TP 13366E

Analysis of the Friction Factors Measured by the Ground Vehicles at the 1998 North Bay Trials

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16. Abstract

This report covers the analysis of friction factors measured by the ground vehicles tested during the 1998 North Bay Joint Winter Runway Friction Measurement Program. Correlation analyses were done to relate the friction factors measured by the devices to each other for a number of cases (e.g., all test speeds vs. 65 km/h only; all surfaces tested, including bare and dry pavement vs. only surfaces covered by snow and ice). The results obtained from the various studies (e.g., to investigate the effects of load and pressure, speed, tire type, temperature, decelerometer performance, and ribbed vs. smooth tires) are outlined and analysed.

The friction factor was found to be most strongly related to the vertical load applied by the device; this issue warrants further investigation.

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16. Résumé

Ce rapport rend compte des analyses effectuées sur les coefficients de frottement mesurés par les véhicules spécialisés utilisés lors des essais tenus à North Bay en 1998, dans le cadre du Programme conjoint de recherche sur la glissance des chaussées aéronautiques. Les chercheurs ont soumis les données recueillies à des analyses de corrélation en vue d'établir des relations entre les coefficients de frottement mesurés par les divers appareils, en isolant certaines variables (p. ex., la vitesse - toutes vitesses confondues par opposition à la vitesse de 65 km/h; la surface - toutes surfaces confondues, y compris les chaussées sèches et dégagées, par opposition aux surfaces enneigées et glacées). Les résultats des diverses analyses (portant sur les effets de la charge et de la pression, de la vitesse, du type de pneu, de la température, du décéléromètre, de la bande de roulement du pneu – lisse ou striée) sont présentés et commentés.

Parmi les divers facteurs étudiés, la charge verticale appliquée par l'appareil de mesure est le plus étroitement relié au coefficient de frottement; il y a lieu de se pencher plus avant sur cette relation.

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EXECUTIVE SUMMARY

This project covers the analysis of the data collected by the ground vehicles during the 1998 North Bay Joint Winter Runway Friction Measurement Program. The work focused on:

- reducing and presenting the data; and
- conducting basic analyses.

Certain trends became evident and the following conclusions can be drawn:

- **Effect of vertical load** – Tests with the instrumented tire test vehicle (ITTV) indicated clearly that the vertical load is a major parameter controlling friction. Tests done with the ITTV on bare and dry pavement, on rough ice, and on loose snow over a packed snow base indicated that the friction factor was reduced with increasing vertical load.

  The test data collected with the other ground vehicles generally support the above conclusion for the tests done on ice, compacted snow, and bare and dry pavement. No clear trend was observed for the tests done on wet ice, slush, and loose or fresh snow. This variation is believed to be related to the amount of contaminant drag.

  Note that trends cannot be established for the other ground vehicle data with the same clarity as for the ITTV because the variation in vertical load among the other ground vehicles is relatively small and because the results contain more scatter.

- **Correlation among the devices** – Lower friction factors were more often measured with the ITTV and electronic recording decelerometer (ERD) than with the other devices, although there were a few exceptions. This trend is believed to be related to differences in vertical load, as the ITTV and ERD conduct friction factor measurements at higher vertical loads than do the other ground vehicles.

  The correlation was greatly affected by whether or not the bare and dry test data were included because this effectively divided the data set into two data clusters that were widely separated in magnitude. As a result, the degree of fit (for a linear regression) was much better when the bare and dry data were included in the analyses. Correlations using only the snow and ice-covered surfaces were much less consistent and reliable.

  Correlations based on all test speeds were similar to those obtained using only data collected at 65 km/h.

- **Tire study: effect of tire tread** – In some cases, higher friction was recorded using a ribbed tire rather than a smooth one. However, clear, consistent trends are not evident over the full range of conditions tested, since in other cases, similar friction was measured using ribbed and smooth tires. More investigation and testing are required before definitive conclusions can be made.

- **Tire study: effect of inflation pressure** – The effect of inflation pressure depended on the nature of the surface and whether or not the tire was treaded. Similar results were obtained at vehicle ground speeds of 40 and 65 km/h.

- **Tire study: effect of ground vehicle device** – The KJ Law runway friction tester (RFT) consistently recorded higher friction than the other devices. The reasons for this variation should be investigated further.

- **The effect of temperature on friction** – Clear, consistent trends were not observed over the full range of tests. In some cases, the friction factors reduced with increasing surface temperature, while for others the friction did not change significantly as the surface temperature was increased.

  This variation indicates that other processes and factors (other than temperature changes) were affecting the friction. Significant factors could include "polishing" of the surfaces during the tests, differences in temperature variations, and varying surface textures. More testing and investigation are required before definitive conclusions can be made.

- **Decelerometer study** – Higher friction factors were measured with the Bowmonk and Tapley meters than with the ERDs. The effect of the operator was variable. In one case, different friction factors were measured between two different operators while in the other case, two operators produced similar results.

- **Effect of speed** – Friction is not strongly related to the ground vehicle speed.

  The slip speed was also found to not have a strong effect, although in some cases the friction was observed to decrease with increasing slip speed. However, the results have considerable scatter, and in some cases, the friction did not appear to be related to the slip speed.

Recommendations

The test results indicate that the friction factor is most strongly related to vertical load and contact pressure. An understanding of this relationship is required for the development of more general correlations among the devices.

Consequently, it is recommended that this be investigated further. The processes causing this relationship should be investigated in relation to the heat build-up that occurs and the strength, temperature, and type of surface.

SOMMAIRE

Ce projet consistait à analyser les données recueillies par les véhicules spécialisés utilisés lors des essais tenus à North Bay en 1998, dans le cadre du Programme conjoint de recherche sur la glissance des chaussées aéronautiques. Le gros du travail a consisté à :

- dépouiller et présenter les données;
- soumettre ces données à des analyses élémentaires.

À la lumière des tendances mises au jour par ces analyses, les conclusions ci-après peuvent être tirées :

- **Effet de la charge verticale –** Des essais réalisés à l'aide de l'ITTV (*instrumented tire test vehicle*), il est clairement ressorti que la charge verticale joue un rôle prépondérant sur le coefficient de frottement. En effet, les essais sur chaussée sèche et dégagée, sur surface glacée rugueuse et sur neige folle recouvrant une base de neige tassée, ont révélé que le coefficient de frottement diminuait en raison inverse de la charge verticale.

  Cette relation est généralement corroborée par les données recueillies par les autres appareils de mesure, lors d'essais sur glace, sur neige tassée et sur chaussée sèche et dégagée. Mais les essais sur glace mouillée, sur neige fondante et sur neige folle ou fraîche n'ont pas permis de dégager la même tendance. On verrait là un effet de la traînée due aux contaminants.

  Il convient de noter que, outre l'ITTV, aucun des appareils de mesure n'a permis de dégager une tendance aussi nette, en raison de la variation relativement faible de la charge verticale appliquée par ces appareils et d'une plus grande dispersion des résultats.

- **Corrélation des appareils de mesure entre eux –** À quelques exceptions près, l'ITTV et le décéléromètre électronique (ERD) ont enregistré des coefficients de frottement plus faibles que les autres appareils. Cette tendance peut être associée, croit-on, aux différences de charge verticale appliquée par les appareils, l'ITTV et l'ERD appliquant des charges verticales plus fortes que les autres appareils.

  La corrélation s'est révélée fortement influencée par la prise en compte ou l'exclusion des données colligées sur chaussée sèche et dégagée, l'ensemble de données étant alors scindé en deux groupes, de deux ordres de grandeur différents. Par conséquent, l'adéquation des données (dans le cas d'une analyse de régression linéaire) était beaucoup plus satisfaisante lorque les données obtenues sur chaussée sèche et dégagée étaient prises en compte.
  À l'inverse, les corrélations établies uniquement à partir des données obtenues sur surfaces enneigées et glacées étaient beaucoup moins cohérentes et fiables.

  Les corrélations établies à partir de toutes les vitesses d'essai étaient comparables à celles obtenues en tenant compte uniquement des données colligées à 65 km/h.

- **Effet du pneu : bande de roulement –** Dans certains cas, une bande de roulement striée a produit un coefficient de frottement plus élevé qu'une bande lisse. Il n'a toutefois pas été possible de dégager des tendances nettes et cohérentes dans toute la gamme des conditions d'essai, car il est aussi arrivé que des coefficients de frottement identiques aient été obtenus au moyen de pneus à bande de roulement striée et lisse. D'autres études et essais s'imposent avant que des conclusions définitives puissent être tirées.

- **Effet du pneu : pression de gonflage –** L'effet de la pression de gonflage s'est révélé tributaire de la nature de la surface et de la bande de roulement (striée ou lisse). Des résultats comparables ont été obtenus à 40 et à 65 km/h.

- **Effet du pneu : appareil de mesure –** Les coefficients de frottement mesurés par l'appareil KJ Law étaient systématiquement plus élevés que les coefficients obtenus à l'aide des autres appareils. Il y aurait lieu d'approfondir les raisons de cette différence.

- **Effet de la température –** Les chercheurs ont été incapables de dégager des tendances nettes et cohérentes de toute la gamme des essais. Dans certains cas, les coefficients de frottement diminuaient lorsqu'augmentait la température de la surface, tandis que dans d'autres, la fluctuation de la température avait peu d'effet sur les coefficients.

  Cette différence donne à penser que d'autres processus et facteurs que les changements de température influent sur la glissance de la chaussée. Parmi les facteurs notables, on peut mentionner le «polissage» des surfaces par les passages répétés des appareils, les différences entre les écarts de températures, et la variation de la texture des surfaces. D'autres études et essais s'imposent avant que des conclusions définitives puissent être tirées.

- **Effet du décéléromètre –** Les appareils Bowmonk et Tapley ont mesuré des coefficients de frottement plus élevés que les décéléromètres électroniques. Un effet «opérateur» a pu être dégagé. Ainsi, lors d'essais équivalents, dans un premier cas, deux opérateurs ont mesuré des coefficients de friction différents, alors que dans l'autre cas, deux opérateurs arrivaient au même résultat.

- **Effet de la vitesse –** La corrélation de la vitesse de l'appareil de mesure et du coefficient de frottement est faible.

  La vitesse de glissement s'est également révélée faiblement corrélée avec le coefficient de frottement, bien que l'on ait observé, dans certains cas, une diminution du frottement avec l'augmentation de la vitesse de glissement. Les résultats sont toutefois marqués par une grande dispersion, et dans certains cas, le frottement ne semblait pas relié à la vitesse de glissement.

Recommandations

Les résultats des essais révèlent que la charge verticale et la pression de contact sont les facteurs les plus étroitement liés au coefficient de frottement. Il y a lieu d'approfondir ce rapport pour établir des corrélations plus générales entre les appareils de mesure.

Il est donc recommandé d'entreprendre d'autres études pour mieux comprendre les processus qui mettent en relation la charge verticale et le frottement, et qui ont trait à l'échauffement qui se produit à l'interface pneu-chaussée, ainsi qu'au type de surface, à sa résistance et à sa température.

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GLOSSARY

ASTM	American Society for Testing Materials
BV-11	Trade name for friction measuring device manufactured by Skiddometer
ERD	Electronic Recording Decelerometer
FAA SFT	Federal Aviation Administration Saab Friction Tester
FTL	Fleet Technology Limited
IMAG	Friction measuring device manufactured by the French Civil Aviation Administration
IRFI	International Runway Friction Index
ITTV	Instrumented Tire Test Vehicle
NASA	National Aeronautics Space Administration
OC	Operational Condition
PIARC	World Road Congress (French acronym)
RFT	Runway Friction Tester
RUNAR	Friction measuring device manufactured by Norsemeter AS (Norway)
TC SFT	Transport Canada Saab Friction Tester

1. INTRODUCTION AND OBJECTIVES

1.1 Background

An extensive test program was conducted at the North Bay, Ontario, airport over the period from January 27 to March 4, 1998, to:

- measure the friction factors experienced by aircraft operating on various wintertime surfaces;
- measure friction factors using a wide range of ground vehicles on various wintertime surfaces, and to investigate the factors affecting them; and,
- investigate the correlation between the friction factors measured by the ground vehicles and the aircraft.

This report describes a preliminary analysis that was done using the ground vehicle data. The work focused on: (a) reducing and presenting the data; and, (b) conducting basic analyses. Nevertheless, this allowed trends to be documented and some conclusions drawn.

1.2 Scope of Analyses and Information Basis

The work commenced with a review of the collected data.

All analyses presented in this report are based on hard-copy data sheets that were prepared at the time of the 1998 North Bay tests. These sheets were submitted by the individual test device operators to Alice Krol (of Transport Canada's Aerodrome Safety Branch) soon after the tests were conducted.

The information on these data sheets was entered by Fleet Technology Limited (FTL) into electronic spreadsheets prepared in Excel (v5.0), and these were used to conduct the analyses presented here. The spreadsheets prepared by FTL were verified against a separate spreadsheet, also based on the hard-copy data sheets, that was independently prepared by Alice Krol.

The general scope of the analyses is summarized below. Section 2 describes the scope of the test program in more detail, whereas the analyses themselves are presented in the indicated report sections.

- <u>Device correlation</u> – The correlation among the various ground vehicles tested was investigated and quantified (Section 3).
- <u>The effect of load and tire pressure</u> – Tests were done to investigate this, using NASA's (National Aeronautics Space Administration) ITTV (instrumented tire test vehicle), and these data were analyzed. This was also investigated using the measured ground vehicle data. These analyses are described in Section 4.

- The "Tire Study" – This test series was done to investigate the effect of tire type for Transport Canada's Saab Friction Tester (TC SFT'79), the Federal Aviation Administration's (FAA) SFT, and the K.J. Law runway friction tester (RFT). These results are presented in Section 5.
- The effect of temperature – This was investigated during a number of test series, which are described in Section 6.
- The "Decelerometer Study" – These tests were conducted to compare different decelerometers and to investigate the effect of different operators. The results are presented in Section 7.
- The effect of ribbed vs smooth tires – These tests are described in Section 8.
- The effect of speed – Tests were done at a range of speeds, and in a few cases, at various slip ratios, to investigate the effect of ground vehicle speed and slip speed. These results are presented in Section 9.
- The effect of an application of de-icing chemical on bare ice – The effect of this operation on the friction factor was measured. The results are presented in Section 10.

2. TEST PROGRAM SUMMARY

2.1 Devices Used

Up to 10 different ground vehicles were tested, as summarized below. Because these devices have been described in previous reports (e.g., [1], [2], [3]), this information is not repeated here. The devices and their test configurations (i.e. tire inflation pressure, slip ratio, tire type, vertical load) for each test are detailed in Appendix A.

- Instrumented Tire Test Vehicle (ITTV);
- RUNAR;
- IMAG;
- BV-11;
- Griptester;
- Transport Canada’s 1979 Saab friction tester (TC SFT’79);
- the Federal Aviation Administration’s Saab Friction Tester (FAA SFT);
- the K.J.Law runway friction tester (KJ Law RFT);
- Transport Canada’s 1985 Saab friction tester (TC SFT Turbo);
- the electronic recording decelerometer (ERD).

2.2 Test Matrix

The test matrix is detailed in Appendix A and summarized in Table 2.1.

Table 2.1: Test Matrix Summary

Date	Test # (note 1)	General Description	Test Surface (note 1)
Jan 27	27.1	Comparative test	3 mm freshly-fallen natural snow
Jan 27	27.2	Comparative test	30 mm natural snow over an ice base
Jan 28	28.1 (A)	Tire study	5-20 mm loose snow over compacted snow
Jan 28	28.1 (B)	Tire study	Semi-compacted snow
Jan 28	28.2	Comparative test	5-20 mm fresh snow
Jan 28	28.3 A&B	Before and after Falcon runs	40 mm snow
Jan 29	None	Decelerometer correlation tests	Thin layer of compacted snow
Jan 29	29.1	Comparative test	2-12 mm light, wet snow, semi-compacted
Jan 29	29.3	Comparative test	5-12 mm light, wet snow, semi-compacted
Jan 30	30.1 A	Comparative test	34-100 mm natural snow and snow drifts
Jan 30	30.1 B	Comparative test	5-50 mm regraded snow
Jan 30	30.2 A,B&C	Comparative test	10-15 mm compacted snow
Jan 31	31.1	Comparative test	Bare and dry
Jan 31	31.2	Comparative test	Bare and dry
Jan 31	31.3 A	Comparative test	Snow with patches of bare and dry
Jan 31	31.3 B	Comparative test	Snow with patches of bare and dry
Jan 31	31.3 C	Comparative test	Snow with patches of bare and dry
Feb 2	33.1A&B	Decelerometer study	Rough ice with patches of loose to packed snow
Feb 2	33.2 A&B	Comparative test	Rough ice with patches of thin, wet, loose snow and water covered compacted snow
Feb 3	34.1 A,B, C&D	Comparative test	Rough ice with dusting of dry snow (0 to 5 mm)
Feb 3	34.3 A, B, C&D	Comparative test	Rough ice with dusting of dry snow (0 to 5 mm)
Feb 4	35.1 A&B	Comparative test	Smooth ice
Feb 4	35.2	Comparative test	Smooth ice
Feb 4	35.3	Comparative test	Smooth ice
Feb 4	35.5	Comparative test	Ice with slush (after application of de-icer)
Feb 4	35.4	Comparative test	Drifting snow on ice
Feb 5	36.1	Temperature gradient	Rough ice
Feb 5	36.2	Temperature gradient	Compacted snow
Feb 6	37.1	Temperature gradient	Compacted snow
Feb 6	37.2	Temperature gradient	Rough ice
Feb 6	37.3	Speed effect on snow	5-10 mm loose and dry granular snow on compacted snow and ice
Feb 8	39.1	Speed effect at various slip ratios	East side – rough ice West side – 2-5 mm loose snow over compacted snow
Feb 8	39.2 A	Effect of load	0-10 mm loose and dry granular snow over compacted snow and ice
Feb 8	39.2 B	Effect of load	Rough ice
Feb 8	39.3 A	Effect of inflation pressure	Rough ice
Feb 8	39.3 B	Effect of inflation pressure	0-10 mm loose and dry granular snow over compacted snow and ice

Table 2.1(cont'd): Test Matrix Summary

Date	Test # (note 1)	General Description	Test Surface (note 1)
Feb 9	40.2	High speed test	25-30 mm compacted snow
Feb 9	40.3	Temperature gradient	25-30 mm compacted snow
Feb 9	40.4 A&B	Comparative test	Bare and dry
Feb 9	40.5	Operational condition	Compacted snow and bare and dry
Feb 10	41.1 A&C	Ribbed vs. smooth test tire	Compacted snow, ice and loose snow
Feb 10	41.1 B&D	Ribbed vs. smooth test tire	Ice
Feb 10	41.2 A&B	Comparative test	Bare and dry
Feb 11	42.1	Temperature gradient	Compacted snow
Feb 11	42.2	Temperature gradient	Wet ice (run # 1-4); Slush (run # 5-16)
Feb 12	43.1	Comparative test	7.5 mm wet compacted snow
Feb 12	43.2 A&B	Before and after Falcon 20 test runs	5 mm loose wet snow
Feb 13	44.1 A&B	Before and after Falcon 20 test runs	Graded compacted snow with ice
Feb 14	45.1 A&B	Before and after Dash 8 tests	Hard-packed snow with ice and bare patches
Feb 15	46.1 A&B	Before and after Dash 8 tests	Hard-packed snow with ice, and bare and dry patches
Feb 15	46.2 A&B	Before and after Dash 8 tests	Hard-packed snow with ice and sand, and bare and dry patches
March 3	62.1	After Falcon 20 tests	25% bare and wet, 25% slush, 25 % snow and 25% standing water
March 4	63.1 A&B	Before and after Falcon 20 tests	90% 1 cm snow, 10% bare and wet

Note:

1. The above test numbers and surface descriptions are taken from an electronic spreadsheet prepared by Alice Krol (Transport Canada, Aerodrome Safety Branch).

3. CORRELATION ANALYSES

3.1 Objectives and Approach

The correlation among the various test devices was analyzed by grouping the data by time and speed, which produced data pairs for analysis. The analyses were done for a number of cases, as follows:

- All test speeds vs. only a speed of 65 km/h – The devices were tested over a range of ground speeds from about 40 to 90 km/h. The correlations obtained from the whole data set were compared with those given by analyzing only the 65 km/h data. The ERD data were not subdivided by speed because these tests are not conducted at constant speed. For the ERD, each test was begun by accelerating the test vehicle to 50 km/h, and friction data were obtained while the vehicle decelerated from 50 km/h.
- All surfaces vs. only the snow and ice-covered surfaces – Tests on bare and dry pavement were included in the program. Because the friction measured on bare and dry pavement was much higher than on the other winter surfaces, the inclusion of the bare and dry data produced relatively high correlations in almost all cases (because this practically divided the data set into two data clusters). As a result, the bare and dry test data had a disproportionate effect on the correlations produced. Consequently, correlations were done for both the whole data set (which included the bare and dry tests) and for only the snow and ice-covered surfaces.
- Interpolation vs. no interpolation for the ERD and ITTV data – The ERD was usually not used at the same time as the other devices. Typically, the ERD was used before and after the test runs made by the other devices. As a result, a rigorous data grouping by time results in much fewer data for the ERD, which reduces the confidence that can be placed in the correlation results. This is true for the ITTV as well, although to a lesser extent.

  In an effort to gain as much information as possible, the correlation analyses were conducted for two cases:
  - A relatively rigorous data grouping by time (within about 5 minutes);
  - Interpolating the measured data to intermediate time points. This was done by averaging the "before and after" ERD and ITTV data.

Other data groupings were also considered. Some of the tests conducted during the program were intended for use as input to the development of an International Runway Friction Index (IRFI), whereas others were considered to be Operational Condition (OC) tests.

Because the IRFI surfaces were scrutinized more carefully for consistency, correlations were tried using only the IRFI data. As this did not have a significant effect on the results obtained, all tests were grouped together to maximize the size of the available data set.

The effect of partitioning the data set by surface type (e.g., bare ice vs. packed snow) was also investigated. However, because friction factor magnitudes vary significantly between these various surfaces, this partitioning did not provide improved understanding since it greatly limited the friction factor range over which correlations could be developed. By combining all winter surfaces, correlations were produced over a wider range of friction factor magnitudes. This approach also adds simplicity because it avoids the requirement for a user to identify a particular winter surface when applying a given correlation.

The configuration of the RUNAR varied over the test program. It was tested at a fixed slip of 13-15% up to and including January 31, and at variable slip for all tests after then (Appendix A). All friction factors reported by the RUNAR after January 31 are peak values. This was accounted for in the analyses by sub-dividing the data for the RUNAR by date.

All correlations were done by presuming that the relationship between the friction factors measured by each device is linear, and that the intercept is non-zero, as indicated below.

$$\text{Friction Factor}_{\text{device 1}} = a + b * \text{Friction Factor}_{\text{device 2}} \qquad [3.1]$$

3.2 Results

Plots showing the correlations between the various devices are contained in the following appendices:

- Case: All speeds and no interpolation for the ERD or ITTV data - Appendix B
- Case: All speeds and interpolation used for the ERD and ITTV data - Appendix C
- Case: 65 km/h speed and no interpolation for the ERD or ITTV data - Appendix D
- Case: 65 km/h speed and interpolation used for the ERD and ITTV data - Appendix E

The slopes and intercepts (i.e., “b” and “a”, respectively in equation [3.1]) obtained from the correlation analyses done for all surfaces (which included the bare and dry data) are listed in Tables 3.1 and 3.2, respectively. The correlation coefficients (i.e., r^2) for these cases, and the number of data pairs used for these analyses, are listed in Tables 3.3 and 3.4, respectively.

The slopes, intercepts, correlation coefficients, and number of data pairs used for the analyses done with only the snow and ice-covered surfaces (which did not include the bare and dry tests) are listed in Tables 3.5 to 3.8, respectively.

Table 3.1: Slopes Obtained from the Regression Analyses Using All Surfaces

Case: All speeds; all surfaces (including bare and dry); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Gripteste r	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	0.6361						
TC SFT'79	1.0433	1.4610					
Griptester	1.2708	1.2149	0.8272				
BV-11	1.5340	1.1516	0.8073	0.9530			
RUNAR - 15% slip	Too few pts	1.0016	.6991	.897	.9876		
RUNAR - peak	1.077	1.256	.4814	.5076	.3854		
IMAG	0.6662	1.0902	0.7353	0.8481	0.8360	1.115	.886

Case: 65 km/h Speed; all surfaces (including bare and dry) and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	Not						
TC SFT'79	Enough	1.4718					
Griptester	Data	1.1617	0.7170				
BV-11	Pairs	1.1118	0.7586	0.9900			
RUNAR - 15% slip & peak	For	Too few data for analysis					
IMAG	Analysis	1.1518	0.7504	0.9652	0.963	Too few data	

Interpolated data included for the ERD and ITTV; all surfaces (including bare and dry)

All Speeds				65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)			Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV			ERD	ITTV
ERD				ERD		
ITTV	0.8148			ITTV	0.8222	
TC SFT'79	1.1926	1.4482		TC SFT'79	1.2204	1.4639
Griptester	1.0259	1.2171		Griptester	0.9657	1.1568
BV-11	0.9959	1.1496		BV-11	0.9914	1.1300
RUNAR-15% slip	.8688	0.9844		RUNAR-15% slip	Too few data	
RUNAR - peak	1.0658	1.1444		RUNAR - peak	Too few data	
IMAG	0.8814	1.0868		IMAG	0.9305	1.1463

Table 3.2: Summary of the Intercepts Obtained from the Regression Analyses Done with All Surfaces

Case: All speeds; all surfaces (including bare and dry); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	0.0356						
TC SFT'79	0.0394	-0.0022					
Griptester	0.0358	0.0592	0.0599				
BV-11	0.0336	0.0945	0.0920	0.0423			
RUNAR - 15% slip	Too few pts	0.0864	0.081	-0.0103	-0.0760		
RUNAR - peak	0.1149	0.110	0.1525	0.1403	0.1498		
IMAG	0.1069	0.0625	0.0713	0.0300	0.0127	-0.0604	-0.0179

Case: 65 km/h speed; all surfaces (including bare and dry); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	Not						
TC SFT'79	Enough	-0.0135					
Griptester	Data	0.0622	0.0932				
BV-11	Pairs	0.1288	0.1337	0.0411			
RUNAR-15% & peak	For	Too few data for analysis					
IMAG	Analysis	0.0400	0.0711	-0.0151	-0.0548	too few data	

Interpolated data included for the ERD and ITTV; all surfaces (including bare and dry)

All Speeds

Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	-0.0024	
TC SFT'79	-0.0022	0.0030
Griptester	0.0529	0.0592
BV-11	0.0815	0.0982
RUNAR-15% slip	0.0743	0.0957
RUNAR - peak	0.1139	0.1138
IMAG	0.0695	0.0681

65 km/h Speed

Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	-0.0081	
TC SFT'79	-0.0324	-0.0185
Griptester	0.0462	0.0653
BV-11	0.0764	0.1202
RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data	
IMAG	0.0471	0.0367

Table 3.3 Correlation Coefficients (r^2) Obtained from the Regression Analyses Done with All Surfaces

Case: All speeds; all surfaces (including bare and dry); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	0.4959						
TC SFT'79	0.3864	0.9381					
Griptester	0.5079	0.9231	0.9646				
BV-11	0.4889	0.8818	0.9235	0.9631			
RUNAR - 15% slip	Too few pts	0.9495	0.9918	0.9934	0.9822		
RUNAR - peak	0.4296	0.4592	0.6747	0.7515	0.6827		
IMAG	0.3316	0.9189	0.9716	0.9326	0.9079	0.9818	0.7082

Case: 65 km/h speed; all surfaces (including bare and dry); no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	Not						
TC SFT'79	Enough	0.9351					
Griptester	Data	0.9557	0.9011				
BV-11	Pairs	0.9663	0.9402	0.9392			
RUNAR-15% & peak	For	Too few data for analysis					
IMAG	Analysis	0.8869	0.9154	0.7817	0.9248	Too few data	

Interpolated data included for the ERD and ITTV; all surfaces (including bare and dry)

All Speeds		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	0.9243	
TC SFT'79	0.9073	0.9226
Griptester	0.9076	0.9182
BV-11	0.8934	0.8732
RUNAR-15% slip	0.9664	0.9487
RUNAR - peak	0.5114	0.3997
IMAG	0.9152	0.9125

65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	0.9668	
TC SFT'79	0.9305	0.9028
Griptester	0.9598	0.9503
BV-11	0.9935	0.9605
RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data	
IMAG	0.9501	0.8733

Table 3.4: Number of Data Pairs for the Regression Analyses Done with All Surfaces

Case: all speeds; all surfaces (including bare and dry); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	67						
TC SFT'79	77	168					
Griptester	76	145	171				
BV-11	71	143	169	175			
RUNAR-15% slip	4	43	36	34	40		
RUNAR-peak	64	67	75	76	76		
IMAG	83	177	163	145	140	63	101

Case: 65 km/h Speed; all surfaces (including bare and dry); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	4						
TC SFT'79	5	27					
Griptester	5	23	30				
BV-11	5	23	30	36			
RUNAR-15% slip	2	15	12	10	14		
RUNAR-peak	1	5	4	4	4		
IMAG	4	28	24	20	20	12	11

Interpolated data included for the ERD and ITTV; all surfaces (including bare and dry)

All Speeds				65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)			Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV			ERD	ITTV
ERD				ERD		
ITTV	263			ITTV	45	
TC SFT'79	199	203		TC SFT'79	32	40
Griptester	190	181		Griptester	26	34
BV-11	196	178		BV-11	30	34
RUNAR-15% slip	48	50		RUNAR-15% slip	16	14
RUNAR - peak	101	91		RUNAR - peak	11	11
IMAG	208	214		IMAG	37	37

Table 3.5: Slopes Obtained from the Regression Analyses Done by Excluding the Bare and Dry Data

Case: all speeds; winter surfaces (no bare and dry data); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	0.6361						
TC SFT'79	1.1616	1.3272					
Griptester	1.2708	1.1981	0.8416				
BV-11	1.5340	1.7106	1.2753	1.1268			
RUNAR-15% & peak	Too few data for analysis						
IMAG	0.6662	0.9477	0.6936	0.7254	0.3695	Too few data	

Case: 65 km/h speed; winter surfaces (no bare and dry data); and no data interpolation for ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	Not						
TC SFT'79	Enough	1.3479					
Griptester	Data	0.9769	0.5190				
BV-11	Pairs	1.0973	0.9148	1.0906			
RUNAR-15% & peak	For	Too few data for analysis					
IMAG	Analysis	0.6199	0.4511	0.6110	0.0506	Too few data	

Interpolated data included for the ERD and ITTV; excluding the bare and dry data

All Speeds		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	0.4762	
TC SFT'79	0.7386	1.3187
Griptester	0.9602	1.2186
BV-11	1.1862	1.7479
RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data	
IMAG	0.4388	0.9452

65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	0.4884	
TC SFT'79	0.2791	1.0157
Griptester	0.7779	1.0210
BV-11	1.0001	1.2562
RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data	
IMAG	0.1575	0.4483

Table 3.6: Intercepts Obtained from the Regression Analyses
Done by Excluding the Bare and Dry Data

Case: all speeds; winter surfaces (no bare and dry data); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	0.0356						
TC SFT'79	0.0283	0.0172					
Griptester	0.0358	0.0609	0.0536				
BV-11	0.0336	0.0306	0.0137	0.0073			
RUNAR-15% & peak	Too few data for analysis						
IMAG	0.1069	0.0800	0.0750	0.0531	0.1032	Too few data	

Case: 65 km/h speed; winter surfaces (no bare and dry data); and no data interpolation for ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Gripteste r	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	Not						
TC SFT'79	Enough	0.0127					
Griptester	Data	0.0905	0.1265				
BV-11	Pairs	0.1304	0.0962	0.0177			
RUNAR-15% & peak	For	Too few data for analysis					
IMAG	Analysis	0.1257	0.1246	0.0707	0.1867	Too few data	

Interpolated data included for the ERD and ITTV; excluding the bare and dry data

All Speeds		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	0.0479	
TC SFT'79	0.0662	0.0232
Griptester	0.0626	0.0587
BV-11	0.0539	0.0294
RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data	
IMAG	0.1303	0.0815

65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV
ERD		
ITTV	0.0514	
TC SFT'79	-0.1404	0.0536
Griptester	0.0810	0.0848
BV-11	0.0748	0.1026
RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data	
IMAG	0.1859	0.1477

Table 3.7: Correlation Coefficients (r^2) Obtained from the Analyses Done by Excluding Bare and Dry Data

Case: all speeds; winter surfaces (no bare and dry data); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	0.4959						
TC SFT'79	0.4522	0.6671					
Griptester	0.5079	0.6783	0.8711				
BV-11	0.4889	0.5530	0.8471	0.9051			
RUNAR-15% & peak	Too few data for analysis						
IMAG	0.3316	0.5488	0.7956	0.6994	0.6924	Too few data	

Case: 65 km/h speed; winter surfaces (no bare and dry data); and no data interpolation for ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD	Not Enough Data Pairs For Analysis						
ITTV							
TC SFT'79		0.4277					
Griptester		0.7018	0.6559				
BV-11		0.5212	0.4404	0.7468			
RUNAR-15% & peak		Too few data for analysis					
IMAG		0.1060	0.2752	0.1518	0.0372	Too few data	

Interpolated data included for the ERD and ITTV; excluding the bare and dry data

All Speeds			65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)		Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV		ERD	ITTV
ERD			ERD		
ITTV	0.4652		ITTV	0.4852	
TC SFT'79	0.3571	0.6258	TC SFT'79	0.0537	0.2631
Griptester	0.5692	0.6643	Griptester	0.6960	0.7256
BV-11	0.5921	0.5582	BV-11	0.8984	0.5847
RUNAR-15% slip	Too few data		RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data		RUNAR - peak	Too few data	
IMAG	0.2904	0.5328	IMAG	0.0615	0.0683

Table 3.8: Number of Data Pairs Used for the Analyses
Done by Excluding the Bare and Dry Data

Case: all speeds; winter surfaces (no bare and dry data); and no data interpolation for the ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	67						
TC SFT'79	77	146					
Griptester	76	128	154				
BV-11	71	125	151	162			
RUNAR-15% & peak	Too few data for analysis						
IMAG	83	153	141	128	122	Too few data	

Case: 65 km/h speed; winter surfaces (no bare and dry data); and no data interpolation for ERD or ITTV

Device 1 (Eq'n 3.1)	Device 2 (Equation 3.1)						
	ERD	ITTV	TC SFT'79	Griptester	BV-11	RUNAR 15% slip	RUNAR peak
ERD							
ITTV	4						
TC SFT'79	5	21					
Griptester	5	21	28				
BV-11	5	17	24	34			
RUNAR-15% & peak	Too few data for analysis						
IMAG	4	22	18	18	14	Too few data	

Interpolated data included for the ERD and ITTV; excluding the bare and dry data

All Speeds				65 km/h Speed		
Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)			Device 1 (Eq'n. 3.1)	Device 2 (Eq'n 3.1)	
	ERD	ITTV			ERD	ITTV
ERD				ERD		
ITTV	243			ITTV	39	
TC SFT'79	181	179		TC SFT'79	26	34
Griptester	177	164		Griptester	24	32
BV-11	178	160		BV-11	24	28
RUNAR-15% slip	Too few data			RUNAR-15% slip	Too few data	
RUNAR - peak	Too few data			RUNAR – peak	Too few data	
IMAG	190	188		IMAG	31	31

Discussion of Results

3.3.1 Friction Factor Magnitudes

In most cases, the ITTV recorded lower friction than did the other devices, with the exception of the ERD. This can be seen by inspecting the raw data plots (in Appendices B to E) and by reviewing the slopes listed in Tables 3.1 and 3.5. The analyses and plots prepared to document the effect of vertical load (in Section 4 and Appendix F) clearly show this result as well.

The friction factors magnitudes measured by the ERD and the ITTV were generally similar for most surfaces.

At first glance, the RUNAR data indicate significantly different correlations for the peak friction and the value at 13-15% slip (Tables 3.1 and 3.5). However, CARE MUST BE TAKEN IN INTERPRETING THESE DATA because the RUNAR was not tested on bare and dry pavement in the variable slip mode. As a result, the correlations done with the peak friction do not include a data cluster for bare and dry pavement whereas this is included for the results from the fixed slip tests, which were at about 13-15% slip (Appendices B to E). This is discussed further in the next section.

3.3.2 Effect of Including or Excluding the Bare and Dry Data

Greatly different results were obtained depending on whether or not the bare and dry data were included in the analyses (Tables 3.1 to 3.8 and Appendices B to E). For most devices, the data tend to fall into two general groups:

- bare and dry pavement; and,
- snow and ice-covered surfaces.

Because these two data clusters have significantly different friction factor magnitudes, a regression analysis done using the whole data set is essentially based on two general points. As expected, these line fits tend to have a relatively high slope, a low intercept, and a relatively high correlation coefficient.

However, significantly different results were obtained when the bare and dry data were excluded because the friction factors for the snow and ice-covered surfaces were all within a relatively small range of magnitudes, and they contained a relatively large amount of scatter for most devices. As a result, regression analyses done using only these data tend to have relatively flat slopes, high intercepts, and lower correlation coefficients (Tables 3.5 to 3.8).

3.3.3 Effect of Speed (all speeds vs. 65 km/h only)

The results obtained using the whole data set (which includes the bare and dry data) were generally similar for both cases, as the slopes obtained were usually within about 10 % for most cases (Table 3.1). However, the degree of fit (as defined by the correlation coefficient) was usually better when all speeds were included in the analyses because the line fits were based on significantly more data. In some cases, the quantity of the available data at 65 km/h speed was considered to be insufficient for analysis.

It is more difficult to assess the effect of speed on the results obtained using only the snow and ice-covered surfaces because these analyses contain more variability, due to the nature of the underlying data (described above).

It should be noted that the ERD data was not subdivided by speed because all of the ERD measurements were made by decelerating the test vehicle from 50 km/h. The full ERD data set was used for correlation analyses that included the ERD.

3.3.4 Effect of Including Interpolated Data for the ERD and ITTV

As described in section 3.1 – point (c), the ERD and ITTV were often not tested at the same times as the other devices. Correlations were done for two cases: (a) a relatively rigorous grouping of the data pairs by time; and (b) interpolating the measured data to intermediate time points.

This had a great effect on the results obtained for the ERD for two reasons:

- It caused data pairs for bare and dry pavement to be included in the analyses. No bare and dry results were available when interpolated data were not included. (Compare plots in Appendices B vs C, and D vs E). As a result, the analyses done without including interpolated data were based solely on results obtained from the snow and ice-covered surfaces. As discussed in section 3.3.2, the results obtained when the bare and dry data were excluded were greatly different than those for the case where these data were included.

- It produced a large increase (by a factor of about 3 to 4) in the number of data pairs available for analysis (Tables 3.4 and 3.8).

For the analyses done using the whole data set (which included the bare and dry data), the slopes for the ERD were affected by up to about 50% depending on whether or not interpolated data were included (Table 3.1). For the case where the analyses were based only on snow and ice-covered surfaces, the slopes were also affected by whether or not interpolated data were included (Table 3.8). However, in this case, this variation produced less of a difference in slope because bare and dry data were not included in the regressions performed using the whole data set with no interpolation for the ERD.

As expected, the correlation coefficients for the ERD for both cases (i.e., bare and dry data included or excluded) were greatly improved when interpolated data were included (Tables 3.3 and 3.7). The greatest effect was observed for the analyses done using the whole data set because, in this case, the inclusion of interpolated data caused results on bare and dry pavement to be included in the analyses.

Further analyses were conducted to investigate the confidence levels in the ERD data, and to investigate the sampling requirements. These analyses are presented in section 3.3.5.

The results obtained for the ITTV were also affected by whether or not interpolated data were included, although to a lesser extent than for the ERD. This is due to the fact that the number of data pairs for the ITTV was not increased by the same amount when interpolated data were included (Tables 3.4 and 3.8).

For the analyses done using the whole data set (which included the bare and dry data), the variation in slope introduced by including interpolated data for the ITTV was within about +/- 10% (Table 3.1). The results conducted using data from only snow and ice-covered surfaces also showed that the variation in slope introduced by including interpolated data for the ITTV was within about +/- 10% (Table 3.5).

The correlation coefficients for the ITTV for both cases (i.e., bare and dry data included or excluded) were improved slightly (by up to about 10%) when interpolated data were included (Tables 3.3 and 3.7). This follows the expected trend as the inclusion of interpolated data pairs provides a larger database with less variability.

3.3.5 Confidence Levels in the ERD Data and Sampling Requirements

Analyses were undertaken to investigate the confidence levels inherent in the ERD data, and the sampling requirements for it. This is especially important for the ERD because it does not measure the friction factor continuously.

The analyses were performed using the following index:

$$\frac{\text{Half of the 99\% confidence interval for the mean friction factor}}{\text{mean friction factor}} \qquad [3.2]$$

The analyses were conducted using data collected on the following surfaces from the following tests:

- “rough ice” - tests 36.1 and 37.2 on February 5 and 6, respectively;
- “compacted snow” - tests 36.2 and 37.1 on February 5 and 6, respectively.

ERD data were collected at several times during the above tests. Usually, two or more “sets” of ERD data were collected at each time, with each “set” consisting of 6-12

individual ERD friction factor measurements. The above index was calculated for each of these data “sets”, and for the whole data set collected at a given time.
The results are shown in Figures 3.1 to 3.4. As expected, the value of the above index decreases steadily as more ERD samples are included in the mean value. It has a value of about 5-10% when the mean value is based on about 15 individual ERD friction factor measurements.

The variability between individual ERD means is equally important for assessing the confidence that can be placed in the ERD data. Figures 3.1 to 3.4 show that the above index is highly variable when the mean ERD value is based on six or less ERD individual friction factor measurements. This has important implications for assessing the correlation between the ERD and the other devices because most of the mean ERD friction factors are based on about six individual measurements.

It is of interest to compare the value of the above index for the ERD with that for other devices. For the Griptester and BV-11 (which are the only devices that listed the standard deviation on the hard copy data sheets that were submitted), the above index was estimated to be within the range of 1 to 10% for the above tests. This result supports the previous analyses as it shows that more individual ERD friction factor measurements (than six) are required.

This issue should be investigated further. However, it appears clear that more individual ERD friction factor measurements (than six) are required, and that about 15 measurements would be necessary to obtain mean ERD values that have confidence levels similar to the other devices.

Figure 3.1

Effect of Sampling Frequency on the ERD Data Confidence:
IRFI Temperature Gradient Tests (Test 36.1) on Feb. 5 on Rough Ice

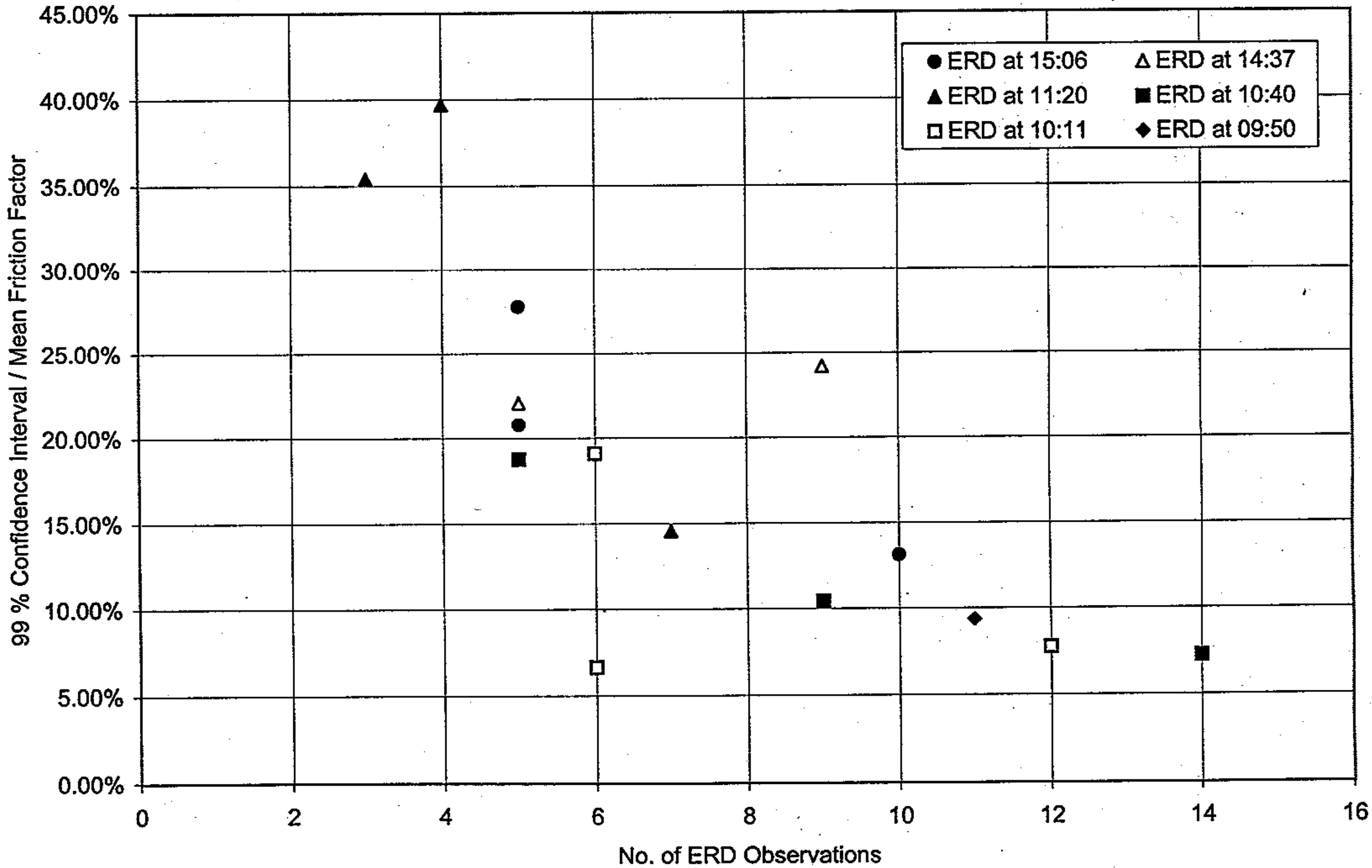


Figure 3.2

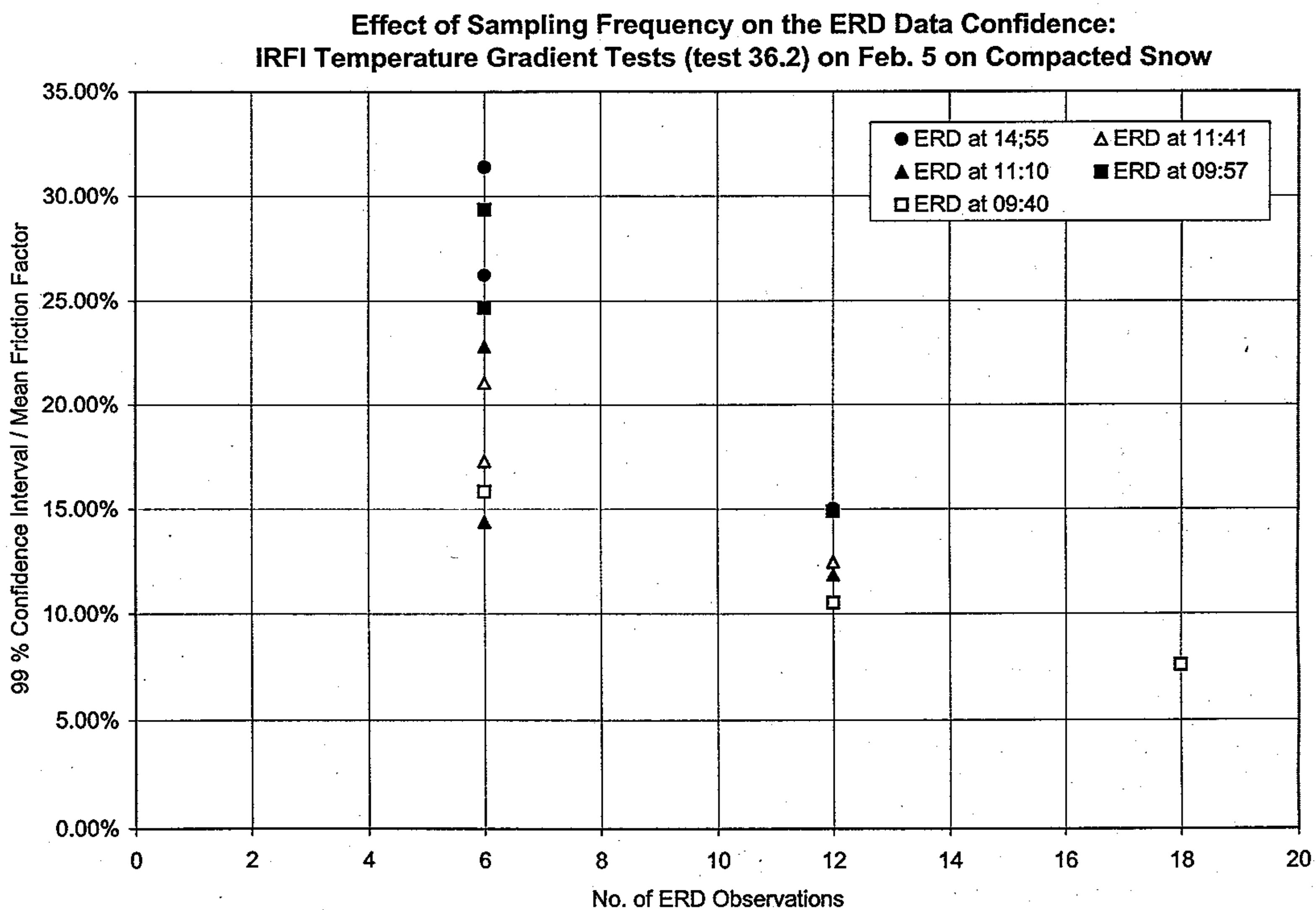

Effect of Sampling Frequency on the ERD Data Confidence:
IRFI Temperature Gradient Tests (test 36.2) on Feb. 5 on Compacted Snow
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
99 % Confidence Interval / Mean Friction Factor
0
2
4
6
8
10
12
14
16
18
20
No. of ERD Observations
ERD at 14;55
ERD at 11:41
ERD at 11:10
ERD at 09:57
ERD at 09:40

Figure 3.3

Effect Of Sampling Frequency On The ERD Data Confidence :
IRFI Temperature Gradient Tests (test 37.2) On Feb. 6 On Rough Ice

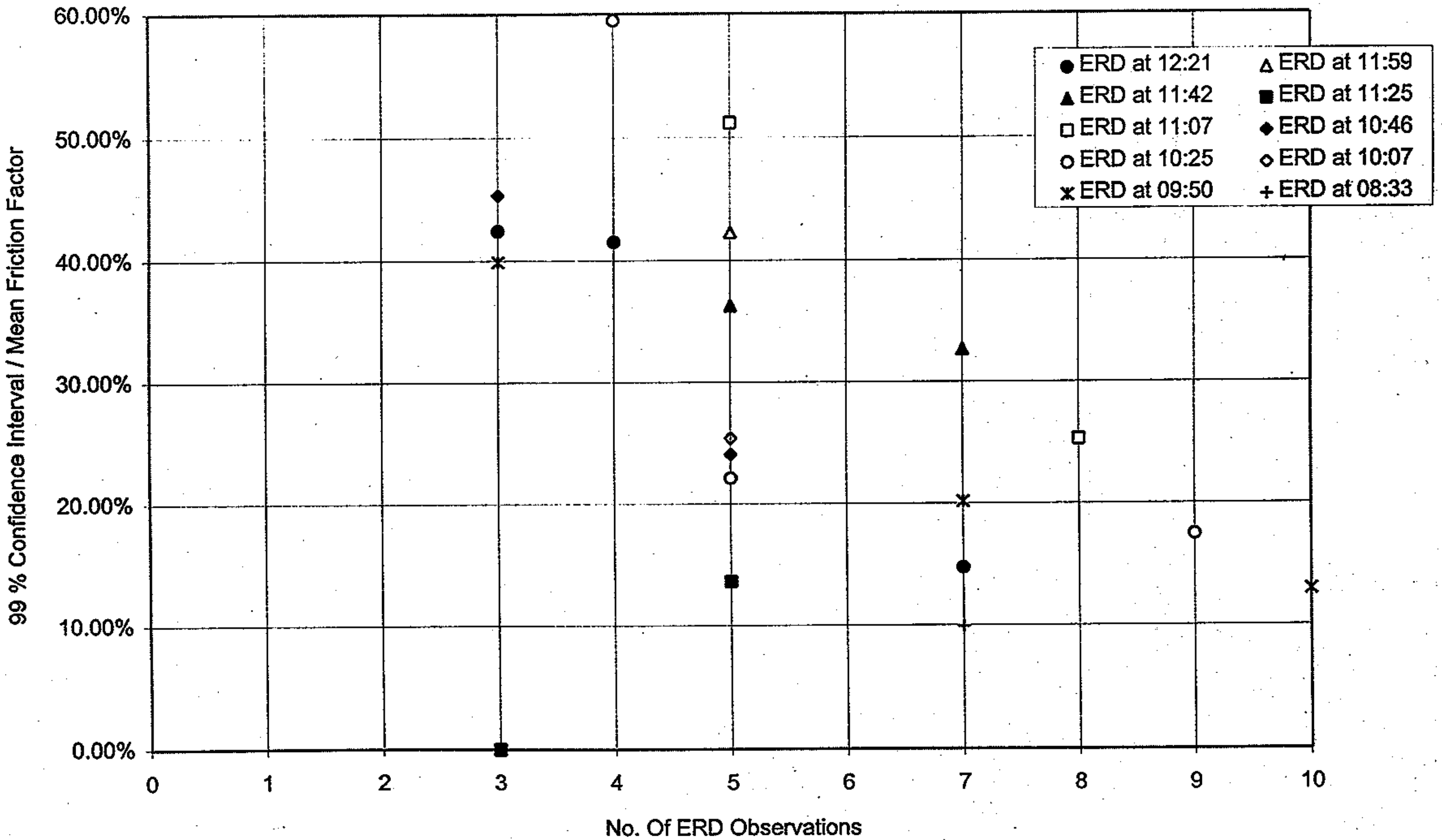
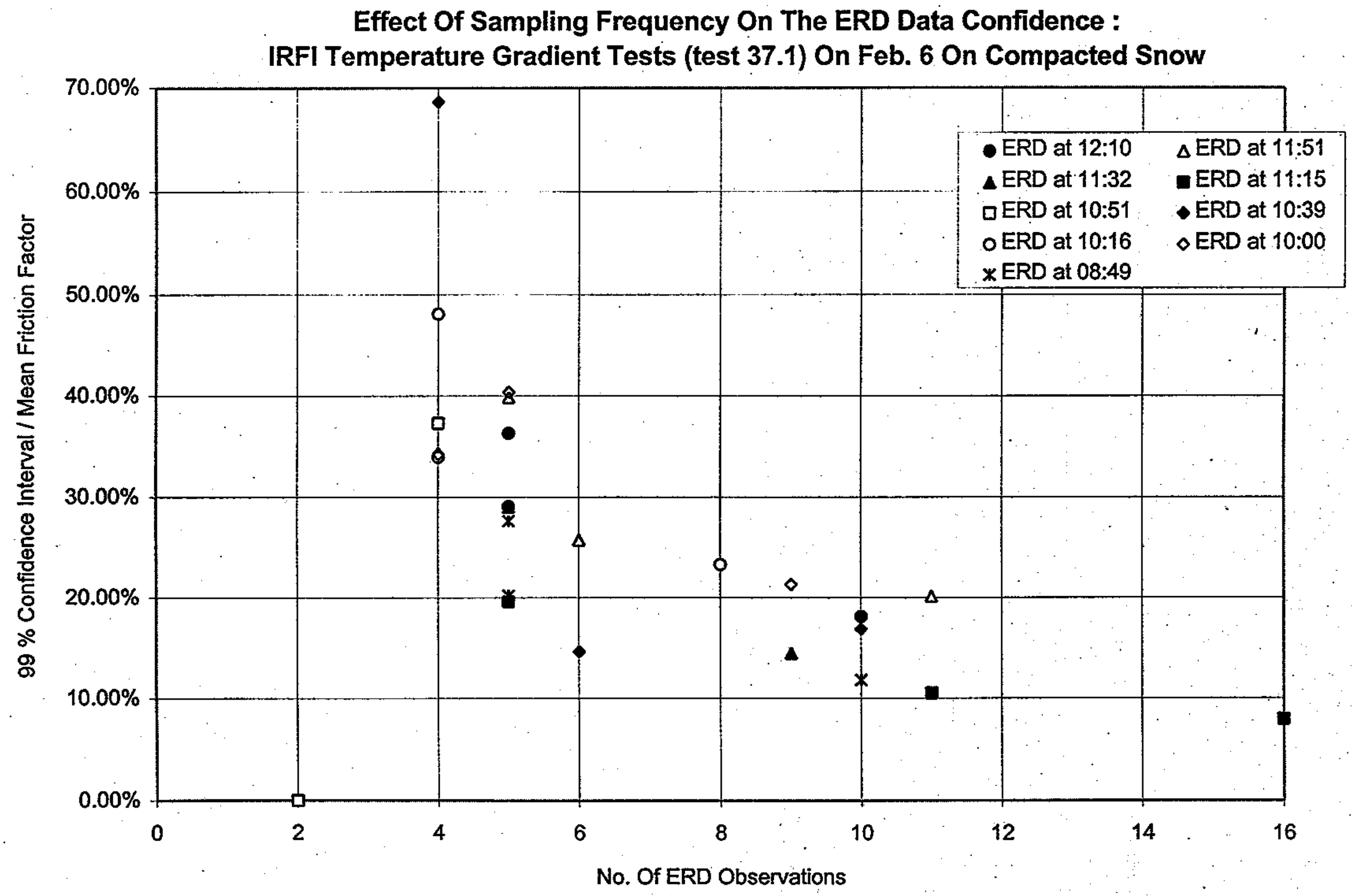


Figure 3.4


Effect Of Sampling Frequency On The ERD Data Confidence :
IRFI Temperature Gradient Tests (test 37.1) On Feb. 6 On Compacted Snow
99 % Confidence Interval / Mean Friction Factor
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
0
2
4
6
8
10
12
14
16
No. Of ERD Observations
ERD at 12:10
ERD at 11:51
ERD at 11:32
ERD at 11:15
ERD at 10:51
ERD at 10:39
ERD at 10:16
ERD at 10:00
ERD at 08:49

4. THE EFFECT OF LOAD AND PRESSURE

4.1 Data Sources

Information from two general sources was analyzed:

(a) Tests done with the ITTV during which the vertical load and tire inflation pressure were parametrically varied. Tests were done: (i) on rough ice (on Feb. 8 - Table 2.1); (ii) on compacted snow and ice with 0-10 mm loose and dry granular snow over it (on Feb. 8 - Table 2.1); and, (iii) on bare and dry pavement (on Feb. 10 - Table 2.1).

(b) Tests done with the ground vehicles over the course of the program. These data provided information as well because the individual devices apply different vertical loads during friction factor measurement (Appendix A).

4.2 The "Load and Pressure" Study Conducted with the ITTV

4.2.1 Test Results

The ITTV friction factors are plotted in relation to the load and tire inflation pressure in Figure 4.1.

Before drawing conclusions, it is useful to check whether or not the ice and packed snow surfaces (tested on Feb. 8) changed with time over the duration of the survey. Figure 4.2 shows that the friction factors measured by the other devices that were tested concurrently were relatively consistent over the time period of the study. Their variability with time is much less than the friction changes measured during the load and pressure study (compare Figures 4.1 and 4.2). It is concluded that the results on ice and packed snow were not affected by changes in friction over the duration of the surveys.

The results of the ITTV "load and pressure" study indicate that:

(a) vertical load - the vertical load is a very important parameter affecting the friction factor for each surface tested.
- For the "loose snow on top of packed snow" surface, the friction factor reduces with increasing vertical load over the full range tested (Figure 4.1).
- For the ice surface, the friction reduces with increasing load up to about 2500 lb, and then it "levels off", indicating that it is insensitive to the vertical load for larger loads (Figure 4.1).
- For bare and dry pavement, the friction reduced with the vertical load (Figure 4.1).

(b) Tire inflation pressure - the friction is not sensitive to the tire inflation pressure. Similar friction was measured for each of the three surfaces for the two pressures tested (210 kPa [30 psi] and 940 kPa [136 psi]).

4.2.2 Effect of Tire Footprint Area and Contact Pressure

From measurements made during the 1998 North Bay tests, Dr. J. Wambold (of CDRM Inc.) developed the following equations to quantify the ITTV's tire footprint area and contact pressure:

- Gross Tire Footprint Area (in^2) = 16.991 * ln (vertical load, in lbs) - 108.13 [4.1]
- Net Tire Footprint Area (in^2) = 12.882 * ln (vertical load, in lbs) - 80.956 [4.2]
- Gross Contact Pressure (psi) = $105.3\ e^{9E\text{-}05\ *\ (\text{vertical load, in lbs})}$ [4.3]
- Net Contact Pressure (psi) = $89.275\ e^{8E\text{-}05\ *\ (\text{vertical load, in lbs})}$ [4.4]
- Conditions And Range of Applicability For Equations 4.1 to 4.4 :
  - Tire inflation pressure : 940 kPa (136 psi)
  - Vertical Load : 4.4 kN (1000 lb) to 21.6 kN (4860 lb)

Equations 4.2 and 4.4 were used to determine the net tire footprint area and contact pressure for the tests done during the "Load and Pressure Study".

The effects of tire footprint area and contact pressure are shown on Figures 4.3 and 4.4, respectively. These results show that the friction factor reduces with the net footprint area and the net tire contact pressure in a manner similar to that observed for the vertical load.

Figure 4.1 ITTV Load And Pressure Study Results

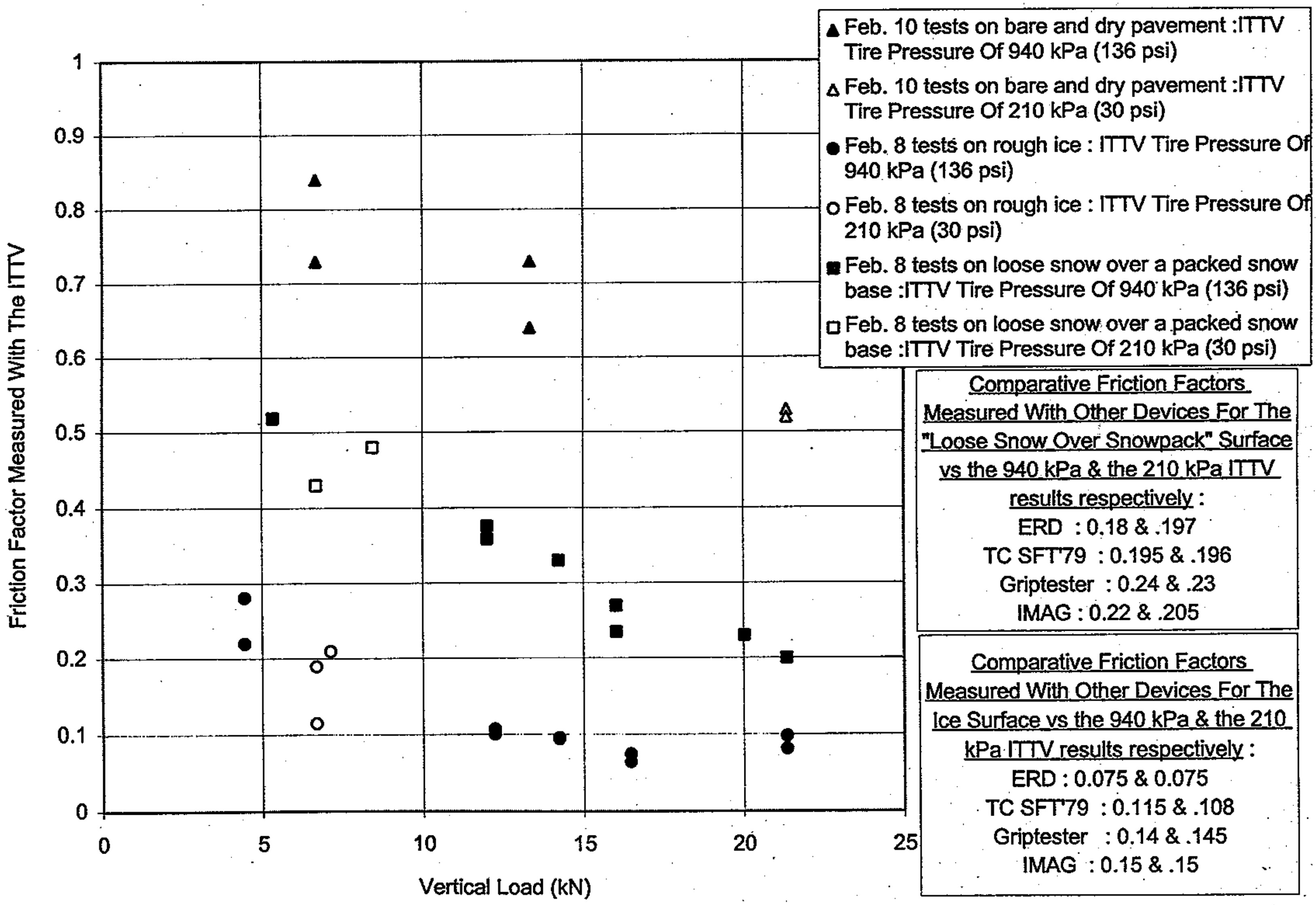


Figure 4.2
Load And Tire Pressure Study (Feb. 8) : Surface Variability With Time

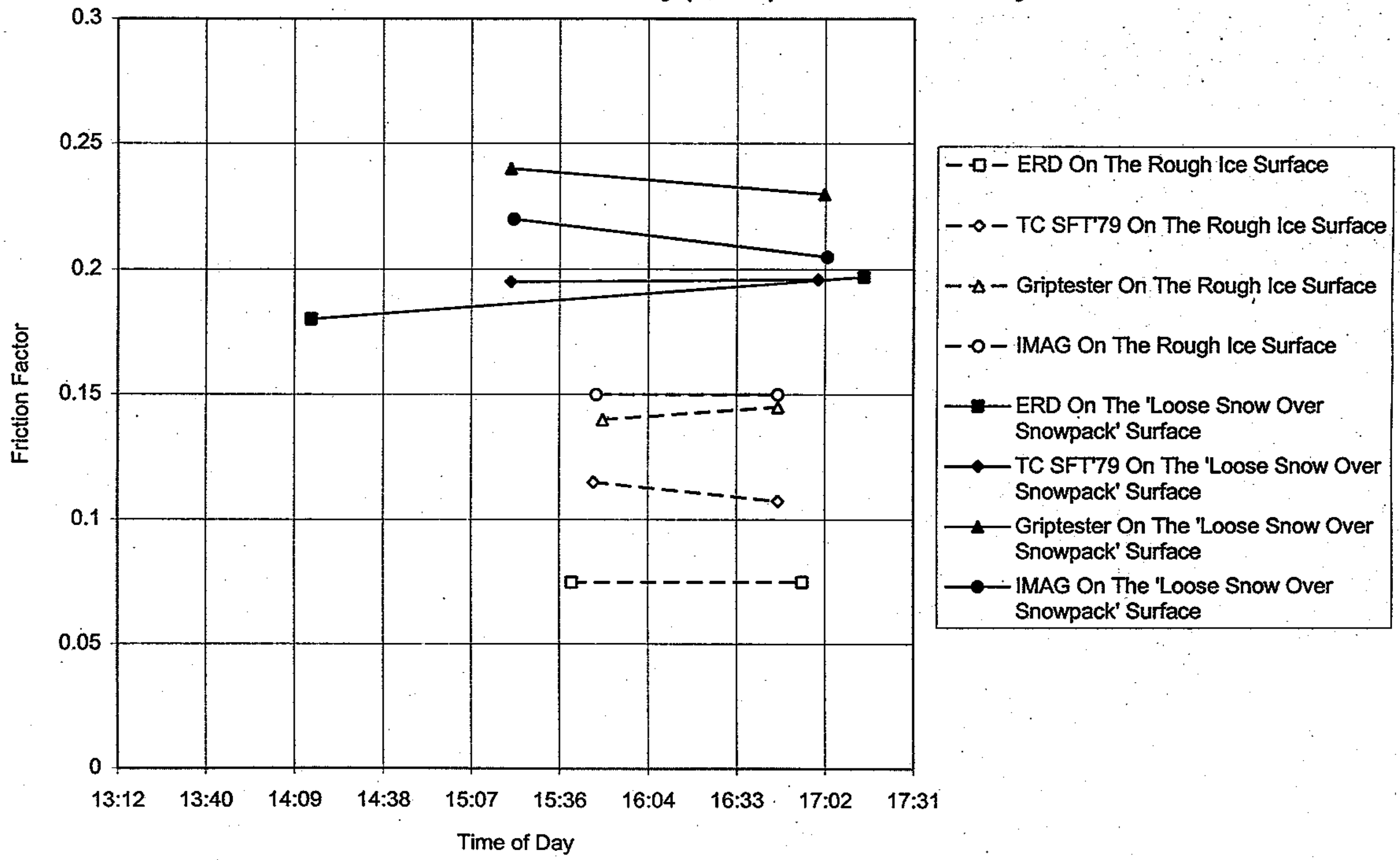


Figure 4.3
ITTV Load And Pressure Study : Effect Of Net Tire Footprint Area

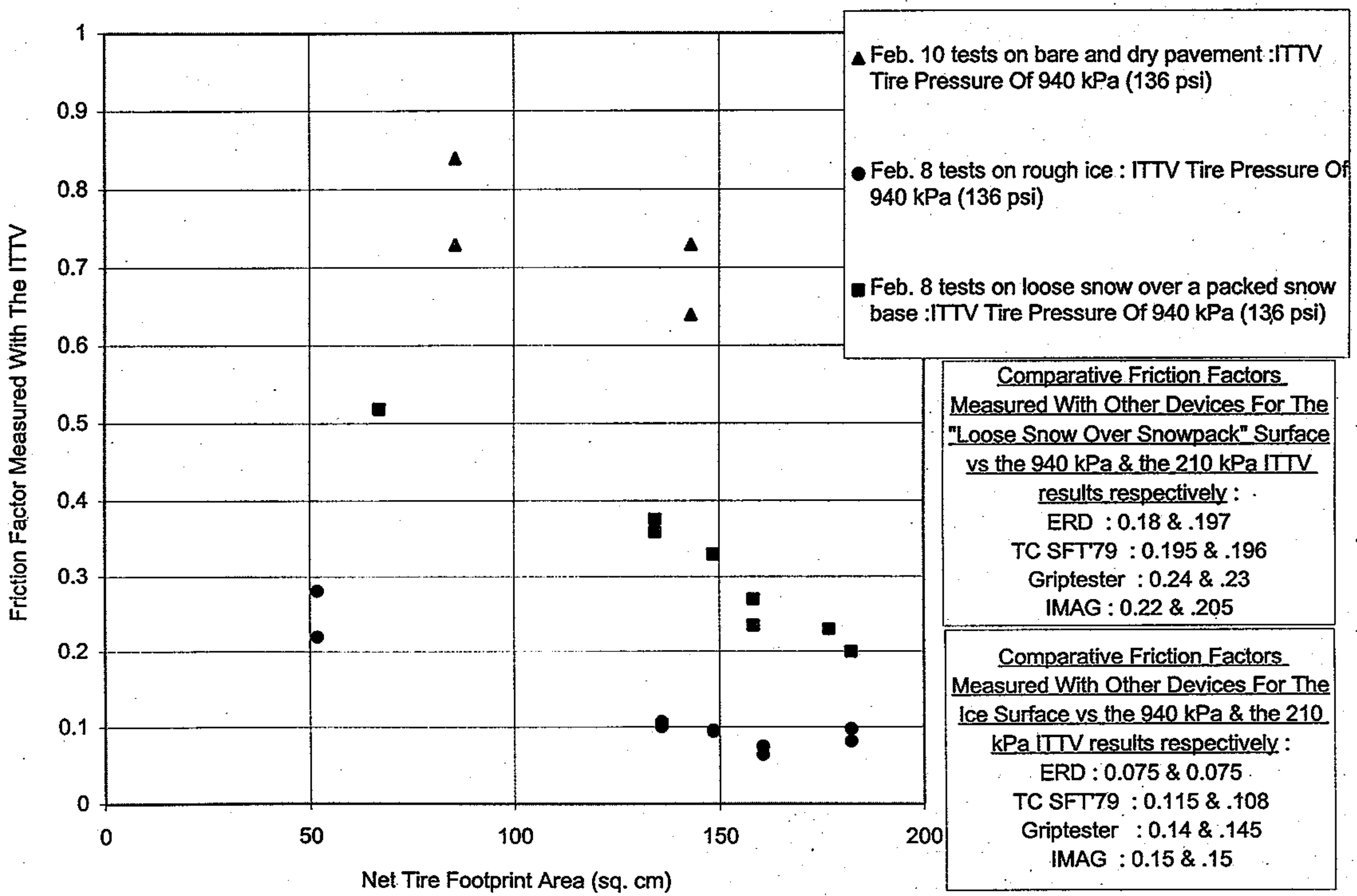
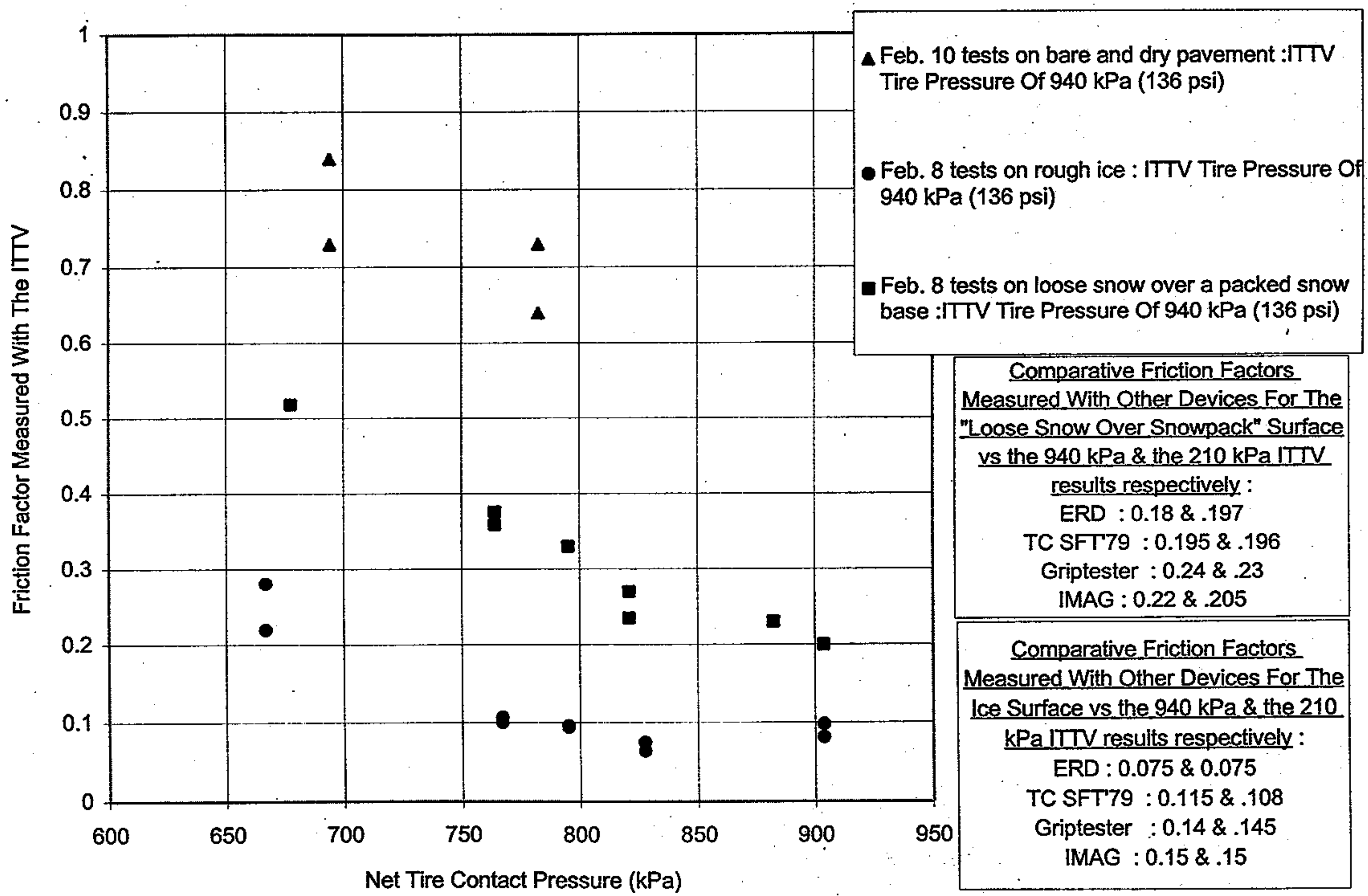


Figure 4.4
ITTV Load And Pressure Study : Effect Of Net Tire Contact Pressure



The Effect of Vertical Load on the Ground Vehicle Data

This was investigated by plotting the friction factors measured on each test day by each device against the applicable vertical load for that device. See Appendix F for plots. It should be noted that no data groupings were applied and therefore, the data points plotted on these figures span the range of speeds tested on that day. As well, no efforts have been made to correct for any surface condition changes that may have occurred on that particular test day over the duration of the friction survey.

Nevertheless, for most cases, these data show the same general trend indicated from the "ITTV load and pressure" study as the friction decreases with increasing vertical load. However, there are exceptions and the relationship appears to be surface-dependent, as summarized in Table 4.1.

The following observations are made:

- a trend (of decreasing friction with increasing load) is evident for the tests done on ice, compacted snow, and bare and dry pavement;
- opposite trends (as the friction increases with load), or no trends, are evident for the tests done on "wet" ice, slush, and loose or fresh snow;
- this variation in trend is probably related to the amount of contaminant drag. For the "hard" surfaces, this component is expected to be relatively small (compared to the braking component) and for these surfaces, a trend (of decreasing friction with increasing load) is evident. For the "loose" surfaces, the contaminant drag is more significant which alters the relationship between load and friction.

Effect of Load on the Correlation among the Devices

The effect of load is probably part of the explanation for the variation in friction factor magnitudes that was observed among the ground vehicles (discussed in Section 3). In most cases, the ITTV recorded lower friction factors than did the other devices, and this can be attributed to its higher vertical load. Also, the ERD often measured lower friction factors than did the other devices (with the exception of the ITTV), and this is likely also related to the higher vertical load associated with this test method.

Table 4.1 Effect of Vertical Load: Summary of Trends Observed

Date	Test No	Surface	General Trend
Jan. 27	27.1	3 mm freshly-fallen snow	Scattered relationship - no clear trend
Jan. 27	27.2	30 mm natural snow over an ice base	Scattered relationship - no clear trend
Jan. 28	28.2	5-20 mm fresh snow	Not a strong relationship - friction increases slightly with increasing vertical load although the data are scattered
Jan. 28	28.3 A&B	40 mm snow	Not a strong relationship - friction increases slightly with increasing vertical load although the data are scattered
Jan. 29	29.1	2-12 mm light, wet snow, semi-compacted	Clear trend - friction decreases with increasing vertical load
Jan. 29	29.3	5-12 mm light, wet snow, semi-compacted	Clear trend - friction decreases with increasing vertical load
Jan. 30	30.2 A,B, C	10-15 mm compacted snow	Clear trend - friction decreases with increasing vertical load
Jan. 31	31.1 & 31.2	bare and dry pavement	Clear trend - friction decreases with increasing vertical load
Jan. 31	31.3 A,B,C	snow with patches of bare and dry	Clear trend - friction decreases with increasing vertical load
Feb. 2	33.2 A and B	rough ice with patches of thin wet loose snow and water-covered compacted snow	Clear trend - friction decreases with increasing vertical load
Feb. 3	34.1 A to D	rough ice with dusting of dry snow (0-5 mm)	Clear trend - friction decreases with increasing vertical load
Feb. 3	34.3 A to D	rough ice with dusting of dry snow (0-5 mm)	Clear trend - friction decreases with increasing vertical load
Feb. 4	35.1 to .35.3	smooth ice	Clear trend - friction decreases with increasing vertical load
Feb. 4	35.4	drifting snow on ice	Clear trend - friction decreases with increasing vertical load
Feb. 5	36.1	rough ice	Clear trend - friction decreases with increasing vertical load
Feb. 6	37.2	rough ice	Clear trend - friction decreases with increasing vertical load
Feb. 9	40.3	25-30 mm compacted snow	Clear trend - friction decreases with increasing vertical load
Feb. 9	40.4 A and B	bare and dry	Clear trend - friction decreases with increasing vertical load
Feb. 9	40.5	compacted snow and bare and dry	Clear trend - friction decreases with increasing vertical load
Feb. 11	42.2	AM tests: wet ice PM tests: slush	No clear trend - friction is independent of load
Feb. 11	42.1	Compacted snow	No clear trend - friction is independent of load
Feb. 12	43.1 and 43.2	7.5 wet compacted snow; 5 mm loose wet snow	Opposite trend - friction increases with load

5. THE TIRE STUDY

5.1 Test Program Scope

Tests were conducted on Jan. 28 (test numbers 28.1 A & B - Table 2.1) using the following devices and tires on the following surfaces:

Devices Tested : Transport Canada's 1979 Saab Friction Tester (TC SFT'79) the Federal Aviation Administration's SFT (FAA SFT) the K.J.Law Runway Friction Tester (K.J. Law RFT)

- Tires Tested : ASTM E1551 Smooth tire at 690 kPa (100 psi)
  ASTM E1551 Smooth tire at 210 kPa (30 psi)
  ASTM E1551 Ribbed tire at 690 kPa (100 psi)
  ASTM E1551 Ribbed tire at 210 kPa (30 psi)
  the Trelleborg Aero tire at 690 kPa (100 psi)
- Surfaces Tested : semi-compacted snow
  5-20 mm loose snow over compacted snow

Comparative data were also acquired using the ERD in some cases.

5.2 Results

The results are plotted in Figures 5.1 to 5.4.

Before drawing conclusions, efforts were made to assess whether or not the test surfaces were changing over the duration of the friction survey (which lasted about seven hours). The friction factors measured by the ERD did not change significantly (within the variability of the data) from about 12:00 to 17:00 for all tests (Figures 5.1 to 5.4). Checks were also made based on the friction data recorded by the three other devices versus the time of day. Trends related to the time of day (e.g., increasing or decreasing friction in the latter part of the day) were not apparent. Therefore, it was concluded that the surfaces were not changing significantly over the duration of the friction survey.

The following conclusions are indicated:

(a) Effect of tire pressure - the effect of tire pressure varied with the tire tread type (i.e., ribbed vs smooth) and the surface type.

For the smooth tires, lower friction was measured at a tire inflation pressure of 210 kPa (30 psi) than at 690 kPa (100 psi) for both speeds and surfaces.

For the ribbed tires, the trends varied with the surface type. On "semi-compacted snow", lower friction was measured at a tire inflation pressure of 210 kPa (30 psi) than at 690 kPa (100 psi) for both speeds. On the surface consisting of "5-20 mm loose snow over compacted snow", the friction was insensitive to pressure for both speeds.

(b) Effect of smooth vs ribbed tires - higher friction factors were measured for the ribbed tires on "semi-compacted snow" in all cases except for the tests done with the TC SFT'79 at 690 kPa inflation pressure at 65 km/h. In that case, the friction was similar for the ribbed and the smooth ASTM tires (Figures 5.1 and 5.2).

The results on "5-20 mm loose snow over compacted snow" (Figures 5.3 and 5.4) show higher friction for the ribbed tires in all cases except for the following ones (in which similar friction was measured for the ribbed and smooth tires):

- tests with the TC SFT'79 at 65 km/h using the ASTM tire at 210 kPa inflation pressure;
- tests with the TC SFT'79 at 40 km/h using the ASTM tire at 690 kPa inflation pressure;
- tests with the TC SFT'79 at 65 km/h using the ASTM tire at 690 kPa inflation pressure.

(c) Effect of ground vehicle speed - the friction was insensitive to speed (within the variability of the data) for most cases (i.e., devices, surfaces and speeds).

(d) Effect of device - this had a very significant effect on the measured friction for the "loose snow over compacted snow" surface. The K.J. Law RFT measured significantly higher friction for all tires at both speeds. The TC SFT and the FAA SFT measured similar friction (within the variability of the data).

On "semi-compacted snow", the K.J. Law RFT measured slightly higher friction for all tires at both 40 and 65 km/hr. However, the variations in the friction factors measured by three devices are relatively small within the variability of the data.

The reasons for the variation between the K.J. Law RFT and the other two devices should be investigated further.

Figure 5.1
Tire Study Results on Semi-Compacted Snow:
Nominal Test Speed: 40 km/h

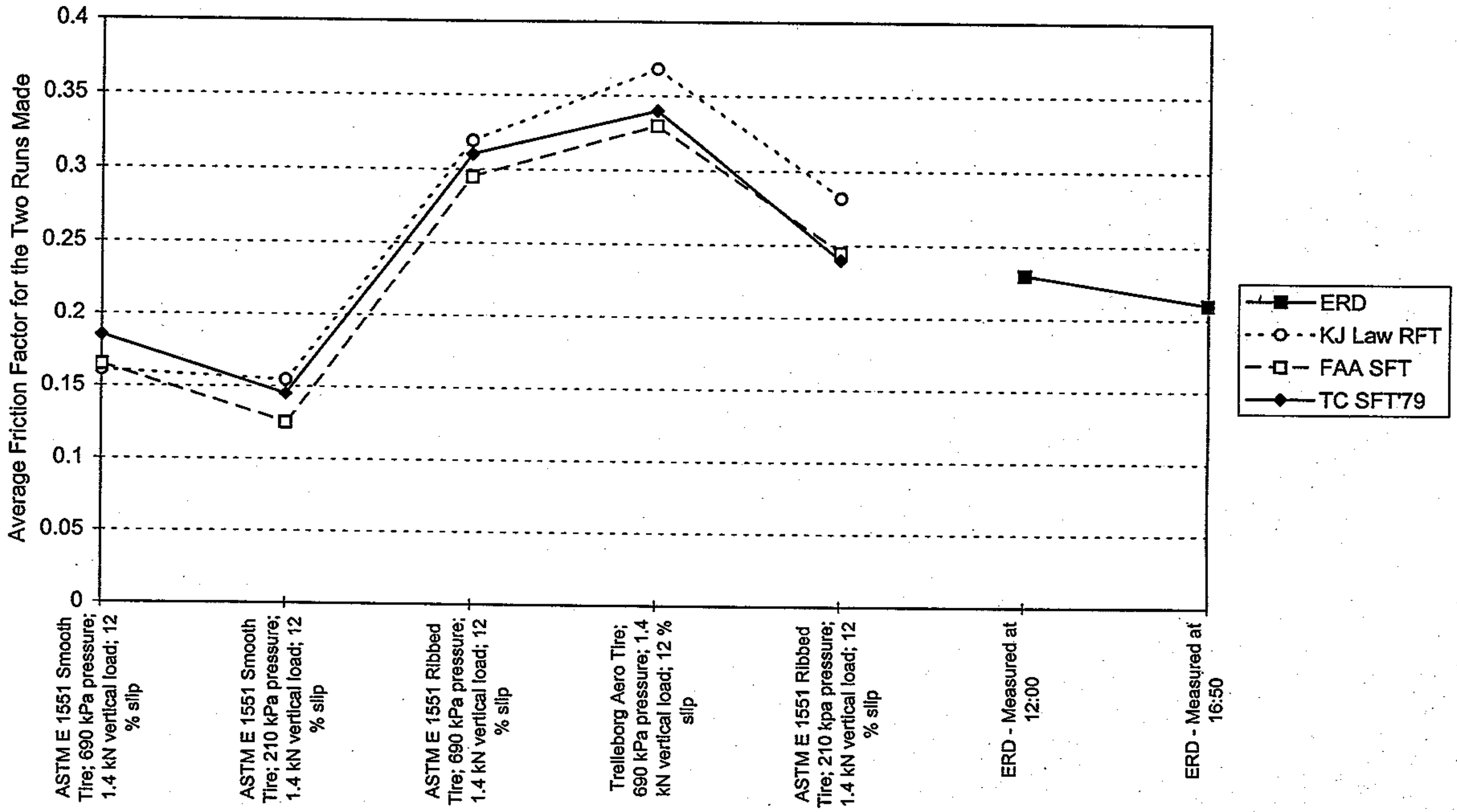


Figure 5.2
Tire Study Results on Semi-Compacted Snow:
Nominal Test Speed: 65 km/h

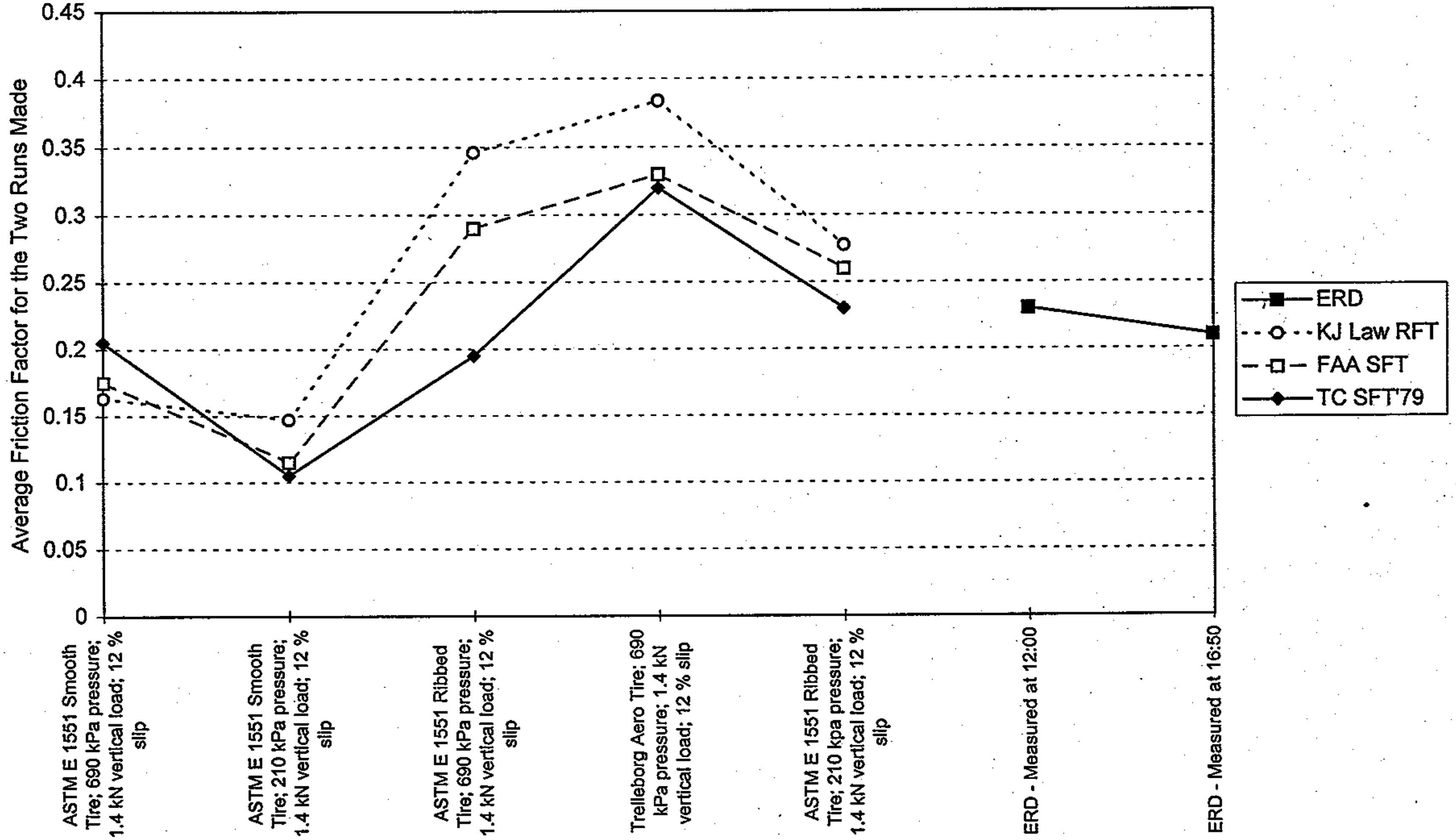


Figure 5.3
Tire Study Results on 5-20 mm Loose Snow over Compacted Snow:
Nominal Test Speed: 40 km/h

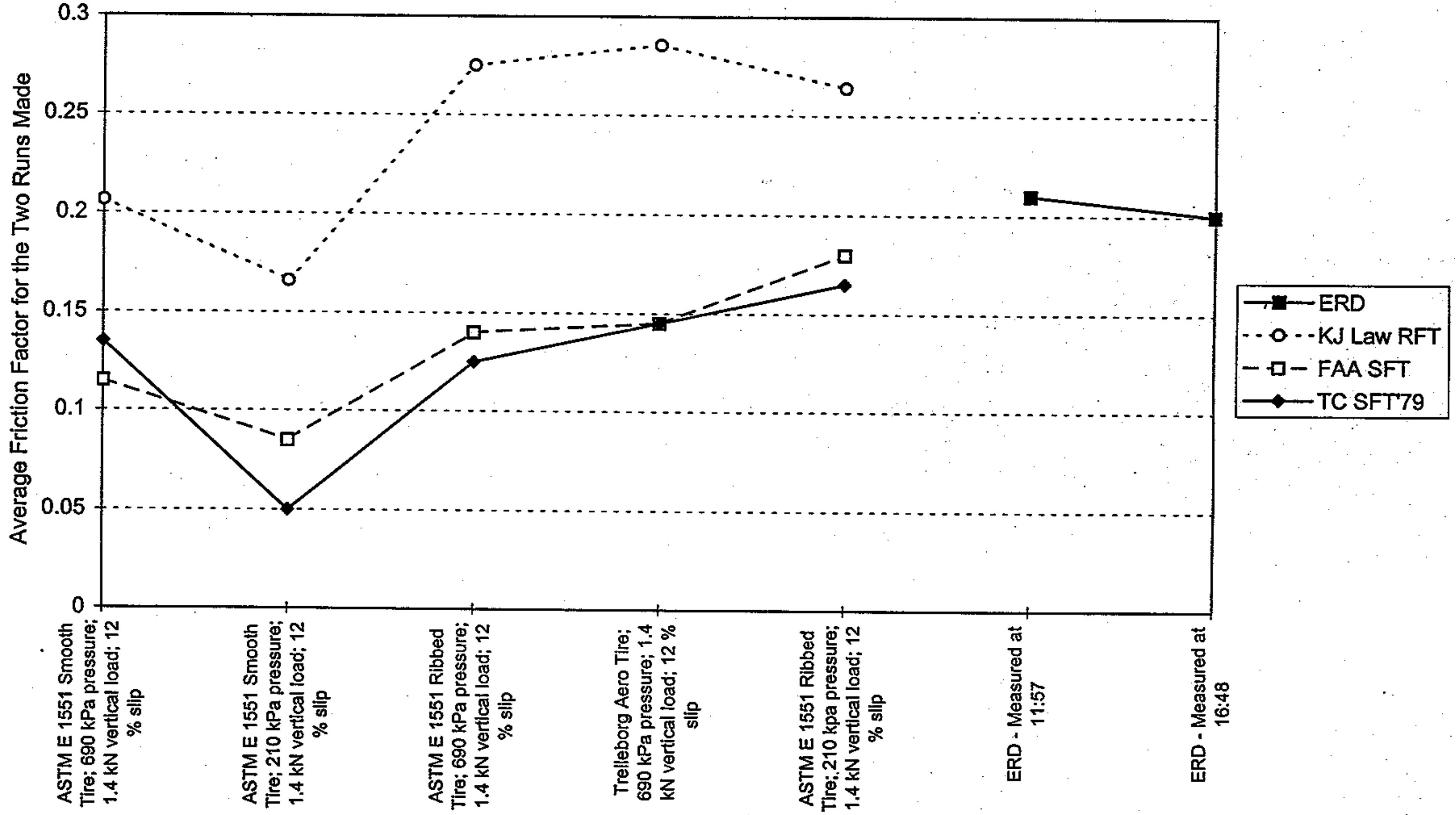
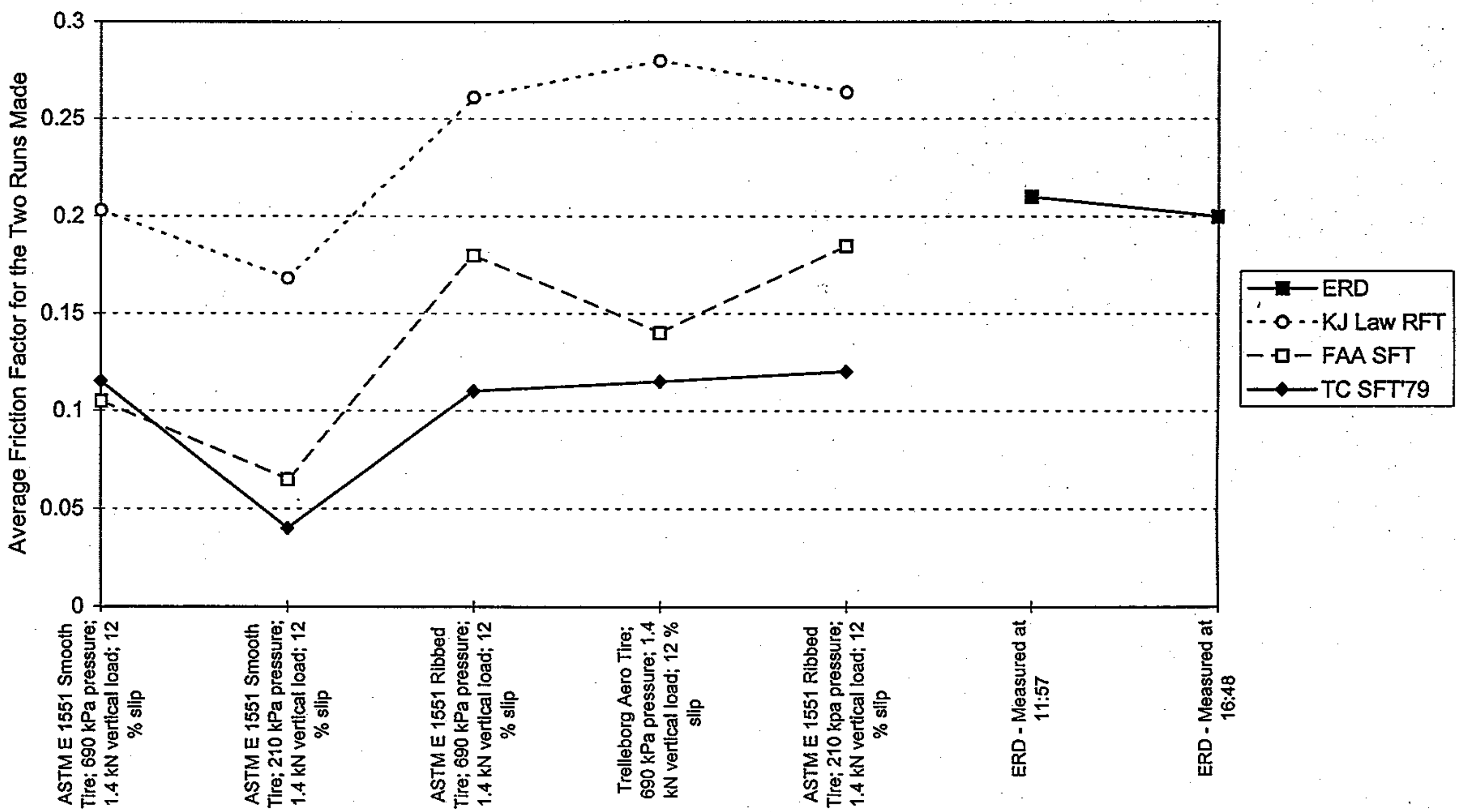


Figure 5.4
Tire Study Results on 5-20 mm Loose Snow over Compacted Snow: Nominal Test Speed: 65 km/h



6. THE EFFECT OF TEMPERATURE

6.1 Data Sources

This was investigated during the North Bay trials by repeatedly measuring the friction of various test surfaces over several hours during a day. The following data sources were analyzed:

- Tests 35.1 A&B, 35.2, and 35.3 - done on Feb. 4 on smooth ice;
- Tests 36.1 and 37.2 - done on Feb. 5 and Feb. 6, respectively on rough ice;
- Tests 36.2 and 37.1 - done on Feb. 5 and Feb. 6, respectively on compacted snow;
- Test 40.3 - done on Feb. 9 on 25-30 mm compacted snow.

6.2 Results

Plots showing the friction factors measured by the devices over the test duration, and the surface and air temperatures as well, are provided in Appendix G. The temperature changes that occurred are summarized in Table 6.1.

Table 6.1: Temperature Change Summary

Date	Test No.	Approx. Surface Temperature Changes Over The Test Duration		
		Initial Temp. (°C)	Final Temp. (°C)	Temp. Rise (C°)
Feb. 4	35.1 to 35.3	-14	-2	12
Feb. 5	36.2	-12	no data (estim. at -1)	11 (estimated)
	36.1	-12	-1	11
Feb. 6	37.1	-10	no data (estim. at -2)	8 (estimated)
	37.2	-10	-2	8
Feb. 9	40.3	-3	-1	2

The following observations are made:

- Surface temperatures - The initial and final temperatures were generally similar for the Feb. 4, Feb. 5 and Feb. 6 tests. The surface was much warmer for the Feb. 9 test.

- Friction on a bare ice surface : There was a variation between the Feb. 4 and the Feb.5 & Feb. 6 tests. On Feb. 4, the friction factors steadily reduced with time, and increasing surface temperature (Appendix G). However, during the Feb. 5 and 6 tests, the friction did not change significantly over the test duration, and as the surface temperature increased on those days (Appendix G).

  This variation is believed to be related to the initial texture of the ice surfaces, and the "polishing" that tended to occur over the test duration due to the repetitive friction measurements. The ice surface on Feb. 4 was "smooth", and consequently, the "polishing" caused by repetitive measurements brought about a drop in friction.

However, the ice surface tested on Feb. 5 and 6 was “rough”, and it is believed that sufficient texture remained in this surface to maintain higher friction levels over the duration of the friction survey.

- Friction on a compacted snow surface: For the Feb. 5 and Feb. 6 tests, the friction decreased over the test duration for most devices (Appendix G). This is especially evident for the Feb. 6 tests. For the Feb. 5 tests, the friction also decreased with time although the trends or the changes in friction are not as great as for Feb. 6. The Feb. 9 results differ as the friction remained essentially constant over the test duration, as the temperature increased.

- There are a number of possible explanations for this variation. The initial friction factors were higher on Feb. 5 and Feb. 6, than on Feb. 9, which may indicate that the compacted snow tested on Feb. 5 and 6 had more texture. This texture is more likely to be “lost” by “polishing” caused by the repetitive friction measurements, which would result in a drop in friction.

- The surface temperatures were also much colder on Feb. 5 and 6 than on Feb. 9. As a result, the temperature changes on Feb. 5 and 6 were much greater than on Feb. 9. Consequently, the compacted snow surfaces on Feb. 5 and 6 probably had higher shear strength. This would have decreased as the surface warmed up which would also bring about a drop in friction. Because the compacted snow tested on Feb. 9 was already quite warm at the start of the test, little change in shear strength is to be expected over the test duration.

- Concluding remarks: Different trends have been observed, and a number of explanations have been suggested. It is believed that more investigation and testing is required before definitive statements can be made.

7. THE DECELEROMETER STUDY

7.1 Data Sources

The available data to compare the results from different decelerometers consist of:

- tests conducted on Jan. 29 (no test number) on a “thin layer of compacted snow”;
- tests conducted on Feb. 2 (tests 33.1 A&B) on “rough ice with patches of loose to packed snow”.

Tests comparing the results obtained from different operators were conducted on:

- Feb. 2 (tests 33.1 A&B) on “rough ice with patches of loose to packed snow”;
- Feb. 5 (no test number) on “loose drifted snow on ice”.

7.2 Results

The results are plotted in Figures 7.1 and 7.2. They show that:

- Effect of Device Type - higher friction factors were measured with the Bowmonk and Tapley meters than with the ERDs.
- Effect of Operator - Similar friction factors were measured by Operators 2 and 3 for the ERD. Higher friction factors were measured by Operator 1 than Operator 2 for each of the devices tested.

Figure 7.1

Decelerometer Study Results: Comparison of Devices

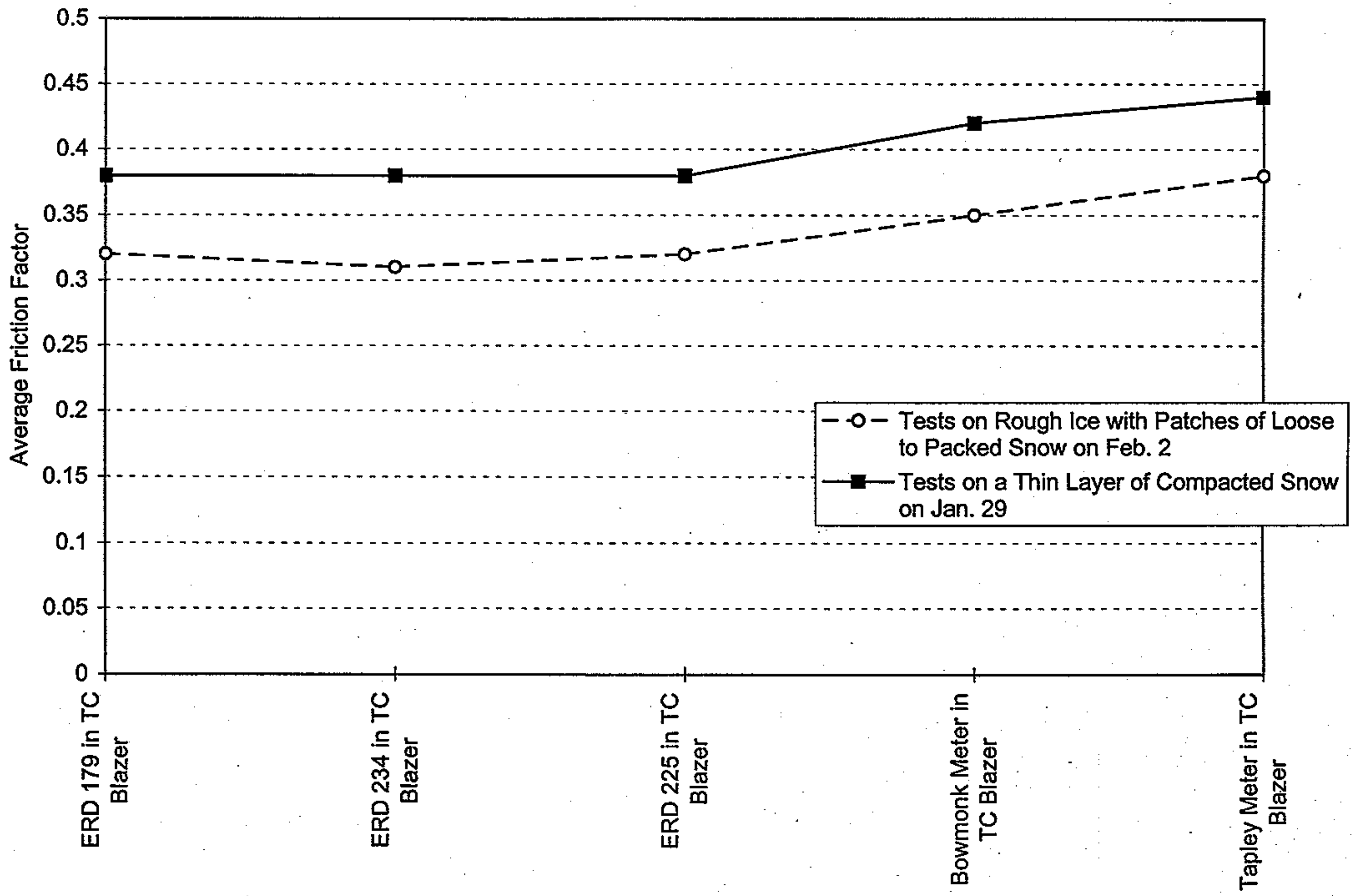
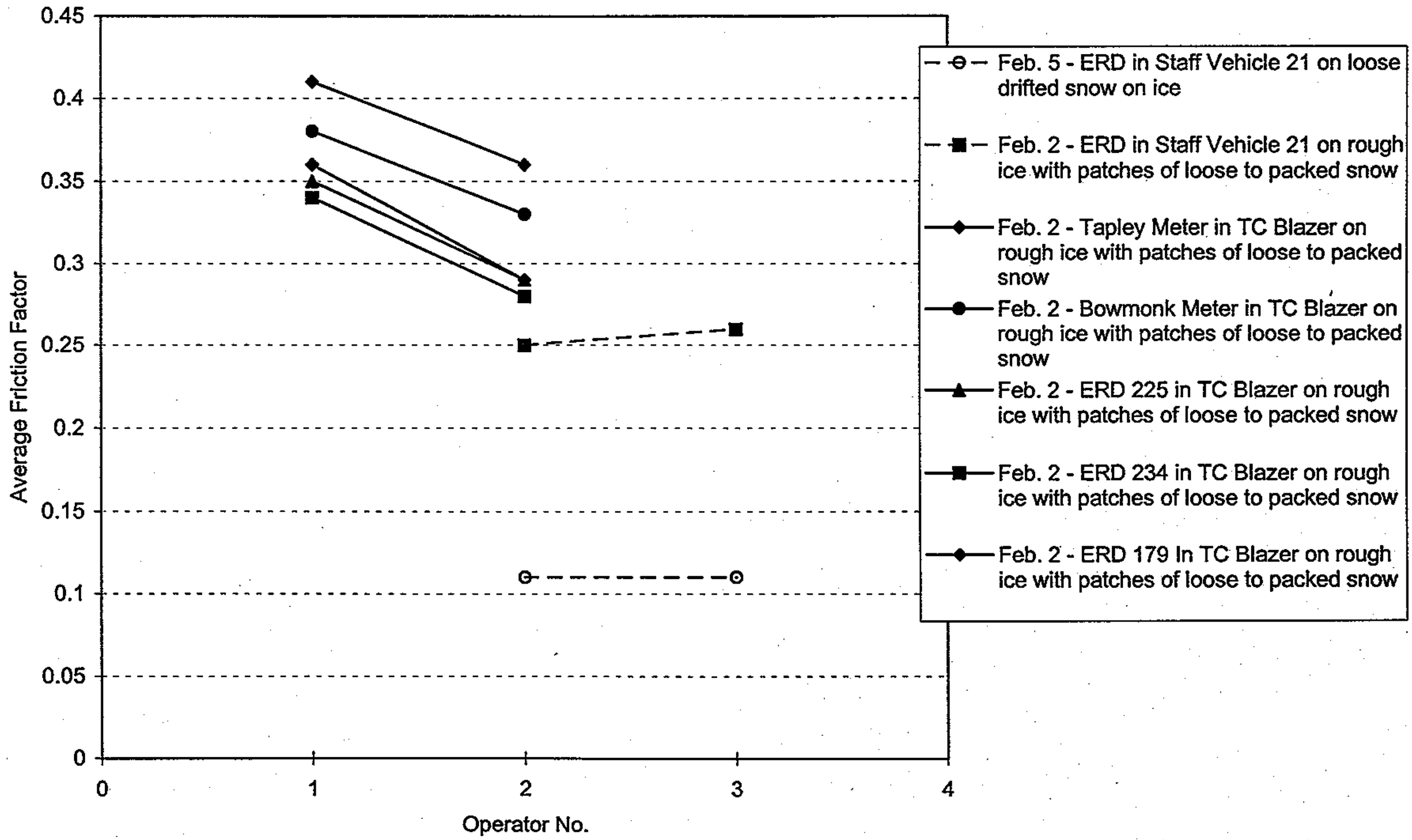


Figure 7.2

Decelerometer Study Results: Effect of Operator



8. THE EFFECT OF TIRE TREAD

8.1 Data Sources

Information from the following sources was analyzed:

(a) Tests 41.1 A&C, and 41.1 B&D - The IMAG was tested using the smooth and ribbed PIARC tire while the Griptester was tested using the ASTM tire and the Slushcutter tire. Comparative data were acquired with the ITTV during these tests.

(b) Tests 28.1 A&B – The TC SFT, the FAA SFT and the KJ Law RFT were each tested with several tires on "semi-compacted snow" and on "5-20 mm loose snow over compacted snow". These test results are plotted in Section 5.

8.2 Results

8.2.1 Tests 41.1 A&C, and 41.1 B&D

The results for "compacted snow, ice and loose snow" (test 41.1 A&C) and "ice" (test 41.1 B&D) are plotted in Appendix H. The observed trends are summarized below:

- Results on "Ice":

(a) IMAG - On average, higher friction was measured with the ribbed PIARC tire than for the smooth one. However, the friction data for the two tires are quite variable, and as a result, this conclusion can not be drawn with a high degree of confidence.

(b) Griptester - On average, higher friction was measured with the Slushcutter tire than for the ASTM one. However, as for the IMAG data, the friction data for the two tires are quite variable, and as a result, this conclusion can not be drawn with a high degree of confidence.

(c) Comparison to the ITTV - the friction factors measured by the IMAG and the Griptester, using each of the two tires tested, were all higher than that for the ITTV.

- Results on "compacted snow, ice and loose snow":

(a) IMAG - Similar friction was measured with the ribbed PIARC tire and the smooth one, which indicates that this parameter does not affect the friction on this surface.

(b) Griptester - Higher friction was measured with the Slushcutter tire than for the ASTM one. However, the friction data for the two tires are quite variable, and as a result, this conclusion can not be drawn with a high degree of confidence.

(c) Comparison to the ITTV - the friction factors measured by the IMAG and the Griptester, using each of the two tires tested, were all higher than that for the ITTV.

8.2.2 Tests 28.1 A&B

Higher friction factors were measured for the ribbed tires on "semi-compacted snow" in all cases except for the tests done with the TC SFT'79 at 690 kPa inflation pressure at 65 km/h. In that case, the friction was similar for the ribbed and the smooth ASTM tires (Figures 5.1 and 5.2).

The results on "5-20 mm loose snow over compacted snow" (Figures 5.3 and 5.4) show higher friction for the ribbed tires in all cases except for the following ones (in which similar friction was measured for the ribbed and smooth tires):

- tests with the TC SFT'79 at 65 km/h using the ASTM tire at 210 kPa inflation pressure;
- tests with the TC SFT'79 at 40 km/h using the ASTM tire at 690 kPa inflation pressure;
- tests with the TC SFT'79 at 65 km/h using the ASTM tire at 690 kPa inflation pressure

Conclusion

Clear, consistent trends are not evident over the full range of conditions tested. More testing is required before definitive statements can be made.

9. THE EFFECT OF GROUND VEHICLE SPEED AND SLIP SPEED

9.1 Data Sources

Information from the following sources was analyzed:

- Parametric and high speed tests conducted with the IMAG (during which the ground speed and slip ratio were both varied) and with the TC SFT'79. The applicable tests for the IMAG were test 37.3 (on Feb. 6), test 39.1 (on Feb. 8), test 40.2 (on Feb. 9) and tests 42.1 & 42.2 on Feb. 11. High speed tests were conducted with the TC SFT'79 on Feb. 9 (test 40.2).

- Data collected during the comparative runs made during the program, which were conducted over a range of ground vehicle speeds from about 40 to 90 km/h.

9.2 Effect of Ground Vehicle Speed

Selected results from the comparative runs made during the program (i.e., item (b) above) are plotted in Appendix I. Results from the parametric and high speed tests (i.e., item (a) above) are plotted in Appendix J.

The results from both of these data sets are scattered. However, in general, they indicate that the friction is not strongly dependent on the ground vehicle speed over a range from about 40 to 90 km/h.

Effect of Slip Speed

Because the tests with the IMAG provided the largest range of slip speed variation (as the slip ratio and the ground speed were both varied), these results were plotted separately (Figure 9.1). The "High Speed Tests" done with the IMAG and TC SFT'79 (in which only the vehicle ground speed was varied) are plotted in Figure 9.2.

The range of slip speed variation for all tests was relatively small, which makes it difficult to draw general conclusions. The friction appears to be decreasing with increasing slip speed for the IMAG results on "rough ice" and "2-5 mm loose snow over compacted snow" (Figure 9.1). However, for all of the other tests, the relationship is scattered, and the friction does not appear to depend on the slip speed.

Figure 9.1

Effect of Slip Speed:
Tests Done by Varying the Slip Ratio and Vehicle Speed

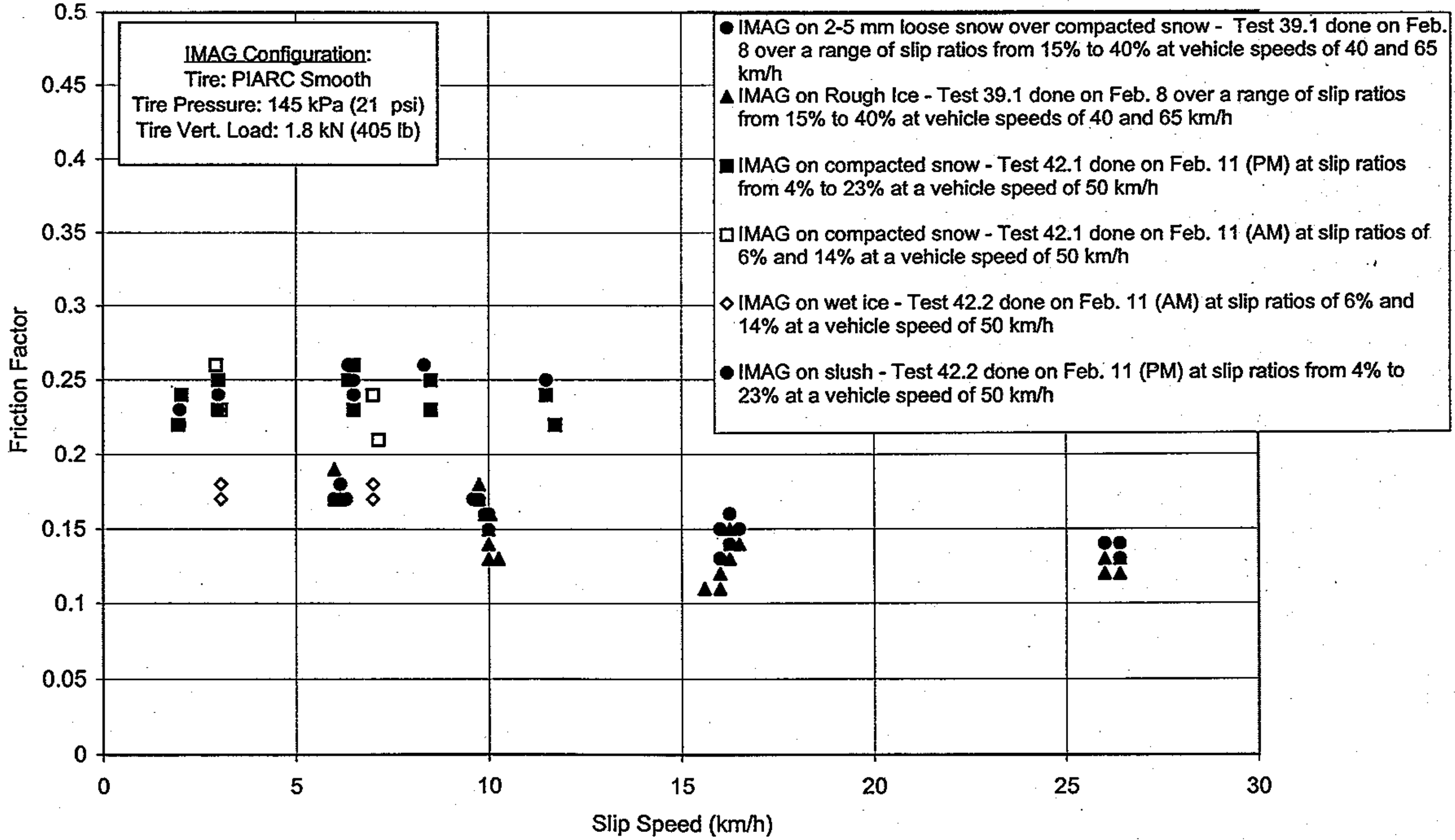
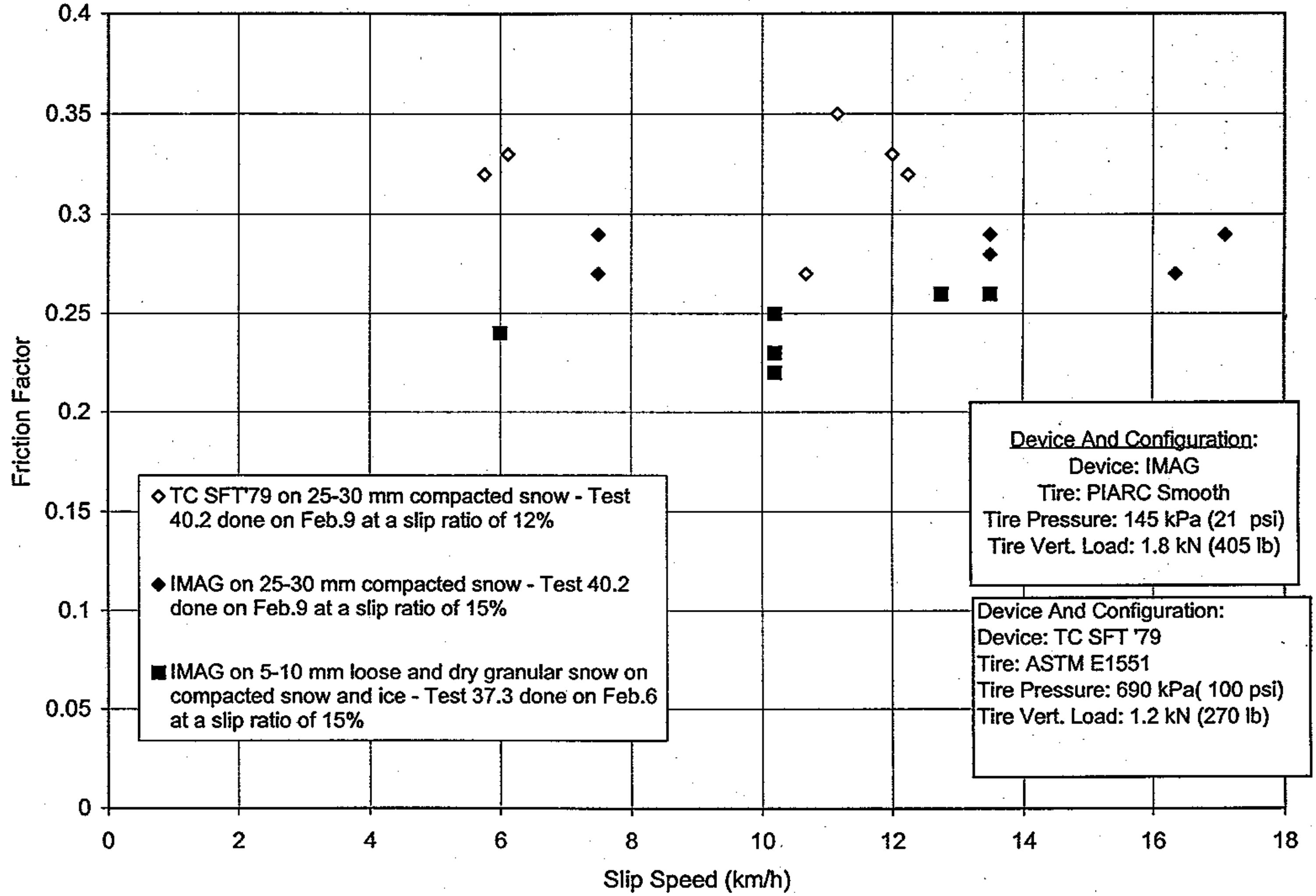


Figure 9.2
Effect of Slip Speed:
Tests Done by Varying the Vehicle Speed Only



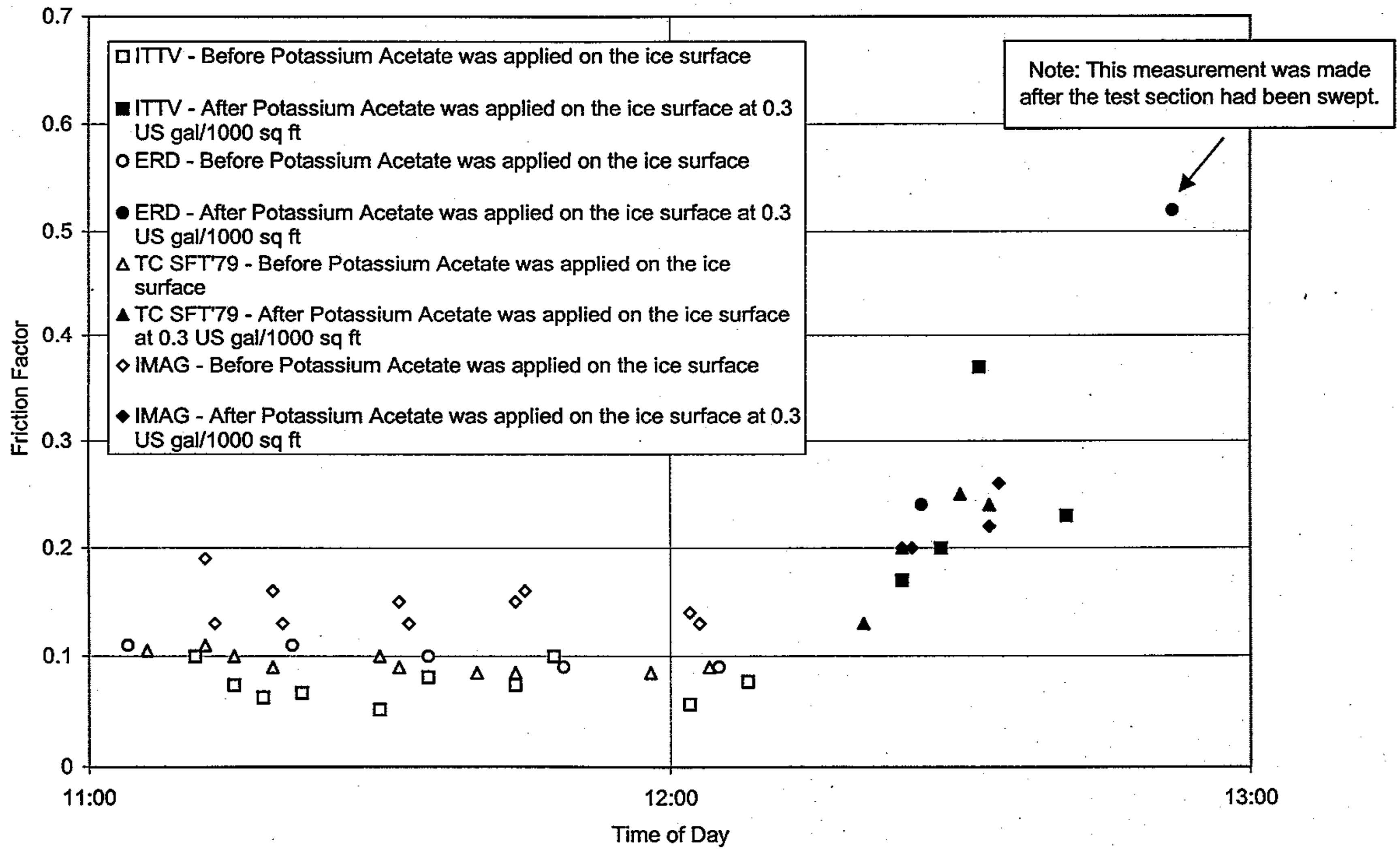
10. AN APPLICATION OF DE-ICING CHEMICAL ON BARE ICE

The results are plotted in Figure 10.1. They show that:

- Effect on Friction - each of the four devices tested (i.e., the ITTV, the ERD, the TC SFT'79, and the IMAG) recorded a rapid increase in friction when potassium acetate was applied on the bare ice surface.

- Correlation Between the Devices - Because the friction was changing rapidly, direct comparisons are not possible. However, each of the devices recorded friction factor magnitudes, and increases, that were generally similar.

Figue 10.1
Tests on Feb. 4 on Ice with Slush
with and without Potassium Acetate Applied on it



11. CONCLUSIONS AND RECOMMENDATIONS

11.1 Summary and Conclusions

The data collected by the ground vehicles during the 1998 North Bay Joint Winter Testing Program was analyzed. The work focused on: (a) reducing and presenting the data; and (b) conducting basic analyses. From this work, some trends are evident and the following conclusions can be made:

- Effect of vertical load – Tests with the ITTV showed clearly that the vertical load is a major parameter controlling the friction factor. Tests done with the ITTV on bare and dry pavement, on "rough ice" and on "loose snow over a packed snow base" showed that the friction factor reduced with increasing vertical load.

  The test data collected with the other ground vehicles generally support the above conclusion for the tests done on ice, compacted snow, and bare and dry pavement. No clear trend was observed for the tests done on "wet" ice, slush, and loose or fresh snow. This variation is believed to be related to the amount of contaminant drag that occurs.

  It should be noted that trends cannot be established for the other ground vehicle data with the same clarity as for the ITTV because the variation in vertical load among the other ground vehicles is relatively small, and also, because the results contain more scatter.

- Correlation among the devices – Typically, lower friction factors were measured with the ITTV and ERD than with the other devices, although there were a few exceptions to this "rule". This general trend is believed to be related to differences in vertical load as the ITTV and ERD conduct friction factor measurements at higher vertical loads than do the other ground vehicles.

  The correlation was greatly affected by whether or not the bare and dry test data were included because this effectively divided the data set into two data clusters that were widely separated in magnitude. As a result, the degree of fit (for a linear regression) was much better when the bare and dry data were included in the analyses. Correlations done using only the snow and ice-covered surfaces were much less consistent and reliable.

  The correlations developed based on all test speeds were similar to those obtained using only data collected at 65 km/h.

- Confidence levels and sampling requirements for the ERD – the ERD data appear to have lower confidence than do the data from the other devices. This is partly due to poorer sampling with the ERD, which does not measure friction continuously. About 15 individual ERD friction factor measurements would be required to produce a mean ERD value that has similar confidence to the mean friction factors recorded by the other devices.

- Tire study: Effect of Tire Tread – In some cases, higher friction was recorded using a ribbed tire compared to a smooth one. However, clear consistent trends are not evident over the full range of conditions tested as for other cases, similar friction was measured using ribbed and smooth tires. More investigation and testing is required before definitive statements can be made.

- Tire study : Effect of Inflation Pressure – The effect of inflation pressure depended upon the surface and whether or not the tire was treaded. Similar results were obtained at 40 and 65 km/h vehicle ground speed.

- Tire study : Effect of Ground Vehicle Device –The KJ Law RFT consistently recorded higher friction than did the other devices during this study. The reasons for this variation should be investigated further.

- The effect of temperature on friction – Clear consistent trends were not observed over the full range of tests. In some cases, the friction factors reduced with increasing surface temperature while, for others, the friction did not change significantly as the surface temperature was increased.

  This variation indicates that other processes and factors (than changes in temperature) were affecting the friction as well. Other important factors could include "polishing" of the surfaces during the tests, differences in the temperature variations that occurred, and texture differences for the various surfaces tested. More testing and investigation is required before definitive statements can be made.

- The decelerometer study – Higher friction factors were measured with the Bowmonk and Tapley meters than with the ERDs. The effect of the operator was variable. Different friction factors were measured between two different operators in one case, while for the other case, two different operators produced similar results.

- Effect of speed – The friction is not strongly related to the ground vehicle speed.

  The slip speed was also found to not have a strong effect, although in some cases the friction was observed to decrease with increasing slip speed. However, the results have considerable scatter, and in some cases, the friction did not appear related to the slip speed.

Recommendations

The test results indicate that the friction factor is most strongly related to the vertical load and contact pressure. An understanding of this relationship is required for the development of more general correlations between the devices.

Consequently, it is recommended that this be investigated further. The processes causing this relationship should be investigated in relation to the heat build-up that occurs, the strength of the surface, and its temperature and type.

REFERENCES

[1] Wambold, J.C., 1996, "Evaluation of Ground Test Friction Measuring Equipment on Runways and Taxiways under Winter Conditions", Transport Canada report TP 12866E.

[2] Federal Aviation Administration, 1997, Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces, FAA Advisory Circular 150/5320-12C.

[3] Yager, T., Stubbs, S., Howell, W., and Webb, G., 1993, NASA Evaluation of Type II Chemical Depositions, SAE technical paper 932582.

APPENDIX A

TEST LOG AND SUMMARY OF DEVICES TESTED

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

APPENDIX B

CORRELATION AMONG THE DEVICES:

- ALL TEST SPEEDS INCLUDED
- NO INTERPOLATED DATA INCLUDED FOR THE ERD OR ITTV

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

APPENDIX C

CORRELATIONS AMONG THE DEVICES:

- ALL TEST SPEEDS INCLUDED
- INTERPOLATED DATA INCLUDED FOR THE ERD AND ITTV

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

APPENDIX D

CORRELATION AMONG THE DEVICES:

- 65 KMH TEST SPEED
- NO INTERPOLATED DATA INCLUDED FOR THE ERD OR ITTV

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

APPENDIX E

CORRELATION AMONG THE DEVICES:

- 65 KMH TEST SPEED
- INTERPOLATED DATA INCLUDED FOR THE ERD AND ITTV

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

APPENDIX F

EFFECT OF VERTICAL LOAD ON THE FRICTION FACTORS MEASURED BY THE DEVICES

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

APPENDIX G

EFFECT OF TEMPERATURE

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

APPENDIX H

EFFECT OF TIRE TREAD

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

APPENDIX I

EFFECT OF GROUND VEHICLE SPEED: COMPARATIVE TESTS

(Not available in electronic format/
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APPENDIX J

EFFECT OF GROUND VEHICLE SPEED: HIGH SPEED TESTS

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