the current data is insufficient and thus all the data were combined to do the correlations. With future tests and more data points on both bare surfaces and snow and ice, it will be possible to make a distinction, if one exists.

The data from the January tests show all correlations of the ground devices to the Falcon to be very good. The highest correlation was between the ERD and the Falcon 20 at a ground speed of 111 km/h (60 knots). When all speeds are included, the ERD always gives the the highest correlations (varying from 0.756 to 0.877); however, the RUNAR peak measurement is a close second.

Consistently the lowest correlations are the SFT and the RUNAR values at the same percentage of slip as the SFT. These R^2 values range from a low of 0.679 to a high of 0.771, not very much lower than the ERD's values of 0.756 to 0.877. While the data show a 15 percent slip to be the lowest correlation to the Falcon 20, they also show that RUNAR does an excellent job of predicting the SFT and the GT results.

When the data corresponding to tests where the ground vehicles ran at just 65 km/h are used, the correlations change, but not with any great significance. The ERD's correlations go up, as do those for the rest of the ground devices. This indicates that a run at 65 km/h gives the best correlation.

Table 8
Flight and ground measurement data

TEST	SPEED	Rc	%s	Rspk	Rpk	R15	SFT	R18	GT	RF60	ERD	FLT	185	111	37	mean	COMMENTS
2.3	65						0.68		0.58		0.56	4	0.348	0.333	0.318	0.33	Bare/wet-post
	90						0.71		0.6		0.56	4	0.348	0.333	0.318	0.33	Bare/wet-post
5.1	65	3.9	26	17	0.41	0.38	0.26	0.4	0.3	0.37	0.36	7	0.326	0.222	0.153	0.23	1/8-1/4 LS-pre
	90	1.8	30	27	0.52	0.42	0.29	0.45	0.34	0.45	0.36	7	0.326	0.222	0.153	0.23	1/8-1/4 LS-pre
5.3	65	2.7	32	21	0.53		0.31	0.47	0.33	0.41	0.37	7	0.326	0.222	0.153	0.23	1/8-1/4 LS-post
	90	3.01	24	22	0.49		0.35	0.48	0.34	0.31	0.37	7	0.326	0.222	0.153	0.23	1/8-1/4 LS-post
5.7	65	4.06	28	19	1.12	1.03	0.96	1.08	0.93	0.67	0.74	7.2	0.394	0.39	0.385	0.39	Bare/dry-pre
6.1	65	4.99	31	20	0.36	0.32	0.14	0.34	0.27	0.26	0.35	8	0.258	0.2	0.109	0.18	1" LS-pre
	90	3.6	31	28	0.42	0.31	0.12	0.39	0.3	0.34	0.35	8	0.258	0.2	0.109	0.18	1" LS-pre
6.3	65	2.9	35	23	0.38	0.31	0.12	0.33	0.26	0.28	0.36	8	0.258	0.2	0.109	0.18	1" LS-post
	90	1.74	30	27	0.42	0.28	0.08	0.37	0.3	0.24	0.36	8	0.258	0.2	0.109	0.18	1" LS-post
6.4											0.39	9	0.281	0.238	0.176	0.23	1.5-1.75" LS-pre
6.6	65	2.87	29	19	0.36	0.32	0.04	0.33	0.32	0.92	0.37	9	0.281	0.238	0.176	0.23	1.5-1.75" LS-post
	90	3.83	23	21	0.41	0.38	0.07	0.4	0.37	0.92	0.37	9	0.281	0.238	0.176	0.23	1.5-1.75" LS-post
9.2	65	2.85	26	17	1.09	0.98	0.92	1.05	0.92	0.55	0.57	11	0.384	0.331	0.279	0.33	60% BD, 40% PS-pre
	90	2.75	28	25	1.06	0.92	0.88	1	0.92	0.73	0.57	11	0.384	0.331	0.279	0.33	60% BD, 40% PS-pre
9.4	65	4.03	26	17	1.12	1.04	0.96	1.09	0.95	0.58	0.57	11	0.384	0.331	0.279	0.33	60% BD, 40% PS-post
	90	4.56	24	22	1.1	1.05	0.89	1.08	0.86	0.8	0.57	11	0.384	0.331	0.279	0.33	60% BD, 40% PS-post
9.6											0.25	12	0.286	0.223	0.176	0.23	1-1.25" LS & MPS-pre
9.8	65	2.31	32	21	0.37	0.2	0.03	0.32	0.31	0.4	0.29	12	0.286	0.223	0.176	0.23	1-1.25" LS & MPS-post
	90	1.13	27	24	0.42	0.3	0.06	0.37	0.43	0.2	0.29	12	0.286	0.223	0.176	0.23	1-1.25" LS & MPS-post
10.1	30	2.96	33	10	0.3	0.25	0.26	0.27	0.3	0.08	0.28	13	0.284	0.226	0.162	0.22	0.5-1.5" LS on PS-pre
	65	2.74	30	20	0.36	0.29	0.21	0.33	0.34	0.18	0.28	13	0.284	0.226	0.162	0.22	0.5-1.5" LS on PS-pre
10.3	65	1.43	35	23	0.31	0.16	0.17	0.23	0.32	0.14	0.28	13	0.284	0.226	0.162	0.22	0.5-1.5" LS on PS-post
	90	0.72	34	31	0.46	0.14	0.14	0.27	0.34	0.16	0.28	13	0.284	0.226	0.162	0.22	0.5-1.5" LS on PS-post
10.4	65	3.23	38	25	0.38	0.31	0.2	0.32	0.31	0.14	0.2	14	0.196	0.146	0.113	0.15	70% I, 30% BD-1 appl. sand-pre
	90	2.74	24	22	0.42	0.38	0.29	0.41	0.3	0.24	0.2	14	0.196	0.146	0.113	0.15	70% I, 30% BD-1 appl. sand-pre
10.7											0.26	14.2	0.236	0.176	0.117	0.18	2nd sand on I/PS-pre

pre - pre aircraft
post - post aircraft

LS - loose snow
PS - packed snow
MPS - medium PS

BD - bare/dry
I - ice

Typically, all the ground measurements have the best correlations with the three speeds (30, 60, and 90 km/h) and they best correlate with the Falcon 20 speed of 111 km/h. However, the correlation to the Falcon mean values are generally as good or better than those with the 111 km/h Falcon speed.

Additional test data and tests on other aircraft and brake systems are needed to see whether these relations hold up. Certainly the data so far is not sufficient to allow any conclusions to be drawn. In any future work, the effects of aircraft drag should be eliminated before doing the correlations with ground devices. The correlations found in this study were generally very good, and it is expected that they would improve with the drag removed.

Table 9
Correlation R^2 of the Falcon 20 with the ground devices

		Falcon	**Falcon at speed in km/h**		
All speeds		**mT mean**	**185**	**111**	**37**
	ERD	0.841	0.756	0.887	0.794
	Peak	0.803	0.699	0.798	0.789
	GT	0.803	0.686	0.798	0.765
	RR18	0.787	0.686	0.782	0.773
	SFT	0.771	0.681	0.752	0.750
	RR15	0.756	0.679	0.751	0.749
Device at 65 km/h					
	ERD	0.883	0.783	0.918	0.845
	RR18	0.831	0.745	0.827	0.802
	Peak	0.830	0.735	0.824	0.807
	GT	0.812	0.706	0.810	0.777
	SFT	0.801	0.727	0.793	0.769
	RR15	0.791	0.729	0.797	0.769

9. CONCLUSIONS

If aircraft braking is at or near the peak, then a fixed slip device should use a different slip value at or near 32 percent slip on ice and snow. The correlations to the NRC Falcon and later tests with the NASA 737 will need to be completed to verify the proper correlations of ground vehicles and aircraft.

The major test findings and conclusions are summarized below.

- Contamination with ice and snow has different effects from those of wet pavements.
- The average slip ratio at peak friction on ice and snow is at 32 percent slip or about double that for wet pavements.
- Correlations of ground vehicles on wet pavements do not apply to ice and snow.
- The Rado Friction Model is useful and correlates well with equipment run at fixed percentage of slip when the same slip ratio is calculated.
- The temperature effects on the ASTM and natural tires on the SFT and the GripTester are inconclusive; however, the natural rubber tires measure lower frictional values than the ASTM tire at all slip speeds.
- At 90 km/h it is difficult to steer and control the ground vehicles in snow depth greater than 2 inches (50 mm).
- At speeds of 65 and 90 km/h equipment can have lots of bounce on snow with uneven surfaces.
- A speed of 90 km/h is not safe on ice and deep snow and therefore routine measurements at 90 km/h are not recommended on these types of contaminated surfaces.

10. RECOMMENDATIONS

- Additional tests under winter runway conditions are recommended to further define the influence of temperature and tire heating, and to determine frictional correlations of ground vehicles.

- The aircraft braking performance of several aircraft should be correlated to the ground vehicle friction equipment under ice and snow conditions.

- Further investigation of the temperature effects on the GripTester and SFT tires is needed.

- Longer times after the application of chemicals should be included in future tests.

- Tire temperatures should be measured before and after runs to determine the effects of tire heating.

- The performance of aircraft tires as to peak slip should be investigated to verify that they perform in the same manner as ground vehicle tires. Given that the low shear of ice and snow governed the friction, it would appear that tires will not make a difference.

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APPENDIX A

Photographs of test equipment and personnel

(Not available in electronic format /
Non disponible en format électronique)

APPENDIX B

Test plan

(Not available in electronic format /
Non disponible en format électronique)

APPENDIX C

Test data

***(Not available in electronic format /
Non disponible en format électronique)***

APPENDIX D

Weather and condition data

*(Not available in electronic format /
Non disponible en format électronique)*

APPENDIX E

Norsemeter primer

(Not available in electronic format /
Non disponible en format électronique)

APPENDIX F

Ground vehicle correlations

(Not available in electronic format /
Non disponible en format électronique)

APPENDIX G

Falcon correlations with ground equipment

(Not available in electronic format /
Non disponible en format électronique)