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MEASURING TIRES FOR HARMONIZED FRICTION MEASUREMENTS OF RUNWAY SURFACES AND PREDICTION OF AIRCRAFT WHEEL BRAKING

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February 1998

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16. Abstract

This project compares the various tires used to measure runway friction, for both summer and winter conditions. This is a necessary step in achieving harmonization of different friction measurement devices. Measurements with the various tires were compared to measurements with the NASA ITTV system using an aircraft tire. Subsequently, comparisons will be made with the NASA ITTV and actual aircraft braking. Ribbed treaded tires versus smooth treaded tires are discussed based on the literature and actual test results. The effects of natural rubber versus the ASTM compounds were also studied, and the FAA repeatability study found the DICO tire to be unsatisfactory for friction measurement on fixed and variable slip devices.

The general trends found from the field tests are as follows:

- Bare and dry: the AERO tire produces a lower reading than other tires.
- Wet: all devices produce similar values – lower friction than on dry pavement, and a speed effect that depends on the surface texture. The exception to this is that the ASFT gave a value higher than its dry value and gave about the same value as the dry measurements by force devices.
- Rough ice produces higher values than smooth ice.
- Coefficient of friction decreases with increased vertical load (tire contact pressure).

Based on the results of this study it is recommended that the ASTM smooth treaded test tire (E1551) be used with 207 kPa (30 psi) pressure for summer or surface maintenance testing and with 690 kPa (100 psi) pressure for winter contaminated surfaces.

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16. Résumé

L'objectif de ce projet est de comparer les divers types de pneus utilisés pour déterminer la glissance des chaussées aéronautiques, tant en conditions hivernales qu'estivales. Il s'agit d'une étape nécessaire à l'harmonisation des différents appareils pour mesurer la glissance des chaussées. Les données obtenues dans le cadre d'essais réalisés au moyen de différents pneus ont été comparées à celles produites par l'appareil ITTV (pour *Instrumented tire test vehicle*) de la NASA sur lequel ont été installés des pneus d'avion. Les données recueillies au moyen de l'appareil ITTV seront comparées à celles obtenues en situation réelle de freinage d'un avion. À la lumière de la documentation et des résultats d'essais en vraie grandeur, on tentera de déterminer s'il faut utiliser des pneus à rainures ou des pneus lisses. Les effets du caoutchouc naturel et des différents composés ASTM ont fait l'objet d'analyses. Une étude de reproductibilité, réalisée par la FAA, a permis de conclure que le pneu DICO se prêtait très mal aux mesures de la glissance réalisées à l'aide d'appareils d'essais à taux de glissement constant et variable.

Les essais réalisés sur le terrain ont permis de dégager les tendances suivantes :

- Sur chaussée sèche et dégagée : le coefficient de frottement du pneu AERO est inférieur à celui des autres pneus.
- Sur chaussée mouillée : tous les appareils de mesure ont produit des valeurs semblables, c'est-à-dire un coefficient de frottement inférieur à celui d'une chaussée sèche et un effet dû à la vitesse qui dépend de la texture de la piste. On a toutefois observé une exception : l'appareil ASFT a produit un indice de glissance supérieur à celui obtenu sur une chaussée sèche. Il a également produit un indice semblable à celui obtenu sur une chaussée sèche au moyen d'appareils de mesure de la force.
- Les essais réalisés sur des surfaces recouvertes de glace rugueuse ont produit des indices plus élevés que ceux obtenus lors d'essais réalisés sur des surfaces recouvertes de glace lisse.
- Le coefficient de frottement est inversement proportionnel à la charge verticale (pression de contact des pneus).

À la lumière des résultats de cette étude, on recommande l'utilisation de pneus d'essai lisses ASTM E1551, gonflés à une pression de 207 kPa (30 lb/po^2) pour les essais en période estivale ou pour les essais reliés à l'entretien de la chaussée. De plus, il est recommandé de gonfler ces pneus à 690 kPa (100 lb/po^2) pour mesurer les surfaces contaminées par des précipitations hivernales.

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SUMMARY

This project compares the various tires used to measure runway friction, for both summer and winter conditions. This is a necessary step in achieving harmonization of different friction measurement devices. Measurements with the various tires will be compared to measurements with the NASA ITTV system using an aircraft tire. Subsequently, comparisons will be made with the NASA ITTV and actual aircraft braking. The project uses the test data and results from the ongoing Joint Winter Runway Friction Measurement Program. Ribbed treaded tires versus smooth treaded tires are discussed based on the literature and actual test results. The effects of natural rubber versus the ASTM compounds for temperature and slip speed were studied, and a review of a study by the FAA found that the repeatability of the natural rubber tire (DICO tire) was unsatisfactory for friction measurement on fixed and variable slip devices.

The general trends found from the field tests are as follows:

- Bare and dry: the AERO tire produces a lower reading than other tires.
- Wet: all devices produce similar values, lower friction than on dry pavement, and a speed effect that depends on the surface texture. The exception to this is that the ASFT gave a value higher than its dry value and gave about the same value as the dry measurements by force devices.
- Rough ice produces higher values than smooth ice.
- Coefficient of friction decreases with increased vertical load (tire contact pressure).

On bare and dry or bare and wet pavements the AERO tire (natural rubber) produces lower friction values than the ASTM tire; however, the ribs on the AERO tire make it insensitive to the macrotexture. Thus, the ASTM smooth treaded tire is far superior in evaluating the surface condition for surface maintenance.

Under snow and ice conditions the performance of the tires is very nearly the same so that either tire could be used. However, due to the fact that a tire at 207 kPa (30 psi) is very close to V_{crit} (the critical hydroplaning speed) in slush, the 690 kPa (100 psi) pressure appears to be preferable. The effects of braking rate and contact pressure have by far the most significant effect on friction values. Because of the effects of tire contact pressure, friction force values increase by decreasing the contact area or increasing the load on the tire. The 1998 test data indicates that the ASTM 1551 ribbed 100 psi tire, the AERO 100 psi tire, and the ASTM 1551 ribbed 30 psi tire all give higher frictional values than the ASTM smooth 100 psi or 30 psi tires when mounted on the KJ Law Runway Friction Tester on snow surfaces. These tests further support the effect of contact pressure on snow surfaces and the need for further study of the effect for each type tire used to measure winter friction.

Based on the results of this study the following actions are recommended:

1. The ASTM smooth treaded test tire should be used with 207 kPa (30 psi) pressure for summer or surface maintenance testing.
2. A high contact pressure tire should be used for winter measurements, especially for torque measuring devices on loose snow. On packed snow and ice surfaces any tire will give satisfactory correlation. However, if a single tire is to be used, a high contact pressure tire is recommended.
3. Tests should be conducted to determine the braking rate on aircraft tires using anti skid systems. Since variable slip testers have an advantage in that they can adjust their braking rate, tests should be made with different rates to determine an equivalent rate for fixed slip tests. Tire testing should be performed in the

laboratory, where possible, to reduce the amount of field-testing required. Limited field tests were performed in 1998 with the IMAG and RUNAR, and the limited results further support the need for these tests in the coming year.

4. Since braking or wrap-up rate and loading or contact pressure will vary with tire type (stiffness and pressure), it is recommended that a new tester similar to the variable slip ITTV be constructed that can test all of the ground vehicle tire types as well as some aircraft tires.
5. Load tests should be performed on each of the tires used to measure winter friction to determine each tire's contact pressure effect on the friction forces on ice and snow.

SOMMAIRE

L’objectif de ce projet est de comparer les divers types de pneus utilisés pour déterminer la glissance des chaussées aéronautiques, tant en conditions hivernales qu’estivales. Il s’agit d’une étape nécessaire à l’harmonisation des différents appareils employés pour mesurer la glissance des chaussées. Les données obtenues dans le cadre d’essais réalisés au moyen de différents pneus ont été comparées à celles produites par l’appareil ITTV (pour *Instrumented tire test vehicle*) de la NASA sur lequel ont été installés des pneus d’avion. Les données recueillies au moyen de l’appareil ITTV seront comparées à celles obtenues en situation réelle de freinage d’un avion. Le projet utilise les données et les résultats d’essais recueillis lors du Programme conjoint de recherche sur la glissance des chaussées aéronautiques l’hiver, un programme de longue durée. À la lumière de la documentation et des résultats d’essais en vraie grandeur, on tentera de déterminer s’il faut utiliser des pneus à rainures ou des pneus lisses. Les effets du caoutchouc naturel et des différents composés ASTM sur la température et la vitesse de glissement ont fait l’objet d’analyses. Une étude de reproductibilité, réalisée par la FAA, a permis de conclure que le pneu DICO se prêtait très mal aux activités de mesure de la glissance réalisées à l’aide d’appareils d’essais à taux de glissement constant et variable.

Les essais réalisés sur le terrain ont permis de dégager les tendances suivantes :

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- Le coefficient de frottement est inversement proportionnel à la charge verticale (pression de contact des pneus).

Sur les chaussées sèches et dégagées, ou sur celles qui sont mouillées et dégagées, le pneu AERO (en caoutchouc naturel) produit des indices de frottement inférieurs à ceux du pneu de l’ASTM. Toutefois, les nervures du pneu AERO rendent ce dernier insensible aux macrotextures. Ainsi, le pneu lisse de l’ASTM se prête mieux à l’évaluation des besoins d’entretien de la surface de la piste.

Lorsque la chaussée est glacée ou enneigée, la performance des différents pneus est sensiblement la même, de sorte que n’importe quel d’entre eux pourrait être utilisé. Cependant, étant donné qu’un pneu gonflé à une pression de 207 kPa (30 lb/po^2) est au seuil de la valeur V_{crit} (vitesse critique d’aquaplanage) dans la neige mouillée, il semble préférable de le gonfler à 690 kPa (100 lb/po^2). Les effets liés à la force du freinage et à la pression de contact sont sans contredit les facteurs qui influencent le plus les indices de glissance. À cause des effets de la pression de contact des pneus, l’indice de glissance augmente lorsque la surface de contact du pneu diminue ou que la charge verticale exercée sur le pneu augmente. Les données expérimentales obtenues en 1998 démontrent que lorsqu’ils sont installés sur l’appareil d’essai KJ Law et utilisés sur une chaussée enneigée, le pneu nervuré ASTM 1551, gonflé à 100 lb/po^2, le pneu AERO, gonflé à 100 lb/po^2 et le pneu ASTM 1551 gonflé à 30 lb/po^2 ont tous des indices de glissance plus élevés que le pneu lisse ASTM à 100 lb/po^2 ou à 30 lb/po^2. Ces

essais confirment les effets de la pression de contact sur les surfaces enneigées et témoignent de la nécessité de mener une étude plus approfondie des effets de chaque type de pneu utilisé pour mesurer la glissance des chaussées en conditions hivernales.

À la lumière des résultats de cette étude, on recommande les actions suivantes :

1. Gonfler les pneus d'essai lisses ASTM à une pression de 207 kPa (30 lb/po^2) pour les essais en période estivale ou pendant les essais reliés à l'entretien de la chaussée.
2. Utiliser un pneu à grande surface de contact pour les essais réalisés en période hivernale, particulièrement lorsque le pneu est installé sur un dispositif de mesure de couple et qu'il est utilisé dans de la neige poudreuse. Utilisés sur une surface glacée ou enneigée, les différents pneus présentent tous une corrélation satisfaisante. Toutefois, si un seul pneu est utilisé, il est recommandé d'utiliser une grande surface de contact.
3. Réaliser des essais pour déterminer la capacité de freinage des pneus montés sur des avions équipés d'un système antidérapant. Étant donné que les appareils de mesure à taux de glissement variable sont avantagés du fait que la force de freinage peut être réglée, il conviendrait de réaliser des essais à différentes valeurs de freinage afin d'établir une équivalence pour les appareils à taux de glissement constant. La mise à l'essai des pneus devrait être réalisée en laboratoire, si ce dernier le permet, afin de réduire le nombre d'essais devant être menés sur le terrain. Un certain nombre d'essais sur le terrain ont été réalisés en 1998 au moyen des appareils IMAG et RUNAR. Les résultats obtenus confirment la nécessité de mener des essais plus poussés au cours de l'année qui s'annonce.
4. Étant donné que le comportement au freinage et le chargement (pression de contact) varieront en fonction du type de pneu utilisé (rigidité et pression), il est recommandé de mettre au point un nouvel appareil d'essai, semblable à l'ITTV, à taux de glissement variable, qui serait capable de tester l'ensemble des pneus pour véhicules au sol, ainsi que des pneus d'avion.
5. Chaque pneu servant à mesurer la glissance de la chaussée en période hivernale devrait être soumis à des essais en charge pour déterminer les effets de la pression de contact sur les indices de glissance des surfaces glacées et enneigées.

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1.0 INTRODUCTION

Measuring the capability of the runway surface to provide aircraft braking action is fundamental to airport-related aviation safety. Especially during winter conditions, the runway may have contaminants of varying nature and quality with reduced friction capabilities. Also in the wintertime, the operational window for aircraft movements can change so rapidly and frequently that a measuring service of surface friction run by airport ground staff is warranted.

The measured results of the service have had serious deficiencies, which have been acknowledged by experts worldwide:

1) The equipment used and procedures followed in this measuring service report non-calibrated values with respect to a common unit of measure of surface friction. One number from one type of device at one airport does not mean the same as a number from another device operated at another airport. In general, a simple transformation of measured values of one device to another is not possible.

2) No satisfactory method or techniques have been engineered to predict the wheel braking action of aircraft using ground vehicle measured friction information. Only limited indirect correlation of selected ground friction measuring devices with a few aircraft types has been achieved to date. A technique that has been used is based on a grading scale with respect to experienced braking action quality created by panels of pilots and the corresponding measured friction values of the device used.

Transport Canada/NASA/FAA Joint Winter Runway Friction Measurement Program

The five year government/industry study, called the Joint Winter Runway Friction Measurement Program (JWRFMP), is being led by NASA and Transport Canada with support from the Federal Aviation Administration (FAA) and National Research Council Canada (NRC). Also participating are organizations and equipment manufactures from Europe and several Scandinavian countries. The primary objective is to perform instrumented aircraft and ground vehicle tests aimed at improving the safety of aircraft ground operations. Flight crew recognition of less than acceptable reported runway friction conditions prior to the “go/no go” or the “land/go around” decision point is one of the near-term program goals. With these goals in mind related studies are being conducted to study contaminant drag, effects of runway treatments on friction, and harmonization of ground vehicle friction measurement. This will enable the report of a unified value worldwide, and then the use of that index to predict aircraft braking performance.

A variety of instrumented test aircraft and ground friction measurement vehicles have been used at several different test sites in North Bay, Ontario, Canada. An instrumented NASA Langley Boeing 737 Transport and an NRC Dassault Falcon-20 aircraft were used during January and March of 1996 at the Jack Garland Airport in North Bay, Ontario, Canada. Seven ground friction measuring devices from six different countries resulted in aircraft and/or ground friction measurements for over 30 winter runway conditions including ice, loose snow, compacted snow, and ice and snow with sand and/or urea. In the January-March 1997 winter season, similar tests were performed with the FAA Boeing 727 transport, the NRC Falcon-20 and a DeHavilland Dash 8 aircraft together with 13 ground friction measuring devices. Data obtained during these investigations quantifies the severe reduction in runway friction, particularly in the 0°C range. The 1998 testing was conducted at North Bay and at the new airport in Oslo, Norway. The testing dealt with special tests to verify the International Runway Friction Index (IRFI) on packed snow and ice. One special test of interest was on the effect of load.

Future testing will involve the present aircraft and other aircraft types such as the new NASA 757, wide-body aircraft, and a military cargo aircraft along with new or improved ground testing equipment. Dissemination, acceptance and implementation of the test results by the aviation community is expected through the guidance and assistance of several organizations including the International Civil Aviation Organization (ICAO), the American Society for Testing and Materials (ASTM), the Joint Aviation Authority (JAA), the International Federation of Air Line Pilots (IFALPA), the Air Line Pilots Association (ALPA), the Air Transport Association (ATA) and Airports Council International (ACI).

This is the first extensive set of runway friction data ever collected at temperatures at and below 0°C. The data is being added to NASA's tire friction database and disseminated to the aviation community. Through the subcommittee E17 of ASTM, work is ongoing to develop a harmonized friction index (International Runway Friction Index or IRFI). The IRFI is anticipated to become a standard criterion used by airports to access the condition of a runway under winter conditions. Safe take off and landing decisions will then be facilitated by use of a standard index worldwide.

The JWRFMP has objectives set at resolving major elements of the two deficiencies given above. After three years of testing in the program with the participation of experts from several countries, an approach is emerging to perform the developments necessary for achieving harmonized friction measurements. This will lead to a means of predicting how aircraft wheel braking may experience the latest reported runway friction properties.

This approach was generally introduced by several speakers at the International Meeting on Aircraft Performance on Contaminated Runways held in Montreal, Quebec, Canada, on October 20-22, 1996, and is recognized by many as the most viable. The approach is based on concepts and elements of the proposed International Friction Index proposed by the World Road Association (PIARC) and the use of inexpensive digital computing to handle more detailed and numerous bits of information necessary to reach the objectives of harmonization and better aircraft wheel braking predictions.

The results reported here will provide comparisons the different tires used to measure runway friction, for both summer and winter conditions. This is a necessary step in achieving harmonization of different friction measurement devices. Also it will be necessary to compare the results of these tires to the aircraft tire friction. First, the results from the NASA Integrated Tire Test Vehicle (ITTV) with an aircraft tire will be compared to the different ground friction measuring tires and then comparisons will be made with actual aircraft braking. The elements compared include the effects of temperature, rubber compound, tire pressure, tire contact pressure, slip speed and vehicle speed. The project will require use of the test data and results from the ongoing JWRFMP and NASA annual friction workshop. The results of this study will be required for the development of the IRFI, in particular the harmonizing of the different friction measuring devices.

2.0 PROGRAM OBJECTIVE

In cooperation with other researchers from Transport Canada, NASA, and FAA, the objective is to establish the best tire for use in the development of the International Runway Friction Index (IRFI).

2.1 Program Sub-Objectives

- Compile a database containing all test data available of winter and summer runway friction measurement using different tires and aircraft tire braking performance.
- Correlate the data to determine the best tire performance to measure runway friction and to predict aircraft tire friction for use as the “True” value in the development of IRFI.

3.0 DETAILED STATEMENT OF WORK

The following tasks are divided into two principal stages to form parts of the work plan as follows:

3.1 Stage 1- Friction Tire Performance Data

This task is aimed at developing and documenting a database needed to correlate the different tires used to measure runway friction. The data primarily came from the two years of testing at North Bay and the tests at NASA Wallops Facility in Virginia. Other sources of data reviewed were from past Norway, Sweden and NASA winter testing; however, this data did not include direct comparisons of the different tires. The past data from other sources includes different tires, but on different equipment and therefore could not be used in comparisons since it would not be possible to separate the effects of the tire and the equipment. While it is realized that some tire manufacturers have highly variable tires, the database represents tires used in the different tests and the average of these tests will have to be considered as representative of those tires.

3.1.1 Tires

The database includes the following tires:

ASTM E501 (ribbed treaded)
ASTM E524 (smooth treaded tire)
ASTM E1551 (smooth treaded tire)
Special 3 ribbed treaded ASTM E1551
GripTester ASTM tire
GripTester slush natural rubber tire
PIARC smooth treaded tire
Trelleborg High Pressure, Natural Rubber
Standard Truck tires such as used on the ERD vehicles
Aircraft Tires- mainly Falcon 20

The summary of the data is given in Section 4.

3.1.2 Tire Properties

The database includes the following tire properties:

Rubber Compound
Tire Size
Hardness
Tread Design
Inflation Pressure
Vertical Load
Aspect Ratio
Gross Contact Pressure
Net Contact Pressure
Tire wear/remaining tread depth if reported

The data is given in Section 4.

3.1.3 Surface Conditions

The database includes the following surface conditions:

Bare and Dry above Freezing
Bare and Dry below Freezing
Bare and Wet
Wet Ice (IB near 0°C)
Dry Ice (IB)

Slush
Loose Snow (SD)
Wet Compacted Snow (SB with high % water)
Dry Compacted Snow (SB)

The data includes depth, temperature, texture on bare pavement, vehicle speed and slip ratio.

3.2 Stage 2 – Analysis

The analysis involves the correlation of the different tire types, in particular the friction measuring tires to establish which properties of the tires are important for the different surface conditions. A list of the “best properties” that produce the best correlation for each of the surface conditions will be compiled. With this list, the best tire(s) will be recommended for use in the harmonization of runway friction with ground equipment. Thus, the signatures will be related to these tires or “True curves” and final correlation for each tire to the “True curve” will be established in the development of IRFI. As in any study, the factors other than tire effects may influence the analysis. Everything that can be done to minimize other non-tire effects will be attempted. To hold all other variables constant would be almost impossible and would require a very expensive laboratory experiment that is well beyond the scope of this study.

4.0 DISCUSSION

The discussion below is divided into seven sections. The discussions are based on a literature review and the data from the database: Section 4.1 debates ribbed tire versus smooth treaded tire. Section 4.2 is about natural versus compounded artificial rubber; Section 4.3 discusses the database. Section 4.4 covers hydroplaning speeds. Section 4.5 is about tire foot print data. Section 4.6 is on special tire tests, and Section 4.7 is on load/contact pressure.

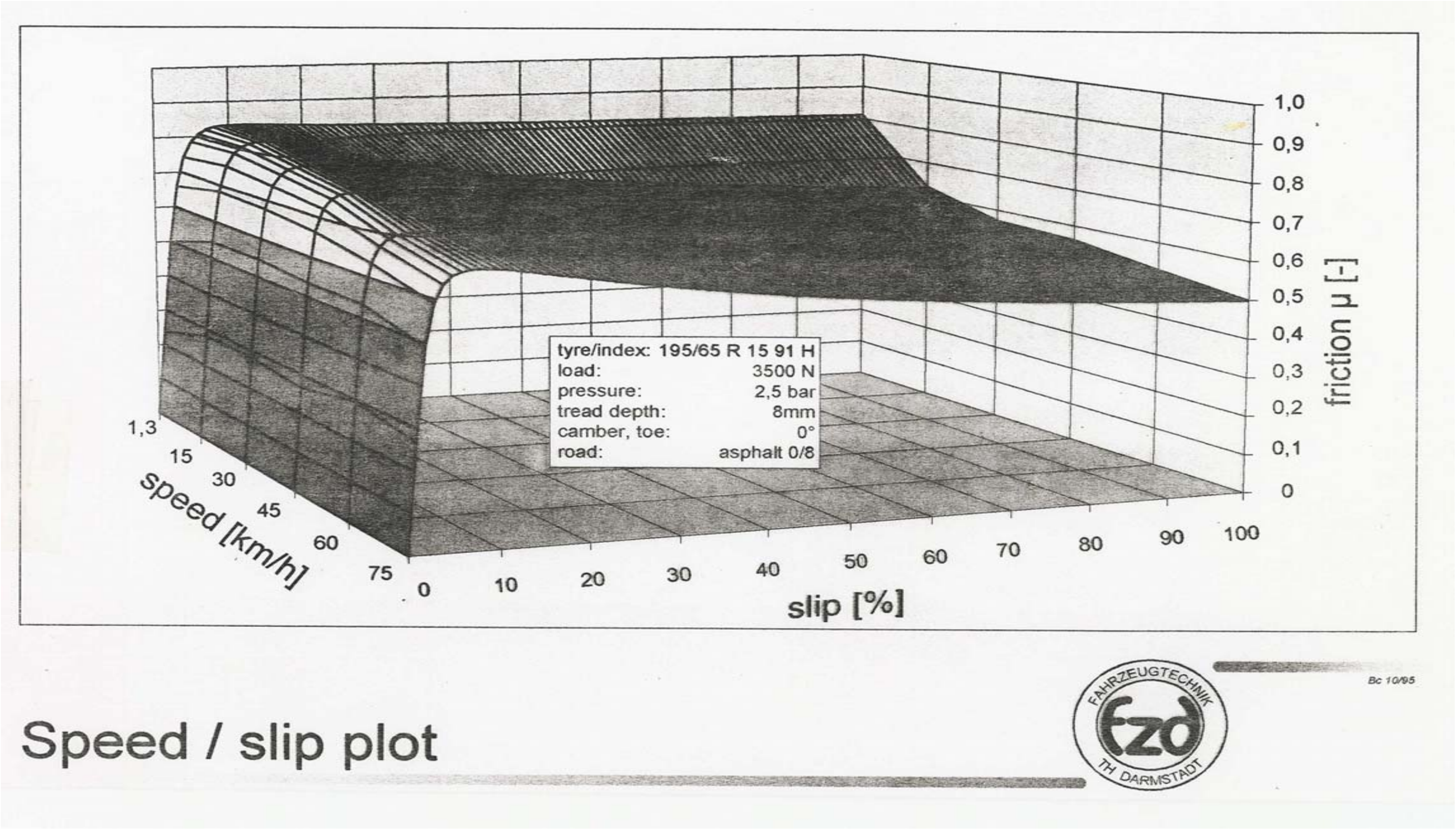
4.1 Ribbed Treaded Tire verses Smooth Treaded Tire

There are many papers on this subject in the literature; however, the most recent ones are in ASTM STP 929 [1, 2] and 1164 [3] and from a Transportation Research Board (TRB) session [4-7] on the subject. The reader is referred to the references list at the end of this report for some of the more relevant ones.

In his doctorate thesis under preparation at the University of Darmstadt, Thomas Bachmann [8] shows a plot of the effect of speed and slip on the frictional characteristics of a tire on the same surface, see Figure 1. The figure clearly shows how the peak value decreases with speed while the slip increases. The figure also shows how the friction decreases with speed. This is due to the reduced time to drain the water from the tire-pavement interface and thus there is less total contact with the pavement.

Williams [3] presented a chart to show the direction that various parameters have on the peak friction and the slip speed at which the peak occurs. Figure 2 is a copy of that plot and shows several things. First, it shows that improved polymers increase peak friction while reducing the percent slip where the peak friction occurs. Second, rapid brake application reduces the peak friction and decreases where the percent slip (at peak friction) occurs. Next, increased stiffness has little effect on the peak friction, but decreases where the percent slip (at peak friction) occurs. Then, increasing vehicle speed reduces peak friction with a slight increase in the percent slip (at peak friction). And lastly, improved surface texture increases the peak friction and increases the percent slip (at peak friction). To this figure, the effect of ice and snow has been added based on North Bay tests showing that snow and ice reduce the peak friction and increases the percent slip (at peak friction).

Henry [2] reports of testing on a pavement section before and after grooving (see Figure 3). The results clearly show that a ribbed tire can not sense any difference, while the smooth treaded tire makes a significant increase. Figure 4 is from papers by Wambold and Henry [6, 9] that shows the ribbed treaded tire is not very sensitive to macrotexture, whereas the smooth treaded tire is very sensitive. In fact test data shows that, when regressions are made, the friction from a ribbed treaded tire is almost entirely a function of microtexture and that the smooth treaded tire friction depends almost equally upon macrotexture and microtexture. Similar results have also been reported by other authors [5, 7, 10] (71st TRB annual meeting). The main reason for the independence on macrotexture is that the ribbed treaded tire has extensive water drainage capability provided by its ribs. As the ribbed tire wears, it changes its ability to pass water and snow; therefore, as the tread wears, it becomes more and more sensitive to macrotexture. Thus, one has to be very careful not to wear a ribbed treaded tire or the frictional characteristics will change. This is not the case with a smooth treaded tire where there are no ribs to wear. One other report addressing smooth versus ribbed treaded tires is given in [11].



tyre/index:	195/65 R 15 91 H
load:	3500 N
pressure:	2,5 bar
tread depth:	8mm
camber, toe:	0°
road:	asphalt 0/8

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Speed / slip plot

Figure 1 Speed/slip plot from Thomas Bachmann’s thesis [8]

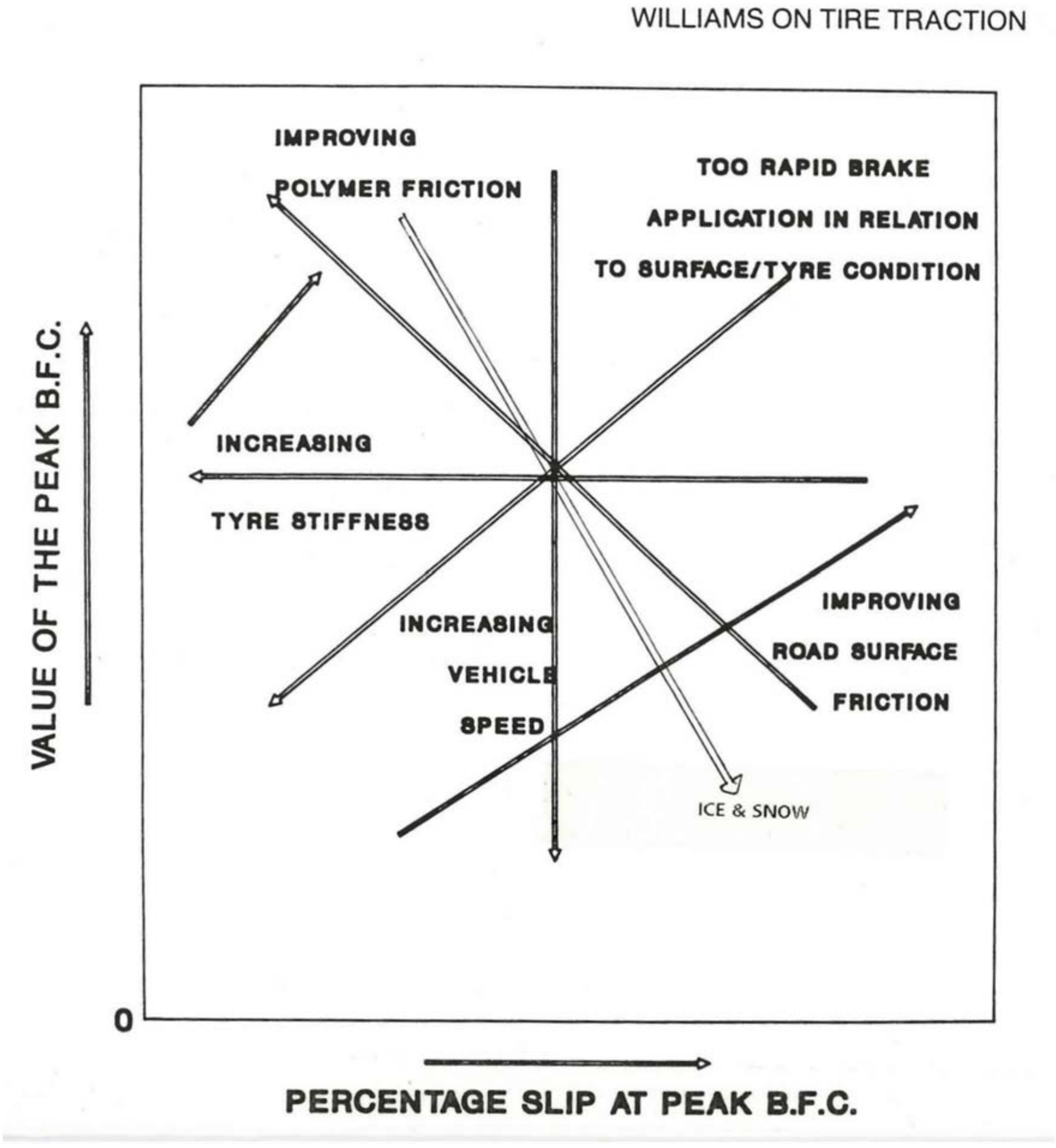

Figure 2 The influence of tire/pavement variables on friction [3]

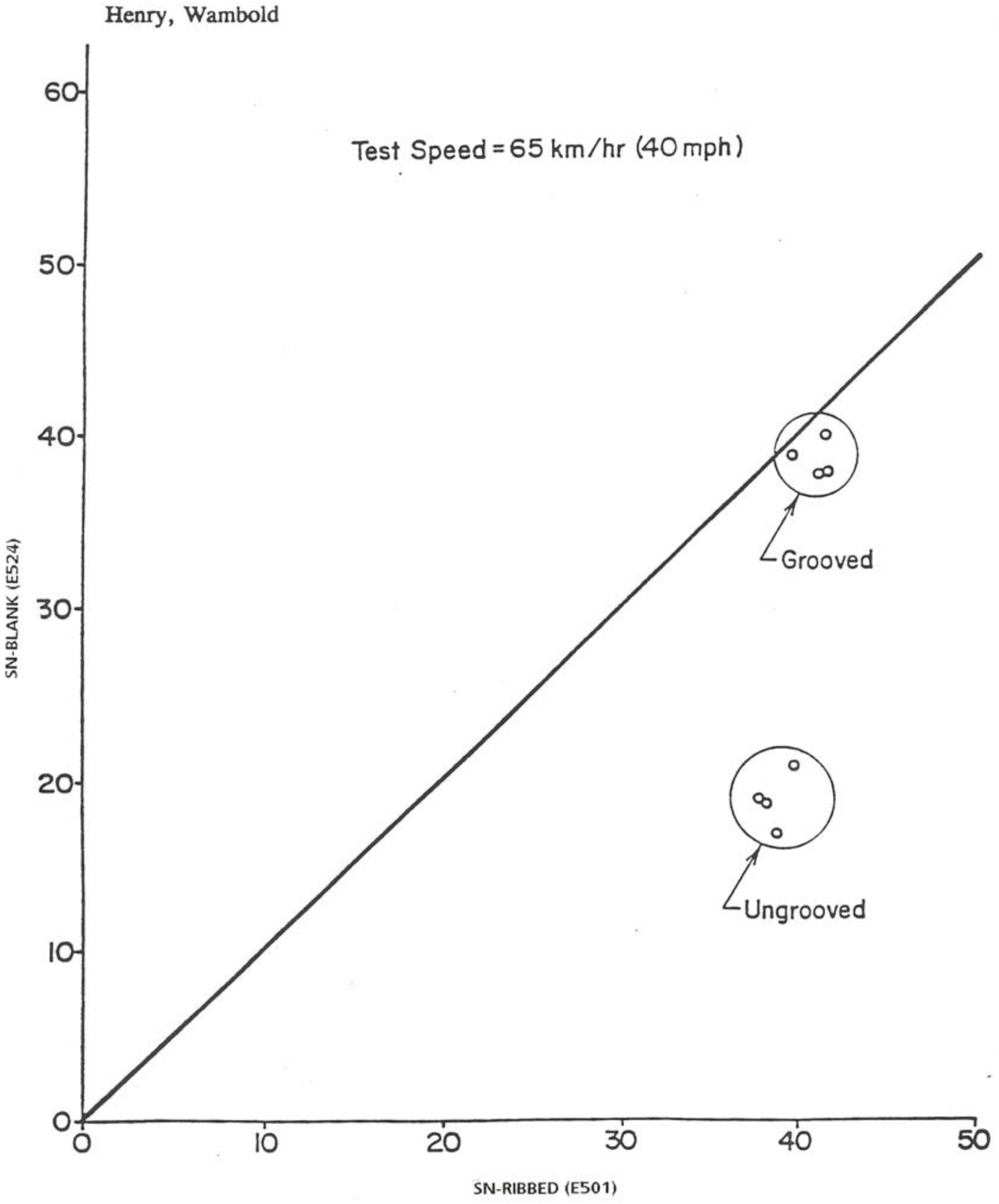

Figure 3 Skid numbers of grooved and ungrooved PCC pavements [4, 6]

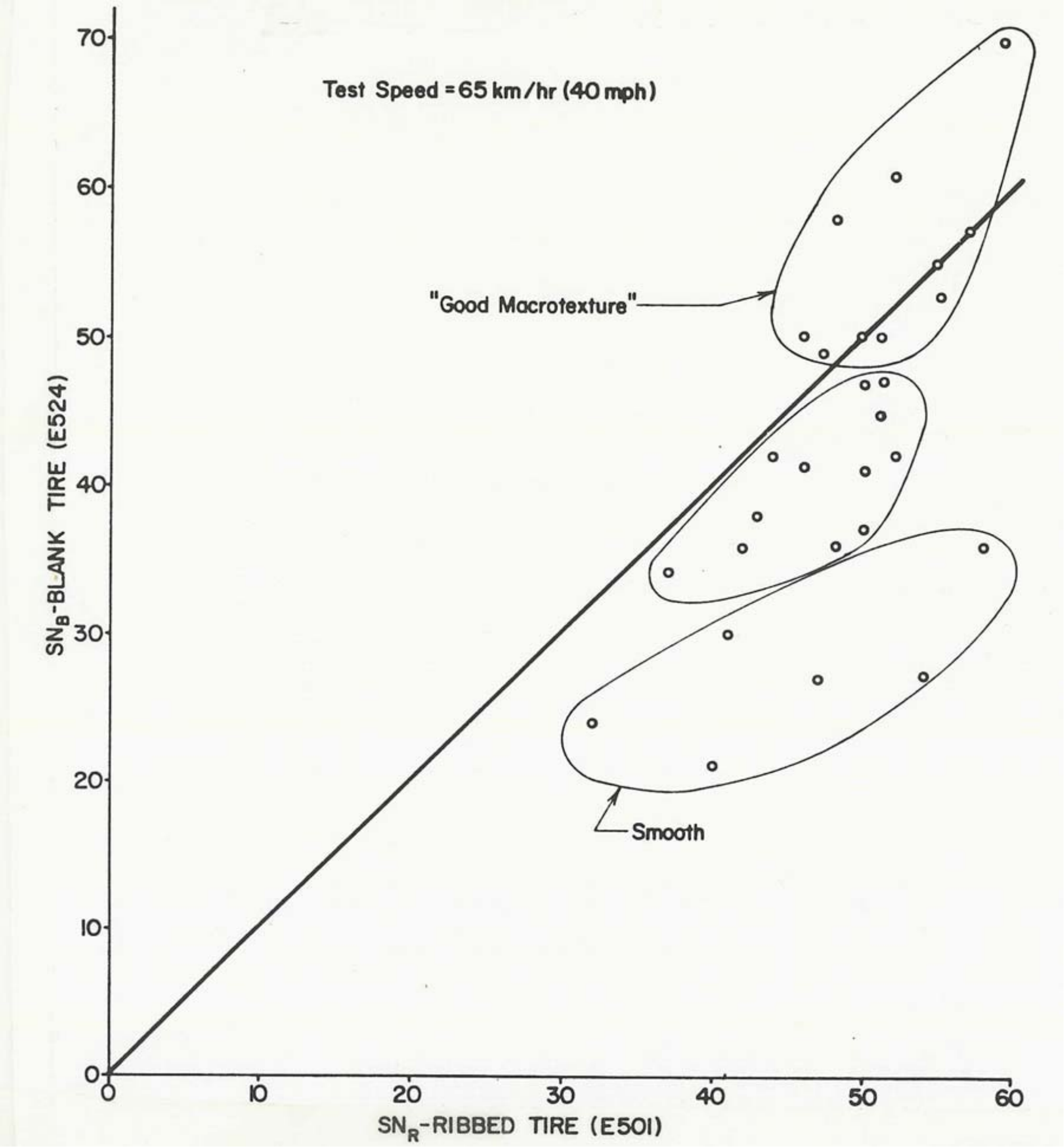

Figure 4 Skid numbers for sites in Virginia [4, 6]

4.2 Natural Rubber verses ASTM Compounds

4.2.1 Temperature

It has been known for some time and reported that natural rubber has temperature dependence. In fact the ASTM compound was formulated by tire experts to provide a constant friction with temperature in order to minimize this dependence. Figure 5 shows the data obtained at North Bay with a Surface Friction tester where the same device was used with two tires. Each time the temperature dropped 5°C, a measurement was made with one tire and then the tire was changed and the test repeated. All tests were run on a bare and dry surface on a day when the temperature ranged from +5°C to -20°C during the same day. There is a question that there may have been some ice forming at the -2°C point. Some drop is indeed correct. It is suggested that this test be repeated and perhaps run in laboratory where any ice can be avoided as the temperature is dropped below freezing. Even if the -2°C point is removed there is still a large difference in the natural rubber tire as the temperature drops below freezing.

4.2.2 Repeatability

The FAA ran repeatability tests of the ASTM E1551, DICO and Dunlop tires (see Morrow [12]). The DICO (AERO) and Dunlop tires are made of natural rubber. The results reported by Morrow showed the DICO tire was not repeatable, except for the Mu Meter, and that the Dunlop tire did not meet the performance criteria, see Table 1. This work led the FAA to adopt the ASTM E1551 tire. At present there is no standard for the DICO (AERO) tire, even though the ASTM compound has been in use for some time with the E505 and E524 tires with no problems. However, the E1551 tires have been found periodically to not provide the same measurements. As a result, sampling is used to eliminate tires that measure out of specification (see three T.C. reports [13, 14, 15] on wear and hardness testing and its SFT and GripTester calibration program). A task group of ASTM E-17.24 on tires is looking into this problem. The problems with the DICO tire cannot be addressed since there is no standard to follow at this time.

Table 1 Percent of performance meet (from Table 16 by Morrow [12])

Device	ASTM Tire	DICO Tire	Dunlop Tire
Law RFT	98	36	--
Saab SFT	98	15	39
Skiddometer BV-11	98	36	41
Mu Meter	47	97	22

Other reports of interest on studies of tires for runway friction measurement are given in [16, 17, 18] and on studies of tire tread for aircraft are given in references [18, 19, 20].

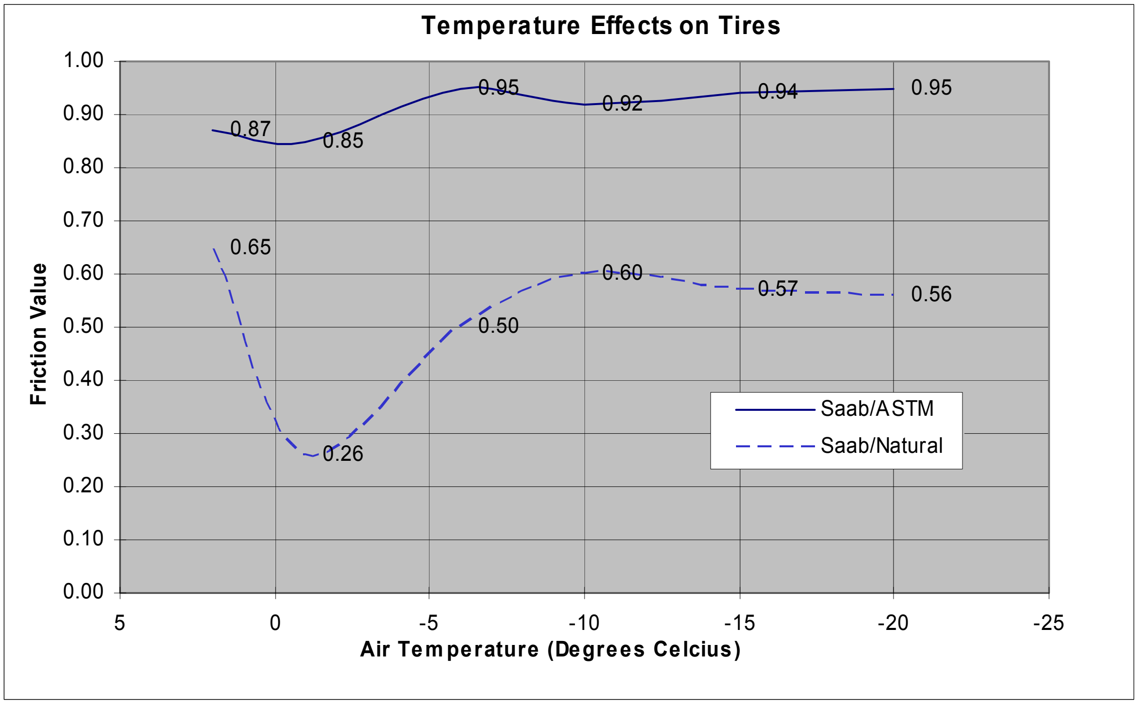

Figure 5 Temperature effects of tire rubber on friction

4.3 Database

Table 2 is the summary of the tire database, which is discussed below in separate parts by surface type.

4.3.1 Bare and Dry or Wet

Measurements on bare and dry pavement show the following (see Figure 6):

- Bare and dry shows little speed effect.
- Force devices are generally in the range of 0.9 with peaks in the 1.0 to 1.1 range.
- Torque devices generally measure friction levels at:
  0.9 with the ASTM tire,
  0.7 with the AERO tire and
  0.75 with the PIARC tire (by IMAG).

Table 2 Tire friction data

Target	mm			%			Accel.		Force:						Torque:			ASTM						
										slush	ASTM	FAA			FAA	ASTM	AERO	RIB	AERO	ASTM	AERO	ASTM		
Speed	depth	C^2	Spk	Slip	F60		ERD		RRpk	GT081	GT103	RFT	ITTV		SFT	TC-SFT1	TC-SFT1	TC-_SFT2	TC-SFT3	TC-SFT3	ASFT	ASFT	IMG	Comments
30		23.6	9.5	31.7	0.72		0.71		1.12	0.89	0.96				0.96	0.96		0.87	0.72		0.74			Bare & Dry
40		5.4	11.8	29.5	0.58		0.48		1.00	0.91	0.85	1.06			0.92			0.85	0.66					Bare & Dry
65		5.9	19.9	30.6	0.70				1.07	0.88	0.92	1.04			0.93	0.93		0.85	0.67		0.70		0.74	Bare & Dry
90		38.2	24.7	27.4	0.89		0.50		1 .15	0.86	0.91				0.93	0.90		0.80	0.69		0.70		0.76	Bare & Dry
40		7.0	10.6	26.5	0.61				0.94	0.75						0.92		0.87	0.68		0.68		0.76	Bare & Wet
65		5.0	19.5	30.0	0.78		0.62		1.05	0.65	0.67					0.82		0.90	0.68		0.67		0.71	Bare & Wet
90		11.7	27.0	30.0	0.85				1.09		0.67					0.78					0.64			Bare & Wet
120		3.6	34.5	28.8	0.86				1.07		0.62					0.75								Bare & Wet
30		5.3	14.8	49.3	0.17		0.23		0.25	0.30	0.29	0.26			0.17	0.17		0.22	0.23				0.15	Misc Snow
40		41.9	15.2	38.0	0.25		0.25		0.26	0.27	0.31	0.28			0.16	0.18		0.17	0.20		0.48			Misc Snow
50		6.2	18.5	37.0	0.24				0.30	0.26	0.32	0.26			0.14			0.15	0.09					Misc Snow
65		23.4	21.6	33.2	0.34		0.36		0.36	0.28	0.36	0.27			0.12	0.23		0.15	0.19		0.41		0.12	Misc Snow
90		2.7	24.4	27.1	0.30		0.31		0.41		0.33	0.31				0.14					0.41		0.16	Misc Snow
40	<10	3.3	14.7	36.8	0.18		0.23		0.35	0.31	0.31	0.17			0.25	0.15		0.19	0.28		0.26			Snow<10mm
65	<10	96.0	20.6	31.7	0.34		0.38		0.34	0.29	0.32	0.29			0.20	0.21		0.18	0.25		0.22			Snow<10mm
90	<10	2.0	29.3	32.6	0.41				0.53		0.33	0.41				0.24								Snow<10mm
40	13	7.9	13.1	32.8	0.23				0.31	0.24	0.30	0.19				0.32	0.23	0.21		0.18	0.26		0.24	Snow=13mm
65	13	2.9	18.6	28.6	0.24		0.38		0.39	0.33	0.29	0.16				0.16	0.29	0.19	0.05	0.19	0.19		0.17	Snow=13mm
90	13	1.7	26.7	29.7	0.35		0.38		0.51	0.39	0.36					0.26		0.16	0.09		0.06		0.16	Snow=13mm
40	13-25	5.4	12.4	31.0	0.23		0.27		0.36	0.29	0.30					0.19		0.21	0.23		0.18		0.21	Snow 13-25mm
65	13-25	3.6	19.9	30.6	0.26		0.26		0.36	0.33	0.33					0.18		0.19	0.17		0.17		0.19	Snow 13-25mm
90	13-25	1.2	28.6	31.8	0.27		0.26		0.42	0.48	0.34					0.13		0.17	0.09		0.18		0.14	Snow 13-25mm
40	25	7.2	14.4	36.0	0.20		0.22		0.26	0.29	0.17	0.24			0.22	0.15		0.21	0.19		0.26	0.15	0.14	Snow=25mm
65	25	15.6	20.1	30.9	0.28				0.30	0.29		0.24			0.26	0.17		0.23	0.22		0.29	0.15	0.13	Snow=25mm
90	25																					0.16		Snow=25mm
40	25-38	67.6	17.5	43.8	0.24		0.29		0.25	0.20	0.27	0.31			0.10	0.14		0.12	0.14		0.11		0.08	Snow 25-38mm
65	25-38	12.1	20.6	31.7	0.26		0.33		0.29	0.36	0.29	0.30			0.21	0.07		0.22	0.17		0.13		0.14	Snow 25-38mm
90	25-38	2.3	23.8	26.4	0.26		0.36		0.37	0.49	0.37					0.08		0.06	0.10		0.13		0.07	Snow 25-38mm
40	25-75	4.2	13.4	33.5	0.18		0.31		0.31		0.26	0.28				0.13								Snow 25-75mm
65	25-75	2.9	22.2	34.2	0.26		0.31		0.36	0.26	0.26	0.29				0.13		0.24	0.19		0.21		0.20	Snow 25-75mm
90	25-75	1.7	24.9	27.7	0.29				0.46	0.27	0.29	0.28				0.11		0.21	0.16		0.21		0.19	Snow 25-75mm
40	50-100	55.7	13.8	34.5	0.24		0.28		0.25	0.27	0.35	0.24			0.16	0.17		0.16	0.14				0.14	Snow 50-100mm
65	50-100	15.7	22.8	35.1	0.26		0.31		0.28	0.31	0.35	0.25			0.11	0.15		0.14	0.14				0.12	Snow 50-100mm
90	50-100	2.5	23.8	26.4	0.27		0.36		0.38		0.33	0.27				0.12							0.14	Snow 50-100mm
40		12.2	10.0	25.0	0.18		0.16		0.24	0.21	0.26	0.17			0.19	0.18		0.17	0.22		0.23	0.15	0.16	Smooth Ice
65		2.5	20.0	30.8	0.20				0.32	0.29	0.24	0.17			0.17	0.17		0.13	0.19		0.21	0.15	0.13	Smooth Ice
90		1.7	25.1	27.9	0.26		0.28		0.41		0.27				0.14	0.16			0.21		0.21			Smooth Ice
40		33.1	12.2	30.5	0.19		0.17		0.21	0.23	0.23	0.20			0.18	0.22		0.17	0.20		0.15		0.16	Rough Ice
65		83.0	19.3	29.7	0.28		0.28		0.28	0.25	0.25	0.22			0.21	0.23		0.21	0.24		0.16		0.16	Rough Ice
90		1.6	22.1	24.6	0.19				0.35	0.19	0.32	0.20				0.27								Rough Ice

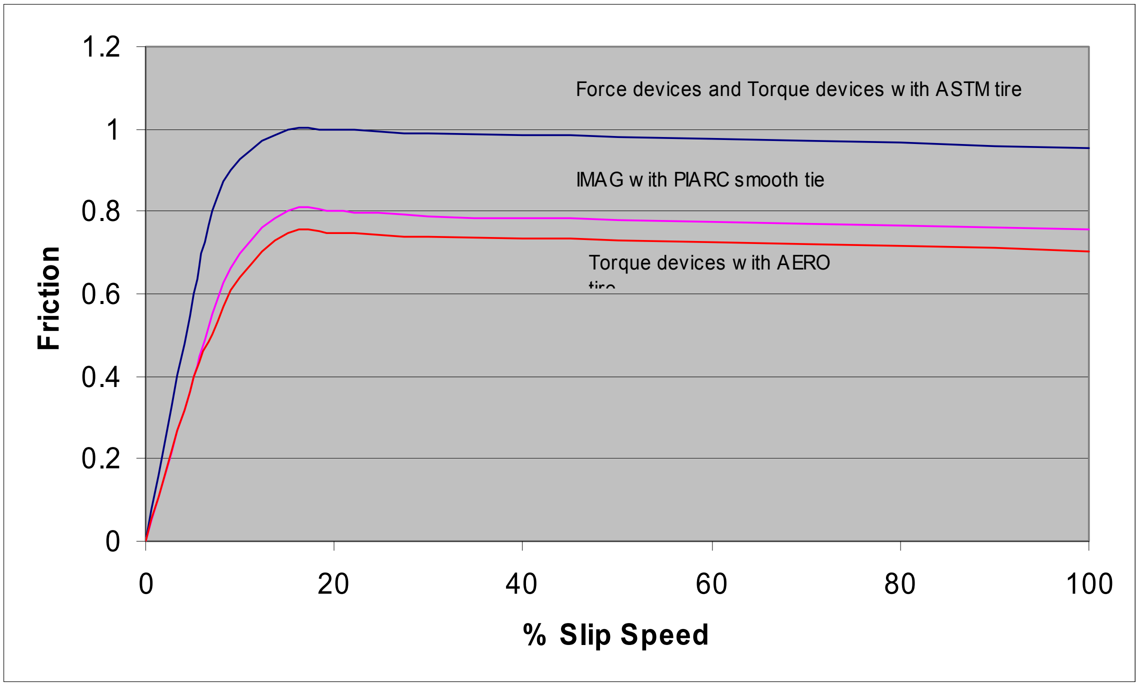

Figure 6 General trends on bare and dry pavement

On the other hand on a bare and wet surface the data generally shows the following (see Figure 7):

- Friction drops with increasing speed.
- The peak friction values are around 1.0.
- The GripTester measures friction from 0.75 to 0.62 (dropping with speed).
  - Torque devices generally measure friction levels at:
    0.9 to 0.75 (dropping with speed) with the ASTM tire
    0.7 to 0.64 (dropping with speed, but not much) with the AERO tire
    0.75 (same wet or dry? And no speed effect?) with the PIARC tire (by IMAG).

4.3.2 Ice

On ice there is some speed effect with the force measuring devices, while the torque measuring devices show almost none. If there is any speed effect, it is a drop in friction with increasing speed. Most devices report friction values in the 0.16 to 0.28 range. The torque measuring devices give a somewhat lower value with the ASTM and PIARC tires than with the AERO tire (see bottom of Table 2).

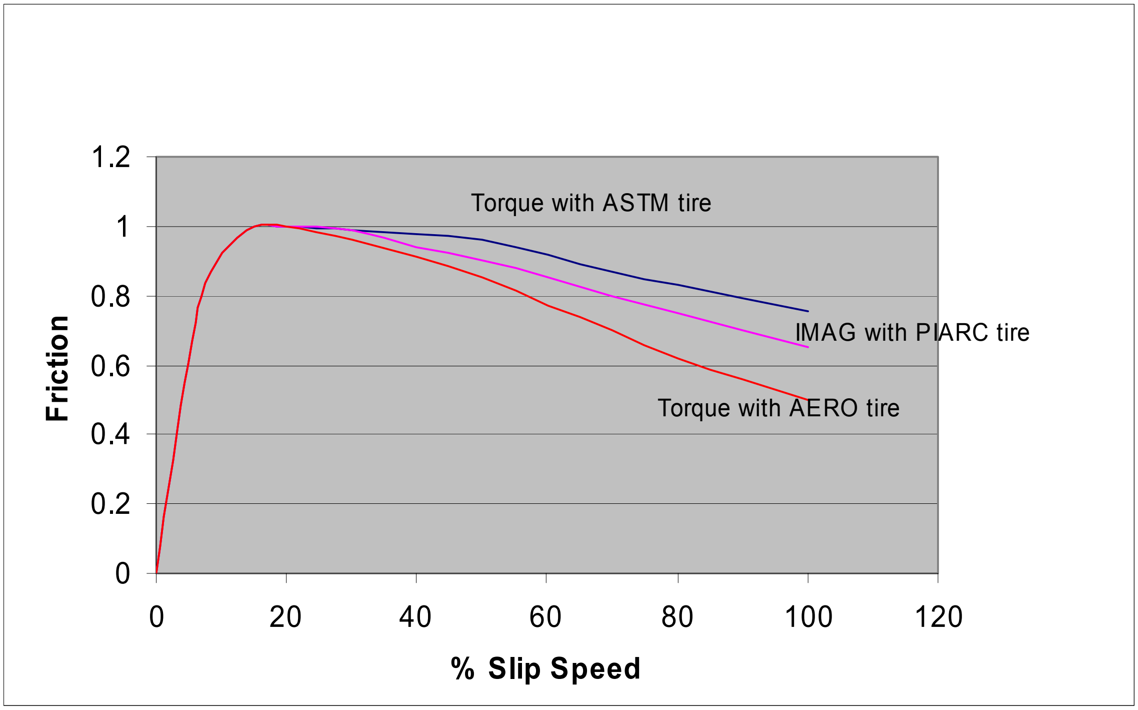

Figure 7 General trends on bare and wet pavements

4.3.3 Snow

Generally friction increases with speed with the force devices while the torque devices drop with speed, sometimes dramatically. Torque measurement has been shown not to measure correct friction forces on thick water film or in deep snow (a condition these devices are not designed to operate in).

Using the ERD as a reference:

- Force measuring devices give about the same range of friction
- Torque measuring devices give low (sometimes very low) values, especially at depths greater than 13 mm.
- On the tests in which both tires were used on the SFT, no clear trend is apparent: it is sometimes higher and sometimes lower or the same. On both snow and ice the ASFT had lower values with the ASTM tire than the AERO tire:

  0.15 verses 0.27 on snow and

  0.15 verses 0.22 on ice.

It would appear that the high pressure tire does help the torque devices measure somewhat higher values on ice and snow because of the higher contact pressure. This is to be expected since the loss of friction force measurement of a torque measurement is helped with a stiffer tire (higher pressure); however, it only helps to a small degree and is insufficient to recover the true friction forces.

4.3.4 Summary

Figure 8 is a bar chart of the tire database with the exception that the snow depth is divided into depths less than and greater then 13 mm (0.5 inches). The bar chart shows pictorially the data without speed effects. Since the frictional values are averaged for all speeds, it shows the differences of the conditions versus the devices (or tires). Note again how the friction of the torque devices drops for the deeper snow condition, whereas the ERD and force devices do not.

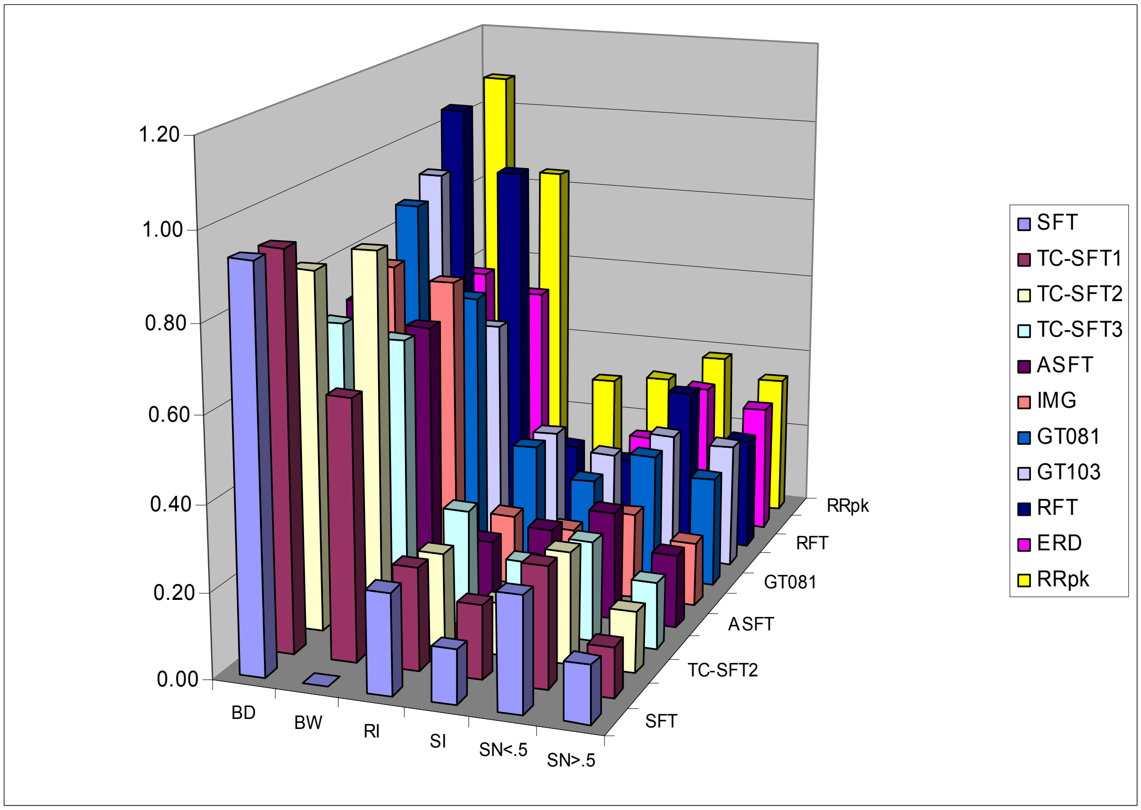

Figure 8 Bar chart of the tire database

On other surfaces the general trends are as expected:

- Bare and dry: the AERO tire provides a lower reading than other tires.
- Wet: all devices provide similar numbers except for the anomaly that ASFT gives a value higher than its dry value and about the same value as dry measurements by force devices. Since these results represent only a few test runs, more data is needed to verify whether the trends are representative.
- Rough ice produces higher values than smooth ice. As in the tire database, the bar chart shows a lot more data and comparisons, but that is for another report since this report is to sort out only the tire effects.

4.4 Hydroplaning

Figure 9 gives the critical hydroplaning speeds using the well known NASA model for hydroplaning, $V_P = 3.4 \bullet p^{1/2}$ where V_P is in knots and p is in kPa (or $V_P = 9 \bullet p^{1/2}$ where V_P is in knots and p is in psi or multiply V_P by 1.84 to get km/h or by 1.15 to get mph). The NASA model has been used for aircraft for over 30 years. In addition the model can be modified for use with other contaminates by dividing the tire pressure by the specific gravity (γ): $V_P = 3.4 \bullet (p/\gamma)^{1/2}$. The following specific gravities (γ) are used:

$\gamma = 1.0$ for water

$\gamma = 0.8$ for slush

$\gamma = 0.5$ for wet snow

$\gamma = 0.3$ for dry snow

The figure shows that at 207 kPa (30 psi) tire pressure, V_{crit} is:

48 knots (88 km/h or 55 mph) for wet
52 knots (96 km/h or 60 mph) for slush
70 knots (128 km/h or 80 mph) for wet snow.

These speeds are marginal at test speeds of 52 knots (96 km/h or 60 mph) and would give low friction readings. If 690 kPa (100 psi) is used, the V_{crit} is over 87 knots (160 km/h or 100 mph). Horne ran hydroplaning tests at Wallops with the Swedish high pressure AERO tire (690 kPa or 100 psi) and the PIARC low pressure tire (185 kPa or 27 psi). His testing gave a measured V_{crit} 73 knots (134 km/h or 84 mph) for the AERO tire. Based on calculation using the tire pressure of 690 kPa (100 psi), V_{crit} is 90 knots (165 km/h or 103 mph (same as Figure 7 for γ of 1.0)). However, if the contact pressure of 370 kPa (54 psi) is used instead of tire pressure, V_{crit} is 66 knots (122 km/h or 76 mph). Similarly for the PIARC tire, V_{crit} was found to be 57 knots (106 km/h or 66 mph) and calculated to be 47 knots (86 km/h or 54 mph) using tire pressure of 185 kPa (27 psi). However, V_{crit} is 48 knots (88 km/h or 55 mph) using contact pressure of 191 kPa (27.7 psi).

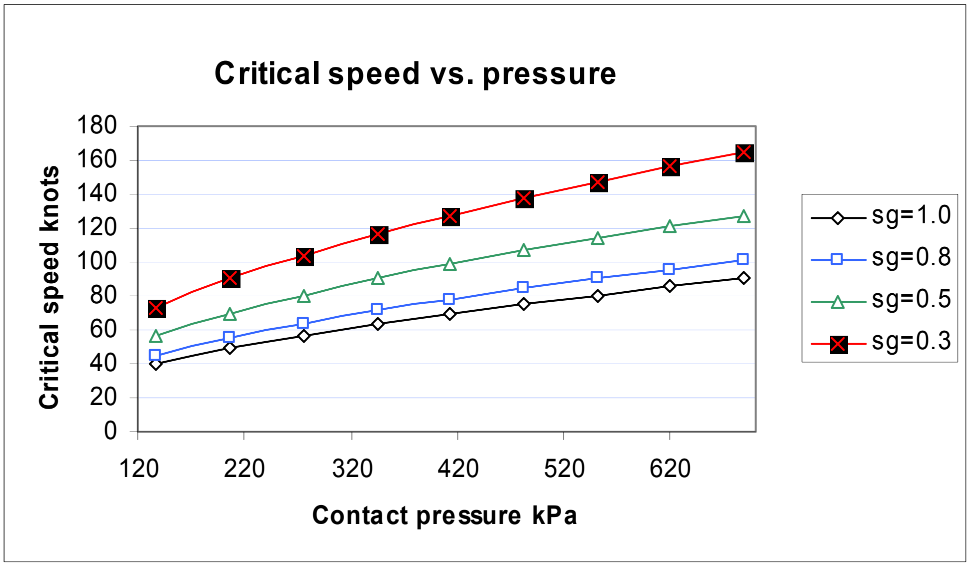

Figure 9 Critical speed versus contact pressure

4.5 Tire Foot Print Data and Calculated Critical Hydroplaning Speed

Table 3 gives the tire footprint data for the tire types, loads, pressures, contact pressures and aspect ratios (ratio of length over width of the footprint), and the estimated hydroplaning speeds using tire pressure, gross contact pressure and net contact pressure.

Aspect Ratio:

GT tires 0.6 to 0.7

ASTM E-1551 tire 0.66 to 0.77

AERO tire 0.71 to 0.75

PIARC tire 0.64

DBV ASTM E-501 tire 0.87

The AERO tire was measured on the ITTV under varying loads and tire pressures. The results show that:

- At 207 kPa (30 psi) the aspect ratio changes from 1.4 down to 0.65 when the load is varied from 47 to 186 kg (104 to 410 lb.).
- At 690 kPa (100 psi) the aspect ratio changes from 1.34 down to 0.78 when the load is varied from 41 to 186 kg (90 to 410 lb.).

Similar tests should be run on the ASTM tire to obtain the same information.

Table 3 Ground vehicle test tire footprint data

		TIRE	DATA				FOOTPRINT			AREA		CONTACT			
			INFLATION	VERTICAL					AREA	sq.mm	pressure	kPa		Vcrit	knots/hr
		TREAD	PRESSURE	LOAD	SHORE	WIDTH	LENGTH	ASPECT							TIRE
VEHICLE	TYPE	DESIGN	kPa	kg	HARDNESS	mm	mm	RATIO	GROSS	NET	GROSS	NET	GROSS	NET	pressure
ASFT	ASTM	SMOOTH	207	141		63.50	86.36	0.74	5303	5303	261	261	54	54	48
ASFT	ASTM	SMOOTH	207	141		61.47	96.52	0.64	5368	5368	258	258	54	54	48
ASFT	AERO	3-GROOVE	689	141		53.85	76.20	0.71	6452	2839	214	487	49	74	88
ASFT-1999	AERO	3-GROOVE	689	140		57	62	0.92	3850	2450	357	561	64	80	88
BV11	McCreary	SMOOTH	207	100		66.04	91.44	0.72	5245	5245	187	187	46	46	48
BV11-FAA	McCreary	SMOOTH	207	100		55	55	1.00	2530	2530	388	388	66	66	48
BV11-FAA	AERO	3-GROOVE	689	100		56	47.5	1.18	2600	1850	377	530	65	77	88
DBV	ASTM	SMOOTH	165	636		146.05	167.64	0.87	23226	23226	269	269	55	55	43
FAA SFT	ASTM	S MOOTH	207	141		64.01	83.31	0.77	5110	5110	271	271	55	55	48
FAA SFT	ASTM	S MOOTH	207	134		66.04	88.90	0.74	4968	4968	265	265	55	55	48
FAA SFT	ASTM	S MOOTH	207	133		63.50	96.52	0.66	5019	5019	260	260	54	54	48
GT	ASTM	SMOOTH	138	21		32.00	52.07	0.61	1626	1626	126	126	38	38	40
GT	ASTM	SMOOTH	158	21		29.46	52.07	0.57	1394	1394	147	147	41	41	42
GT	SLUSH	SMOOTH	689	21		24.38	31.75	0.77	839	839	245	245	53	53	88
GT	SLUSH	SMOOTH	207	21		24.13	40.64	0.59	903	903	227	227	51	51	48
GT	SLUSH	SMOOTH	172	21		24.13	33.02	0.73	794	794	258	258	54	54	44
GT	SLUSH	SMOOTH	172	21		23.88	34.54	0.69	787	787	261	261	54	54	44
IMAG	PIARC	SMOOTH	172	142		76.20	118.36	0.64	7690	7690	181	181	45	45	44
ITTV	AERO	3-GROOVE	207	47		50.29	35.56	1.41	1574	1058	295	438	58	70	48
ITTV	AERO	3-GROOVE	207	93		52.83	53.59	0.99	2632	1884	346	483	63	74	48
ITTV	AERO	3-GROOVE	207	141		53.34	69.09	0.77	3619	2581	382	536	66	78	48
ITTV	AERO	3-GROOVE	207	186		52.83	81.28	0.65	4258	3168	429	577	70	81	48
ITTV	AERO	3-GROOVE	689	41		47.50	35.56	1.34	1290	897	311	448	59	71	88
ITTV	AERO	3-GROOVE	689	108		52.83	54.86	0.96	3258	1968	326	539	61	78	88
ITTV	AERO	3-GROOVE	689	166		53.09	63.50	0.84	3245	2426	503	673	75	87	88
ITTV	AERO	3-GROOVE	689	186		53.34	68.58	0.78	3587	2523	510	725	76	91	88
MUMETER	McCreary	SMOOTH	69	61	0.25	53.09	74.68	0.71	3529	3529	169	169	44	44	28
MUMETER	McCreary	SMOOTH	69	110	0.69	58.42	114.30	0.51	6594	6594	164	164	43	43	28
MUMETER	McCreary	SMOOTH	69	159	0.94	63.50	142.49	0.45	8735	8735	179	179	45	45	28
MUMETER	McCreary	SMOOTH	69	219	1.38	65.02	180.34	0.36	11568	11568	186	186	46	46	28
RFT	McCreary	SMOOTH	207	136		63.50	88.90	0.71	5477	5477	244	244	53	53	48
RUNAR	ASTM	SMOOTH	207	155		59.94	84.33	0.71	4658	4658	325	325	61	61	48
RUNAR	AERO	3-GROOVE	689	155		53.34	71.12	0.75	3639	2374	417	639	69	85	88
SALTAR	135Rx12	Tread	207	70		34	41	0.83	1325	750	518	916	77	102	48
SALTAR	135Rx13	Tread	207	130		45	64	0.70	2750	1700	464	750	72	92	48
SFT	McCreary	SMOOTH	207	141		64.77	92.71	0.70	5529	5529	250	250	53	53	48
SFT 79	ASTM	3-GROOVE	689	145		65.02	99.06	0.66	5884	4142	243	345	52	62	88
SFT900	AERO	3-GROOVE	689	145		54.36	76.20	0.71	3755	2619	380	545	66	79	88
SFT-Munich	AERO	3-GROOVE	689	120		55	60	0.92	3500	2175	336	541	62	78	88

From the contact pressures and tire pressures the critical hydroplaning speed was calculated. The results show that:

- The GT slush tire improved the contact pressure and thus increased V_{crit} from 41 to 55 knots (75 to 100 km/h or 47 to 63 mph).
- The ASTM smooth tire's critical speed is around 55 knots (100 km/h or 63 mph) when inflated at 207 kPa (30 psi). The ribbed version has a similar value.
- The PIARC tire has a critical speed of about 46 knots (85 km/h or 53 mph).
- The high-pressure AERO tire has a critical speed around 77 to 86 knots (140 to 159 km/h or 88 to 99 mph), depending on the normal load.

4.6 Special Tests, Direct Comparison Testing

Perhaps the most enlightening information of tire type comes from the special tests conducted in North Bay in 1997 using RUNAR. In these special tests all three tires (ASTM E1551, ASTM E1551 with ribs (tire pressure of 207 kPa), and the high pressure AERO (tire pressure of 690 kPa)) were run on the following three surfaces at two speeds, 22 and 35 knots (40 and 65 km/h or 25 and 40 mph): bare and dry, ice, and packed snow). Each tire and condition was run at various fixed slips and at variable slip. In the 1998 tests, a set of tests was run with three devices, the K.J. Law RFT, the TC SFT, and FAA SFT. Each device made a run with the following tires: the E1551 at 207 and 690 kPa, a special E1551 with ribs at 207 and 690 kPa, and the AERO tire at 690 kPa. The tests were run on packed snow and then on packed snow with loose snow on top.

4.6.1 Bare and Dry

(Figure 10 at 22 knots and Figure 11 at 35 knots)

22 knots (40 km/h or 25 mph): The ASTM smooth tire produces higher values than AERO tire for both variable fixed slip and variable slip. Variable slip produces higher friction values than variable fixed slip. Also the slope of the mu-slip curve before the peak (the wrap-up part) is steeper. This indicates that the rate of wrap-up or rate of braking has an influence on friction levels, which is in agreement with the trends reported by Williams (Figure 2).

35 knots (65 km/h or 40 mph): Similar results are also obtained at vehicle speeds of 65 km/h. Maximum friction levels are not influenced by speed on bare and dry, but show a faster rise on the tire wrap-up part of the mu-slip curve (i.e., to the left of the peak).

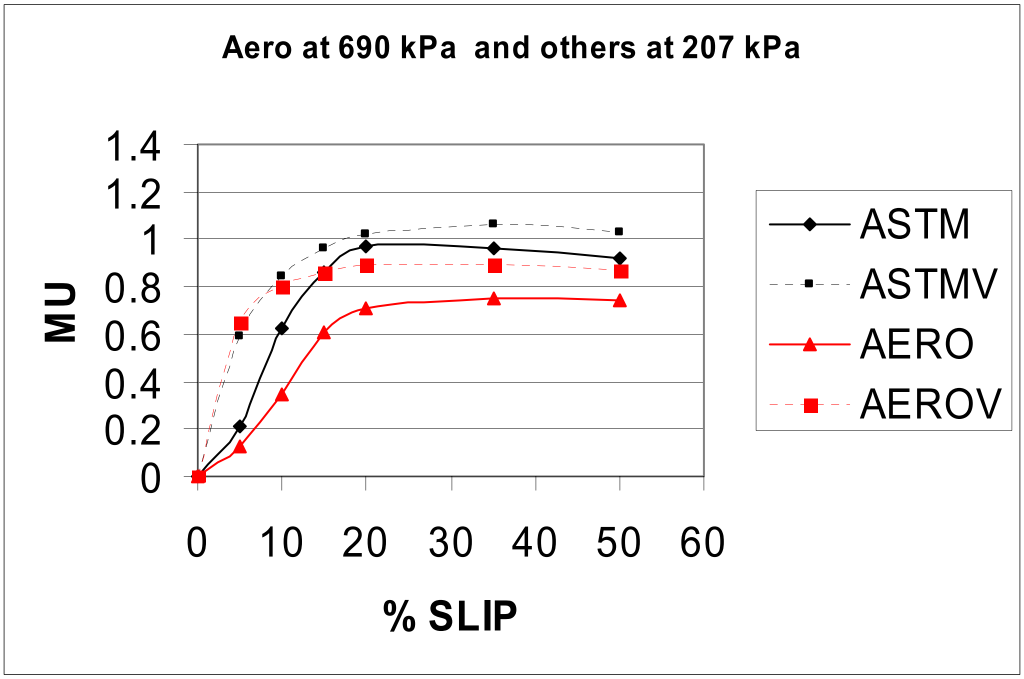

Figure 10 Friction (mu) versus percent slip on bare and dry at 22 knots

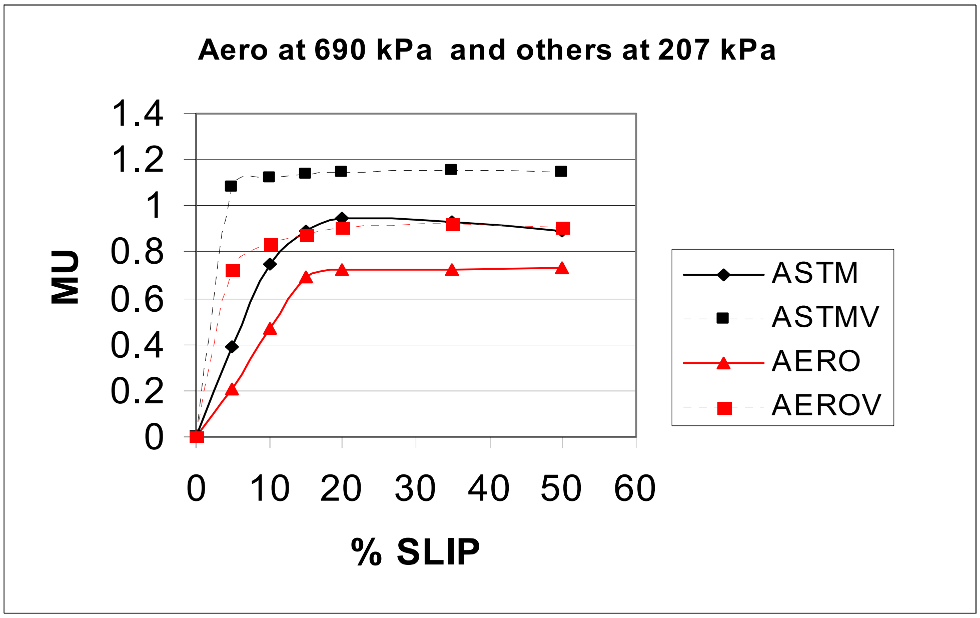

Figure 11 Friction (mu) versus percent slip on bare and dry at 35 knots

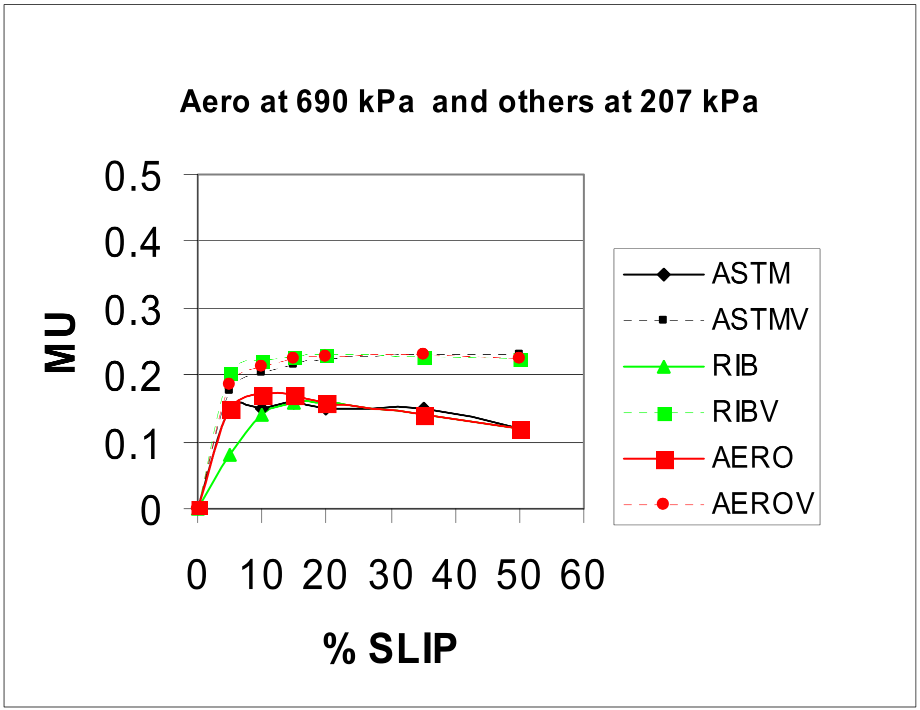

Figure 12 Friction (mu) versus percent slip on ice at 22 knots

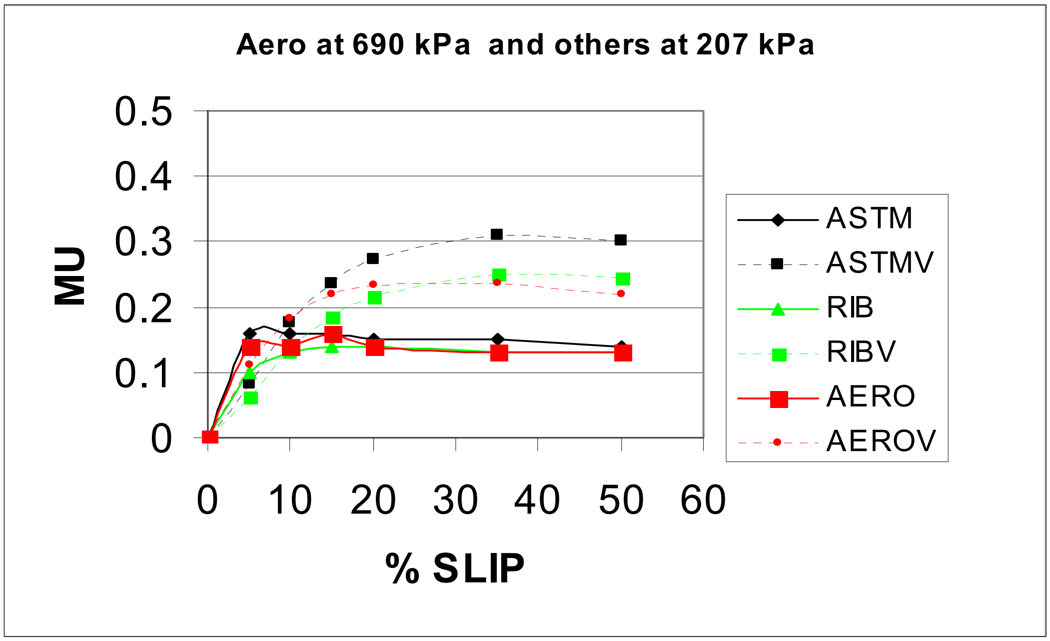

Figure 13 Friction (mu) versus percent slip on ice at 35 knots

4.6.2 Ice

(Figure 12 at 22 knots and Figure 13 at 35 knots)

On ice friction is higher at the greater wrap-up rates of variable slip than variable fixed slip. However, all tires give the same maximum friction. Thus when the surface becomes the sacrificial member of the friction pair, the tires no longer show differences. The higher values at higher braking rates are also expected since the shear strength is strain rate sensitive. Also values at 35 knots (65 km/h or 40 mph) are about the same as at 22 knots (40 km/h or 25 mph) with the exception of the variable slip test with an ASTM tire which gave values about 0.05 higher.

4.6.3 Packed Snow

(Figure 14 at 22 knots and Figure 15 at 35 knots)

Packed snow also shows the same general trends, except that the peak friction continues to increase in several cases of the AERO tire at variable fixed slip at both speeds. In the 35 knots (65 km/h or 40 mph) variable slip test the AERO tire gives values slightly higher than the ASTM tire (about 0.025).

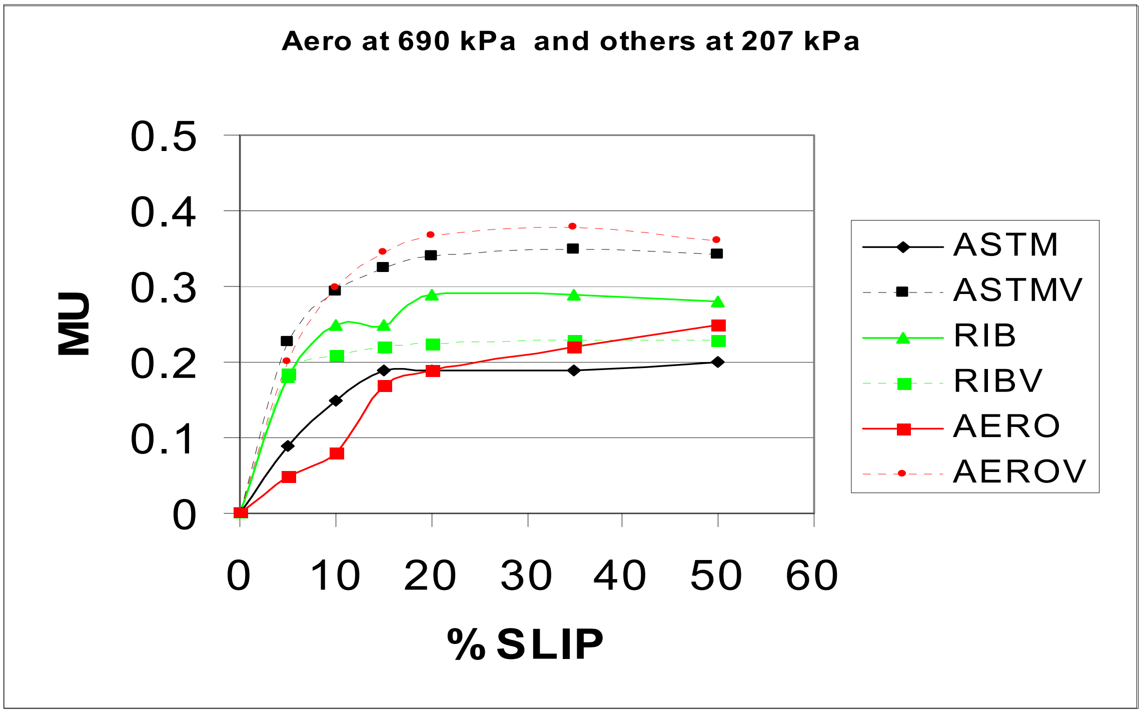

Figure 14 Friction (mu) versus percent slip on packed snow at 22 knots

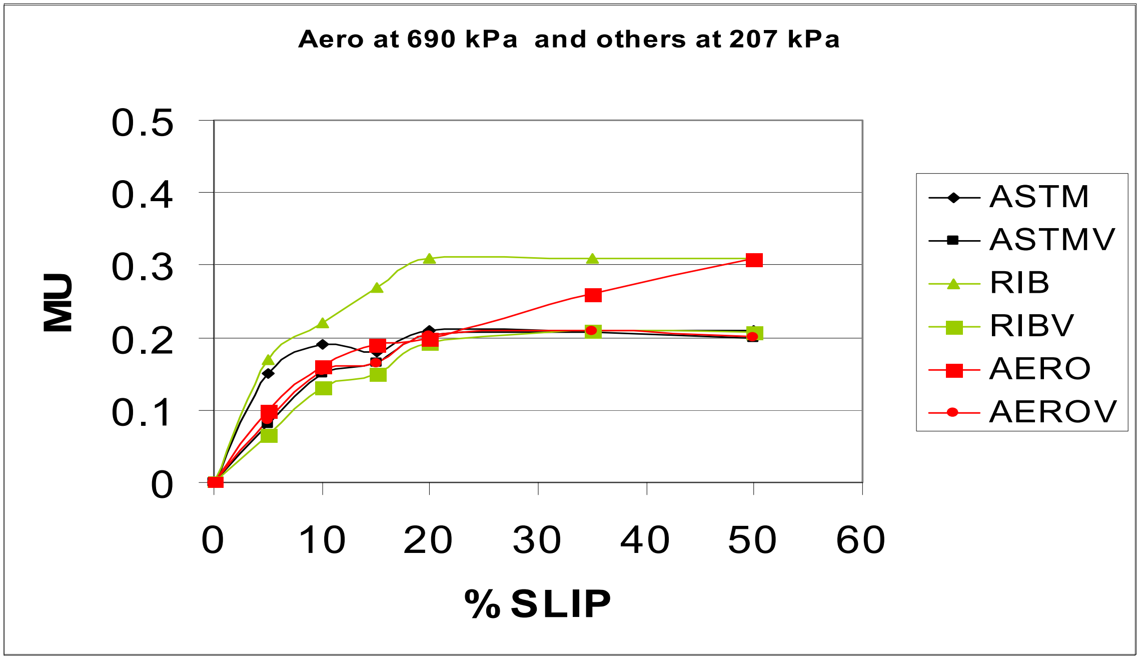

Figure 15 Friction (mu) versus percent slip on packed snow at 35 knots

4.6.4 Three Devices

Figure 16 shows the results of the three devices with the five different tire configurations on taxiway Lima with packed snow and on taxiway Charley with the same packed snow under 25 to 50 mm of fresh loose snow. The RFT is a force device and the two SFTs are torque devices. For all three testers and on both sites, it is clear that the ribbed tires give a higher friction than does the blank E1551. In all cases the 690 kPa pressure in the E1551 gives higher friction than the same tire with 207 kPa. On the loose snow, the AERO tire always gives the highest value, but on the packed snow it does not give any higher values than the E1551 with ribs. For the FAA SFT it gives a somewhat lower value. This data once again supports the theory that a higher contact pressure produces a higher friction reading with the ground measuring equipment.

4.7 Load/Contact Pressure

In the 1998 tests the ITTV was used in a series of tests using a 22 x 6 aircraft tire (the same as the nose wheel tire on the Falcon 20). The series consisted of running variable loads (455 kg to 2270 kg, 1000 to 5000 lb.) on an ice surface and a packed snow surface. Figure 17 shows a clear drop in friction as the load is increased on both surfaces. Figure 18 shows the same data where friction force rather than friction is plotted against load. Here the force increases with load and is reaching a constant level at higher loads. It appears that at about 4000 lb. (1818 kg) the shear strength of the snow is reached and there is no further increase in friction force.

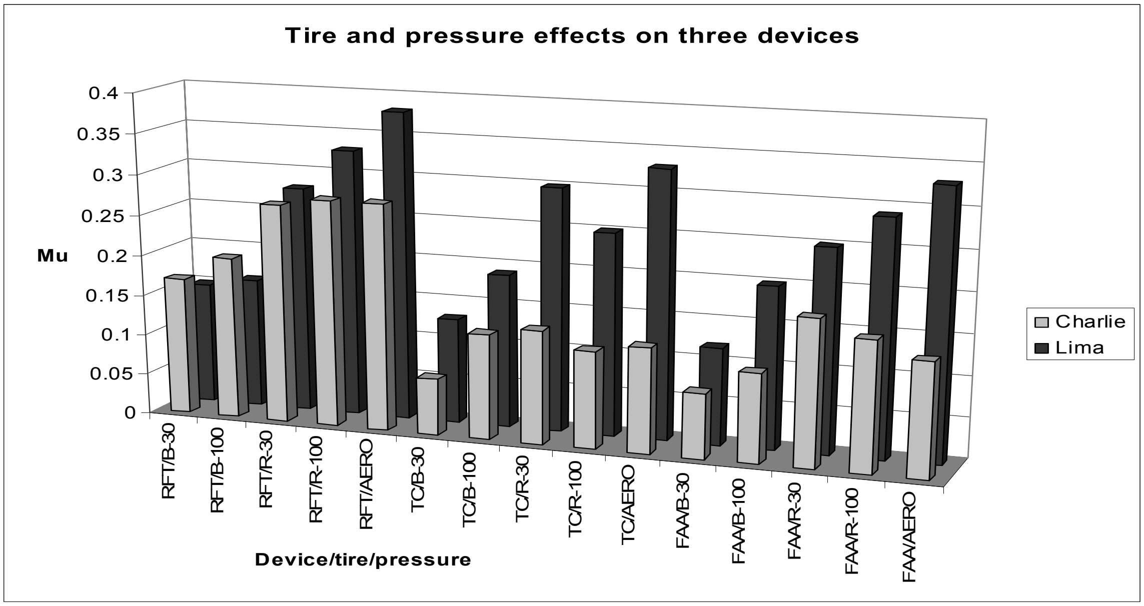

Figure 16 Tire and pressure effects on three devices on two sites

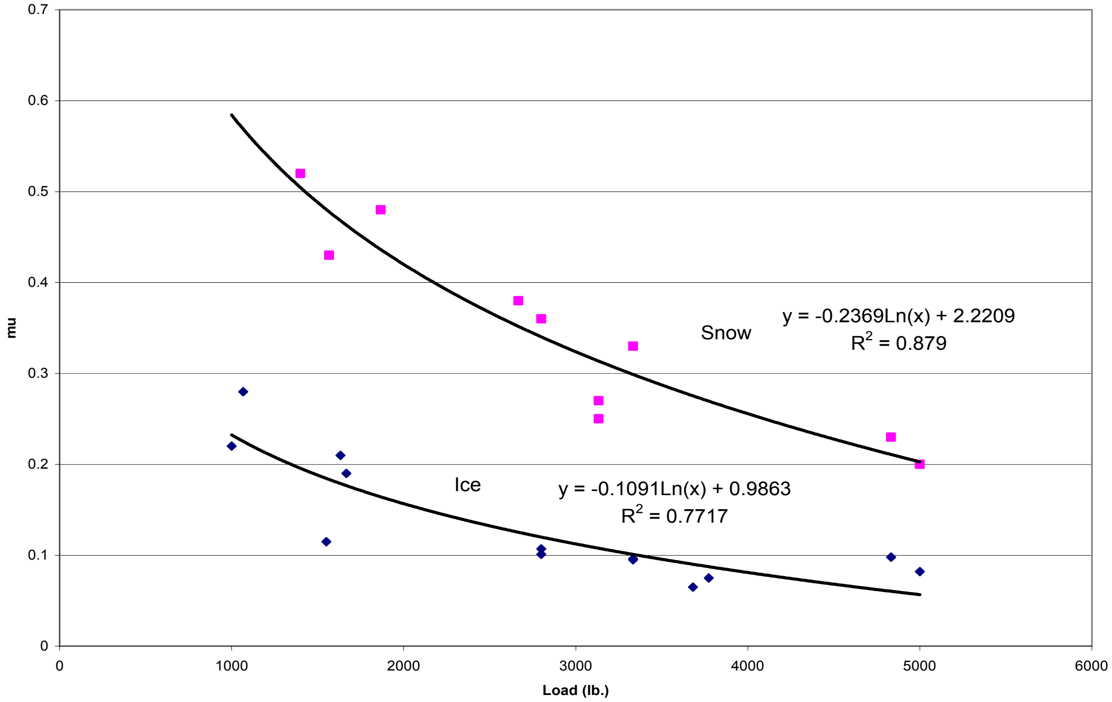

Figure 17 Friction (mu) versus tire load on the ITTV

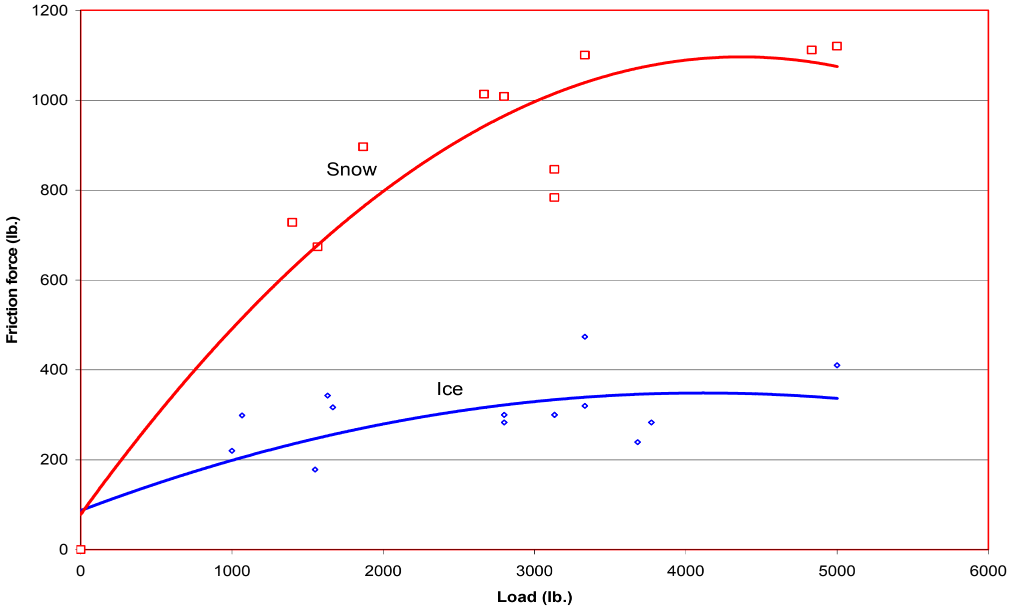

Figure 18 Friction force (shear) versus tire load on the ITTV

These tests show the importance of load (contact pressure) on this tire and thus the need to have similar characteristics for all of the tires being used if one is to model one tire and test with another. In the case of the smaller, lighter loaded ground friction tires, we have seen that increased contact pressure has increased the friction, while for the larger, much higher loaded aircraft tire we see the opposite. This finding was expected since the aspect ratio of the aircraft tires is nearly constant with load, while the ground test tires have a constant width with a change in length and thus a changing aspect ratio with load

5.0 CONCLUSIONS AND RECOMMENDATIONS

On bare and dry or bare and wet pavements the AERO tire (natural rubber) gives lower friction values than the ASTM tire; however, the ribs on the AERO tire make it insensitive to the macrotexture. Thus, the ASTM smooth treaded tire is far superior in evaluating the surface condition for surface maintenance.

Under snow and ice conditions the performance of the tires is very much the same, which means that either tire could work. However, due to the fact that a tire at 207 kPa (30 psi) is very close to V_{crit} in slush, the 690 kPa (100 psi) pressure appears to be preferable. The effect of braking rate has by far the most significant effect on friction values.

Based on the results of this study, the data indicates that the following actions are recommended:

1. The ASTM smooth treaded test tire should be used with 207 kPa (30 psi) for summer or surface maintenance testing.
2. A high contact pressure tire should be used for winter measurements, especially for torque measuring devices on loose snow. On packed snow and ice surfaces any tire will give satisfactory correlation. However, if a single tire is to be used, a high contact pressure tire is recommended.
3. Tests should be conducted to determine the braking rate on aircraft tires using anti skid systems. Since variable slip testers have an advantage in that they can adjust their braking rate, tests should be made with different rates to determine an equivalent rate for fixed slip tests. Tire testing should be performed in the laboratory, where possible to reduce the amount of field-testing required. Limited field tests were performed in 1998 with the IMAG and RUNAR, and the limited results further support the need for these tests in the coming year.
4. Since braking or wrap-up rate and loading or contact pressure will vary with tire type (stiffness and pressure), it is recommended that a new tester similar to the variable slip ITTV be constructed that can test all of the ground vehicle tire types as well as some aircraft tires.
5. Load tests should be performed on each of the tires used to measure winter friction to determine each tire's contact pressure effect on the friction forces on ice and snow.

It is also recommended that the following tests (with respect to tire issues) be conducted in the 1998-99 testing at North Bay and Wallops Island:

1. All test tires in use should be tested for their critical speed.
2. All tires should have the aspect ratio and tire contact area measured on the ITTV under varying load and tire pressures.
3. The AERO, the ASTM E1551 smooth treaded tire and the ASTM E1551 ribbed tire should be run on the FAA RFT and an SFT at 689 kPa (100 psi) on slush so that comparisons can be made to the ITTV with a 22 x 6 aircraft tire.
4. All test tires in use should be tested at three wrap-up (braking) rates.
5. The AERO, the ASTM E1551 smooth treaded tire, the ASTM E1551 ribbed tire, and the ITTV with a 22 x 6 aircraft tire should be run at various temperatures (one test at 0°C to -5°C, one test at -5°C to -10°C, and one test below -15°C) on bare, snow and ice.

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