TP 13579

PROCEEDINGS of the 2nd International Meeting on Aircraft Performance on Contaminated Runways

COMPTE RENDU de la 2e Réunion internationale sur la performance des avions utilisant des pistes chargées de contaminants

November 2-4, 1999
2-4 novembre 1999

IMAPCR '99

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The opinions expressed reflect the views of the speakers and not necessarily the official views of the sponsoring organizations.

Papers and presentations are in the language in which they were delivered. Not all materials were available for publication.

Les opinions exprimées dans ce compte rendu sont celles des conférenciers et ne reflètent pas nécessairement celles des organismes parrains.

Les communications et présentations sont dans la langue dans laquelle elles ont été faites. Les documents n'ont pas tous été soumis pour publication.

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16. Abstract

This document is a record of the proceedings of IMAPCR '99, held 2-4 November 1999 in Montreal, Quebec.

The meeting was held to review current and future initiatives for improving the understanding and application of measured winter runway friction values and relating them to aircraft performance.

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16. Résumé

Ce document est le compte rendu de IMAPCR '99, qui a eu lieu du 2 au 4 novembre 1999 à Montréal, Québec.

La réunion avait pour objectif de passer en revue les initiatives en cours et futures devant mener à une meilleure compréhension et une meilleure utilisation des mesures de glissance des chaussées aéronautiques et à des liens plus clairs entre ces mesures et la performance des avions.

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PREFACE

IMAPCR ’99 took place in Montreal, Quebec, on 2-4 November 1999. One hundred and forty delegates from nine countries attended the meeting. They included representatives from government, industry, national and international organizations, researchers interested in aircraft operations in severe winter conditions, aircraft certification and operating authorities, aircraft and equipment manufacturers, airport authorities, airlines, pilots’ professional associations, and the military.

The meeting’s overall objective was to review current and future initiatives for improving our understanding and application of measured runway friction values and related aircraft performance.

This record of proceedings reviews the agenda and the meeting’s objectives and summarizes the presentations, the panel discussion, and the resulting action plan. Presentations and papers are also included.

PRÉFACE

IMAPCR ’99 a eu lieu à Montréal, Québec, du 2 au 4 novembre 1999. Cent quarante délégués de neuf pays ont assisté à la réunion. Ils comprenaient des représentants des milieux gouvernementaux, de l’industrie, d’organismes nationaux et internationaux, des chercheurs s’intéressant aux opérations aériennes dans des conditions hivernales rigoureuses, ainsi que des membres d’organismes chargés de la certification des aéronefs et de la délivrance de permis, et des porte-parole d’avionneurs et d’équipementiers, d’administrations aéroportuaires, de compagnies aériennes, d’associations professionnelles de pilotes et de forces militaires.

L’objectif global de la réunion était de passer en revue les initiatives en cours et futures devant mener à une meilleure compréhension et une meilleure utilisation des mesures de glissance des chaussées aéronautiques, et à des liens plus clairs entre ces mesures et la performance des avions.

Ce compte rendu présente l’ordre du jour et les objectifs de la réunion, puis résume la teneur des présentations et de la discussion en groupe, avant de formuler le plan d’action qui a résulté de l’ensemble des travaux. On trouvera en annexe le texte intégral des communications et présentations.

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IMAPCR ’99 was made possible by the sponsorship of Transport Canada and the U.S. National Aeronautics and Space Administration. We also acknowledge the support of the U.S. Federal Aviation Administration, the National Research Council of Canada, the International Civil Aviation Organization, the American Society for Testing and Materials, le Service technique des bases aériennes (France), la Direction générale d’aviation civile (France), and the Norwegian Civil Aviation Administration.

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GLOSSARY

ABS	Antilock Braking System
AFI	Aircraft Friction Index
AFM	Aircraft Flight Manual
AFMLD	Aircraft Flight Manual Landing Distance
AIP	Aeronautical Information Publication
AMJ	Advisory Material Joint
AMS	Aerospace Material Specification
AOM	Airport Operating Manual (Canada)
ARAC	Aviation Rulemaking Advisory Committee
ARFI	Aircraft Runway Friction Index
ASTM	American Society for Testing and Materials (U.S.)
ATA	Air Transport Association
ATC	Air Traffic Control
BFL	Balanced Field Length
CAA	Civil Aviation Authority
CAR	Canadian Aviation Regulations
CFME	Continuous Friction Measuring Equipment
CRFI	Canadian Runway Friction Index
CRJ	Canadiar Regional Jet
DBV	Diagonally Braked Vehicle (NASA)
DGAC	Direction générale d'aviation civile (France)
DGPS	Differential GPS (Global Positioning System)
DND	Department of National Defence (Canada)
ERD	Electronic Recording Decelerometer
ESDU, U.K.	Engineering Sciences Data Unit (of the Royal Aeronautical Society)
EWD	Equivalent Water Depth
FAA	Federal Aviation Administration (U.S.)
FAAAC	FAA Advisory Council (U.S.)
FAR	Federal Aviation Regulations (U.S.)
GPS	Global Positioning System
IATA	International Air Transport Association
ICAO SNOWTAM	see SNOWTAM
ICAO	International Civil Aviation Organization (U.N.)
IFALPA	International Federation of Airline Pilots Associations
IFI	International Friction Index
ILS	Instrument Landing System
IMAG	Instrument de mesure automatique de glissance (France)
IMAPCR	International Meeting on Aircraft Performance on Contaminated Runways
IRFI	International Runway Friction Index
IRI	International Roughness Index
ISA	International Standard Atmosphere
ITTV	Instrumented Tire Test Vehicle (NASA)
JAA	Joint Aviation Authority (EU)

JAR	Joint Aviation Regulations (EU)
JAROPS	Joint Aviation Regulations Operations
JBI	James Brake Index
JWRFMP	Joint Winter Runway Friction Measurement Program
LD	Landing Distance
LRPC	Previously LCPC – company name (France)
MFL	Minimum Friction Level
MFT	Mobility Friction Technology (Norway)
MOTNE	Meteorological Operational Telecommunication Network Europe (ICAO)
MOTNE Code	Eight-Digit Group
MOTNE – RPG	MOTNE – Regional Planning Group
NASA	National Aeronautics and Space Adminstration (U.S.)
NCAA	Norwegian Civil Aviation Adminstration (Norway)
NLR	National Aerospace Laboratory (the Netherlands)
NRC	National Research Council Canada
NRC – IAR	NRC Institute for Aerospace Research
NOTAM	Notice to Airmen
PIARC	Permanent International Association of Road Congresses
OEI	One Engine Inoperative
R&D	Research and Development
RCR	Runway Condition Reporting
RFI	Runway Friction Index
RFT	Runway Friction Tester
ROAR	Road Analyser & Recorder
RTO	Rejected Take-Off
RUNAR	Runway Analyser and Recorder (Norway)
SDR	Stopping Distance Ratios
SG	Specific Gravity
SNOWTAM	Snow Notice to Airmen
SOP	Standard Operating Procedures
STBA	Service technique des bases aériennes
TC	Transport Canada (Canada)
TDC	Transportation Development Centre (Canada)
UK CAA	Civil Aviation Authority (U.K.)
USAF	United States Air Force
WG	Working Group

GLOSSAIRE

ABS	Dispositif antiblocage de freins
AFI	Coefficient de frottement des pneus d'avions
AFM	Manuel de vol de l'avion
AFMLD	Distance d'atterrissage selon le manuel de vol de l'avion
AIP	Publication d'information aéronautique
AIPCR	Association internationale permanente des congrès de la route
AMJ	Advisory Material Joint (document consultatif de la JAA)
AMS	Aerospace Material Specification (norme de la SAE)
AOM	Manuel d'exploitation des aéroports (Canada)
ARAC	Aviation Rulemaking Advisory Committee (É.-U.)
ARFI	Coefficient de frottement pneu / chaussée
ASTM	American Society for Testing and Materials (É.-U.)
ATA	Association du transport aérien
ATC	Contrôle de la circulation aérienne
BFL	Longueur de piste équivalente
CAA	Civil Aviation Authority (R.-U.)
CDT	Centre de développement des transports (Canada)
CFME	Appareil de mesure en continu du frottement
CNRC	Conseil national de recherches du Canada
CNRC – IAR	CNRC - Institut de recherche aérospatiale
CRFI	Indice canadien de glissance des chaussées aéronautiques
CRJ	Canadair Regional Jet
DBV	Véhicule freiné en diagonale
DGAC	Direction générale de l'aviation civile (France)
DGPS	GPS (Système de positionnement global) différentiel
ERD	Décéléromètre électronique
ESDU, R.-U.	Engineering Sciences Data Unit (de la Royal Aeronautical Society, R.-U.)
EWD	Profondeur d'eau équivalente
FAA	Federal Aviation Administration (É.-U.)
FAAAC	FAA Advisory Council (É.-U.)
FAR	Federal Aviation Regulations (É.-U.)
GPS	Système de positionnement global
IATA	Association du transport aérien international
IFALPA	Fédération internationale des associations de pilotes de ligne
IFI	Indice international de glissance
ILS	Système d'atterrissage aux instruments
IMAG	Instrument de mesure automatique de glissance (France)
IMAPCR	Réunion internationale sur la performance des avions utilisant des pistes chargées de contaminants
IRFI	Indice international de glissance des chaussées aéronautiques
IRI	Indice international de rugosité
ISA	Atmosphère type internationale
ITTV	Véhicule d'essai instrumenté (NASA)

JAA	Joint Aviation Authority (UE)
JAR	Joint Aviation Regulations (UE)
JAROPS	Joint Aviation Regulations Operations (UE)
JBI	Indice de freinage James
LD	Distance d’atterrissage
LRPC	Autrefois LCPC – raison sociale d’une société (France)
MDN	Ministère de la Défense nationale (Canada)
MFL	Degré de frottement minimal
MFT	Mobility Friction Technology (Société de Norvège)
MOTNE	Groupe des télécommunications météorologiques d'exploitation en Europe (OACI)
MOTNE Code	Code MOTNE (groupe de huit chiffres)
MOTNE – RPG	Groupe de planification régional
NASA	National Aeronautics and Space Administration (É.-U.)
NCAA	Administration de l’aviation civile de Norvège
NLR	Laboratoire national de recherche aérospatiale (Pays-Bas)
NOTAM	Avis aux navigateurs aériens
OACI	Organisation de l’aviation civile internationale (organisation de l’ONU)
OACI, SNOWTAM	voir SNOWTAM
OEI	Un moteur inopérant
PCRGCAH	Programme conjoint de recherche sur la glissance des chaussées aéronautiques l’hiver
R&D	Recherche et développement
RAC	Règlement de l'aviation canadien
RCR	Compte rendu de l'état de la piste
RDA	Rapport de distance d’arrêt
RFI	Indice de glissance des chaussées aéronautiques
RFT	Véhicule de mesure de l’indice de glissance de la piste
ROAR	Analyseur de surface
RTO	Décollage interrompu
RUNAR	Analyseur de profil (Norvège)
SG	Densité
SNOWTAM	Avis de neige aux navigateurs aériens
SOP	Procédures d'utilisation normalisées
STBA	Service technique des bases aériennes (France)
TC	Transports Canada (Canada)
UK CAA	Civil Aviation Authority (R.-U.)
USAF	United States Air Force (É.-U.)
WG	Groupe de travail

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SESSION 1 – OPENING PLENARY SESSION

Welcome

1. Al Mazur, Chief, Technical Evaluation Engineering, Aerodrome Safety, Transport Canada (TC), brought the meeting to order.

2. Art Laflamme, Director General, Civil Aviation, Transport Canada, remarked that the first IMAPCR meeting was held on 22-23 October 1996, in Montreal, and was attended by 137 delegates from eight countries. He then welcomed the 140 delegates from nine countries to this second IMAPCR meeting taking place in Montreal on 2-4 November 1999.

3. Mr. Laflamme stated that Transport Canada's vision is to achieve the safest aviation system in the world. Transport Canada's Flight 2005 Safety Plan focusses on aviation safety and on maintaining a high level of public confidence in civil aviation.

4. The five-year JWRFMP arose from the Dryden Commission Implementation Project. Mr. Laflamme reviewed the history of the program and its accomplishments to date:
   - the increasing level of participation and support (funding and collaboration) from stakeholders, from the original four (TC, NRC, NASA, and the FAA) to ten (with the addition of Norway, France, ASTM, ICAO, the U.K., and the Netherlands);
   - the growing interest from aircraft manufacturers, commercial airline operators, and airport administrators in supporting the adoption of a common measurement standard, such as the IRFI;
   - the extensive testing on a variety of aircraft and ground vehicles at four test facilities: North Bay (Ontario), Hampton (Virginia), Gwinn (Michigan), and Oslo (Norway);
   - the establishment of a database using five types of test aircraft (Falcon 20, Dash 8, Boeing 727, Boeing 737, and Boeing 757) under a variety of test conditions;
   - the establishment of accredited draft standards and the move to establish and accept a common standard, IRFI.

5. Mr. Laflamme expressed satisfaction with the program's progress and confirmed TC's continuing support. He underlined the importance of these meetings in bringing together operators, regulators, researchers, and manufacturers to review problem areas and to discuss future approaches.

6. A short video of the JWRFMP was presented.

Management of the Joint Winter Runway Friction Measurement Program, JWRFMP

7. Angelo Boccanfuso, Senior Development Officer, Transportation Development Centre (TDC), TC, and Project Manager of the JWRFMP, outlined the program to date, with particular emphasis on program costs, management structure, and future requirements.

8. The program costs were reviewed. They include contributions in kind, e.g., aircraft testing, facilities, and analysis. Contributors include NASA, TC, NRC, the FAA, DND, Norwegian CAA, French DGAC, and Bombardier Aerospace. Other funding sources for research are always needed, as the costs of running the program are too great for any one organization to cover.

9. The program is managed by a steering committee, with rotating chairmanship, drawn from six sponsoring organizations. Industry and governments participate in program implementation and are assisted by individual project technical committees.

10. In terms of results, the program has generated over 20 published reports, with an additional 20 upcoming publications.

11. Future requirements include testing on wide-bodied aircraft, harmonization of testing methodologies, and the development of a common friction index.

Review of Agenda and Objectives

12. John Maxwell, Director of Aerodrome Safety, stated that the overall objective of IMAPCR '99 was to improve the understanding and application of measured runway friction values and related aircraft performance, thereby advancing safe operation of aircraft at aerodromes.

13. He outlined five specific objectives for the meeting:
    - review results of the JWRFMP tests to date;
    - review the International Runway Friction Index (IRFI);
    - review IRFI validation method and sensitivity analysis;
    - discuss merits of establishing uniform winter friction measurements and develop the concept of a common friction reporting number (IRFI);
    - obtain support and advice from the international aviation community, including civil aviation authorities, for the winter test program.

14. Mr. Maxwell pointed out that the Canadian results have shown real progress; however, the key challenges still relate to the incompatibility of friction measurement devices and how to provide accurate information to pilots for effective braking performance. He invited feedback on what remains to be done, as wet and icy conditions have been shown to be the foremost cause of landing accidents.

SESSION 2 – SUMMARY OF AIRCRAFT PERFORMANCE TESTING, 1996-99

Braking Performance of the NASA Boeing 737 and 757 Aircraft

15. Tom Yager, Senior Research Engineer, NASA, detailed the highlights of the braking performance test runs to date on the Boeing 737 and 757. The 737 tests were carried out at North Bay, in 1996, while the 757s were tested at the larger runway facility in Sawyer, Michigan, in February 1999. Twenty-nine test runs were carried out over seven different runway conditions, which included dry, wet grooved, dry loose snow, wet non-grooved, patchy thin ice, and compacted snow. The 737 was subject to five runway conditions and 23 test runs. Bare dry or slush conditions were not examined.

16. A summary of test results indicated that the B 757 braking performance was better than the B 737 under similar conditions, as measured by the effective braking friction coefficient. However, contaminant drag was similar for both aircraft types. Mr. Yager did caution that the data collection and analysis are still incomplete. Negotiations are currently under way to use European facilities to carry out wide-body testing. A summary report is to be issued in January 2000.

17. Comments were made about the impact that the weight and tire size differentials between the two aircraft might have on braking performance. The effects of depth of the contaminant and outside temperature on drag measurements, impingement, and use of anti-skid systems were also discussed. A point was made that handling snow, and bringing it back to the runway, alters the characteristics of the snow particles. Mr. Yager replied that recent tests use only unhandled snow. He also said that Armann Norheim of the Norwegian Civil Aviation Authority is working on an American Society for Testing and Materials (ASTM) report to better define winter runway contaminants.

NRC Falcon 20 Braking Performance on Winter Contaminated Runways – 1996 to 1999

18. John Croll, Research Test Pilot with the National Research Council Canada, spoke about the Falcon 20 testing program, which included tests on over 40 different runway surface conditions for a total of 241 test points (126 runs for braking coefficient and 115 for contaminant drag). Aircraft test objectives were to determine the effect of contaminant drag on takeoff and rejected takeoff (RTO) distances, the effect of reduced braking coefficients on landing and RTO distances, and the landing distance as a function of CRFI. Ground vehicle tests were carried out to develop IRFI standards. Examples of aircraft braking coefficient μ were shown for three cases: moderate surface friction on compacted snow, high surface friction on 60 percent bare and dry, 40 percent loose snow; and low surface friction on smooth ice.

19. Mr. Croll presented several overheads showing correlation between aircraft μ braking versus ground speed; the Falcon 20 μ braking versus CRFI; slip ratios; and directional control problems on low friction surfaces. He presented a video that elaborated on the test program. It also showed instances where snow was ingested into the engines, causing a flameout, and two recorded cases of aircraft lateral departure from the test section.

20. Conclusions of these tests indicated no consistent variation of aircraft braking coefficients with ground speed. A good correlation existed between the Falcon 20 and the CRFI on uniformly contaminated surfaces. Increase in wheel slip ratios with decreasing ground speed was noted. Reduction in directional control at lower speeds on ice-covered surfaces was also recorded. Mr. Croll recommended that additional testing should be done using different aircraft and runway conditions, including slush and chemicals. Other testing on the Falcon 20 should include contaminant drag and crosswind effect.

21. Questions were raised about using different braking coefficient measures in testing (Falcon tests versus the NASA tests). Mr. Croll replied that a need exists to standardize the coefficient given to the pilot. In response to other questions, Mr. Croll explained that tests were not done on damp or wet runway conditions; the antilock braking system (ABS) was disabled on the test runs and thrust reversers were not used.

Dash 8 Aircraft Performance Testing on Contaminated Runway Surfaces

22. Edward Lim, Chief of Performance at Bombardier Aerospace, de Havilland division, Canada, presented the results of testing done in February 1998 at North Bay. The test sequence was:
    - ground vehicle tests;
    - RTO and landing tests;
    - ground vehicle re-tests.

23. The objective was to determine contaminant drag and aircraft braking coefficients for the Dash 8 under three contaminant types: rough ice, moderately smooth ice, and sand on moderately smooth ice.

24. Test results indicated no appreciable impingement or displacement drag on the three surface types. Second, brake friction coefficient (as a percentage of dry) was established for all three surface types.

25. In response to questions on the test, Mr. Lim pointed out that a triple axis accelerometer was used. The outside temperature was -10°C, and there was no evidence of the aircraft breaking through the ice surface.

Comparison of Aircraft Braking Performance on Contaminated Runways

26. Mathew Bastian, Software Engineer, Flight Research Laboratory, National Research Council Canada, discussed two methods that were developed to test braking friction and contaminant drag of a B 727 on contaminated runways. The results show that the strain gauge method for determining μ rolling is of limited value for low friction points. The μ braking yields the same results as the decelerometer aerodynamics model. The μ braking suggested a linear relationship similar to that of other aircraft. Contaminant drag may indicate variance from AMJ 2581591.

27. Preliminary results of braking performance of the Falcon 20, Dash 8, B 737, and B 757 indicate that:
    - the aircraft compare well with each other;
    - anti-skid systems work at similar efficiencies;
    - mathematical models validate the removal of aircraft-specific aerodynamic effects;
    - μ braking versus CRFI is independent of aircraft types.

28. In response to a question, Mr. Bastian indicated that the Falcon was not tested in slush/wet snow conditions, but that future testing would include them. Consideration would also be given to creating slush by using chemicals when the temperature is right.

29. On the question of thrust reversers, Mr. Bastian indicated that for the sake of proper comparisons between the aircraft, use of thrust reversers was eliminated as a variable. However, they are being included in new testing.

30. Several participants commented on the lack of standardization of tires for testing. Testing was done using a variety of aircraft types and tires with different tread depths, etc. Al Mazur explained that tests done a few years ago suggested that tires did not make much difference. However, it is recognized that since then tires have changed considerably and most vehicles are now equipped with ABS and front-wheel drive.

SESSION 3 – AIRCRAFT PERFORMANCE ON CONTAMINATED RUNWAY SURFACES

Aircraft Takeoff Performance on Contaminated Runways

31. Jim Martin, Flight Test Engineer, Aircraft Certification, Transport Canada, described the takeoff performance model, which is capable of representing a wide range of transport category aircraft and runway conditions.

32. This model was developed under the sponsorship of the JWRFMP. It can be used to examine the relative effects of various parameters on the takeoff performance of sample

aircraft. However, Mr. Martin cautioned that the data cannot replace aircraft flight manual (AFM) data from the manufacturer.

33. In response to a query, Mr. Martin said that no airline had used the takeoff performance program. He suggested that the airlines should follow the AFMs supplied by the manufacturer. Each aircraft manufacturer has a similar model, but these are not in the public domain. As previously stated, the model could be used to assess the relative effects of different parameters.

Operations on Contaminated Runways – Harmonization of FAR/JAR Operating Rules

34. Don Stimson, Flight Test Engineer, U.S. Federal Aviation Administration (FAA), spoke about the activities of the Aircraft Performance Harmonization Working Group, chartered in November 1997 to harmonize the performance-related operating rules for JAR-OPS1 and Federal Aviation Regulation (FAR) Parts 121-135. The working group has members from regulatory authorities, aircraft manufacturers, aircraft operators, and pilots' associations from the U.S., Europe, and Canada.

35. While JAA contaminated runway requirements include engine failure accountability for takeoff and takeoff weight limitations for forecast landing conditions, the FAR does not have specific requirements concerning contaminated runways.

36. Although the working group has not yet reached a consensus on the harmonization of requirements, the majority support the Joint Aviation Regulations (JAR) takeoff requirements and in-flight check for landing suitability.

37. The stumbling block to a consensus appears to be economics (e.g. off-loading of payload). The goal is to reduce payload penalty. The working group is preparing recommendations.

38. Addressing the question of whether more accurate reporting of runway conditions would be useful, Mr. Stimson suggested that while that would help, other variables must be considered. For instance, slush presents a more complex problem. Its thickness, water content, and specific gravity have to be considered, as they also contribute to slush drag. In addition, the maintenance level of the surfaces changes over time.

39. In response to further questions on slush, Mr. Stimson suggested that it is extremely useful to measure slush drag. However, the lack of suitable technology to measure it in a dynamic environment poses a problem. He suggested that IMAPCR participants should insist on more research and data in this area.

40. As to the question of whether airport operators were members of the working group, Mr. Stimson responded in the negative. He added, however, that the airport operators have been working together on these issues.

Predicting Aircraft Stopping Distance – Another Approach

41. Oddvard Johnsen, retired pilot, Norway, highlighted the problems of inconsistent approaches, e.g.:
   - aircraft certification FAA FAR Part 25 uses 0.8 μ for balanced field length (BLF);
   - ICAO Annexes are only advisory and are to be used as recommendations. However, some countries have chosen to use them as rules;
   - FAA Advisory Circulars AC 150/5320 (measurement, construction, and maintenance of skid-resistant airport pavement surfaces) uses ASTM as reference, although ASTM itself has not ratified friction measurement equipment usage.

42. Mr. Johnsen said he thought that very little relationship existed among the above. Rules and regulations based on ASTM standards lag far behind R&D and current R&D must be harmonized with aircraft operations.

43. Mr. Johnsen presented two models:
   - model for tire footprint appearance on contaminated surfaces (zone 1: frozen microstructure, zone 2: transition – frozen/melted ice, and zone 3: melted snow/ice);
   - Horne model of tire aquaplaning (zone 1: bulk fluid – drainage through macrostructure, zone 2: thin fluid film – drainage through microstructure, and zone 3: dry contact region).

44. When asked whether the three-zone model was universal and whether ice is broken through (melted) in zone three, Mr. Johnsen replied in the affirmative to both questions.

45. Mr. Stimson of the FAA observed that FAA FAR Part 25 does not specify μ of 0.8 for wet surfaces. The 0.8 μ refers to dry runway. Part 25 states that the measured μ after a flight test should be used. Aircraft manufacturers sometimes use μ of 0.45.

46. Mr. Johnsen agreed, but indicated that inconsistencies remained, as outlined in his preamble.

Determination of Aircraft Landing Distance on Winter Contaminated Runways

47. John Croll, Research Test Pilot, National Research Council Canada, presented a methodology for determining landing distance on winter contaminated runways based upon flight test data (μ braking of various aircraft).

48. Good correlation was found between Falcon 20 μ braking and CRFI on runway surfaces with uniform contaminant distribution. While more limited tests were undertaken with other aircraft, similar correlation was found between μ braking coefficients and CRFI. The deceleration model developed from Falcon 20 test results allows prediction of braking distance on contaminated runways. By incorporating safety factors in the computation model based on flight test data, a 95 percent confidence level is achieved.

49. Tables of stopping distances are generated that include the effect of reverse thrust or propeller discing.

50. When asked whether the data could be used for 0°C with melting snow/ice, Mr. Croll indicated that the tables were good for Falcon 20. However, the response from the airlines has been that the tables are conservative.

51. On the question of testing for significance, Mr. Croll suggested that while the distribution was normal, no real test of significance has been applied. He further stated that the methodology developed was not an exact science. The results are presented for guidance only and are applicable to snow and ice. The effect of slush was not known.

52. A question was asked about the legal status. Paul Carson replied that the methodology was published in the Aeronautical Information Publication (AIP). It is for information and guidance only and is not a regulation.

53. Concerning the effect of aircraft size, Mr. Martin observed that the size is not significant – if the methodology is correct.

54. For operational use a hierarchy exists for the use of data, i.e., from AFM to AOM to third party to the AIP.

55. Responding to a question about the obligation of airport operators in Canada to report CRFI, Mr. Mazur informed the audience that no such requirement exists.

Statistical Analysis of Stopping Performance on Wet Runways

56. Ken Balkwill, Consulting Aerodynamicist and Chairman, Performance Committee, ESDU International, U.K., presented a statistical analysis of stopping performance on wet runways.

57. Starting with existing data derived from flight tests, Mr. Balkwill first presented the friction database in graphic form and went on to describe a three-zone physical model and a statistical model.

58. Some of the factors that affect braking on wet runways are:
- speed;
- macro- and micro-texture;
- water depth;
- tire pressure, temperature, and state of wear;
- tire constituents and structure tread pattern;
- braking system efficiency, torque capability, and wheel slip ratio;
- braking effort.

59. The statistical model is based on a simple physical model that may have water depth limitations and a braking system limited only by friction.

60. Mr. Balkwill suggested that the model could be further refined by conducting comprehensive testing of new systems and by extending the methodology to other kinds of contaminants.

Summary of Falcon 20 Contamination Drag Results, 1996 to 1999

61. Jim Martin, Flight Test Engineer, Aircraft Certification, Transport Canada, summarized Falcon 20 contamination drag results spanning four years of tests (1996-1999).

62. Mr. Martin first defined contamination drag and equivalent water depth (EWD) and described test conditions and aircraft configurations. This was followed by:

- analysis method for contamination drag and results;
- analysis method for aircraft braking coefficient and results.

63. Based on 61 data points collected on 18 different loose snow conditions, the aircraft contamination drag results show that:

- although the results are highly variable, a clear trend exists;
- contamination drag (D_{CONTAM}) is a function of equivalent water depth (EWD);
- for the Falcon 20, D_{CONTAM} is negligible below 0.1 inch EWD (approximately 3 mm);
- the D_{CONTAM}/EWD parameter is constant with EWD;
- D_{CONTAM}/EWD is constant with groundspeed;
- for the Falcon 20, D_{CONTAM} / EWD equals 2000lbf/inch;
- JAA AMJ 25X1591 methodology for estimating contamination drag (based on water/slush test) does not appear to be valid for loose snow.

64. Based on 42 data points collected on 12 different loose snow conditions, the aircraft braking coefficient results show that:

- aircraft braking coefficient (μ_B) is constant with groundspeed,
  - while μ_B may be dependent on CRFI, for loose snow conditions, the range of CRFI variation is small;
  - the average CRFI for loose snow = 0.32;
  - the average μ_B for loose snow = 0.17.

65. Mr. Martin concluded by cautioning that the performance measurement on contaminated runway surfaces is not an exact science and that care should be taken with the interpretation of results from a limited number of test points and test conditions.

66. In the question and answer session, disappointment was expressed that while European countries were abandoning the use of EWD for snow, Canada was continuing its use. Disagreement arose with the conclusion that groundspeed has no relationship with μ and also with the overall approach and conclusions. Mr. Martin stated that despite the variability

of the conditions and test results, the data was a significant large set of results on many different runway conditions.

67. Regarding the question of whether year-to-year variations and ground temperatures were factored into the analysis, the answer was that while the information was available on yearly variations, it was not included in the study.

68. A question was asked about the realism of test conditions as compared to "real life". Mr. Martin replied that actual conditions could be less than one half or as little as one quarter of all test conditions.

69. The use of EWD was raised again in view of hydroplaning on water and snowplaning/aquaplaning above 120 kt. Mr. Martin replied that a number of factors were at work.

70. An observation was offered from the floor that tire contact pressure was more important than the tire pressure.

71. On the question of the type of snow used for testing, Mr. Martin replied that for some of the "non real-life" test conditions it was machine-worked snow consisting of very small crystals.

Wrap-up for Tuesday, 2 November 1999

72. In closing the day's session, Mr. Mazur commented that the presentations and queries pointed to the fact that attention must be paid in three areas:
- *Validation of research methodologies and testing*
  - general consensus indicated that more testing, analysis, and validation of results are required in the following areas:
    - different surface conditions;
    - aircraft types;
    - special aircraft operations, such as reverse thrust; and
    - harmonization of ground vehicle types used in testing.
- *Achievement of stated objectives*
  - He stressed the importance of working together to achieve the objectives of the JWRFMP in general and the IMAPCR conference in particular.
- *Partnerships and collaboration*
  - Mr. Mazur emphasized the importance of joint partnerships and support from all stakeholders in providing resources, equipment, and research and analysis facilities to meet these objectives.

Takeoff and Landing on Runways Contaminated by Standing Water, Slush, or Snow

73. Anders Andersson, Senior Engineer, SAAB Aircraft AB, outlined three objectives of the tests:
    - to provide information for takeoff and landing, taking into account runway surface conditions (JAR OPS 1: Single V1 requirement);
    - to review validity of AMJ 25X1591 (supplementary performance information for takeoff from wet runways and for operations on runways contaminated by standing water, slush, loose snow, compacted snow or ice) for small and commuter aircraft;
    - to investigate precipitation drag encountered by an aircraft on contaminated runways with wheels free to roll (no braking).

74. Mr. Andersson outlined the approach and methodology that included theoretical study of spray impingement, analysis of existing data, Citation II tests, intermediate tests, complementary tests, and synthesis.

75. Mr. Andersson concluded by presenting the final synthesis:
    - the flight tested hydrodynamic drag is different from that obtained with the current AMJ formulae;
    - the current AMJ underestimates drag at low speeds, but overestimates it at high speeds;
    - the overestimation at high speeds can be attributed to the fact that the theoretical calculation of aquaplaning speed does not correspond clearly to the peaking of hydrodynamic drag;
    - the updated ESDU data items seem to provide a reasonable estimation of the hydrodynamic drag for the SAAB 2000, although it is very sensitive to the implementation of the geometry;
    - the methodology applied to CITATION II and to Falcon 2000 shows that at low speeds, the drag is underestimated, probably because of an extra drag produced by the main gear bow wave;
    - the EWD concept, as used in the AMJ, is valid down to 0.5 in specific gravity;
    - the speed for maximum hydrodynamic drag was not affected by the specific gravity of wet snow/slush down to 0.5.

76. When asked whether a proof existed for the underestimation of drag at low speeds, Mr. Andersson stated that while Falcon 2000 and Citation II tests show better agreement with the updated AMJ, it is not enough. He thought that the forward spray hitting the wings may be a contributing factor.

77. When asked about the types of tires used, Mr. Andersson said that Dassault had radial tires and Citation II had bias ply tires. Falcon 2000 and Citation have chines on the side wall of the nose wheel.

Contamrunway Snow Tests

78. Marijn Giesberts, Research Engineer, National Aerospace Laboratory (NLR), The Netherlands, stated that the current JAR AMJ 25X1591 is only advisory. It does not provide correct answers for water precipitation drag for smaller types of aircraft. The models are based on the theory of EWD for snow.

79. The objectives of the European Project were to improve the AMJ models concerning:
- precipitation drag of smaller aircraft when operating from runways covered with water, slush, or dry natural snow;
- evaluation of hydroplaning speed and associated effects.

80. Mr. Giesberts stated that because of the physical differences between snow and water, AMJ's theory of EWD is basically wrong. Snow is permeable and porous. It can take on a variety of forms and densities and is thermodynamically unstable.

81. Snow/slush tests were conducted on three aircraft under the following conditions:
- SAAB 2000 at the Malmen Airport (Sweden) with 100 mm of fresh snow (SD [snow density] = 0.1) and 30 mm slush (SD = 0.56);
- NLR CITATION II at the Skavata Airport (Sweden) with 40 mm of fresh snow (SD = 0.125);
- Dassault Falcon 2000 at the Ivalo Airport (Finland) with 100 mm snow (SD = 0.11).

82. The tests show that:
- precipitation drag in natural dry snow at low speeds is substantial because of compression drag;
- no hydroplaning occurs on dry snow;
- the snow drag increases with speed, but is less than what AMJ predicts;
- for SD > 0.5 (slush), precipitation behaves like a fluid;
- dry snow has no impingement on wings or fuselage.

83. Based on the test results, a new theoretical model was developed for predicting spray patterns and impingement drag by the National Aerospace Laboratory (NLR). A new method was also developed for predicting drag due to dry snow. The Engineering Sciences Data Unit (ESDU) spray patterns method (item 83042) was updated and the ESDU model of drag calculation due to impingement (item 98001) was improved.

84. The overall conclusions were:
- the current AMJ 25X1591 underestimates the drag due to water/slush for smaller aircraft;
- the drag by dry snow as predicted by AMJ 25X1591 is incorrect;
- the new NLR model for dry snow drag looks promising;
- the NLR theoretical model for spray prediction and precipitation drag looks promising.

85. Mr. Giesberts concluded by recommending that the NLR method be tested on large aircraft on dry, snow-covered runways. He recommended that further research be carried out on aircraft tire friction on wet and contaminated runways.

86. In response to a question about the specific gravity at which impingement drag would disappear, Mr. Giesberts replied that more testing needed to be done under slush conditions, considering that only one such test was carried out by SAAB.

87. Concerning the use of idle or full thrust, Mr. Giesberts indicated that idle thrust was used since it is well defined. A comment was made that there would still be an aerodynamic effect.

88. An audience member suggested that a common methodology should be formulated for testing and for determination of μ.

89. Mr. Giesberts added that when tests are done at high thrust levels, errors are large and prediction is difficult.

90. A suggestion was made that it was not necessary to know the thrust; other data can be used.

91. Mr. Giesberts indicated that both methods were used and that they agreed very well with each other.

92. Someone observed that it was advantageous to perform the testing with both the nose gear and the main gear (entering and leaving).

A Model for Predicting Rolling Resistance of Aircraft Tires in Dry Snow

93. Gerard W.H. van Es, Research Engineer, National Aerospace Laboratory (NLR), The Netherlands, stated that AMJ 25X1591, a document providing information, guidelines, and recommendations for calculating the rolling resistance of aircraft tires in dry snow, gives unsatisfactory results when compared to experimental data.

94. He then described a new method for predicting the rolling resistance of aircraft tires rolling in dry snow. His mathematical model takes into account resistance due to compression as well as to motion.

95. Mr. van Es then compared the results of both methods with the available experimental results for single tires and for full-scale aircraft.

96. He concluded that, in general, the new method offered much better agreement with the experimental data than the AMJ method offered.

97. Mr. van Es then recommended that the presented method instead of the JAA AMJ 25X1591 be used for predicting the rolling resistance due to dry snow. He added that this new method should be validated, especially with larger aircraft with bogie landing gears.

98. An audience member was surprised at the perfect correlation produced by the model. He inquired about the degree of correlation and accuracy. Mr. van Es offered the following figures:
- standard deviation for the AMJ model: 50-100 percent;
- standard deviation for the NLR model: 20-30 percent;
- R^2 for the AMJ model: 0;
- R^2 for the NLR model: 0.6 – 0.9.

Hydroplaning of Modern Aircraft Tires

99. Mr. van Es stated that most of the current knowledge of hydroplaning was obtained in the 1960s by mainly NASA studies. Since then, new tire types like radials have been introduced for civil aviation and, since hydroplaning of aircraft tires is often a contributing factor in overrun and veer-off accidents, a fresh look at hydroplaning is needed.

100. A distinction was made between dynamic hydroplaning and viscous hydroplaning. Although they can occur simultaneously, the focus of the study was on dynamic hydroplaning, because it is the dominant one.

101. Hydroplaning can occur when the water depth is so high that both the tire tread and the surface macrostructure cannot drain the water sufficiently and quickly.

102. A mathematical model was then presented and hydroplaning characteristics of three different types of aircraft tires were analysed, i.e., bias-ply, type H, and radial belted, each having different footprint dimensions for the same tire size, tire pressure, and load.

103. A comparison was made between the calculated and experimental hydroplaning speeds (vs tire pressure) for the three types of tires.

104. Based on the results, Mr. van Es concluded that modern aircraft tires have lower hydroplaning speeds than those predicted by the well-known and commonly accepted equation developed by Mr. Horne of NASA. He stated that this was because of the differences in the footprint dimensions of the newer tires as compared to the older bias-ply tires.

105. He recommended that these results be validated by conducting systematic tests on the footprint characteristics of modern aircraft tires in combination with hydroplaning tests. He suggested that the Aircraft Landing Dynamics Facility at the Langley Research Center (NASA) be considered for these tests.

106. In response to a question, Mr. van Es added that aspect ratio was included in the model.

107. When asked whether hydroplaning accidents occurred on grooved runways, he responded that such accidents could occur on any runway. Mr. Balkwill (U.K.) added that hydroplaning accidents have occurred on grooved runways in the U.K. and that risk of overrun on non-grooved runways was higher.

What Do We Know about Snow and Ice?

108. Nirmal Sinha of the NRC, Canada, spoke about the need to understand the physical properties of snow and ice, particularly micro-mechanics.

109. He said that a better perspective is obtained when we look at ice forming at 273°K instead of at 0°C.

110. Snow is both elastic and plastic. It is capable of being compacted and deformed.

111. Mr. Sinha indicated that the NRC has developed techniques to look at the micro-mechanics of snow and ice (but not slush). These can be applied to the interaction between the surfaces of tire, snow, ice, and pavement.

SESSION 4 – INTERNATIONAL RUNWAY FRICTION INDEX (IRFI)

112. Tom Yager, Senior Research Engineer, NASA, moderated the discussion on the IRFI.

JAR Regulations on Contaminated Runways, Update – November 1999

113. Graham Skillen, Head of Flight Tests, CAA, U.K., stated that the main areas of work were:
- basic aircraft dispatch;
- advice on braking action for landing.

114. Mr. Skillen first highlighted the sensitivity of contaminant data (how fine, how accurate, how quick) and the factors to be considered (e.g., effort/result and cost/benefit).

115. He stated that the current JAR-OPS poses the problem of high penalties. He suggested that the solution might lie in providing an increased number of alternatives and in relying on in-flight checks.

116. The Joint Aviation Authority (JAA) is dealing with these issues by rewriting AMJ 25X1591 (airworthiness regulation), by contributing to the Performance Harmonization Working Group (ARAC), and by supporting European test work.

117. A rewrite of AMJ 25X1591 items is almost complete. Open items are V_{MCG} and use of reverse thrust.

118. Issues related to braking include:
- shortage of available data, e.g., minimal data for very wet or flooded surfaces, reasonable quantity of data available for snow, some data available for icy surfaces;
- ESDU wet statistical method can be extended to contaminated surfaces;
- low speed (less than 50 kt) flooded testing is helpful;
- controllability is important; high data accuracy is not necessary.

119. Landing braking reports may be summarized as follows:
- ESDU statistical methods are useful;
- drag and friction need to be segregated;
- banding of values leads to accuracy;
- operational flexibility is needed;
- speed and accuracy of measurements are important;
- pragmatism is essential.

120. Mr. Skillen concluded by saying that calculation of effects is at hand. He stressed that operational considerations are important and must not be subordinated to technical purity.

121. A participant agreed that focus on pragmatism, as suggested by Mr. Skillen, was indeed important and highly desirable.

122. The following comments and suggestions were offered from the floor:
- what is needed is good ground sample data that a pilot can use;
- the effects of crosswinds should be in the operating manual;
- wet runways and crosswinds do not make a good combination;
- the flight manual is not wrong – even if the AMJ is wrong;
- the assumption of uniform depth of snow/ice is not realistic.

123. When asked whether a new approval of AMJ was required, Mr. Skillen replied that it was not. The data in the AFM is different from that in the AMJ. Authorities accept the AFM instructions.

124. Mr. Skillen agreed that the contaminant thickness on the runway surface is not uniform. He said, however, that one starts with the assumption of uniform thickness and then applies correction factors.

125. A comment was made about adjustments to V_{mcg} for slippery conditions and crosswinds. Mr. Skillen responded that determining V_{mcg} is tricky and that manufacturers resolve this by adding 6kt in the calculation. He also raised concerns about the assumption of using $V_1=V_R$ to balance the field calculation.

Safety Oversight – ICAO Documents

126. Armann Norheim, Senior Engineer, Norwegian Civil Aviation Administration, stated that the classical friction formula describing linear relationship between the normal load and the horizontal force is not valid for pneumatic tires. It is a more complicated exponential function.

127. Mr. Norheim added that ICAO documents dealing with snow, slush, ice, and water on the movement area are simplistic. Consequently, safety barriers exist for certification and airworthiness of aircraft. He went on to enumerate specific safety barriers:
   - in Annex 8 of ICAO documents (airworthiness of aircraft), no standards or recommended practices related to snow, slush, ice, and water exist;
   - the smooth runway of typical construction is not defined;
   - no guidance is provided for measuring tire wear and incorporating this information into performance calculations;
   - the lower depth limit for contaminants in calculations is different from that for assessment and reporting purposes;
   - the *Airworthiness Technical Manual* and Annex 14 do not have the same definition for slush;
   - the *Preparation of an Operations Manual* gives examples of a direct relationship between aircraft performance and friction measurements. Annex 14 and Airport Service Manual – Pavement Surface Conditions provide information suggesting that there is no general agreement that such a relationship exists;
   - the *Preparation of an Operations Manual* gives examples of a relationship between aircraft performance and friction measurements taken in wet, loose contaminants;
   - the *Airworthiness Technical Manual* does not list friction as a variable under such conditions;
   - the acceptable error $\pm 6\ \mu = 12\ \mu$ represents almost the whole reporting band of 15 μ between "good and poor";
   - the total acceptable uncertainty for a single measurement is not described;
   - the Notice to Airmen (NOTAM) code according to document 8400 does not distinguish between wet snow and slush;
   - the operational significance and relationship to aircraft performance is not addressed for all terms used in the NOTAM and SNOWTAM such as damp, rime or frost covered, frozen ruts, and ridges;
   - the ICAO documentation does not include or categorize all common contamination types relative to airworthiness and operation of aircraft and reporting of surface conditions;
   - the SNOWTAM format and the MOTNE Code do not use the same scale.

128. Mr. Norheim added that deficiencies in ICAO documentation amount to "safety oversight". They were summarized as:
   - for certification and airworthiness of aircraft, Annex 8 includes no standards related to snow, slush, ice, or standing water on the movement area.

- for operation of aircraft, the acceptable uncertainties related to measuring the variables for calculating different tribosystems are not described.
- the ICAO documentation indicates an accuracy for reporting of friction characteristics (wet friction, compacted snow, and ice) that cannot be met because of uncertainties in the measurement methods used.
- the language used in ICAO documents dealing with snow, slush, ice, and water on the movement area is not consistent and does not reflect all types of operational surfaces.

129. To ensure effective implementation of the safety-related Standards and Recommended Practices, Mr. Norheim recommended that ICAO address the discrepancies outlined and that the current knowledge of different scientific disciplines be applied in the updating process.

130. The moderator added that the concern expressed in Mr. Norheim's presentation was shared by those present and that ICAO needs to address and clarify the documentation.

Statistical Methodology for International Runway Friction Index (IRFI)

131. James C. Wambold, CDRM, Inc., State University, Pennsylvania, spoke of two objectives:
- to compile a database containing all available data from winter and summer conditions using different measuring devices, tires, and aircraft tire braking performances;
- to correlate the data to determine a harmonized runway friction index: the International Runway Friction Index (IRFI).

132. Mr. Wambold introduced the concept of a reference device – an arbitrary device that makes use of virtual reference, i.e., using an average of all participating devices (used in the IFI).

133. He then presented a statistical model:
IRFI = a + b DEV
where a & b were calibrated by regressing REF DEV = a + b DEV

134. By regressing and calibrating the formula, an average R^2 of 0.928 was achieved.

135. Mr. Wambold concluded that:
- a reference device for the IRFI is needed;
- the Statistical IRFI has been developed;
- an ASTM Standard has been drafted.

International Runway Friction Index (IRFI) – Validation vs Sensitivity

136. Mr. Wambold stated that the validation method for the IRFI consists of a four-step process:
- all new data are collected in pairs.
- the IRFI constants from the previous year are applied for each paired 100 m and compared to the reference for standard deviation, coefficient of variation, and the root mean square error.
- the data for the present year are then used to calculate the IRFI constants for comparison to the previous IRFI constants.
- the paired data for the current year are combined with all previous paired data, and the IRFI constants are recalculated.

137. In the first effort to validate the harmonization of the statistical IRFI, the IRFI constants, as determined from the 1998 Oslo data, were applied to an independent data set (the 1998 North Bay data).

138. Mr. Wambold concluded that:
- a reference device for the IRFI is needed;
- devices must be calibrated periodically against the reference;
- annual calibration is recommended;
- with a fixed reference, the IRFI is stable;
- the statistical IRFI has acceptable error.

139. Responding to a question about differences in measuring devices, Mr. Wambold stated that they arose from differences in contact pressures.

140. When asked whether the IRFI can be combined with standardized contaminants, Mr. Wambold said that it has been validated for ice, snow, and compacted snow, but not for deep snow.

141. When asked who calibrates the calibrator, Mr. Wambold recommended that two centres each have one master device, but that ideally three devices should be used for cross-reference.

International Runway Friction Index (IRFI) – Virtual Reference vs Real Reference

142. Mr. Wambold further elaborated the concept of a “reference device”.

143. Ideally, a set of reference devices would be designed and built. Virtual references would be an average of all participating devices (used in the IFI) or an average of a limited number of devices (used in 1998-99). An interim reference (2000), loaned by Service technique des bases aériennes (STBA), was used as an arbitrary reference device.

144. To perform a linear regression, a virtual reference device made up of combinations of devices was constructed (IRFI Reference Selection 1998).

145. Mr. Wambold concluded that:

- a reference device for the IRFI is needed;
- STBA device is offered as an interim reference device;
- devices must be calibrated periodically against the reference;
- calibration against the reference device should be carried out annually.

146. When asked whether each device will have its own "a" and "b" in the statistical model IRFI = a + b DEV (even if the devices are of the same make), Mr. Wambold confirmed that each device will have its own unique set of parameters, a and b.

147. Comments were offered from the floor that tires, tire pressures, and load make the difference and not the measuring devices, and that the test surface conditions should be invariable. Mr. Wambold added that all tests were done with standard tire pressure of 100 psi.

Physical Methodology for IRFI

148. Arild Andresen, Mobility Friction Technology, Norway, and Chairman of the ASTM Subcommittee, proposed a standardized test methodology for calculating the IRFI for operational use.

149. The physical methodology for the IRFI comprises a number of fixed surface classes, master models for each friction measuring device, pavement friction differentiated by segment, and computer programs.

150. The advantage of the proposed methodology is that it is based on a universal concept and has potential for higher precision and reproducibility.

151. Identification of friction characteristics by surface classes offers more flexibility and comprehensiveness in making rules, and the methodology can be adapted to differences in wheel-braking performances of different types of aircraft.

152. A comment was offered from the floor that the methodology was interesting, but that slush and dust on ice are missing.

153. Another comment was that drag and friction are different entities; consequently, a dual wheel system may be used for measuring friction and drag separately. Mr. Andresen replied that no such device exists.

154. When asked whether the IRFI will be qualified by surface conditions (e.g., wet pavement), Mr. Andresen replied that calculations will be made, but that only one number will be

reported to the pilot. A suggestion was made that since a single number may refer to an icy surface or to a snow-covered surface, the IRFI plus surface conditions should be reported and that definitions are needed.

155. Other observations from the floor were:
- for heavy aircraft, reporting of texture of ice at or close to 0°C was important – textured ice is less sensitive than polished ice;
- it is important to create standards, but they would be useless if not combined with aircraft – i.e., correlation is needed between the IRFI and aircraft;
- regulatory bodies should play a role in formulating standards;
- a decision should be made on whether standards should be regulatory or advisory.

IRFI Reference Device

156. Jean-Claude Deffieux, Civil Engineer, STBA, France, outlined the following objectives:
- to improve the database;
- to complete harmonization;
- to validate the IRFI.

157. New data were acquired and analysed under surface conditions, as defined in the IRFI concept, with all previously used devices and with a reference device.

158. The reference friction device was chosen from those that are used in the JWRFMP and meet the specified technical requirements.

159. The technical requirements of a reference friction device included measurement mode, braking mode, vibrational stability, test tire, calibration maintenance, acceptable error of measurements, and recording of measurement results.

160. Mr. Deffieux then presented and described the STBA reference device in detail. He added that the device exhibits operational flexibility: it can be set up immediately, it uses an automatic process, and it can provide instantaneous results in real-time visual form.

161. When asked why low wheel load was used in relation to the wheel size, Mr. Deffieux replied that increasing the load would create technical difficulty. The tire size is 64 in. By increasing the load, it would be difficult to run tests on bare runways because of high torque values.

162. It was suggested that to approach higher surface pressure, a bigger tire would have to be made. Mr. Deffieux said that, ideally, the tire should be 2 m, but that the advantage of the current tire is its small size and the fact that it is more sensitive to the runway profile.

163. On a related issue, Mr. Deffieux added that grooved tires were used at all French airports. When ice or snow is on the ground, a low load on the wheel increases the contact pressure

(150 kPa). A comparison was made between smooth and grooved surfaces; no real difference was found.

Joint Winter Runway Friction Test Program Database

164. George Comfort, Senior Engineer, Fleet Technology, Canada, outlined the following objectives:
- to store and organize ground vehicle data, reduced aircraft data, and environment data;
- to contain search routines and to write the search results to external files.

165. The system is based on Windows platform (95/98/NT), Access 97, and 2 MB. The minimum hardware requirements for Windows 95/98 are: 32 MB RAM, Pentium 150 MHz. CPU, and 100 MB hard drive space. For Windows NT, the minimum hardware requirements are: 64 MB RAM, Pentium II 200 MHz. CPU and, 100 MB hard drive space.

166. The database includes ground vehicle data from the following tests:
- North Bay (1996, 1997,1998, and 1999);
- Norway (1998, 1999);
- Sawyer (1999).

167. At present, the database only includes data for the Falcon 20. Inclusion of data for the Boeing 727, 737, and 757, and for the Dash 8 is planned.

168. The database can be searched through the following fields:
- test year and site;
- test number or date;
- type of aircraft;
- type of manoeuvre;
- aircraft configuration;
- braking action;
- speed range;
- surface base type;
- surface condition;
- maintenance action;
- depth of contaminant.

169. The output generates three files:
- aircraft data;
- associated ground vehicle data;
- associated environment data.

170. Mr. Comfort concluded his presentation by saying that the database has been produced and tested, ground vehicle data are essentially complete, but some environmental data are missing.

171. When asked whether this database will be accessible by Internet, Mr. Comfort said that it will be available soon, but first it needs fine-tuning.

172. It was suggested that guidance be provided on the pairing of data – the conventional way of pairing data was not reliable.

173. Mr. Comfort agreed with the suggestion that actual slip ratios be used instead of the manufacturers' slip ratios.

Wrap-up for Wednesday, 3 November 1999

174. In closing the day's session, Mr. Yager remarked that the presentations and discussions indicated clear interest in determining IRFI values and provided valuable suggestions for test planning. He emphasized the vital importance of harmonizing and calibrating all ground friction devices to determine braking performance, passing usable information to the pilot, equating the IRFI to all types of aircraft worldwide, and maintaining and enhancing global support for the program.

175. Mr. Yager said that the issues and concerns raised during the day's presentations indicated that the following actions are needed:
- update and revise AMJ in a pragmatic way, in such areas as the underestimation of hydrodynamic drag at high speeds;
- investigate slush properties and crosswinds and their impact on aircraft braking;
- standardize methodologies;
- study performance using idle and full thrust;
- focus on calibrating IRFI devices and the use of two or three reference devices;
- work on slip ratios;
- study means of equating the IFI with IRFI.

176. Mr. Yager went on to discuss the work on hydroplaning in the Netherlands, the JAR regulations, and related concerns of the airline industry.

177. He commented that the NRL model looked promising. However, he recommended comparison tests with larger aircraft on snow covered surfaces, as well as hydroplaning tests to determine footprint dimensions of modern tires.

178. Mr. Yager talked about the need to revise JAR regulations on contaminated surfaces. This also applies to ICAO documents, which contain quite a few discrepancies, such as no standard definition of contaminants. He recommended that ICAO address these areas to update current knowledge.

179. He recommended that due consideration be given to the aviation industry's concerns about economics pertaining to the variability of the friction coefficient given to the pilot and the impact on payload. Mr. Yager concluded by again asking for guidance and support.

Surface Friction and Index Development

180. Thomas Thorsten Meyer, Operations Manager, Munich International Airport, began by remarking that winter runway conditions are one of the last major safety issues that the airports face. Over 75 percent of aircraft accidents take place near airports and most accidents are due to winter conditions. The key to safety is to provide pilots with the assistance necessary to conduct the flight safely, by recording and reporting runway conditions and communicating them to the pilot. Airport authorities also require this information.

181. Mr. Meyer said that while the program is still an American, Canadian, and Norwegian endeavour, the European Union is interested in close partnership and sponsoring, as evidenced by a friction conference held in Munich in October 1999. He called on airlines to take a more active role in offering their aircraft for tests. The Munich Airport facility will be used to test wide-body aircraft in winter 2000.

182. Mr. Meyer also touched on environmental protection as a critical issue, particularly as it relates to deicing materials used on runways.

183. In response to questions about testing at Munich International Airport, Mr. Meyer said that Lufthansa and Condor Airlines plan to participate in the testing by providing equipment and friction figures from black boxes. The work will be dedicated aircraft testing, performed at night, with in-line crew on board.

184. Other issues raised in the question period related to the use of old technology in measurement devices. Comments were made regarding program support and opportunities to engage manufacturers in the development of new devices and prototypes, as many opportunities are available for their participation.

185. In response to a comment that pressure to use the index might impose a burden on operators who rely on other monitoring methods and experience, Mr. Condon, of the Minneapolis-St. Paul Airport commented that they have been following their own tests and checklists to determine runway and operations safety. They have been using the SAAB continuous friction measurement vehicle to monitor all types of runway conditions, alongside experience and a common sense approach to determine when to shut down runways. This has resulted in fewer and shorter closings and a decrease in the number of incidents. He made the point that many airports are doing things that work without much emphasis on existing regulations and guidance. Mr. Meyer commented that R&D should remain in close touch with the airports to follow up on their practical approaches.

SESSION 5 – FUTURE OF TESTING PROGRAM

186. Tom Yager, Senior Research Engineer, NASA, commented on the future scope and direction of the JWRFMP.

187. He said that the key challenges are harmonization of ground friction measures (currently 13 in use) and relating these measures to an effective index for pilots. Testing on wide-body aircraft is needed. Plans are under way to use UA A320 and possibly military C-17 transports in tests at the Sawyer facility in January 2000. Other areas of research and analysis include reference and master calibration of ground test vehicles, parametric studies for different runway conditions, improved aircraft brake systems, and runway perimeter containment systems.

188. Near-term priorities for the program include establishing the IRFI and getting it approved by the ASTM E17 Committee in December 1999. The reference vehicle testing at North Bay and Sawyer is to be completed in January 2000. Efforts to determine the relationship of the IRFI to aircraft braking performance must be continued. ICAO's support in evaluating and implementing test findings will be required for the universal acceptance of the program.

189. As the current program mandate will end in December 2000, continued international collaboration is required for airlines and airports to collect data, to expand the test procedures and test sites (Munich, Edwards Air Force Base), and to develop additional standards on reference vehicle design and calibration procedures. Mr. Yager proposed that future IMAPCR meetings be held annually, given the widespread interest and involvement expressed at this meeting.

PANEL DISCUSSION

190. Barry Myers, Aviation Winter Operations R&D Program Manager, Transportation Development Centre, Transport Canada, moderated a panel discussion on the future direction of the JWRFP.

191. The following subjects were discussed:
- whether manufacturers/operators should report friction as a direct variable on the performance charts of aircraft
- the degree of importance to a pilot of the operational reporting of a runway friction number
- whether using friction data offers an operational cost advantage
- whether guidelines on airworthiness and operations is required
- whether guidance should be given to operators on when to shut down their airports
- whether an informal working group should be set up to review ICAO working documents

192. Terry Lutz opened the discussion by stressing the need for performance data in aircraft flight manuals (AFM). He noted that, while some aircraft, particularly small aircraft, working for smaller carriers, carry all the performance charts, larger aircraft generally do not. They receive weight information through the Aircraft Communication Addressing and Reporting System (ACARS). What is needed in winter operations is information on runway condition that is equivalent to that provided for wet runways. If that could be achieved, through aggressive measurement and runway clearing and treatment procedures, then pilots could have confidence in this information.

193. Al Mazur questioned whether the AFM have instructions to interpret the friction data to help the pilot land safely. He raised the issue of whether pilots were using friction measures. If they were not being used, are they needed?

194. Terry Lutz responded that friction measures are important and necessary for the pilot to make conditional judgment on safe approaches and taxiing. Jean-Claude Deffieux agreed that it is very important for the pilot to have friction measures, as a visual survey is not adequate.

195. Tom Yager said that airport operators also have a vital interest in having accurate, up-to-date friction information. They can adopt measures to bring friction levels up, such as applying chemicals and grip, or they can close the runway.

196. Panel members agreed on the need to report friction coefficients. Discussion then moved to the best and most efficient ways to report friction. Jim White said that the original reason for CFME (Continuous Friction Measuring Equipment) was not for winter operations particularly, it was for overall maintenance of the airport surface. So only so much value can be extracted from CFME. Mr. Bjorn Bo felt that, given the inaccuracies and variability of reporting (the lack of harmonization between ground and aircraft friction testers, the various types of equipment used, and the dynamic conditions), it might be more useful to report friction descriptively rather than in numbers. He suggested reports be done in terms of good, fair, poor, or nil.

197. Tom Yager said that this system has been in use for the past 20 years and has not been proven useful. Furthermore, he cautioned that qualitative assessments might not be meaningful to pilots who have not had enough experience on wet runways. The descriptive format could also lead to variable interpretations by the pilot or the operator. Classification in ranges is far better than adjectives.

198. Leonard Taylor said that the IRFI should be converted to an index that would incorporate both a qualitative number and a description of the runway. Another participant suggested that a minimum level of friction for safe operations should be established. Paul McGraw countered that airports would not be comfortable with one minimum measure. Armann Norheim said that, as a part of the ICAO documentation, each airport should have a snow

plan based on a dialogue between the major operators of the airport and the airport owner. Such limitations should be taken into account.

199. Graham Skillen suggested that the airport should not make the decisions where information is limited. The final decision should be left to the pilot. Darrel Le Poidvin said that Europe has laws regarding dispatching to contaminated runways, but figures are needed. Some figures indicate that under poor braking action the runway length required increases substantially. Europe also has operational rules regarding crosswinds. Decisions on dispatch and pre-landing check-in are taken on this basis.

200. Mr. Le Poidvin then asked how friction is indicated. He said that aircraft manufacturers supply data for landing length on aircraft braking μs, but one of the biggest questions is how to relate ground vehicle μ to aircraft braking μ. He questioned whether, when that is answered, there will be a temptation to use the actual figure rather than a more conservative one. JAR rules give some indications for braking μs. Some manufacturers give conservative corrections and others rather small ones. He noted that questions remain about every topic discussed at the meeting and warned that right now the important question is what confidence can be placed in the information currently in use.

201. Charles Ayers said that airlines often use only data for dry concrete, because it is not legally required to do otherwise. He added that many operators have spent a lot of energy in delaying such legislation. Therefore, he pointed out, the safety of a flight cannot be guaranteed because pilots are not allowed to use data for contaminated conditions. The data is available from manufacturers and from many airports that are doing their best to provide these tools. However, the legislation is not there on this side of the Atlantic. He asked how the legislative process could be moved along.

202. George Condon briefly described the cumulative information that the Minneapolis/St. Paul Airport uses to provide safe winter operations. Information from pavement conditions guidance systems and wildlife management is combined to provide a complete picture of runway conditions and safe operations. They have achieved a high degree of confidence in the information they monitor. This has resulted in fewer and shorter runway closings.

203. Discussion then moved to the technologies available and the specific limitations of the IRFI.

204. Robert Palmer wondered whether too much effort is being directed at measuring perfect friction levels when runway conditions can change in minutes. He felt the focus of research should be on real-time systems.

205. Pam Walden-Phillips posed a question to aircraft manufacturers about the feasibility of recording real-time information about runway conditions in the cockpit. This information could then be relayed to the tower.

206. Terry Lutz said that software could be developed to correlate μ during an auto braking and anti-skidding sequence for Airbus 320. Since autobraking decelerates at a fixed rate, the distance travelled in that sequence could be used to establish the friction rate. Don Stimson cautioned about the problems of using in-sequence data to derive surface conditions for establishing the ideal friction rate. Jean-Claude Deffieux said that pilots could give valid information based on experience.

207. Jim Wambold talked about a fibre optic system that measures maximum brake friction during cycling. It could be an inexpensive system providing loading and traction information on the aircraft and telemetring friction from the ground vehicles.

208. Tom Yager talked about other options being considered, such as associating runway surface numbers with surface conditions other than just bare and dry, and reporting friction as a percentage of stopping distance. He requested the guidance of the participants in promoting these options among the aviation community.

209. Ernie Tangren felt that information on contaminant drag and crosswinds should be included with the IRFI. He said that one parameter might not be enough to give what the flight crew needs to know about the aircraft's performance. He added that if the industry goes forward with the IRFI, the hope may be that one number will solve the problems, and that this should be reconsidered. Chet Collett mentioned that an airline-specific look-up table might be the ideal format. Jim White countered that the IRFI would not be given as a single number and nothing else, but runway condition reporting could be improved with friction measurements. The IRFI is just one of the numbers to be given and that number would be always on the same scale, not a comparison of apples and oranges.

210. Don Stimson cautioned that the first step is to achieve correlation between ground vehicles and aircraft friction measures. Information must be useful to pilots and airport operators. Even if aircraft performance cannot be determined, the IRFI is a good measure for the airport to maintain safe operations. He said he believed that the program is heading in the proper direction. If nothing else, if IRFI is the end result, that can be of great benefit to the airport operator. He said he would like the work to get as close as possible to the ideal situation of being able to correlate airplane performance. A panel member commented that the Canadian Runway Friction Index was a good first step.

211. Paul Schmid added that to date runways have been categorized, and information has been provided to operators about crosswinds and contaminant drag. What has yet to be improved is aircraft performance correlation to friction, as has been done with the Canadian Runway Friction Index. He said that all aircraft should be tested to get the desired correlation.

212. Charles Ayers wondered whetherTerry Lutz noted that the situation exists today, primarily among the U.S. airlines. Some just do the wet calculations as a conservative way of doing business. For example, the weight that can be carried is the weight for a wet runway, even if the runway is dry. Not all airlines do that. He said that, by legislation, all airlines should be

using wet calculations. Charles Ayers added that while some airlines voluntarily use the wet data, many do not. It is not required, so it's up to the airline. He said that many airlines do not use wet data even when it's wet and that is a problem. Currently no legislation exists in USA or Canada. Al Mazur stated that a working group looking into this issue would meet in December 1999. He recognized that contaminated runways should be addressed.

213. Antil Puronto asked who should deliver friction data – the operator or the manufacturer.

214. George Condon questioned the uniformity of pilot operating manuals, Currently, they describe friction in terms of good, fair, poor, and nil. Variances in interpretation exist from airline to airline on what these terms mean.

215. Armann Norheim referred to the many formats in use today. He recommended that one common language and one format be used. Paul McGraw suggested that a working group be set up to address and review ICAO working documents.

216. Al Mazur informed the participants that an informal group is reviewing Annex #14. Other areas that need review include aircraft performance and operations. A general discussion about the structure and work of the group followed.

217. Arun Rao informed participants that ICAO could not take action at the present time. He talked about the resource conditions and the procedural issues involved. ICAO was willing to form a study group after receiving findings from the ASTM working group. It was proposed that ASTM take up the task. They could work on generic standards first, and on local applications in a second phase.

218. Barry Myers concluded the discussion by proposing that a parallel process is required so that ICAO and ASTM can start working as soon as possible.

219. Al Mazur's concluding remarks summarized the progress made during the meeting and highlighted the issues still outstanding. He indicated that much had been achieved over the past 2½ days. The 1996 meeting set out to harmonize ground friction measures and provide useful information to pilots. This has been achieved, but much more needs to be done. The foremost issue is safety. The accident rates of commercial airlines over the past 20 years have been low. However, the substantial increase in traffic has led to serious concern about higher accident rates. He recommended that efforts be directed towards risk reduction and management so that safety can be further improved.

220. Given that this is the last year of the five-year program, the continuation of the program requires funding and support. The stakeholders need to address the options presented at this conference. Once the IRFI is accepted, efforts should be directed to its implementation.

ACTION PLAN

221. The panel members compiled the following action plan, based on the foregoing discussion:

- Information on winter runway conditions should be equivalent to that provided for wet runways.
- Friction measures are important and necessary for pilots to make conditional judgments on safe approaches and taxiing; the IRFI promises to be of great benefit in helping airport operators maintain safe operations, and the JWRFMP should continue.
- Since CFME (Continuous Friction Measuring Equipment) was originally designed for airport surface maintenance, not winter operations, it may be worthwhile to take a closer look at the harmonization of equipment for winter operations.
- As a part of the ICAO documentation, each airport should have a snow plan based on a dialogue between the major operators of the airport and the airport owner.
- Program partners should promote the establishment of legislation requiring the use of data for contaminated runway conditions.
- Options such as associating runway surface numbers with surface conditions other than just bare and dry, and reporting friction as a percentage of stopping distance, should be considered from the point of view of all stakeholders.
- Work to correlate aircraft performance to friction, similar to that done for the Canadian Runway Friction Index, should continue.
- The JWRFMP partners should apply some political pressure to encourage the use of wet conditions in take-off analysis.
- One common language and format should be used in pilot operating manuals; to this end, a working group should be set up to review ICAO working documents.
- ICAO is to form a study group after receiving findings from the ASTM working group.

CLOSING

222. Mr. Mazur thanked the assembly for their participation and for sharing information.

223. Mr. Yager added that the meeting had renewed enthusiasm for the program and obtained a strong endorsement for its contributions. He sought the guidance of the participants on how to proceed with the outstanding tasks. He asked industry for their continued and active support.

SÉANCE 1 – SÉANCE PLÉNIÈRE D'OUVERTURE

Ouverture de la réunion

1. Al Mazur, chef, Ingénierie de l'évaluation technique, Sécurité des aérodromes, Transports Canada (TC) ouvre la réunion.

2. Art Laflamme, directeur général, Aviation civile, Transports Canada, rappelle que la première réunion IMAPCR a eu lieu les 22 et 23 octobre 1996 à Montréal et réunissait 137 délégués de huit pays. Il souhaite la bienvenue aux 140 délégués de neuf pays présents à cette deuxième réunion IMAPCR, qui se tient de nouveau à Montréal, du 2 au 4 novembre 1999.

3. M. Laflamme formule la vision de Transports Canada, qui est de doter les Canadiens du meilleur réseau de transport au monde. Vol 2005, le nouveau plan de sécurité de Transports Canada, est axé sur la sécurité aérienne et sur le maintien du haut degré de confiance du public à l'égard de l'aviation civile.

4. Le programme PCRGCAH est une initiative quinquennale lancée dans la foulée du Projet de mise en oeuvre de la Commission Dryden. M. Laflamme fait l'historique du programme et énumère ses principales réalisations à ce jour :
   - participation et appui accrus (financiers et en biens et services) des intervenants, dont le nombre est passé de quatre (TC, CNRC, NASA, FAA) à dix (depuis que la Norvège, la France, l'ASTM, l'OACI, le R.-U. et les Pays-Bas se sont greffés au programme);
   - plus grande ouverture des avionneurs, des lignes aériennes et des administrations aéroportuaires à l'égard d'une norme commune de mesure, comme l'IRFI;
   - essais poussés, mettant en jeu une gamme d'avions et de véhicules de mesure au sol, menés à quatre sites : North Bay (Ontario), Hampton (Virginie), Gwinn (Michigan) et Oslo (Norvège);
   - constitution d'une base de données à partir des résultats obtenus lors des essais réalisés avec cinq types d'avions (Falcon 20, Dash 8, Boeing 727, Boeing 737 et Boeing 757), dans diverses conditions;
   - élaboration de projets de normes et démarches en vue de l'établissement et de l'acceptation d'une norme commune, l'IRFI.

5. M. Laflamme se dit satisfait de l'évolution du programme et confirme que TC continuera d'y participer. Il souligne l'importance de ces réunions, au cours desquelles les exploitants, les organismes de réglementation, les chercheurs et les constructeurs peuvent discuter ensemble des problèmes à résoudre et des travaux à entreprendre.

6. Une courte vidéo sur le PCRGCAH est présentée.

Gestion du programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH)

7. Angelo Boccanfuso, agent principal de développement, Centre de développement des transports (CDT), TC, et gestionnaire du projet PCRGCAH, brosse un tableau du programme à ce jour : coûts, structure de gestion, besoins futurs.

8. Les coûts du programme sont passés en revue. Ils comprennent les contributions en biens et services, comme la réalisation des essais, les installations et les analyses. Ce type de contribution provient entre autres de la NASA, de TC, du CNRC, de la FAA, du MDN, de la CAA (Norvège), de la DGAC (France) et de Bombardier Aero Inc. Le programme est constamment à la recherche de nouvelles sources de financement, car les coûts sont trop lourds pour une seule organisation.

9. Le programme est géré par un Comité de direction, dont la présidence est assurée à tour de rôle par six organismes parrains. L'industrie et les gouvernements collaborent à la mise en oeuvre du programme, avec l'aide des comités techniques affectés à chaque projet.

10. Le programme a donné lieu jusqu'à maintenant à la publication de plus de 20 rapports, et 20 autres rapports sont en préparation.

11. Les travaux futurs comportent des essais à l'aide de gros porteurs, l'harmonisation des protocoles d'essai et la mise au point d'un indice de glissance commun.

Revue de l'ordre du jour et des objectifs de la réunion

12. John Maxwell, directeur, Sécurité des aérodromes, mentionne que l'objectif global de IMAPCR '99 est de mieux comprendre et mieux utiliser les mesures de glissance des chaussées aéronautiques et de clarifier leurs liens avec la performance des avions, afin d'accroître la sûreté des opérations aériennes aux aéroports.

13. Il énumère cinq objectifs particuliers de la réunion :
    - passer en revue les résultats des essais du PCRGCAH à ce jour;
    - revoir l'Indice international de glissance des chaussées aéronautiques (IRFI);
    - revoir la méthode de validation et d'analyse de sensibilité de l'IRFI;
    - discuter des avantages d'établir des mesures uniformes de glissance des chaussées aéronautiques en hiver et approfondir le concept d'un chiffre commun pour rendre compte de la glissance des pistes (IRFI);
    - obtenir le soutien et les conseils des milieux internationaux de l'aviation, y compris des autorités de l'aviation civile, en vue du programme d'essai de cet hiver.

14. M. Maxwell signale que les résultats obtenus par le Canada dénotent un progrès réel; mais des obstacles de taille restent à surmonter, qui ont trait aux divergences entre les divers

appareils de mesure du frottement et à la façon de fournir aux pilotes une information précise, qui les aidera à optimiser la performance en freinage de l'avion. Il invite les participants à formuler leurs commentaires sur la suite à donner aux travaux, en se rappelant que les pistes mouillées et glacées figurent au premier rang des causes d'accident à l'atterrissage.

SÉANCE 2 – SOMMAIRE DES ESSAIS DE PERFORMANCE D'AVIONS, 1996-1999

Performance en freinage du Boeing 737 et du Boeing 757 de la NASA

15. Tom Yager, ingénieur de recherche principal à la NASA, expose les faits saillants des essais de performance en freinage réalisés à ce jour à l'aide du Boeing 737 et du Boeing 757. Les essais du Boeing 737 ont eu lieu à North Bay, en 1996, tandis que ceux du Boeing 757 ont eu lieu sur les pistes plus longues de l'aéroport de la base de Sawyer, au Michigan, en février 1999. Vingt-neuf circuits d'essai ont été effectués sur sept états de piste différents, dont : piste sèche, piste rainurée mouillée, piste enneigée (neige folle), piste non rainurée mouillée, piste recouverte de plaques de glace mince, piste enneigée (neige tassée). Vingt-trois circuits d'essai ont été effectués avec le Boeing 737 dans cinq des états de piste. Aucun essai n'a été réalisé sur une «piste dégagée et sèche» et une «piste recouverte de neige fondante».

16. Ces essais ont révélé une performance en freinage du B 757 supérieure à celle du B 737 dans des conditions équivalentes, d'après le coefficient de freinage efficace. Mais la traînée due aux contaminants était semblable pour les deux types d'avions. M. Yager tient à souligner que la collecte et l'analyse des données ne sont pas encore terminées. Des négociations sont en cours en prévision d'essais de gros porteurs qui devraient avoir lieu en Europe. Un rapport sommaire doit paraître en janvier 2000.

17. Des participants s'interrogent sur l'influence des pneus sur la performance en freinage : les deux avions sont en effet équipés de pneus différents par leur poids et leurs dimensions. Les discussions portent également sur les effets de l'épaisseur de la couche de contaminants et de la température extérieure sur la mesure de la traînée, sur l'impact des projections, et sur l'utilisation des systèmes antipatinage. Quelqu'un fait remarquer que la préparation de la neige et son soufflage sur la piste altèrent les caractéristiques des cristaux de neige. Ce à quoi M. Yager répond que les essais récents n'ont eu lieu que sur des surfaces couvertes de précipitations naturelles. Il précise en outre qu'Armann Norheim, Administration de l'aviation civile de Norvège, est à étudier un rapport de l'American Society for Testing and Materials (ASTM) qui pourrait aider à mieux définir les différents contaminants de pistes en hiver.

Performance en freinage du Falcon 20 du CNRC sur des pistes contaminées – 1996 à 1999

18. John Croll, pilote d'essai, Recherche en vol, Conseil national de recherches du Canada, présente le programme d'essai du Falcon 20, qui comprenait un total de 241 circuits d'essai sur plus de 40 états de piste différents (126 circuits visant à mesurer le coefficient de freinage et 115, la traînée due aux contaminants). Ces essais en vol avaient pour but de déterminer l'effet de la traînée due aux contaminants sur les distances de décollage et de décollage interrompu (RTO), l'effet de coefficients de freinage moindres sur les distances d'atterrissage et de RTO, et de corréler la distance d'atterrissage avec le CRFI. Des essais à l'aide de véhicules de mesure au sol ont servi à élaborer des normes IRFI. Quelques coefficients de freinage μ ont été établis pour trois états de piste : glissance modérée (neige tassée), faible glissance (piste dégagée et sèche à 60 p. cent et couverte à 40 p. cent de neige folle) et glissance élevée (glace vive).

19. M. Croll présente plusieurs transparents montrant la corrélation entre le coefficient de freinage μ de l'avion et la vitesse sol, et entre le coefficient de freinage μ du Falcon 20 et le CRFI, et illustrant le taux de glissement des roues du Falcon 20 et la difficulté de guider l'avion sur des surfaces glissantes. Il présente une vidéo qui décrit le programme d'essais, et qui montre des cas où de la neige a pénétré dans les moteurs, causant l'extinction, et deux cas où l'avion a dérivé à côté du tronçon d'essai.

20. Ces essais n'ont révélé aucune fluctuation constante du coefficient de freinage de l'avion en fonction de la vitesse sol. Une bonne corrélation a été observée entre la performance du Falcon 20 et le CRFI, sur des surfaces où les contaminants sont uniformément dispersés. Les chercheurs ont noté une augmentation du taux de glissement des roues en raison inverse de la vitesse sol. Ils ont également enregistré une plus grande difficulté à guider l'avion à basse vitesse, sur des pistes glacées. M. Croll recommande que soient réalisés d'autres essais mettant en jeu des avions et des états de piste différents, y compris des pistes chargées de neige fondante et de fondants chimiques. Les essais futurs du Falcon 20 devraient permettre d'approfondir l'effet de la traînée due aux contaminants et l'effet des vents de travers.

21. Des participants s'interrogent sur l'utilisation de mesures différentes du coefficient de freinage, lors des essais (essais du Falcon et essais de la NASA). M. Croll admet qu'il faut pouvoir fournir aux pilotes des coefficients normalisés. En réponse à d'autres questions, il précise qu'aucun essai n'a été effectué sur des pistes humides ou mouillées, que le dispositif antiblocage de freins (ABS) était désactivé lors des essais et que les inverseurs de poussée n'étaient pas utilisés.

Essais de performance d'un avion Dash 8 sur des pistes chargées de contaminants

22. Edward Lim, chef de la performance, Bombardier Aero Inc., division de Havilland, Canada, présente les résultats des essais réalisés en février 1998 à North Bay. Voici la séquence de ces essais :
   - essais de véhicules de mesure au sol;
   - essais de décollage interrompu et d'atterrissage;
   - contre-essais de véhicules de mesure au sol.

23. L'objectif consistait à déterminer la traînée due aux contaminants et le coefficient de freinage d'un Dash 8 sur trois états de piste : glace rugueuse, glace moyennement lisse, et sable sur glace moyennement lisse.

24. Les essais n'ont révélé aucune traînée appréciable due au déplacement ou à l'impact des projections, sur aucun des trois états de piste. De plus, le coefficient de freinage (en pourcentage du coefficient sur piste sèche) a été établi pour les trois états de surface.

25. En réponse aux questions qui lui sont posées, M. Lim précise qu'un accéléromètre à trois axes a été utilisé en guise de véhicule de mesure au sol. La température extérieure était de -10 °C, et nul n'a constaté que les pneus de l'avion traversaient la couche de glace lors du freinage.

Comparaison de la performance en freinage de différents avions sur des pistes chargées de contaminants

26. Mathew Bastian, ingénieur en logiciel, Institut de recherche aérospatiale, Conseil national de recherches du Canada, expose deux méthodes mises au point pour étudier l'adhérence au freinage et la traînée due aux contaminants lors de l'essai d'un B 727 sur des pistes chargées de contaminants. Les résultats révèlent que la méthode utilisant une jauge extensométrique pour déterminer le frottement de roulement μ est de peu de valeur lorsque le frottement est faible. Le frottement de freinage μ est équivalent à celui obtenu à l'aide du modèle aérodynamique de décélération. Les valeurs de frottement de freinage μ pointent vers une relation linéaire semblable à celle observée avec les autres avions. La traînée due aux contaminants peut révéler un écart par rapport à l'AMJ 2581591.

27. Les résultats préliminaires de performance en freinage du Falcon 20, du Dash 8, du B 737 et du B 757 indiquent ce qui suit :
   - les avions affichent des performances comparables;
   - les systèmes antipatinage montrent une efficacité semblable;
   - les modèles mathématiques confirment l'élimination des effets aérodynamiques propres à l'avion;
   - la relation entre l'adhérence au freinage μ et le CRFI est indépendante du type d'avion.

28. En réponse à une question, M. Bastian précise que le Falcon n'a pas été mis à l'essai dans des conditions de neige fondante / mouillée, mais que les futurs essais incluront ces conditions. On envisage également de produire de la neige fondante à l'aide de fondants chimiques lorsque la température sera propice.

29. Au sujet des inverseurs de poussée, M. Bastian indique que l'on s'est abstenu de les utiliser pour permettre les comparaisons entre avions. Ils seront toutefois utilisés lors des prochains essais.

30. Plusieurs participants s'étonnent que les pneus utilisés pour les essais n'aient pas été normalisés. Les essais mettaient en jeu différents types d'avions et des pneus aux sculptures de profondeurs différentes, etc. Al Mazur explique que selon des essais réalisés il y a quelques années, l'effet des pneus est négligeable. On reconnaît toutefois que les pneus ont considérablement changé depuis et que la plupart des véhicules sont maintenant équipés d'un système ABS et d'une traction avant.

SÉANCE 3 – PERFORMANCES D'AVIONS UTILISANT DES PISTES CHARGÉES DE CONTAMINANTS

Comportement au décollage d'un avion utilisant des pistes chargées de contaminants

31. Jim Martin, surintendant, Essais en vol, Certification des aéronefs, Transports Canada, décrit le modèle de comportement au décollage, capable de représenter un large éventail d'avions de la catégorie transport et d'états de piste.

32. Ce modèle, développé sous l'égide du PCRGCAH, peut être utilisé pour examiner les effets relatifs de diverses variables sur le comportement au décollage d'un avion type. M. Martin prévient toutefois que les données du modèle ne peuvent remplacer celles du manuel de vol de l'avion (AFM), établies par le constructeur.

33. Répondant à une question, M. Martin déclare qu'aucune compagnie aérienne n'a utilisé le programme de modélisation du comportement au décollage. Selon lui, les transporteurs devraient s'en tenir au manuel fourni par l'avionneur. Tous les avionneurs utilisent des modèles semblables, mais ceux-ci ne sont pas du domaine public. Comme mentionné précédemment, le modèle peut être utilisé pour évaluer les effets relatifs des différentes variables.

Opérations sur pistes chargées de contaminants – Harmonisation des règles d'exploitation FAR / JAR

34. Don Stimson, ingénieur d'essais en vol, U.S. Federal Aviation Administration (FAA), donne un aperçu des activités du Aircraft Performance Harmonization Working Group (Groupe de

travail sur l'harmonisation des performances des avions), mis sur pied en novembre 1997 pour harmoniser les règles d'exploitation JAR-OPS1 et les parties 121 à 135 des FAR (Federal Aviation Regulation) touchant les performances des aéronefs. Les membres de ce groupe de travail représentent des organismes de réglementation, des avionneurs, des lignes aériennes et des associations de pilotes des États-Unis, d'Europe et du Canada.

35. Les règles de la JAA sur l'utilisation de pistes contaminées tiennent compte de l'éventualité d'une panne moteur au décollage et fixent des limites de poids au décollage en fonction des conditions prévues à l'atterrissage. En contrepartie, les FAR ne comportent aucune exigence particulière au sujet des pistes chargées de contaminants.

36. Même si aucun consensus ne s'est encore dégagé sur l'harmonisation des règles, la majorité des membres du groupe de travail sont d'accord avec les exigences des Joint Aviation Regulations (JAR) concernant le décollage et avec la nécessité de vérifier en vol l'état des pistes avant l'atterrissage.

37. Le consensus semble achopper sur des enjeux économiques (restriction de la charge utile). Le but est de minimiser ces restrictions. Le groupe de travail se prépare à formuler ses recommandations.

38. Sur la question à savoir s'il serait utile de disposer de comptes rendus plus précis de l'état des pistes, M. Stimson pense que cela pourrait être utile, en effet, mais que d'autres variables doivent aussi être prises en compte. À cet égard, la neige fondante pose un problème relativement complexe. Ainsi, il importe de prendre en considération l'épaisseur, la teneur en eau et la densité de la neige fondante, car ces paramètres influent également sur la traînée due à la neige fondante. De plus, la qualité de l'entretien des pistes n'est pas constante.

39. Réagissant à d'autres questions au sujet de la neige fondante, M. Stimson déclare qu'il est extrêmement utile, certes, de mesurer la traînée due à la neige fondante. Mais le fait qu'on ne dispose pas de technologie pour la mesurer dans un environnement dynamique pose problème. Les participants à la réunion IMAPCR devraient insister pour pousser la recherche et colliger davantage de données sur cette question, estime-t-il.

40. À la question de savoir si des exploitants d'aéroports participent au groupe de travail, M. Stimson répond par la négative. Il ajoute que les exploitants d'aéroports examinent ces questions de leur côté.

Prédiction de la distance d'arrêt des avions - Démarche de rechange

41. Oddvard Johnsen, pilote norvégien à la retraite, met en relief les problèmes soulevés par des démarches incohérentes :

- la partie 25 des FAR de la FAA concernant la certification des aéronefs prescrit une valeur μ de 0,8 pour une longueur de piste équivalente (BLF);

- les annexes de l'OACI sont uniquement consultatives et ne constituent que des recommandations. Mais certains pays en ont fait des règles;
- les circulaires consultatives AC 150/5320 de la FAA (mesure, construction et entretien de chaussées aéronautiques antidérapantes) renvoient aux normes ASTM, même si l'ASTM elle-même n'a pas homologué l'utilisation d'appareils de mesure du frottement.

42. Selon M. Johnsen, les démarches ci-dessus sont passablement décousues. Les règles et règlements fondés sur les normes ASTM accusent un grand retard par rapport à la R&D, et la R&D doit être en prise directe sur les opérations aériennes.

43. M. Johnsen présente deux modèles :
- un modèle de l'aspect des empreintes de pneus sur des surfaces contaminées (zone 1 : microstructures gelées, zone 2 : transition – glace en fusion, et zone 3 : neige/glace fondue);
- le modèle Horne d'aquaplanage (zone 1 : couche épaisse de fluide – écoulement par les macrostructures, zone 2 : couche mince de fluide – écoulement par les microstructures, et zone 3 : zone de contact sèche).

44. Lorsqu'on lui demande si le modèle des trois zones est universel et si la glace est brisée (fondue) dans la zone trois, M. Johnsen répond par l'affirmative aux deux questions.

45. M. Stimson de la FAA fait remarquer que la partie 25 des FAR de la FAA ne prescrit pas une valeur μ de 0,8 pour les surfaces mouillées. Le μ de 0,8 a trait à une piste sèche. Selon la partie 25, il faut utiliser le μ mesuré après un essai en vol. Les avionneurs utilisent parfois un μ de 0,45.

46. M. Johnsen accueille ces nuances mais souligne que des incohérences subsistent, comme il l'a indiqué dans son préambule.

Détermination de la distance d'atterrissage d'un avion sur des pistes chargées de contaminants

47. John Croll, pilote d'essai, Recherche en vol, Conseil national de recherches du Canada, propose une méthode pour déterminer la distance d'atterrissage sur des chaussées contaminées, d'après des données issues de vols d'essai (coefficient de freinage μ de divers avions).

48. Une bonne corrélation a été observée entre le coefficient de freinage μ du Falcon 20 et le CRFI sur des chaussées où les contaminants sont répartis uniformément. Même si les essais à l'aide des autres avions ont été moins poussés, une corrélation semblable a été dégagée. Le modèle de décélération développé à partir des résultats d'essais du Falcon 20 permet de prédire la distance de freinage sur des pistes contaminées. En incorporant un facteur de sécurité au modèle informatique élaboré à partir des données d'essais en vol, on atteint un niveau de confiance de 95 p. cent.

49. Il existe des tables de distances d'arrêt qui tiennent compte de l'effet de l'inversion de poussée ou de la mise des hélices en position «disque».

50. Lorsqu'on lui demande si ces données sont valables pour une température de 0 °C et des pistes couvertes de neige/glace fondante, M. Croll répond que les tables valent pour le Falcon 20. Mais s'il faut en croire les compagnies aériennes, les tables seraient trop prudentes.

51. Au sujet du test de signification, M. Croll souligne que la distribution des données est normale mais qu'aucun test de signification en bonne et due forme n'a été effectué. Il fait en outre remarquer que la méthode utilisée ne relève pas des sciences exactes. Les résultats sont présentés à titre indicatif seulement et ne valent que pour la neige et la glace. L'effet de la neige fondante reste à déterminer.

52. Une question est posée concernant le statut de la méthode sur le plan réglementaire. Paul Carson, inspecteur, Normes opérationnelles, Transports Canada, répond que la méthode a été l'objet d'une Publication d'information aéronautique (AIP). Cela à titre d'information seulement : elle ne constitue pas un règlement.

53. Pour ce qui est de l'effet de la taille de l'avion, M. Martin fait observer que cette variable n'est pas significative – pour peu que l'on puisse se fier à la méthode.

54. Aux fins des opérations, il existe un ordre dans lequel les données doivent être utilisées (du AFM au AOM, à une tierce partie, à l'AIP).

55. Répondant à une question concernant l'obligation des exploitants d'aéroports au Canada de donner le CRFI, M. Mazur indique qu'il n'existe pas de telle obligation.

Analyse statistique des performances d'arrêt sur pistes mouillées

56. Ken Balkwill, expert aérodynamicien et président, Comité des performances, ESDU International, R.-U, présente une analyse statistique des performances d'arrêt des avions sur pistes mouillées.

57. M. Balkwill commence par présenter des données découlant d'essais en vol, avant de proposer une version graphique d'une base de données de coefficients de frottement, et de décrire un modèle physique à trois zones ainsi qu'un modèle statistique.

58. Voici certains des facteurs influant sur le freinage sur pistes mouillées :
    - la vitesse de l'avion;
    - la macro et la microtexture de la piste;
    - l'épaisseur de la nappe d'eau;
    - la pression de gonflage et la température des pneus, et leur degré d'usure;
    - les matériaux constitutifs des pneus et le motif des sculptures;

- l'efficacité du système de freinage, le couple de rotation, et le taux de glissement des roues;
- l'effort de freinage.

59. Le modèle statistique est fondé sur un simple modèle physique auquel on peut appliquer des paramètres de profondeur d'eau et un système de freinage défini uniquement par le frottement.

60. Selon M. Balkwill, il est possible de perfectionner encore le modèle en réalisant des essais approfondis des nouveaux systèmes et en transposant la méthode à d'autres types de contaminants.

Traînée due aux contaminants – Sommaire des résultats – Falcon 20, 1996 à 1999

61. Jim Martin, surintendant, Essais en vol, Certification des aéronefs, Transports Canada, résume les résultats des essais de traînée due aux contaminants réalisés avec le Falcon 20 au cours de quatre saisons d'essais (1996-1999).

62. M. Martin commence par définir la traînée due aux contaminants et la profondeur d'eau équivalente (EWD), puis il décrit les conditions d'essai et les configurations des avions. Il présente ensuite :
    - la méthode et les résultats d'analyse de la traînée due aux contaminants;
    - la méthode et les résultats d'analyse du coefficient de freinage des avions.

63. Après analyse de 61 points de données obtenus dans 18 conditions différentes mettant en jeu une piste couverte de neige folle, voici ce qui est observé au sujet de la traînée due aux contaminants :
    - malgré une grande variabilité des résultats, une tendance claire se dégage;
    - la traînée due à la contamination (D_{CONTAM}) est fonction de la profondeur d'eau équivalente (EWD);
    - pour le Falcon 20, D_{CONTAM} est négligeable lorsque la valeur EWD est inférieure à 0,1 po (environ 3 mm);
    - le paramètre D_{CONTAM}/EWD ne varie pas en fonction de EWD;
    - D_{CONTAM}/EWD ne varie pas en fonction de la vitesse sol;
    - pour le Falcon 20, D_{CONTAM}/EWD est égal à 2000 lbf/po;
    - la méthode JAA AMJ 25X1591, utilisée pour déterminer la traînée due aux contaminants (à partir d'essais dans l'eau et dans de la neige fondante) ne semble pas valide pour la neige folle.

64. Après analyse de 42 points de données obtenus dans 12 conditions différentes mettant en jeu une piste couverte de neige folle, les données relatives au coefficient de freinage de l'avion révèlent ce qui suit :

- le coefficient de freinage de l'avion (μ_B) ne varie pas en fonction de la vitesse sol;
  - μ_B peut être dépendant du CRFI, mais dans des conditions de neige folle, la variabilité du CRFI est faible;
  - le CRFI moyen pour la neige folle = 0,32;
  - le μ_B moyen pour la neige folle = 0,17.

65. En conclusion, M. Martin prévient que la mesure de la performance en freinage sur une piste contaminée n'est pas une science exacte et que les résultats sont sujets à caution, en raison du nombre limité de points de mesure et de conditions d'essais.

66. Au cours de la séance questions-réponses, certains participants se disent déçus que le Canada continue d'utiliser la profondeur d'eau équivalente pour la neige, alors que les pays européens ont abandonné cette pratique. Certains contestent la conclusion selon laquelle la vitesse sol est sans lien avec μ, et contestent aussi la méthode et l'ensemble des conclusions. M. Martin déclare que malgré la variabilité des conditions et des résultats d'essais, les données représentent un vaste ensemble de résultats colligés sur de nombreux états de piste différents.

67. Quant à savoir si on a tenu compte des variations annuelles et des températures sol dans l'analyse, il est précisé que l'information sur les variations annuelles était disponible mais qu'elles n'ont pas été prises en compte.

68. Une question est posée sur le degré de réalisme des conditions d'essai par rapport aux conditions de la «vraie vie». M. Martin répond que les conditions réelles pouvaient représenter moins de la moitié, voire moins du quart, de toutes les conditions d'essai.

69. La question de l'utilisation de la valeur EWD est de nouveau soulevée pour ce qui est de l'aquaplanage sur l'eau et de la perte d'adhérence des pneus sur la neige ou sur l'eau, au-dessus de 120 kt. M. Martin répond que plusieurs facteurs sont alors en jeu.

70. Un participant fait remarquer que la pression de contact des pneus est plus importante que leur pression de gonflage.

71. À une question sur le type de neige utilisée pour les essais, M. Martin répond que pour certaines des conditions d'essai «simulées», il s'agissait de neige travaillée à la machine, faite de très petits cristaux.

Récapitulation des travaux du mardi 2 novembre 1999

72. En clôturant les travaux de la journée, M. Mazur fait observer que les présentations qui ont été faites et les questions qui ont été posées indiquent la nécessité de redoubler d'efforts dans les trois secteurs suivants :

- *Validation des méthodes de recherche et des protocoles d'essai*
  - une idée fait consensus, soit la nécessité de réaliser davantage d'essais, et de pousser l'analyse et la validation des résultats touchant :
    - les différents états de surface;
    - les types d'avions;
    - les conditions d'exploitation spéciales des aéronefs, comme l'inversion de poussée;
    - l'harmonisation des types de véhicules de mesure au sol utilisés lors des essais.
- *Atteinte des objectif fixés*
  - M. Mazur souligne l'importance de collaborer pour atteindre les objectifs du PCRGCAH en général et de la conférence IMAPCR en particulier.
- *Partenariats et collaboration*
  - M. Mazur reconnaît la grande valeur de la coopération et du soutien de tous les intervenants qui fournissent les ressources, le matériel et les installations de recherche et d'analyse essentiels à la réalisation des objectifs du programme.

Essais de décollage et d'atterrissage sur des pistes contaminées par de l'eau stagnante, de la neige fondante ou de la neige

73. Anders Andersson, ingénieur principal, SAAB Aircraft AB, énonce les trois objectifs des essais :
    - recueillir des données concernant le décollage et l'atterrissage, compte tenu de l'état de la piste (exigence JAR OPS 1 : V_1 unique);
    - revoir la validité de l'AMJ 25X1591 (données de performance complémentaires pour le décollage sur pistes mouillées et les manoeuvres sur pistes contaminées par de l'eau stagnante, de la neige fondante, de la neige folle, de la neige tassée ou de la glace) pour des petits avions et des avions de transport régional;
    - étudier la traînée due aux précipitations subie par un avion sur une piste chargée de contaminants, sans freinage.

74. M. Andersson présente la démarche et la méthode de la recherche, qui comprend une étude théorique de l'impact des projections, l'analyse des données existantes, des essais à l'aide d'un Citation II, des essais intermédiaires, des essais complémentaires, et une synthèse.

75. M. Andersson conclut en présentant la synthèse finale des travaux :
    - la traînée hydrodynamique mesurée lors des essais en vol est différente de celle découlant de l'application de la formule AMJ actuellement en vigueur;
    - la formule de l'AMJ sous-estime la traînée aux faibles vitesses, mais surestime celle-ci aux vitesses élevées;
    - la surestimation de la traînée aux vitesses élevées peut être attribuée au fait que le calcul théorique de la vitesse d'aquaplanage ne coïncide pas vraiment avec le maximum de la traînée hydrodynamique;

- les données ESDU mises à jour semblent produire une estimation raisonnable de la traînée hydrodynamique pour le SAAB 2000, même si celle-ci est très sensible à la géométrie de l'avion;
- la méthode appliquée au CITATION II et au Falcon 2000 révèle qu'à faible vitesse, la traînée est sous-estimée, probablement en raison de la traînée supplémentaire produite par la vague à l'avant du train d'atterrissage principal;
- la notion de profondeur d'eau équivalente (EWD), utilisée dans l'AMJ, est valide jusqu'à 0,5 de densité de la contamination;
- la vitesse associée à la traînée hydrodynamique maximale ne varie pas en fonction de la densité de la neige mouillée / fondante, lorsque celle-ci dépasse 0,5.

76. Lorsqu'on lui demande s'il est prouvé que la traînée est sous-estimée aux faibles vitesses, M. Andersson répond que les résultats des essais du Falcon 2000 et du Citation II s'accordent mieux avec l'AMJ révisé, mais cela n'est pas suffisant. Il croit que les projections avant heurtant les ailes peuvent contribuer à la traînée.

77. Lorsqu'on lui demande quels types de pneus ont été utilisés, M. Andersson répond que l'avion Dassault était équipé de pneus à ceinture radiale et le Citation II, de pneus à renfort de carcasse en diagonale. Quant au Falcon 2000 et au Citation, leur atterrisseur avant est équipé de pneus à bavette.

Essais **contamrunway** *sur pistes enneigées*

78. Marijn Giesberts rappelle que la version actuelle de l'AMJ 25X1591 de la JAA est uniquement consultative. Ce document ne fournit pas de réponse précise en ce qui a trait à la traînée due aux précipitations liquides pour les petits avions. Les modèles sont fondés sur le principe qui fait correspondre la neige à une profondeur d'eau équivalente.

79. Les objectifs du projet européen étaient d'améliorer les modèles de l'AMJ concernant :
    - la traînée due aux précipitations exercée sur les petits avions qui utilisent des pistes couvertes d'eau, de neige fondante ou de neige naturelle sèche;
    - l'évaluation de la vitesse d'aquaplanage et des effets connexes.

80. Selon M. Giesberts, les propriétés physiques différentes de la neige et de l'eau enlèvent toute crédibilité à la théorie sur laquelle est fondé l'AMJ. La neige est perméable et poreuse. Plus ou moins dense, elle affecte plusieurs formes et elle est instable sur le plan thermodynamique.

81. Les essais sur piste couverte de neige sèche et de neige fondante mettaient en jeu trois avions, dans les conditions suivantes :
    - SAAB 2000 à l'aéroport de Malmen (Suède), sur 100 mm de neige fraîche (DN [densité de la neige] = 0,1) et 30 mm de neige fondante (DN = 0,56);
    - NLR CITATION II à l'aéroport de Skavata (Suède) sur 40 mm de neige fraîche (DN = 0,125);
    - Dassault Falcon 2000 à l'aéroport de Ivalo (Finlande) sur 100 mm de neige (DN = 0,11).

82. Les essais ont révélé ce qui suit :
- à faible vitesse, la traînée due aux précipitations de neige sèche naturelle est assez importante, car elle s'ajoute à la traînée due à la compression;
- aucun aquaplanage n'a été observé sur la neige sèche;
- la traînée due à la neige augmente en raison directe de la vitesse, mais demeure inférieure aux prédictions de l'AMJ;
- lorsque DN > 0,5 (neige fondante), la précipitation se comporte comme un liquide;
- on n'observe pas de projections de neige sèche qui produiraient un impact sur les ailes ou le fuselage.

83. Le Laboratoire national de recherche aérospatiale (NLR) s'est servi des résultats de ces essais pour élaborer un nouveau modèle théorique pour prédire le comportement des projections et la traînée due au choc des projections. Une nouvelle méthode a également été mise au point pour prédire la traînée due à la neige sèche. La méthode de calcul du comportement des projections de l'Engineering Sciences Data Unit (ESDU) (article 83042) a été mise à jour et le modèle ESDU de calcul de la traînée due au choc des projections (article 98001) a été amélioré.

84. Voici les conclusions de ces travaux :
- l'AMJ 25X1591 actuel sous-estime la traînée due à l'eau et à la neige fondante dans le cas des petits avions;
- la traînée due à la neige sèche prédite par le document AMJ 25X1591 est incorrecte;
- le nouveau modèle NLR pour la traînée due à la neige sèche semble prometteur;
- le modèle théorique du NLR pour la prédiction des projections et la mesure de la traînée due aux précipitations semble lui aussi prometteur.

85. M. Giesberts conclut son exposé en recommandant que la méthode NLR soit mise à l'essai à l'aide de gros porteurs sur des pistes couvertes de neige sèche. Il recommande en outre de poursuivre la recherche sur l'adhérence des pneus d'avions sur des pistes mouillées et chargées de contaminants.

86. En réponse à une question sur la densité à laquelle la traînée due au choc des projections disparaît, M. Giesberts répond qu'il faudra mener d'autres essais sur pistes couvertes de neige fondante. Un seul essai de ce genre a été mené, par SAAB.

87. Concernant l'utilisation de la poussée de ralenti ou de la pleine poussée, M. Giesberts précise qu'on s'est servi de la poussée de ralenti, qui était bien définie. Un participant fait observer que ce type de poussée produit aussi un effet aérodynamique.

88. Selon un participant, il y aurait lieu d'élaborer un protocole commun d'essai pour déterminer la valeur μ.

89. M. Giesberts ajoute que les essais effectués sous poussée optimale débouchent sur des écarts importants et rendent toute prédiction difficile.

90. Selon un participant, il n’est pas nécessaire de connaître la poussée; d’autres données peuvent être utilisées.

91. M. Giesberts souligne que les deux méthodes ont été utilisées et qu’elles concordent très bien.

92. Un participant fait remarquer qu’il est avantageux de réaliser les essais avec l’atterrisseur avant et l’atterrisseur principal (entrée et sortie).

Modèle pour prédire la résistance au roulement des pneus d’avions dans la neige sèche

93. Gerard W.H. van Es, ingénieur chercheur, Laboratoire national de recherche aérospatiale (NLR), Pays-Bas, déclare que le document AMJ 25X1591, qui contient des informations, des lignes directrices et des recommandations sur le calcul de la résistance au roulement des pneus d’avion dans la neige sèche, donne des résultats qui concordent peu avec les données expérimentales.

94. Il expose une nouvelle méthode pour prédire la résistance au roulement des pneus d’avion dans la neige sèche. Son modèle mathématique prend en compte la résistance due à la compression autant qu’au mouvement.

95. M. van Es compare les données issues des deux méthodes avec les résultats expérimentaux découlant d’essais de pneus seuls et d’avions en vraie grandeur.

96. Il conclut que de manière générale, les données découlant de la nouvelle méthode concordent beaucoup mieux avec les données expérimentales que celles résultant de l’application de la méthode AMJ.

97. M. van Es recommande enfin que l’on utilise la méthode qu’il vient d’exposer plutôt que celles du JAA AMJ 25X1591 pour prédire la résistance au roulement due à la neige sèche. Il ajoute que cette nouvelle méthode reste à valider, en particulier avec des avions gros porteurs équipés d’atterrisseurs à bogie.

98. Un participant se dit surpris par la corrélation parfaite produite par le modèle. Il demande des précisions concernant le degré de corrélation et de précision des données. M. van Es donne les chiffres suivants :

- écart type pour le modèle AMJ : 50 à 100 p. 100;
- écart type pour le modèle NLR : 20 à 30 p. 100;
- R^2 pour le modèle AMJ : 0;
- R^2 pour le modèle NLR : 0,6 – 0,9.

Susceptibilité à l'aquaplanage des pneus d'avions modernes

99. M. van Es déclare que la plupart des connaissances actuelles sur l'aquaplanage datent des années 1960 et découlent principalement d'études effectuées par la NASA. Depuis lors, de nouveaux types de pneus, comme les pneus radiaux, ont fait leur apparition dans l'aviation civile et, comme l'aquaplanage des pneus d'avions est souvent un facteur contributif des dépassements et sorties accidentelles de piste, il importe de jeter un regard neuf sur l'aquaplanage.

100. Une distinction est faite entre l'aquaplanage dynamique et l'aquaplanage visqueux. Même si les deux phénomènes peuvent survenir simultanément, l'étude portait sur l'aquaplanage dynamique, la forme d'aquaplanage la plus courante.

101. Il y a un risque d'aquaplanage lorsque l'épaisseur de la nappe d'eau est telle que la bande de roulement et la macrostructure de la surface de la chaussée ne peuvent évacuer assez d'eau assez rapidement.

102. M. van Es présente un modèle mathématique de même qu'une analyse des caractéristiques d'aquaplanage de trois différents types de pneus d'avions : pneus à renfort de carcasse en diagonale, de type H et à ceinture radiale, chacun laissant une empreinte de dimensions différentes pour la même grosseur de pneu, la même pression de gonflage et la même charge.

103. Une comparaison a été faite entre les vitesses d'aquaplanage calculées et expérimentales (en fonction de la pression de gonflage du pneu), pour les trois types de pneus.

104. Cette comparaison a révélé que les pneus des avions modernes affichent des vitesses d'aquaplanage inférieures aux vitesses prédites par l'équation reconnue et communément acceptée, élaborée par M. Horne de la NASA. Selon M. van Es, cela est dû aux dimensions différentes des empreintes des nouveaux pneus par rapport aux anciens pneus à renfort de carcasse en diagonale.

105. Il recommande que ces résultats soient validés au moyen d'essais systématiques sur les caractéristiques des empreintes des pneus d'avions modernes, concurremment à des essais d'aquaplanage. Il propose enfin d'envisager l'Aircraft Landing Dynamics Facility du Langley Research Center (NASA) pour la tenue de ces essais.

106. En réponse à une question, M. van Es ajoute que le facteur de forme a été pris en compte dans le modèle.

107. Lorsqu'on lui demande si des accidents d'aquaplanage surviennent sur des pistes scarifiées, M. Balkwill (R.-U.) répond que de tels accidents peuvent survenir sur n'importe quelle piste. Il ajoute que des accidents d'aquaplanage sont survenus sur des pistes scarifiées au R.-U., mais que le risque de dépassement de piste est plus grand sur des pistes non scarifiées.

Que savons-nous sur la neige et la glace?

108. Nirmal Sinha du CNRC souligne la nécessité de comprendre les propriétés physiques de la neige et de la glace, notamment leur comportement micromécanique.

109. Selon M. Sinha, on a une meilleure perspective lorsqu'on examine la formation de la glace à 273 °K plutôt qu'à 0 °C.

110. La neige est à la fois élastique et plastique. Elle peut être compactée et déformée.

111. M. Sinha signale que le CNRC a mis au point des techniques pour étudier la micromécanique de la neige et de la glace (mais non de la neige fondante). Ces techniques pourraient être appliquées à l'étude de l'interaction des surfaces (pneus, neige, glace, chaussée) en mouvement relatif.

SÉANCE 4 – INDICE INTERNATIONAL DE GLISSANCE DES CHAUSSÉES AÉRONAUTIQUES (IRFI)

112. Tom Yager, ingénieur de recherche principal, NASA, anime la discussion sur l'IRFI.

Règlements JAR relatifs aux pistes chargées de contaminants – Le point – Novembre 1999

113. Graham Skillen, chef des essais en vol à la CAA, R.-U., cite les principaux secteurs d'intérêt de son équipe :
- les autorisations de base accordées aux avions;
- l'information concernant le freinage à l'atterrissage.

114. M. Skillen souligne d'abord la sensibilité des données sur les contaminants (finesse, précision, rapidité de communication) et les facteurs à prendre en compte (p. ex., efforts-résultats, avantages-coûts).

115. Il déclare que la norme JAR-OPS pose un problème en ce qu'elle impose de lourdes restrictions. Selon lui, la solution pourrait consister à offrir davantage de choix et à accorder davantage d'importance aux vérifications en vol.

116. La Joint Aviation Authority (JAA) tente elle-même d'aplanir ces difficultés en procédant à une refonte du document AMJ 25X1591 (règlement sur la navigabilité), en participant au Groupe de travail sur l'harmonisation des performances (ARAC) et en appuyant les essais réalisés en Europe.

117. La première refonte des articles de l'AMJ 25X1591 achève. Les articles en suspens touchent la V_{MCG} et le recours à l'inversion de poussée.

118. Quelques enjeux relatifs au freinage :
- pénurie de données, p. ex., données minimales sur les surfaces très mouillées ou inondées, quantité raisonnable de données sur les surfaces enneigées, quantité limitée de données sur les surfaces glacées;
- possibilité de transposer aux surfaces chargées de contaminants la méthode statistique de l'ESDU pour les chaussées mouillées;
- utilité des essais à faible vitesse (moins de 50 kt) sur surfaces inondées;
- la manoeuvrabilité de l'avion est importante; il n'est pas nécessaire de disposer de données très précises.

119. Les comptes rendus sur le freinage à l'atterrissage peuvent se résumer comme suit :
- utilité des méthodes statistiques de l'ESDU;
- nécessité de distinguer la traînée et le frottement;
- l'aménagement de plages de valeurs conduit à une plus grande précision;
- besoin de souplesse opérationnelle;
- importance de la rapidité et de la précision des mesures;
- importance d'être pragmatique.

120. M. Skillen conclut son exposé en disant qu'il sera possible très bientôt de calculer les effets de la contamination. Il souligne l'importance des considérations opérationnelles, lesquelles ne doivent pas être subordonnées à la pure technique.

121. Un participant abonde dans le sens de M. Skillen lorsqu'il insiste sur la nécessité d'être pragmatique.

122. Quelques commentaires et suggestions formulés par les participants :
- ce qu'il nous faut, ce sont de bonnes données-échantillons de terrain, qu'un pilote peut facilement utiliser;
- les effets des vents de travers devraient être consignés dans le manuel de vol de l'avion;
- une chaussée mouillée et des vents de travers constituent une combinaison perdante;
- le manuel de vol n'est pas faux – même si l'AMJ est faux;
- l'hypothèse d'une épaisseur uniforme de la couche de neige ou de glace n'est pas réaliste.

123. Lorsqu'on lui demande si l'AMJ devra être approuvé de nouveau, M. Skillen répond par la négative. Les données du manuel de vol de l'avion sont différentes de celles de l'AMJ et les autorités se fient aux instructions du manuel.

124. M. Skillen admet que l'épaisseur des contaminants sur la piste n'est jamais uniforme. Mais on fait l'hypothèse d'une épaisseur uniforme pour appliquer ensuite des facteurs de correction.

125. Par suite d'un commentaire sur le rajustement de la V_{mcg} sur chaussée glissante et par vents de travers, M. Skillen répond que la détermination de la V_{mcg} est complexe et que les constructeurs contournent le problème en ajoutant 6 kt à leurs calculs. Il met également en doute l'hypothèse selon laquelle $V_1=V_R$ pour équilibrer les calculs sur le terrain.

Les documents de l'OACI : des brèches à la sécurité

126. Armann Norheim, ingénieur principal, Administration de l'aviation civile de Norvège, déclare que la formule classique du frottement, qui décrit une relation linéaire entre la charge verticale et la force horizontale, ne peut s'appliquer aux pneumatiques : il faut considérer une fonction exponentielle plus complexe.

127. M. Norheim qualifie de simplistes les documents de l'OACI qui traitent de la présence de neige, de neige fondante, de glace et d'eau sur l'aire de mouvement. D'où les menaces à la sécurité associées à la certification des aéronefs et à la délivrance de certificats de navigabilité. Voici quelques-unes de ces menaces :

- à l'annexe 8 des normes de l'OACI (certificats de navigabilité d'aéronefs), on ne trouve aucune norme ou pratique recommandée reliée à la neige, la neige fondante, la glace et l'eau;
- nulle part n'est définie la piste lisse de construction type;
- aucun conseil n'est donné pour mesurer l'usure des pneus et incorporer cette information aux calculs de performance en freinage;
- la limite inférieure de l'épaisseur de la couche de contaminants utilisée dans les calculs est différente de la valeur utilisée à des fins d'évaluation et de compte rendu;
- le *Manuel technique de navigabilité* et l'annexe 14 n'ont pas la même définition de la neige fondante;
- le document *Rédaction d'un manuel d'exploitation* donne des exemples d'une relation directe entre la performance de l'avion et les mesures du frottement. Mais l'annexe 14 et le Manuel des services d'aéroport, État de la surface des chaussées, contiennent des informations donnant à penser que l'existence d'une telle relation ne fait pas l'unanimité;
- *Rédaction d'un manuel d'exploitation* donne des exemples d'une relation entre la performance de l'avion et les mesures de frottement prises sur une piste chargée de contaminants mouillés et lâches;
- le *Manuel technique de navigabilité* ne considère pas le frottement comme une variable dans de telles conditions;
- l'erreur tolérée, de ±6 µ, soit un intervalle de 12 µ, couvre presque toute l'échelle des valeurs de compte rendu (de 15 µ) qui s'étend entre «bon» et «mauvais»;
- l'incertitude totale, acceptée pour une seule mesure, n'est pas précisée;
- le code des Avis aux navigateurs aériens (NOTAM), selon le document 8400, ne fait pas de distinction entre la neige mouillée et la neige fondante;
- la signification opérationnelle et les liens avec les performances de l'avion ne sont pas décrits pour tous les termes utilisés dans les NOTAM et les SNOWTAM, comme «humide, couvert de givre, ornières gelées, stries»;
- les normes de l'OACI ne traitent pas et ne classent pas tous les types de contamination courants pouvant influer sur la navigabilité et l'exploitation d'un aéronef et sur les renseignements concernant l'état des pistes;
- les SNOWTAM et le code MOTNE utilisent des échelles différentes.

128. Pour M. Norheim, les lacunes des documents de l'OACI constituent des «brèches à la sécurité», qu'il résume comme suit :
- pour la certification d'un aéronef et la délivrance d'un certificat de navigabilité, l'annexe 8 ne comporte aucune disposition concernant la présence de neige, de neige fondante, de glace ou d'eau stagnante sur l'aire de mouvement;
- pour l'exploitation d'un aéronef, les marges d'erreur admises dans la mesure des variables pour le calcul de différents systèmes tribologiques ne sont pas précisées;
- les normes de l'OACI demandent, pour les renseignements sur le frottement (sur surface mouillée, neige tassée et glace) un degré de précision impossible à atteindre, en raison des incertitudes reliées aux méthodes de mesure utilisées;
- les divers documents de l'OACI utilisent une terminologie changeante pour décrire la neige, la neige fondante, la glace et l'eau sur l'aire de mouvement, et ne traitent pas de tous les types de surfaces opérationnelles.

129. Pour garantir une mise en oeuvre réussie des normes et pratiques recommandées en matière de sécurité, M. Norheim recommande que l'OACI corrige les lacunes signalées et mette à jour ses normes en y intégrant les connaissances actuelles des différentes disciplines scientifiques.

130. L'animateur ajoute que l'inquiétude distillée par l'exposé de M. Norheim est partagée par les participants et qu'il est urgent pour l'OACI d'améliorer et de clarifier ses documents.

Méthode statistique utilisée pour déterminer l'Indice international de glissance des chaussées aéronautiques (IRFI)

131. James C. Wambold, CDRM, Inc., State University, Pennsylvanie, énonce ses deux objectifs :
- constituer une base de données contenant toutes les données disponibles sur l'état des pistes en été et en hiver, les différents appareils de mesure, les pneus et les performances en freinage des pneus d'avions;
- établir des corrélations entre ces données afin de déterminer un indice harmonisé de glissance des chaussées aéronautiques, soit l'Indice international de glissance des chaussées aéronautiques (IRFI).

132. M. Wambold présente le concept d'appareil de référence – un appareil choisi arbitrairement qui constitue une référence virtuelle, c.-à-d. qui représente la moyenne de tous les appareils utilisés (pour déterminer l'IFI).

133. Il présente ensuite le modèle statistique suivant :
IRFI = a + b DEV (pour *device* ou appareil)
où a et b sont étalonnés par régression de REF DEV = a + b DEV

134. Par régression et étalonnage de la formule, on obtient un R^2 moyen de 0,928.

135. En conclusion, M. Wambold précise ce qui suit :
- un appareil de référence pour l’IRFI est nécessaire;
- l’IRFI statistique a été mis au point;
- un projet de norme ASTM a été élaboré.

Indice international de glissance des chaussées aéronautiques (IRFI) – Validation/sensibilité

136. M. Wambold expose la méthode de validation de l’IRFI, qui comporte quatre étapes :
- toutes les nouvelles données sont recueillies par paires;
- les constantes IRFI des années antérieures sont appliquées à chaque paire de données obtenues sur un même tronçon de 100 m, et mises en relation avec l’appareil de référence pour ce qui est de l’écart type, du coefficient de variation et de l’erreur-type;
- les données de l’année en cours servent ensuite au calcul de nouvelles constantes IRFI, qui sont comparées aux constantes des années antérieures;
- les paires de données de l’année en cours sont combinées à toutes les paires de données des années antérieures, et les constantes IRFI sont recalculées.

137. Lors des premiers travaux visant à valider l’harmonisation de l’IRFI statistique, les constantes IRFI dérivées des données recueillies à Oslo en 1998 ont été appliquées à un ensemble de données indépendant (les données acquises à North Bay en 1998).

138. M. Wambold conclut sur ce qui suit :
- un appareil de référence pour l’IRFI est nécessaire;
- les appareils de mesure doivent être périodiquement étalonnés au moyen de l’appareil de référence;
- il est recommandé de reprendre l’étalonnage tous les ans;
- grâce à un appareil de référence fixe, l’IRFI sera stable;
- l’IRFI statistique comporte une erreur acceptable.

139. En réponse à une question, M. Wambold précise que les différences entre les appareils de mesure tiennent à une pression de contact plus ou moins grande des pneus.

140. Lorsqu’on lui demande s’il est possible de combiner l’IRFI avec des contaminants normalisés, M. Wambold répond que l’indice a été validé pour la glace, la neige et la neige tassée mais non pour une couche épaisse de neige.

141. À savoir qui étalonnera l’étalon, M. Wambold recommande que deux centres possèdent chacun un appareil étalon, mais idéalement, trois appareils devraient être utilisés pour pouvoir établir des références croisées.

Indice international de glissance des chaussées aéronautiques (IRFI) – Appareil de référence virtuelle et réelle

142. M. Wambold explique plus en détail ce qu'est un «appareil de référence».

143. La méthode idéale consisterait à concevoir et construire une série d'appareils de référence. Ces appareils représenteraient la moyenne de tous les appareils utilisés (pour déterminer l'IFI) ou la moyenne d'un nombre limité d'appareils (utilisés en 1998-1999). Un appareil prêté par le Service technique des bases aériennes (STBA) a été utilisé provisoirement à titre d'appareil de référence arbitraire.

144. Pour effectuer une régression linéaire, un appareil de référence virtuelle combinant plusieurs appareils a été construit (choix de l'appareil de référence IRFI,1998).

145. M. Wambold résume :
- un appareil de référence pour l'IRFI est nécessaire;
- l'appareil du STBA est proposé à titre d'appareil de référence provisoire;
- les appareils doivent être étalonnés périodiquement à l'aide de l'appareil de référence;
- l'étalonnage à l'aide de l'appareil de référence devrait être repris tous les ans.

146. Lorsqu'on lui demande si chaque appareil aura son propre «a» et «b» dans le modèle statistique IRFI = a + b DEV (même si les appareils proviennent du même fabricant), M. Wambold confirme que chaque appareil aura son propre ensemble de paramètres a et b.

147. Des participants font remarquer que les pneus, la pression de gonflage des pneus et la charge constituent les facteurs cruciaux, bien plus que les appareils de mesure, et que l'état des surfaces d'essai devrait demeurer constant. À cela M. Wambold répond que tous les essais ont été réalisés avec des pneus gonflés à 100 lb/po².

Méthode physique utilisée pour établir l'IRFI

148. Arild Andresen, de Mobility Friction Technology, Norvège, et président du sous-comité de l'ASTM, propose un protocole d'essai normalisé pour établir un IRFI opérationnel.

149. Cette méthode comporte des catégories de surfaces bien définies, des modèles types pour chaque appareil de mesure du frottement, des coefficients de frottement distincts selon le tronçon de chaussée, et des programmes informatiques.

150. La méthode proposée a pour avantages de reposer sur un principe universel, d'offrir une meilleure précision que les autres, et d'être reproductible.

151. Le fait de définir les caractéristiques de frottement en fonction de catégories de surfaces offre une plus grande souplesse et une perspective plus globale pour établir des règles, sans

compter la possibilité d'adapter la méthode pour tenir compte des performances en freinage des divers types d'avions.

152. Selon un participant, la méthode est intéressante, mais les conditions de neige fondante et de poussière sur de la glace ont été omises.

153. Un autre participant fait remarquer que la traînée et le frottement sont deux choses; on pourrait donc utiliser un appareil à deux roues pour mesurer séparément le frottement et la traînée. M. Andresen répond qu'il n'existe pas d'appareil de ce genre.

154. Lorsqu'on lui demande si on compte caractériser l'IRFI en fonction de l'état de la surface (p. ex., chaussée mouillée), M. Andresen répond que les calculs seront faits, mais que seulement un chiffre sera communiqué au pilote. Quelqu'un suggère que, comme un même chiffre peut se rapporter aussi bien à une surface glacée qu'à une surface enneigée, on donne au pilote non seulement l'IRFI mais aussi l'état de la surface, auquel cas il faudra normaliser la définition des états de surface.

155. Autres observations formulées par les participants :

- pour les gros porteurs, il est important de connaître la texture de la glace lorsque la température avoisine le point de congélation – une glace rugueuse est moins critique qu'une glace lisse;
- il est important d'élaborer des normes, mais de telles normes seront inutiles si elles ne tiennent pas compte du type d'avion (il importe d'établir des corrélations entre l'IRFI et le type d'avion);
- les organismes de réglementation devraient participer à l'élaboration des normes;
- une décision doit être prise quant au caractère obligatoire ou consultatif des normes.

Appareil de référence IRFI

156. Jean-Claude Deffieux, ingénieur civil, STBA, France, énumère les objectifs de son organisation :

- enrichir la base de données;
- harmoniser les appareils de mesure;
- valider l'IRFI.

157. De nouvelles données ont été recueillies et analysées concernant les états de surface, tels que définis dans le système IRFI, à l'aide de tous les appareils de mesure utilisés précédemment et d'un appareil de référence.

158. L'appareil de référence a été choisi parmi ceux qui sont utilisés par le PCRGCAH et qui répondent aux exigences techniques prescrites.

159. Les exigences techniques d'un appareil de référence pour la mesure du frottement visent le mode de mesure, le mode de freinage, la stabilité vibrationnelle, le pneu d'essai, le maintien de l'étalonnage, l'erreur, qui doit être acceptable, et l'enregistrement des résultats de mesure.

160. M. Deffieux décrit en détail l'appareil de référence du STBA. Il ajoute que l'appareil offre une souplesse exceptionnelle : à pied d'oeuvre en un temps record, il est piloté par un processus automatique, et il donne des résultats instantanés, sur média visuel temps réel.

161. Lorsqu'on lui demande si la faible charge sur la roue est liée à la dimension de la roue, M. Deffieux répond qu'une charge plus lourde créerait des problèmes techniques. Le pneu mesure 64 po. Si on accroissait la charge, il serait difficile de mener des essais sur des pistes dégagées, en raison des valeurs de couple élevées.

162. Un participant suggère que pour augmenter la pression de contact, on utilise un pneu plus gros. À cela M. Deffieux répond qu'idéalement, le pneu devrait mesurer 2 m de diamètre, mais que l'avantage du pneu actuel est qu'il est petit et qu'il est donc plus sensible au profil de la chaussée.

163. Sur une question connexe, M. Deffieux ajoute que des pneus à sculptures sont utilisés à tous les aéroports français. Quand la surface est glacée ou enneigée, une faible charge sur la roue augmente la pression de contact (150 kPa). Une comparaison de pneus lisses et de pneus à sculptures n'a révélé aucune différence significative.

Base de données du Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver

164. George Comfort, ingénieur principal, Fleet Technology, Canada, énumère les objectifs de son entreprise :

- enregistrer et organiser des données de véhicules de mesure au sol, des données d'aéronefs réduites, et des données environnementales;
- exécuter des sous-programmes de recherche et consigner les résultats des recherches dans des fichiers externes.

165. Le système utilise une plate-forme Windows (95/98/NT), Access 97, et 2 MB. Les exigences matérielles minimales pour Windows 95/98 sont : 32 MB de mémoire vive, un processeur Pentium 150 MHz, une unité centrale et 100 MB d'espace disque. Pour Windows NT, les exigences matérielles minimales sont : 64 MB de mémoire vive, un processeur Pentium II 200 MHz, une unité centrale et 100 MB d'espace disque.

166. La base de données comprend les mesures prises à l'aide de véhicules au sol lors des essais menés aux endroits suivants :

- North Bay (1996, 1997,1998, et 1999);
- Norvège (1998, 1999);
- Sawyer (1999).

167. À l'heure actuelle, la base de données ne comprend que les données relatives au Falcon 20. Il est prévu d'y incorporer les données concernant les Boeing 727, 737 et 757 et le Dash 8.

168. Les recherches dans la base de données peuvent se faire selon les critères suivants :
- année et site d'essai;
- numéro ou date de l'essai;
- type d'avion;
- type de manoeuvre;
- configuration de l'avion;
- freinage;
- gamme de vitesses;
- type de surface;
- état de la surface;
- mesure d'entretien;
- épaisseur de la couche de contaminants.

169. Les résultats de la recherche sont répartis en trois fichiers :
- données sur l'avion;
- données sur le véhicule au sol associé;
- données environnementales associées.

170. M. Comfort conclut sa présentation en disant que la base de données est maintenant constituée et qu'elle a été mise à l'essai, que les données concernant les véhicules au sol sont à toutes fins utiles complètes, mais qu'il manque encore des données sur l'environnement.

171. Lorsqu'on lui demande si cette base de données sera accessible par Internet, M. Comfort répond qu'elle le sera bientôt, mais qu'il reste encore des mises au point à faire.

172. Il est proposé que des renseignements supplémentaires soient donnés sur l'appariement des données – la méthode conventionnelle de pairage des données n'est pas fiable.

173. M. Comfort appuie la proposition d'utiliser les taux de glissement réels plutôt que les taux de glissement établis par le constructeur.

Récapitulation des travaux du mercredi 3 novembre 1999

174. Mettant un terme aux travaux de la journée, M. Yager note que les présentations et les discussions de la journée témoignent d'un vif intérêt à l'égard de la détermination de valeurs IRFI et que des suggestions très intéressantes ont été faites pour la planification des essais futurs. Il insiste sur l'importance d'harmoniser et d'étalonner tous les appareils de mesure au sol servant à déterminer l'efficacité du freinage, de communiquer au pilote des renseignements utiles, de générer un IRFI pour tous les types d'avions en exploitation dans le monde, et de maintenir et intensifier l'appui international au programme.

175. Selon M. Yager, à la lumière des sujets abordés et des questions soulevées lors des ateliers de la journée, les tâches suivantes deviennent urgentes :

- mettre à jour et réviser l'AMJ en étant avant tout pragmatique; se pencher notamment sur la sous-estimation de la traînée hydrodynamique à haute vitesse;
- étudier les propriétés de la neige fondante et les vents de travers et leurs effets sur le freinage de l'avion;
- normaliser les méthodes;
- étudier les performances des avions en mode poussée de ralenti et en mode pleine poussée;
- se concentrer sur l'étalonnage des appareils utilisés pour établir l'IRFI et s'en tenir à deux ou trois appareils de référence;
- approfondir les taux de glissement;
- étudier des moyens de mettre l'IFI et l'IRFI en équation.

176. Puis, M. Yager discute des travaux sur l'aquaplanage réalisés aux Pays-Bas, des règlements JAR et des préoccupations de l'industrie aérienne à ce sujet.

177. À titre de commentaire, il ajoute que le modèle du NRL semble prometteur. Il recommande toutefois que soient menés des essais comparatifs avec des gros porteurs sur des surfaces enneigées ainsi que des essais d'aquaplanage, afin de déterminer les dimensions des empreintes des pneus modernes.

178. M. Yager signale la nécessité de revoir les règlements JAR sur les surfaces contaminées. Cette nécessité s'applique aussi aux documents de l'OACI, qui contiennent plusieurs incongruités, comme l'absence de définition type des contaminants. Il recommande que l'OACI corrige ces lacunes pour actualiser les connaissances sur la question.

179. M. Yager recommande en outre que l'on accorde toute l'attention voulue aux préoccupations de l'industrie de l'aviation au sujet des impacts économiques de la variabilité du coefficient de friction donné au pilote et des répercussions de celui-ci sur la charge transportée. Il conclut en réitérant son appel à la coopération pour la poursuite du programme.

Coefficient de frottement et élaboration de l'Index

180. Thomas Thorsten-Meyer, chef de l'exploitation, aéroport international de Munich, fait d'abord remarquer que l'état des pistes l'hiver est l'un des derniers grands enjeux en matière de sécurité auquel les aéroports doivent faire face. Plus de 75 p. cent des accidents d'avions ont lieu à proximité des aéroports et la plupart sont dus aux conditions hivernales. La meilleure garantie de sécurité est d'offrir aux pilotes tous les outils nécessaires pour faire leur travail en toute sécurité, en enregistrant et consignant les données sur l'état des pistes et en communicant cette information au pilote. Les administrations aéroportuaires ont elles aussi besoin de cette information.

181. M. Meyer déclare que le programme demeure une initiative conjointe des États-Unis, du Canada et de la Norvège, mais que l'Union européenne est disposée à y collaborer de près, comme en fait foi la tenue d'une conférence sur le frottement à Munich, en octobre 1999. Il invite les compagnies aériennes à jouer un rôle plus actif en mettant leurs avions à la disposition des chercheurs pour des essais. Quant à l'aéroport international de Munich, il accueillera des essais de gros porteurs à l'hiver 2000.

182. M. Meyer aborde brièvement le sujet brûlant de la protection de l'environnement, particulièrement des effets des produits de déglaçage épandus sur les pistes.

183. En réponse à des questions sur les essais prévus à l'aéroport international de Munich, M. Meyer précise que Lufthansa et Condor apporteront leur concours sous la forme de matériel et de chiffres de frottement enregistrés dans des «boîtes noires». Les essais auront lieu la nuit, à l'aide d'avions spécialisés, avec à bord un équipage en communication avec l'équipe au sol.

184. Les autres sujets abordés au cours de la période de questions ont trait aux technologies anciennes mises en oeuvre dans les appareils de mesure. Des commentaires sont formulés quant au soutien du programme et à la façon d'intéresser les fabricants à la mise au point de nouveaux appareils et prototypes, car il existe pour eux de nombreuses occasions de participation.

185. Selon un commentaire, il n'est pas souhaitable de faire pression sur les exploitants pour qu'ils utilisent l'indice, car cela pourrait représenter un fardeau pour ceux qui préfèrent se fier à d'autres méthodes et à leur expérience. George Condon, de l'aéroport Minneapolis-St. Paul, fait remarquer que les responsables de l'exploitation ont procédé à leurs propres essais et ont élaboré des listes de contrôle pour déterminer la sûreté des pistes et des opérations aéroportuaires. Ils ont utilisé le véhicule de mesure continue du frottement de SAAB pour contrôler tous les types d'états de piste et ils se sont aussi fiés à leur expérience et à leur sens commun pour déterminer à quel moment les pistes doivent être fermées. Il en est résulté des fermetures plus rares et plus brèves et une diminution du nombre d'incidents. M. Condon souligne que nombre d'aéroports adoptent une démarche pragmatique sans trop insister sur les règlements et les lignes directrices en vigueur. M. Meyer ajoute que la R&D devrait être en prise directe sur les aéroports, de façon à garantir l'amarrage entre la théorie et la pratique.

SÉANCE 5 – L'AVENIR DU PROGRAMME D'ESSAIS

186. Tom Yager, ingénieur de recherche principal à la NASA, expose sa vision de l'avenir du programme PCRGCAH.

187. Selon lui, les grands défis qui se posent sont l'harmonisation des appareils de mesure au sol du frottement (il en existe présentement 13) et la transposition des mesures prises par ces appareils dans un indice utile pour les pilotes. Des essais au moyen de gros porteurs

s'imposent. On projette d'utiliser un UA A320 et peut-être des avions de transport militaires C-17 lors d'essais au site de Sawyer en janvier 2000. Parmi les autres secteurs de recherche et d'analyse figurent l'étalonnage de référence et l'étalonnage initial des véhicules de mesure au sol, des études paramétriques des différents états de piste, l'amélioration des systèmes de freinage des avions, et les systèmes de rétention des contaminants au périmètre des pistes.

188. Les priorités à court terme du programme comprennent l'établissement de l'IRFI et l'approbation de celui-ci par le comité E17 de l'ASTM en décembre 1999. Les essais des véhicules de référence à North Bay et à la base de Sawyer doivent se terminer en janvier 2000. Les efforts en vue de définir le rapport entre l'IRFI et l'efficacité de freinage des avions doivent se poursuivre. Il faudra s'assurer de l'appui de l'OACI pour évaluer et mettre en oeuvre les résultats des essais, de façon que le programme suscite l'adhésion de tous.

189. Comme le programme actuel prendra fin en décembre 2000, il importe de s'assurer d'une coopération internationale soutenue, pour disposer des données colligées par les compagnies aériennes et les aéroports, pour développer de nouveaux protocoles d'essai et aménager de nouveaux sites (Munich, base des forces aériennes Edwards) et pour élaborer de nouvelles normes sur la conception et l'étalonnage des véhicules de référence. M. Yager propose que les réunions IMAPCR aient dorénavant lieu tous les ans, compte tenu du vif intérêt et de la forte participation constatés à cette réunion.

DISCUSSION EN GROUPE

190. Barry Myers, agent principal de développement chargé du programme de R&D sur les opérations aériennes hivernales, Centre de développement des transports, Transports Canada, anime une discussion sur l'avenir du PCRGCAH.

191. Les thèmes suivants sont abordés :

- les avionneurs/exploitants doivent-ils consigner le frottement en tant que variable directe sur les graphiques de performance des aéronefs?
- à quel point est-il important pour un pilote qu'on lui donne un chiffre de glissance de la piste?
- dans quelle mesure l'utilisation de données de frottement permet-elle de diminuer les coûts d'exploitation?
- dans quelle mesure est-il nécessaire de publier des lignes directrices sur la navigabilité et les opérations aéroportuaires?
- est-il opportun de donner des directives aux administrations aéroportuaires sur les conditions qui doivent les amener à fermer leurs aéroports?
- y a-t-il lieu de créer un groupe de travail informel pour revoir les documents de travail de l'OACI?

192. Terry Lutz lance la discussion en insistant sur la nécessité de consigner des données de performance dans les manuels de vol des avions (AFM). Il fait observer que certains avions, surtout les petits, exploités par de petits transporteurs, ont toujours à leur bord les graphiques de performance. Mais tel n'est pas le cas, généralement, des gros porteurs, qui reçoivent leur information par l'entremise du système d'échange de données techniques avion-sol en temps réel (ACARS, pour *Aircraft Communication Addressing and Reporting System*). Ce qui est essentiel, lors d'opérations hivernales, c'est de disposer d'une information sur l'état de la piste qui soit équivalente à l'information touchant les pistes mouillées. L'application de procédures énergiques de mesure, de dégagement et de traitement des pistes ferait de cet objectif une réalité et les pilotes pourraient alors se fier à l'information qui leur serait transmise.

193. Al Mazur se demande si l'AFM comporte des instructions sur la façon d'interpréter les données de frottement, pour que le pilote puisse atterrir en toute sécurité. Il se demande aussi si les pilotes utilisent de fait les mesures de frottement. Si elles ne sont pas utilisées, sont-elles nécessaires?

194. Terry Lutz répond que les mesures du frottement sont importantes et nécessaires pour le pilote, pour qu'il puisse énoncer un jugement conditionnel sur des approches et un roulage au sol sûrs. Jean-Claude Deffieux estime lui aussi qu'il est très important pour le pilote de disposer de mesures de frottement, car l'inspection visuelle ne suffit pas.

195. Selon Tom Yager, les exploitants d'aéroports ont aussi tout intérêt à disposer de données précises et à jour sur la glissance des pistes. Il peuvent adopter des mesures pour augmenter les coefficients de frottement, par l'épandage de fondants chimiques et d'abrasifs, ou fermer la piste.

196. Les experts conviennent de la nécessité de rendre compte des coefficients de frottement. La discussion se porte ensuite vers les façons les plus commodes et efficaces pour ce faire. Jim White déclare qu'à l'origine, le CFME (*Continuous Friction Measuring Equipment*) n'a pas été expressément conçu pour les opérations hivernales : il servait à l'entretien général des chaussées aéronautiques. Il faut donc interpréter sous toutes réserves les données obtenues à l'aide du CFME. M. Bjorn Bo estime que, compte tenu des inexactitudes et de la variabilité des comptes rendus (absence d'harmonisation entre les appareils de mesure au sol et embarqués, diversité des appareils utilisés, conditions dynamiques), il serait plus utile de fournir un rapport descriptif de l'état des pistes, plutôt qu'un indice. Il suggère d'utiliser les mots «bon, passable, médiocre, nul».

197. Tom Yager déclare que ce système est en usage depuis 20 ans et que son utilité ne s'est pas encore avérée. De plus, il met en garde contre des évaluations qualitatives, qui risquent d'être vagues pour les pilotes ayant peu d'expérience des pistes mouillées. Un format descriptif pourrait aussi mener à des interprétations variables de la part du pilote ou de l'exploitant. Un classement des pistes sur une échelle est de beaucoup supérieur à une évaluation descriptive.

198. Leonard Taylor indique que l'IRFI devrait être converti en un indice qui intégrerait à la fois une échelle de classement et une description de la piste. Un autre participant suggère que l'on établisse un coefficient de frottement minimal «de sécurité». Mais Paul McGraw estime que les aéroports n'aimeraient pas se voir imposer un tel seuil unique. Selon Armann Norheim, chaque administration aéroportuaire devrait établir et faire approuver par l'OACI un plan neige, après consultation des principales compagnies aériennes utilisant l'aéroport et du propriétaire de l'installation. Les limites ainsi définies devraient être prises en compte.

199. Selon Graham Skillen, l'administration aéroportuaire ne devrait prendre de décision que lorsqu'elle dispose de toute l'information nécessaire. La décision finale devrait revenir au pilote. Darrel Le Poidvin signale qu'en Europe, il existe des lois concernant l'autorisation de décollages et d'atterrissages sur des pistes chargées de contaminants, mais on a besoin de chiffres. Certains chiffres révèlent que lorsque le freinage est peu efficace, la longueur de piste nécessaire augmente substantiellement. Il existe également en Europe des règles d'exploitation touchant les vents de travers. Les autorisations de décoller et d'atterrir sont accordées en fonction de ces règles.

200. M. Le Poidvin s'informe de la manière dont les données de frottement sont communiquées. Il signale que les avionneurs déterminent la longueur de piste nécessaire à l'atterrissage d'après les coefficients de freinage de l'avion, mais la grande question est de définir le lien entre le coefficient de frottement enregistré par les véhicules au sol et le coefficient de freinage de l'avion. Il se demande si, lorsque ce problème aura été résolu, on ne sera pas tenté d'utiliser les chiffres réels plutôt que des chiffres qui laissent une marge de sécurité. Les règles JAR donnent certaines indications concernant les coefficients μ de freinage. Certains constructeurs d'avions ajoutent une bonne marge de sécurité à ces chiffres, tandis que d'autres prévoient une faible marge. Il fait remarquer que tous les thèmes discutés au cours de la réunion suscitent encore des points d'interrogation et prévient que pour l'instant, la question importante est de savoir dans quelle mesure on peut se fier à l'information disponible.

201. Charles Ayers ajoute que souvent, les compagnies aériennes utilisent uniquement les données relatives au béton sec, parce que c'est tout ce qu'exige la réglementation. Il fait également remarquer que de nombreux exploitants ont dépensé beaucoup d'énergie pour retarder une réglementation dans ce sens. Par conséquent, la sécurité d'un vol ne peut être garantie, car les pilotes ne sont pas autorisés à utiliser les données concernant les pistes chargées de contaminants. Ces données sont disponibles auprès des avionneurs et de nombreux aéroports qui font de leur mieux pour fournir ces outils. Toutefois, ceux-ci ne sont pas appuyés par la réglementation, de ce côté-ci de l'Atlantique. Il demande comment on pourrait accélérer le processus législatif.

202. George Condon décrit brièvement la conjugaison d'informations qu'utilise l'aéroport de Minneapolis/St. Paul pour améliorer la sûreté des opérations hivernales. Les données provenant des systèmes d'information sur l'état de la chaussée et des systèmes de gestion de la faune sont combinées pour dresser un tableau complet de l'état des pistes et de la sûreté

des opérations. Les responsables ont acquis un degré élevé de confiance dans ces données. Il en résulte des fermetures de pistes plus rares et plus brèves.

203. La discussion porte ensuite sur le thème des technologies disponibles et sur les limites particulières de l'IRFI.

204. Robert Palmer se demande si on ne consacre pas trop d'efforts à établir des coefficients parfaits, alors que l'état des pistes peut changer radicalement en quelques minutes. Selon lui, la recherche devrait porter sur des systèmes en temps réel.

205. Pam Walden-Phillips demande aux avionneurs s'il est possible d'enregistrer en temps réel l'information sur l'état des pistes dans la cabine de pilotage. Cette information pourrait ensuite être relayée à la tour de contrôle.

206. Terry Lutz répond qu'il serait possible de développer un logiciel pour définir la corrélation entre μ pendant une séquence de freinage automatique et de freinage antipatinage, pour l'Airbus 320. Comme le freinage automatique entraîne un taux fixe de décélération, la distance parcourue dans cette séquence pourrait servir à établir le coefficient de frottement. Don Stimson met en garde contre les problèmes associés à l'utilisation de données en séquence pour en déduire l'état de la surface et établir le coefficient de frottement idéal. Jean-Claude Deffieux déclare que les pilotes pourraient donner une information valide fondée sur leur expérience.

207. Jim Wambold évoque un système à fibres optiques qui mesure le frottement maximal en freinage pendant un cycle. Il pourrait s'agir d'un système peu coûteux pour obtenir des données sur la charge et la traction exercées sur l'avion et pour mesurer à distance le frottement enregistré par les véhicules au sol.

208. Tom Yager énumère d'autres options envisagées, dont celles d'associer à des chiffres les états de piste autres que simplement «dégagée et sèche», et de rendre compte du frottement en tant que pourcentage de la distance d'arrêt. Il demande l'avis des participants quant à l'opportunité de promouvoir ces options dans les milieux de l'aviation.

209. Ernie Tangren estime que l'IRFI devrait prendre en compte la traînée due aux contaminants et les vents de travers. Il s'appuie sur le fait qu'un seul paramètre ne suffit pas toujours à informer suffisamment l'équipage de conduite sur la performance de l'aéronef. Il ajoute que si l'industrie va de l'avant avec l'IRFI, cela pourrait donner l'espoir qu'un seul chiffre résoudra les problèmes : il y a lieu de revoir tout cela. Selon Chet Collett, l'outil idéal serait peut-être un tableau préparé expressément pour chaque compagnie aérienne. Jim White dément que l'on veuille limiter le compte rendu au pilote à l'IRFI seul. Il s'agit plutôt d'améliorer le rapport sur l'état de la piste en l'associant au coefficient de frottement. L'IRFI est seulement un des chiffres à communiquer et ce chiffre serait toujours fondé sur une même échelle (il n'est pas question de comparer des pommes et des oranges).

210. Don Stimson avertit que la première étape consistera à établir une corrélation entre les mesures des véhicules au sol et les mesures obtenues avec les avions. Il est essentiel que l'information soit utile aux pilotes et aux exploitants d'aéroports. Même s'il n'est pas possible de déterminer la performance d'un avion, l'IRFI est un indicateur utile à l'administration aéroportuaire pour garantir la sûreté des opérations. M. Stimson estime par ailleurs que le programme est dans la bonne voie. Même si l'IRFI devait en être le seul aboutissement, il reste que cet indice peut être très précieux pour l'exploitant d'un aéroport. Il ajoute qu'il aimerait que les travaux s'approchent le plus possible de la situation idéale, c'est-à-dire qu'ils mènent à l'établissement d'une corrélation entre les mesures des véhicules au sol et la performance de l'avion. Un expert fait observer que l'Indice canadien de glissance des chaussées aéronautiques (CRFI) est un premier pas prometteur.

211. Paul Schmid ajoute qu'à ce jour, les pistes sont classées selon des catégories, et les exploitants reçoivent de l'information sur les vents de travers et la traînée due aux contaminants. Ce qu'il reste à améliorer, c'est la corrélation de la performance de l'avion avec la glissance, comme on l'a fait dans le cas du CRFI. Tous les avions devraient être mis à l'essai jusqu'à ce que soit obtenu le degré de corrélation souhaité.

212. Charles Ayers fait observer à Terry Lutz que sa suggestion (de fournir une information sur l'état de la piste qui soit équivalente à l'information touchant les pistes mouillées) est déjà un fait accompli, principalement chez les transporteurs américains. Certains ne font les calculs que pour une piste mouillée, voyant là une façon prudente d'agir. Par exemple, la charge qui peut être transportée est la charge sur piste mouillée, même si la piste est sèche. Mais toutes les lignes aériennes n'agissent pas ainsi. Selon M. Ayers, tous les transporteurs aériens devraient être tenus par la loi d'utiliser les calculs pour piste mouillée. Car certaines compagnies utilisent volontairement ces données, mais elles sont minoritaires. Si ce n'est pas une exigence, la compagnie a le choix. De plus, dit-il, de nombreuses compagnies n'utilisent pas les données pour piste mouillée même lorsque la piste est réellement mouillée, ce qui pose clairement problème. Actuellement, il n'existe pas de réglementation à cet égard, ni aux États-Unis, ni au Canada. Al Mazur déclare qu'un groupe de travail chargé d'examiner cette question doit se réunir en décembre 1999. Il reconnaît la nécessité de se pencher sur le problème des pistes chargées de contaminants.

213. Antil Puronto demande qui devrait fournir les données sur le frottement – l'exploitant ou le constructeur?

214. George Condon doute de l'uniformité des manuels de vol. Présentement, ceux-ci décrivent le frottement par des qualificatifs : bon, passable, faible, nul. Il existe donc des différences d'interprétation d'une compagnie à l'autre sur la signification de ces termes.

215. Armann Norheim évoque les nombreux formats en usage aujourd'hui. Il recommande qu'une seule langue et un seul format soient utilisés. Paul McGraw propose la mise sur pied d'un groupe de travail chargé d'examiner cette question et de revoir les documents de travail de l'OACI.

216. Al Mazur informe les participants qu'un groupe informel est à revoir l'annexe 14. Parmi les autres enjeux à examiner figurent la performance de l'avion et les opérations aéroportuaires. Une discussion générale sur la structure et le travail du groupe s'ensuit.

217. Arun Rao informe les participants que l'OACI est dans l'impossibilité d'agir présentement, en raison d'obstacles liés aux ressources et aux procédures en jeu. L'OACI est disposée à créer un groupe d'étude une fois qu'elle aura été saisie des conclusions du groupe de travail de l'ASTM. Il est proposé que l'ASTM assume la tâche : elle pourrait élaborer des normes génériques d'abord, puis, dans un deuxième temps, des applications locales.

218. Barry Myers met un terme à la discussion en évoquant la nécessité d'un processus parallèle, pour que l'OACI et l'ASTM puissent entreprendre le travail dans les plus brefs délais.

219. Dans son mot de clôture, Al Mazur résume les progrès accomplis au cours de la réunion et souligne les questions non encore résolues. Un travail immense a été abattu au cours de ces deux jours et demi. La réunion de 1996 avait pour objectif d'harmoniser les mesures au sol du frottement et de fournir une information utile aux pilotes. Cela a été réalisé, mais il reste beaucoup à faire. La question capitale est la sécurité. Les taux d'accidents des transporteurs aériens ont été faibles ces 20 dernières années. Mais l'intensification du trafic aérien fait craindre une augmentation des taux d'accidents. Il recommande que des mesures soient prises pour réduire et gérer le risque, de façon à améliorer encore la sécurité aérienne.

220. Comme le programme arrive à son terme cette année, il faudra trouver de nouveaux appuis, notamment financiers, pour sa poursuite. Les intervenants devront étudier les options exposées pendant la conférence. Une fois que l'IRFI aura été accepté, les efforts devront être orientés vers sa mise en oeuvre.

PLAN D'ACTION

221. Par suite des discussions, les membres du panel ont défini le plan d'action suivant :

- L'information sur l'état des pistes en hiver devrait être équivalente à celle transmise sur les pistes mouillées.
- Les mesures du frottement sont importantes et nécessaires pour le pilote, pour qu'il puisse énoncer un jugement conditionnel sur des approches et un roulage au sol sûrs; l'IRFI est très prometteur pour les exploitants d'aéroport qui pourront s'en servir pour garantir la sûreté de leurs opérations, et le programme PCRGCAH devrait continuer.
- Comme, à l'origine, le CFME (*Continuous Friction Measuring Equipment*) n'a pas été expressément conçu pour les opérations hivernales (mais pour l'entretien général des chaussées aéronautiques) il pourrait être utile d'examiner de plus près l'harmonisation des appareils de mesure utilisés pour les opérations hivernales.
- Au nombre des documents prescrits par l'OACI, chaque administration aéroportuaire devrait élaborer un plan neige, après consultation des principales compagnies aériennes utilisant l'aéroport et le propriétaire de l'installation.

- Les partenaires au programme doivent promouvoir l'établissement d'une législation exigeant l'utilisation de données correspondant aux états de pistes chargées de contaminants.
- Diverses options, comme le fait d'associer à des chiffres les états de piste autres que simplement «dégagée et sèche», et de rendre compte du frottement en tant que pourcentage de la distance d'arrêt, devraient être envisagées en tenant compte du point de vue de tous les intervenants.
- Il y a lieu de poursuivre les travaux visant à obtenir une corrélation entre la performance de l'avion et le frottement, de la même manière que ceux qui ont mené à l'Indice canadien de glissance des chaussées aéronautiques.
- Les partenaires associés au programme PCRGCAH devraient exercer des pressions politiques pour encourager l'utilisation des données pour piste mouillée pour établir les conditions de décollage.
- Une seule langue et un seul format devraient être utilisés dans les manuels de vol; à cette fin, un groupe de travail devrait être mis sur pied pour revoir les documents de travail de l'OACI.
- L'OACI entend créer un groupe d'étude une fois qu'elle aura été saisie des conclusions du groupe de travail de l'ASTM.

CLÔTURE DE LA RÉUNION

222. M. Mazur remercie les personnes présentes de leur participation et des informations qu'elles ont aimablement mises en commun.

223. M. Yager ajoute que la réunion a ravivé l'enthousiasme à l'égard du programme et reçu un appui de taille pour sa contribution. Il invite les participants à se prononcer sur la façon dont devraient se poursuivre les travaux. Il appelle l'industrie à maintenir son soutien actif au programme.

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Welcome

Art Laflamme
Transport Canada, Civil Aviation
Ottawa, Ontario

Welcome to Montreal and the second International Meeting on Aircraft Performance and Contaminated Runways. I would like to thank you for the invitation to speak to you this morning.

I am encouraged to see the large turnout, because programs such as this one make a valuable contribution to Transport Canada's Civil Aviation goal of having the safest civil aviation system in the world.

We have been looking recently at our objective and focus over the next several years.

The global partnership that is integral to this program will not only create opportunities to build on an already strong safety record for Transport Canada, but also contribute to our collective goal of improving aviation safety worldwide.

One of the recommendations resulting from the Dryden Commission Inquiry into the 1989 accident at Dryden, Ontario, was to work with industry to improve the reporting of runway surface conditions during winter and to provide more meaningful information to pilots.

To comply with this recommendation, in 1996 a joint five-year research testing program was initiated by Transport Canada, the National Research Council Canada, the U.S. Federal Aviation Administration, and the U.S. National Aeronautics and Space Administration.

The program has since grown from these four organizing groups to 10, gaining support and participation from the European aviation community, particularly aviation authorities from France, Norway, Sweden, and now Germany.

The purpose of the program is to enhance the safety of aircraft landing and takeoff on runways contaminated with ice, snow, slush, etc., during winter. The main objectives are to harmonize the output of the various ground friction measuring devices used to report runway friction measurements to pilots and to relate the ground friction value to aircraft braking performance.

Following the first year's tests, a meeting held in October 1996 to discuss the results was attended by the aviation community from Europe and North America, including representatives from the International Civil Aviation Organization (ICAO).

At this meeting it was agreed that the American Society for Testing and Materials (ASTM) would develop a standard against which various ground friction devices could be evaluated when conducting friction tests on identical surfaces. This standard is referred to as the International Runway Friction Index or the IRFI.

Following the development of the ASTM standard, it was also agreed that ICAO would establish a working group to make changes to standards on winter operations and friction measurement.

An ASTM working group to develop the IRFI was officially established in June 1997, chaired by Al Mazur from Transport Canada.

ICAO has indicated they will support the work that will be done by the ASTM until such time as they establish their working group.

Series of tests have been conducted from 1997 to the present, covering three critical manoeuvres: takeoff, landing, and rejected takeoff on a variety of surfaces. Over 13 ground vehicles and five specifically instrumented aircraft types have been used in the program.

The test sites are located in North Bay, Ontario; Virginia; Michigan; and Oslo Airport in Norway.

Transport Canada was instrumental in initiating this joint testing program and continues to provide the necessary leadership to ensure that objectives are met.

Draft standards for the IRFI have now been developed and meetings with the participating civil aviation authorities take place at least twice a year to review progress and ensure that regulatory requirements will be met.

Once the IRFI has been finalized, it will be important to ensure that it is accepted and implemented, in order for the aviation community to operate with much greater safety and productivity in winter conditions.

We cannot underestimate the importance of this conference, which brings together operators, regulators, and researchers to review problem areas and discuss approaches to be pursued.

Your agenda is full and your work this week will no doubt add considerable value to the aviation industry. I appreciate your efforts and offer you my encouragement and support. I wish you luck, and look forward to seeing the results of your work.

Management of the Joint Winter Runway Friction Measurement Program

Angelo Boccanfuso
Transport Canada, Transportation Development Centre
Montreal, Quebec

Transport Canada Transports Canada

Management of the Joint Winter Runway Friction Measurement Program

IMAPCR 99
2nd International Meeting on Aircraft Performance on Contaminated Runways
November 1999

Angelo Boccanfuso
Project Development Officer
Transportation Development Centre

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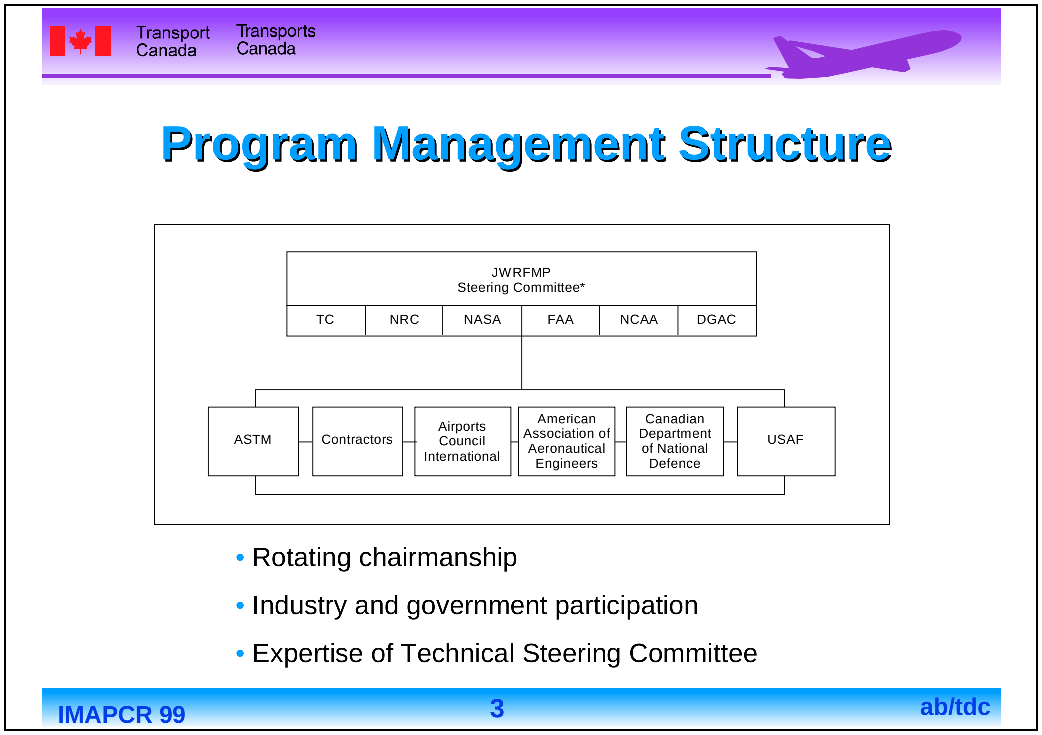
Transport Canada Transports Canada

Presentation Outline

- Program Management Structure
- Program Costs
- Program Reports
- Contributing Organizations
- Future Requirements

IMAPCR 99 2 ab/tdc


Transport Canada
Transports Canada
Program Management Structure
JWRFMP
Steering Committee*
TC
NRC
NASA
FAA
NCAA
DGAC
ASTM
Contractors
Airports Council International
American Association of Aeronautical Engineers
Canadian Department of National Defence
USAF
• Rotating chairmanship
• Industry and government participation
• Expertise of Technical Steering Committee
IMAPCR 99
3
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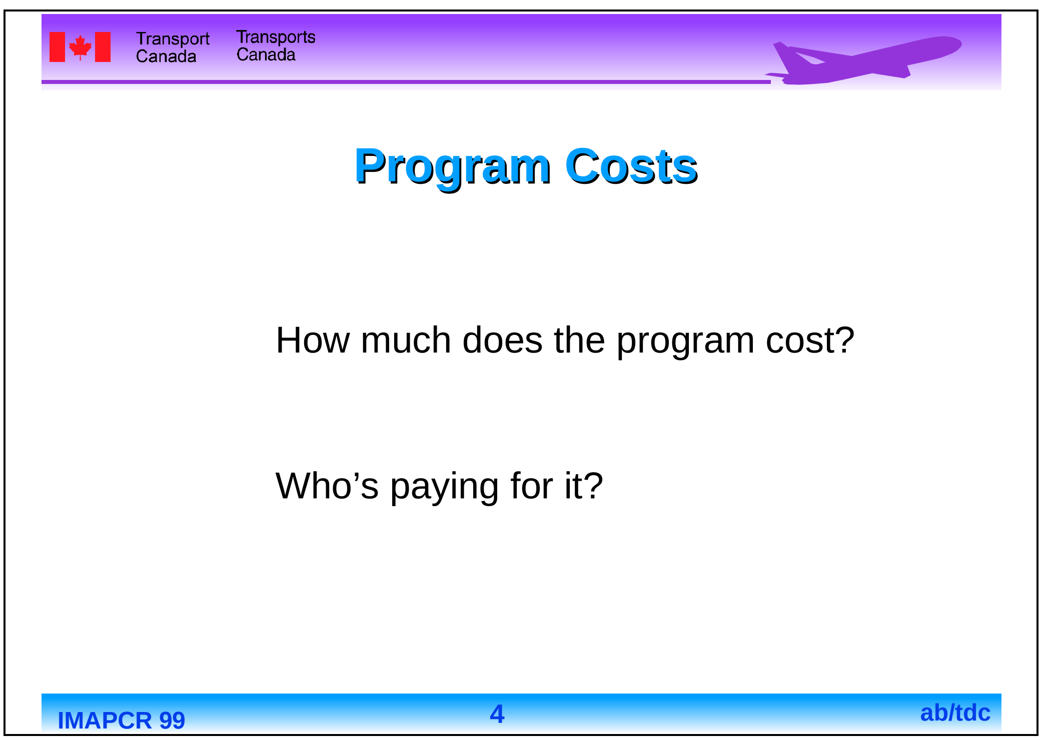
Transport Canada
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Program Costs
How much does the program cost?
Who's paying for it?
IMAPCR 99
4
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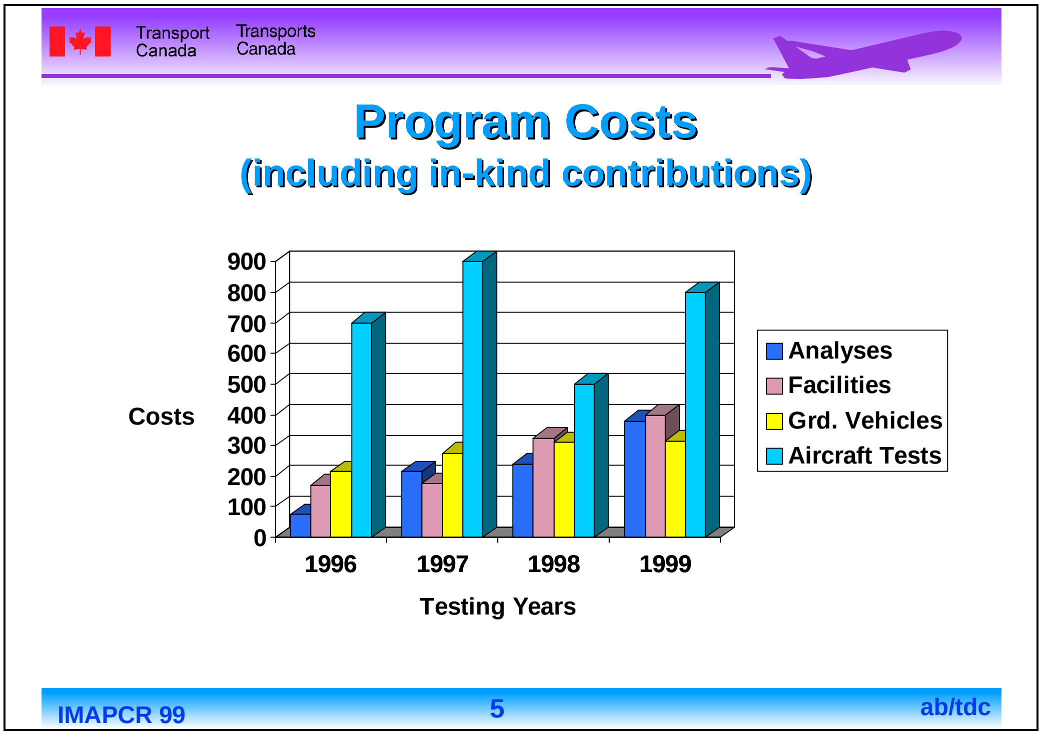
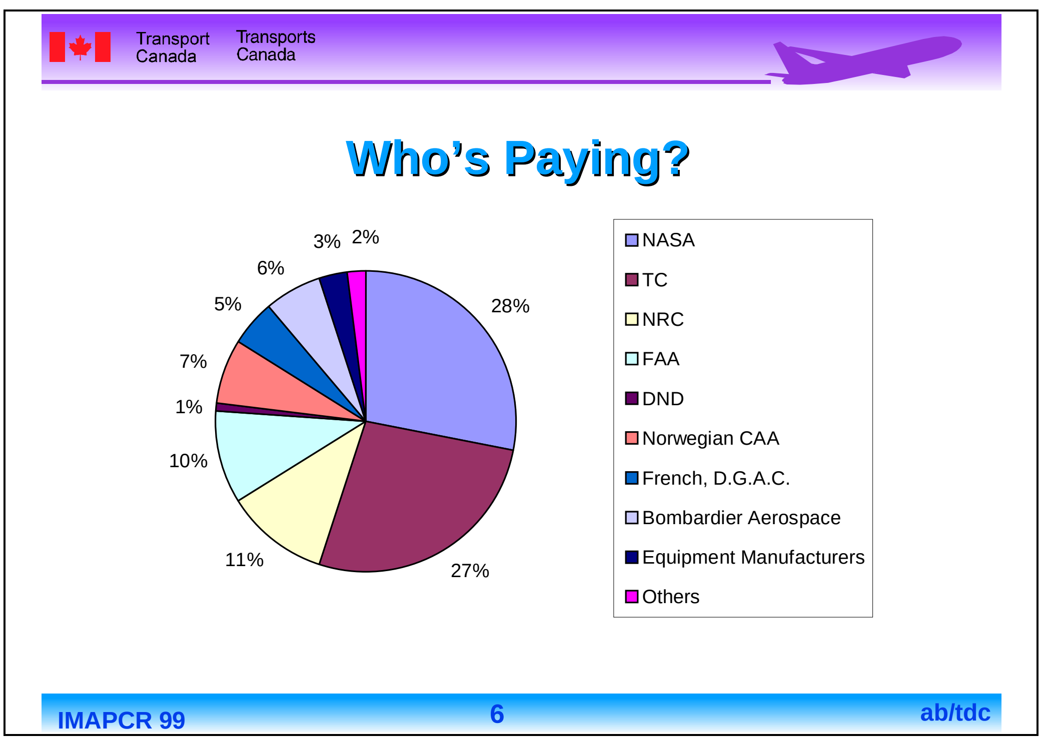

Transport Canada
Transports Canada
Program Costs
(including in-kind contributions)
900
800
700
600
500
400
300
200
100
0
Costs
1996
1997
1998
1999
Testing Years
Analyses
Facilities
Grd. Vehicles
Aircraft Tests
IMAPCR 99
5
ab/tdc


Transport Canada
Transports Canada
Who's Paying?
3%
2%
6%
5%
28%
7%
1%
10%
11%
27%
NASA
TC
NRC
FAA
DND
Norwegian CAA
French, D.G.A.C.
Bombardier Aerospace
Equipment Manufacturers
Others
IMAPCR 99
6
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Program Reports

As of October 29, 1999	
TP number	**Report Title**
TP 12596E	Aeroplane Take-Off and Landing Performance from Contaminated Runways-1995
TP 11966E	Aircraft Take-Off Performance and Risks for Wet and Contaminated Runways in Canada-1994
TP 10888E	Aircraft Take-Off Performance and Risks for Wet and Contaminated Runways in Canada-1991
TP 12866E	Evaluation of Ground Friction Measuring Equipment on Runways and Taxiways under Winter Conditions
TP 13060E LTR-ST-2159	Characteristics of Winter Contaminants on Runway Surfaces in North Bay-January and February-March 1997 Tests
TP 12943	Proceedings of the International Meeting on Aircraft Performance on Contaminated Runways/Compte rendu de la Réunion internationale sur la performance des avions utilisant des pistes chargées de contaminants
TP 13257	Proceedings of the Technical Advisory Group Steering Committee Meeting on Aircraft Performance on Contaminated Runways/ Compte rendu de la réunion du Comité de direction du Groupe de consultation technique sur la performance des aéronefs sur des pistes contaminées

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Transport Canada Transports Canada

Program Reports (cont'd)

As of October 29, 1999	
TP number	**Report Title**
TP 13258E LTR-FR-147	Braking Friction Coefficient and Contaminated Drag of B 727 on Contaminated Runways
TP 13361E	Overview of the Joint Winter Runway Friction Measurement Program
TP 13361F	Survol du Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver
TP 13447E	Evaluation of the Sand Properties Affecting Sand Selection for Airside Applications
TP 13366E	Analysis of the Friction Factors Measured by the Ground Vehicles at the 1998 North Bay Trials
TP 13392E	Laboratory Testing of Tire Friction Under Winter Conditions
TP 13338E LTR-FR-151	Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1997/98
LTR-FR-132	Braking Friction Coefficient and Contamination Drag Obtained for a Falcon 20 Aircraft on Winter Contaminated Runway Surfaces – 1996
IAR-AN-84	Falcon 20 Landing Distances on Winter Contaminated Runways as a Function of the James Brake Index

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Program Reports (cont'd)

As of October 29, 1999	
TP number	**Report Title**
DHC-D4547-97-09	Braking Friction Coefficient and Contamination Drag for the Dash 8 on Winter Contaminated Runways
LTR-FR-130	Flight Validation of Position Accuracies of a Novatel RT-20 Differential GPS Installed in a Falcon 20 Aircraft
TP 12887	Runway Winter Friction Measurement Trials at North Bay Airport: January and March 1996
TP 13338E LTR-FR-137	Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1997/1998
DHC-D4547-98-06	Dash 8 Aircraft Performance Testing on Contaminated Runway Surfaces – Winter 1997/1998
TT 971	Tire-Surface Friction Characteristics of New Pavements 1998
FR-129	First Air B 727-100 Braking Performance on Winter Contaminated Arctic Runway Surfaces

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Program Reports (cont'd)

Upcoming Reports	
	Tribology for Aerospace Systems – Tire/Surface Interaction Ground Vehicle Correlation Report on NASA's Behalf
	Transport Canada Aircraft Certification Flight Test Division: Discussion Paper No. 14 Take-Off Performance Program
	Manual for Tire-Friction Database
	Analyses of Ground Vehicle Friction Data Collected During 1999
	IRFI Computing Tools and Software
	International Runway Friction Index – IRFI – 1999
	Proposed Standard Test Method for Calculating International Runway Friction Index for Operational Use
	The Effect of Vertical Load on Ice, Frozen Snow, and Asphalt
	Laboratory Investigation of Friction on Ice
LTR-FR-158	Falcon 20 Aircraft Performance Testing on Contaminated Runway Surfaces During the Winter of 1998/1999
TP 13331E	Anti-Bonding Performance of Three Runway Chemical De-Icers: Preventive Use
TP 13332E	De-Bonding Performance of Runway Chemical De-Icers: Curative Use

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Acknowledgements

Joint Research Organizations

- **NASA, Langley Virginia**
- **NRC, Flight Research Lab**
- **NRC, Chemical Process and Environmental Technology**
- **FAA, Airports, Atlantic City**
- **DND, USAF**
- **Norwegian Civil Aviation Administration**
- **Direction Générale d'aviation civile, France**
- **Transport Canada, Ottawa**

In-kind contributions

- **First Air, Ottawa**
- **ENSICA, France**
- **Bombardier Aerospace**

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Acknowledgements

In-kind contributions (cont'd)

- **Spar Aerospace**
- **Frontec, Ont.**
- **Canadian Aerospace Group,**
- **ASTM, USA**
- **Griptester, Saab, Ford Taurus**

Contractors

- **Fleet Technologies Ltd., Ottawa**

- **LCPC, France**
- **ESDU, London**
- **CDRM, Pennsylvania**
- **Galaxy, Atlantic City**
- **UQAC, Chicoutimi**
- **MFT, Norway**
- **TES, Ottawa**
- **Sypher: Mueller**
- **Tradewind, Scientific**

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Future Requirements

- Substantial friction data established, but still lack wide-body aircraft friction data
- Data analysis under way to accurately relate an IRFI to an Aircraft Friction Index (AFI)
- Additional tests:
  - contaminant drag
  - slush
  - chemicals
  - crosswinds

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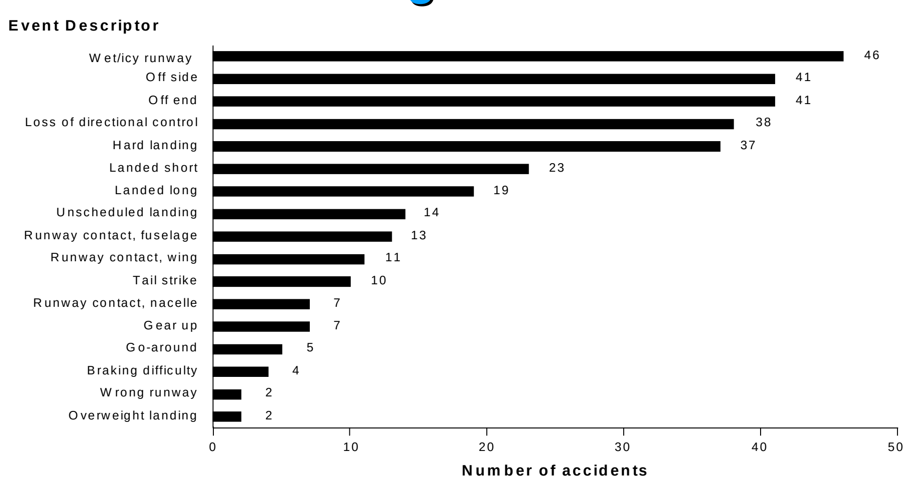
Landing Accidents



Can you afford not to be part of this program?

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Review of Agenda and Objectives

John Maxwell
Transport Canada, Aerodrome Safety
Ottawa, Ontario

Good morning everyone. My name is John Maxwell, and I am the Director of Aerodrome Safety here in Canada. Our Branch provides technical management and some of the financial support for the project. I'll go over a few changes to the agenda with you and then review the objectives of the meeting. I'm pleased to be here today to hear the latest findings from the team and to hear your reactions and suggestions for their future work.

Art Laflamme has provided some history and the objectives of the Joint Winter Runway Friction Measuring Program – the participants, their organization, and their progress to date. Angelo has described the management and funding of the program. We're very proud of the results achieved so far, because not only are we addressing what the aviation world sees as a serious safety issue, but we are making real progress on a problem that for many years was considered to be too difficult to solve.

From the outset, a key feature of this work has been international collaboration. It was obvious to those who initiated the project – and many of you are here today – that no matter how good the technical work was, there had to be international buy-in or the project would fail.

One of the biggest challenges facing this project was the incompatibility of the outputs from the various ground friction measuring devices, and the reluctance of each state to abandon systems which were working well for each of them.

Now, working together to figure out how to report the same thing, and to provide *better* information to pilots on how to compute aircraft braking performance, interest is growing rapidly in the approach.

While we have made substantial strides in meeting the objectives of the program, I recognize that more remains to be done. We would like to obtain your feedback throughout the next three days on what we have achieved to date and where we should be going from here.

Thus, the objectives for this meeting are:

1. To share with the international aviation community information we have obtained to date from the testing program

2. To present the International Runway Friction Index by which all ground friction measuring vehicles will be able to report along the same scale

3. To validate a procedure and sensitivity analysis

4. To discuss the merits of establishing uniform winter friction measurements – and a common friction reporting number – and, finally

5. To obtain your advice – and just as importantly – your support, for the continuation of the program

I think the agenda in front of you will achieve all of these objectives, so I encourage you to listen with a critical ear, tell us what you think, and enjoy the week.

In closing, I appreciate having this opportunity to say hello and hope that you will find the presentations stimulating and beneficial. Thank you.

Braking Performance of the NASA Boeing 737 and 757 Aircraft

Thomas J. Yager
NASA Langley Research Center
Hampton, Virginia

Braking Performance of the NASA Boeing 737 and 757 Aircraft

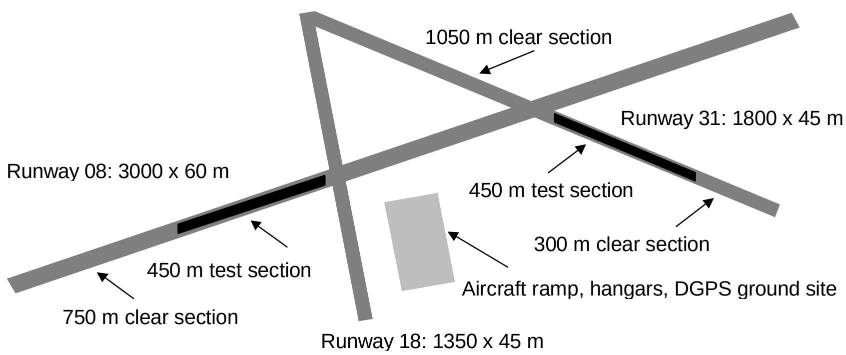
By

Thomas J. Yager
NASA Langley Research Center
Hampton, Virginia

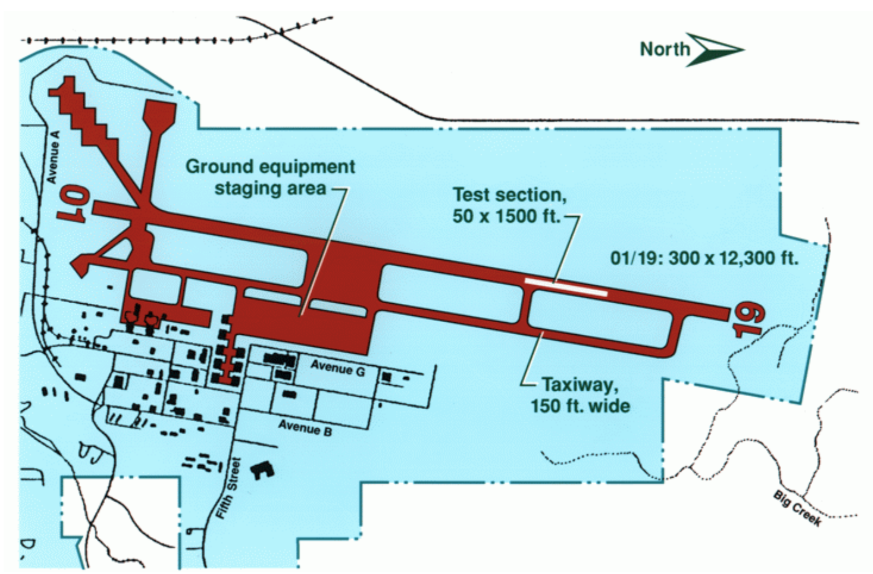
OUTLINE

- Overall joint program review
- Test aircraft and test sites
- Aircraft test results
- Summary
- Future activities

NORTH BAY RUNWAY LAYOUT



K.I. SAWYER AFB – Gwinn, MI

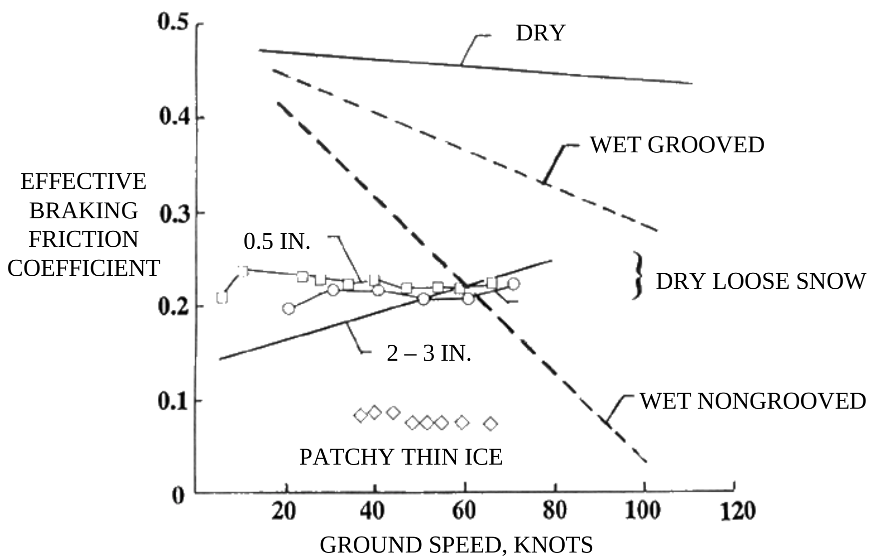


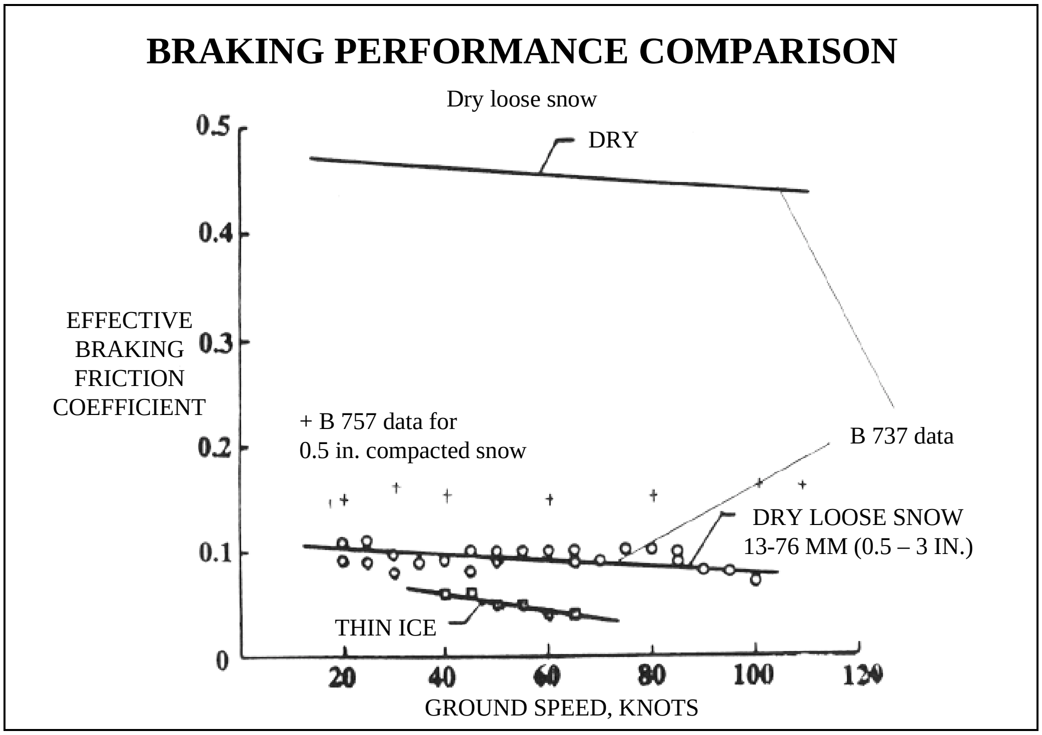
SUMMARY OF AIRCRAFT TEST RUN MATRICES

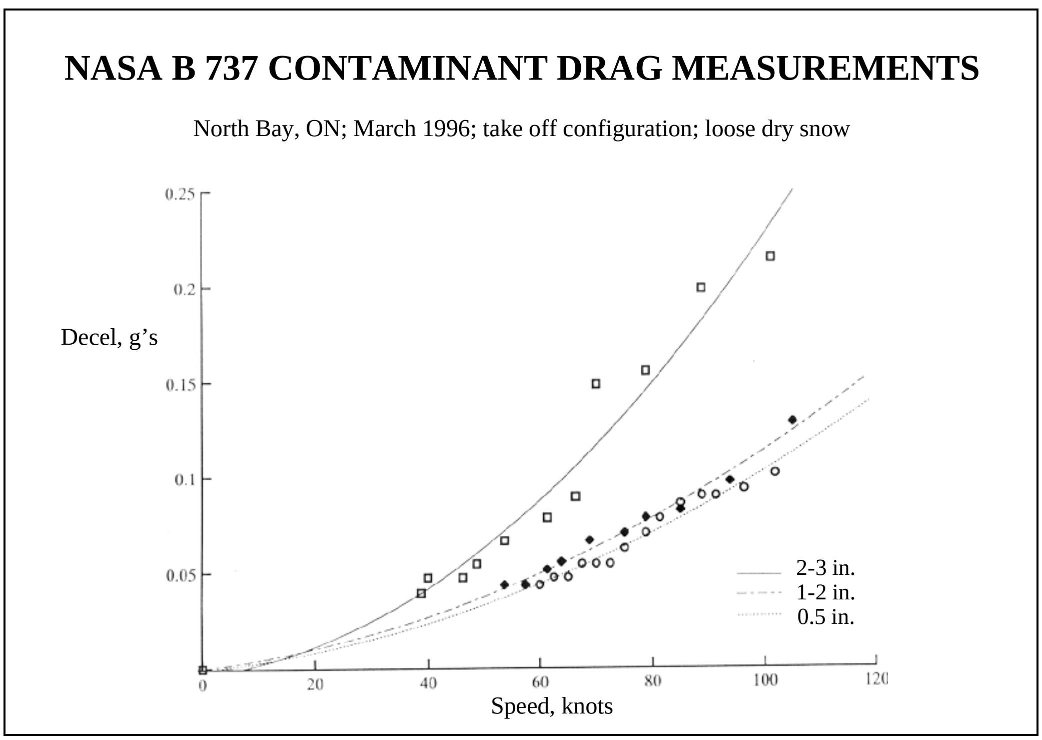
TEST AIRCRAFT:	B 737	B 757
TEST SITE:	North Bay, ON	Sawyer A/P, MI
TEST DATES:	March 5-8, 1996	Feb. 1-7, 1999
NO. OF FLIGHTS:	4	7
NO. OF TEST RUNS:	23	29
R/W CONDITIONS:	5	7

NASA B 737 AIRCRAFT BRAKING PERFORMANCE

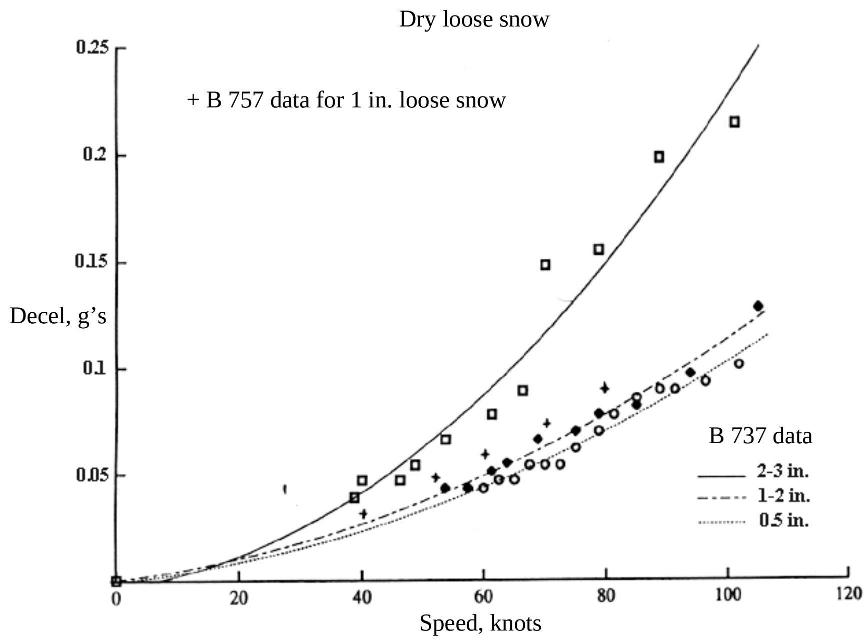
Landing Configuration; North Bay, Ontario; R/W 8/26; March 1996
NASA Wallops Flight Facility; R/W 4/22; August 1996




BRAKING PERFORMANCE COMPARISON
Dry loose snow
DRY
EFFECTIVE BRAKING FRICTION COEFFICIENT
+ B 757 data for 0.5 in. compacted snow
B 737 data
DRY LOOSE SNOW 13-76 MM (0.5 – 3 IN.)
THIN ICE
0
0.1
0.2
0.3
0.4
0.5
20
40
60
80
100
120
GROUND SPEED, KNOTS


NASA B 737 CONTAMINANT DRAG MEASUREMENTS
North Bay, ON; March 1996; take off configuration; loose dry snow
Decel, g's
0.25
0.2
0.15
0.1
0.05
2-3 in.
1-2 in.
0.5 in.
0
20
40
60
80
100
120
Speed, knots

CONTAMINANT DRAG COMPARISON



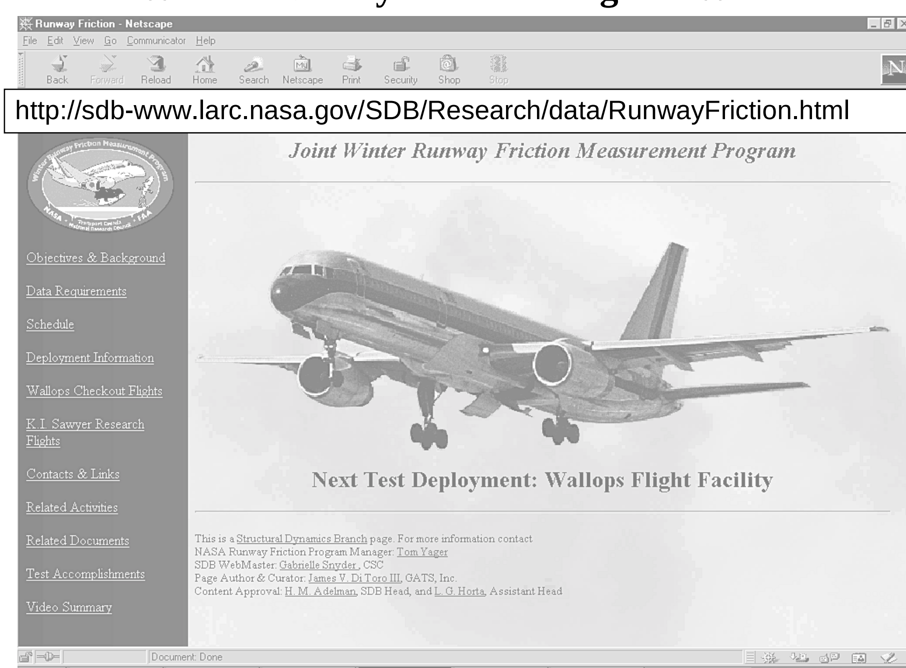
SUMMARY OF AIRCRAFT TEST RESULTS

- B 757 aircraft braking performance better than B 737 aircraft under similar conditions
- B 757 aircraft contaminant drag similar to B 737 aircraft
- Data collection and analysis incomplete
- NASA summary report will be prepared

FUTURE PROGRAM ACTIVITIES

- Munich a/c & grd. Veh. Tests, Nov-Dec
- Warsaw ACI Europe Conf., Nov 22-24
- New Orleans ASTM E17 Mtg., Dec 5-8
- North Bay a/c & grd. Veh. Tests, Jan 2000
- Sawyer B 757 & grd. Veh. Tests, Jan 2000
- Oslo, Norway grd veh tests, Feb-Mar 2000
- Wallops Workshop, May 15-19, 2000

Joint Winter Runway Friction Program Web Access



http://sdb-www.larc.nasa.gov/SDB/Research/data/RunwayFriction.html

NRC Falcon 20 Braking Performance on Winter Contaminated Runways – 1996 to 1999

John Croll
National Research Council Canada
Ottawa, Ontario

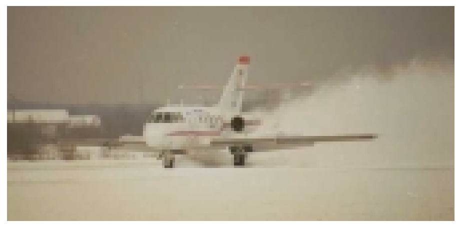
National Research Council Canada · Conseil national de recherches Canada

NRC · CNRC

Falcon 20 Braking Performance on Winter Contaminated Runways – 1996 to 1999

John Croll
Jim Martin
Matthew Bastian

IMAPCR
November 1999



Canada

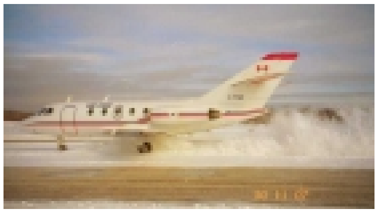
Presentation Outline

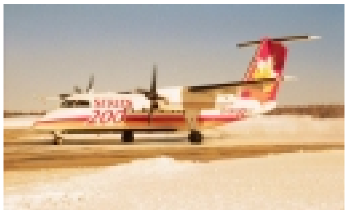
- Winter Runway Friction Program Overview
  - Objectives
  - Equipment
  - Procedures
- Summary of Falcon 20 Test Results
- Falcon 20 Braking Coefficients on Contaminated Runways
- Falcon 20 Slip Ratios
- Conclusions
- Future Testing
- Video Footage
- Questions

NRC · CNRC

Joint Winter Runway Friction Program
Collaborators – Aircraft Testing

Transport Canada
NASA: B 737, B 757
NRC: Falcon 20
FAA: B 727
de Havilland: Dash 8





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Joint Winter Runway Friction Program
Test Objectives

- Program incentive and funding come from recommendations of Dryden Commission following 1989 accident
- **Aircraft** test objectives are to:
    - Determine the effect of **Contaminant Drag** on takeoff distance and rejected takeoff (RTO) distance
    - Determine the effect of reduced aircraft **Braking Coefficients** on landing distance and RTO distance
    - If possible, determine the aircraft landing distance as a function of the measured Runway Friction Index (CRFI)
- **Ground vehicle** friction measuring device tests to develop a standard International Runway Friction Index (IRFI)

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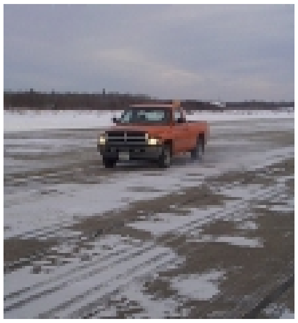
Contaminated Runway Definition

- A contaminated runway has standing water, slush, snow, compacted snow, ice, or frost covering more than 25% of the required length and width of its surface.
  - *Shallow Contamination (slippery)*:
    - Takeoff acceleration comparable to dry runway
    - Braking friction reduced compared to dry runway
    - Ice, frost, chemicals, compacted snow
  - *Deep Contamination (>3 mm equivalent water depth):*
    - Takeoff acceleration reduced compared to dry runway
    - Braking friction reduced compared to dry runway
    - Standing water, slush, snow

Canadian Runway Friction Index (CRFI)

CRFI readings are taken on a contaminated runway and reported, along with RCR, to pilots via NOTAMs, ATIS, or Tower advisory.

CRFI replaces JBI



Vehicle mounted device records deceleration during fully braked skids

- 0.7-0.8 Bare and dry
- 0.45-0.55 Bare and wet
- 0.25-0.35 Loose snow
- 0.2-0.25 Rough ice
- 0.1 Wet ice
- 0.0 Nil braking

NRC Falcon 20 Test Program
Major Resources

- NRC Falcon 20 research aircraft, fully instrumented:
  - angles, rates, accelerations in three axes
  - real-time differential GPS for position and velocity
  - brake pressures, wheel speeds, control positions, etc.
- DGPS ground station equipment
- Playback equipment
- NRC Test Team:
  - Aircraft operations
  - Scientific
- Transport Canada
  - Engineering
  - Operations
- Airport staff support

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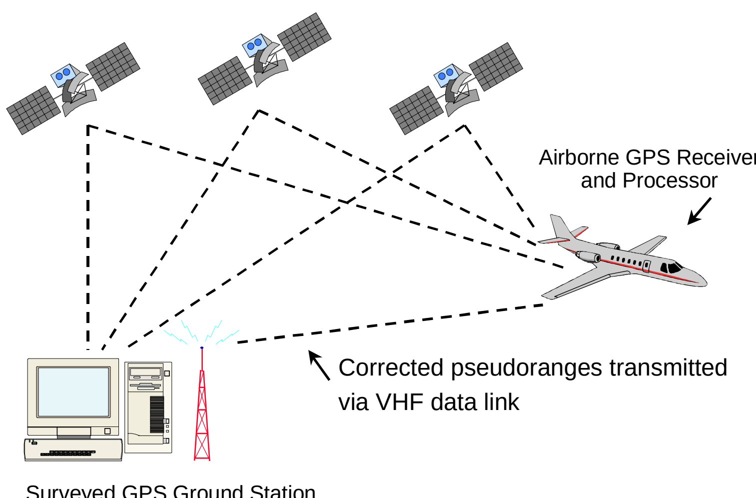
Differential Global Positioning System (DGPS)



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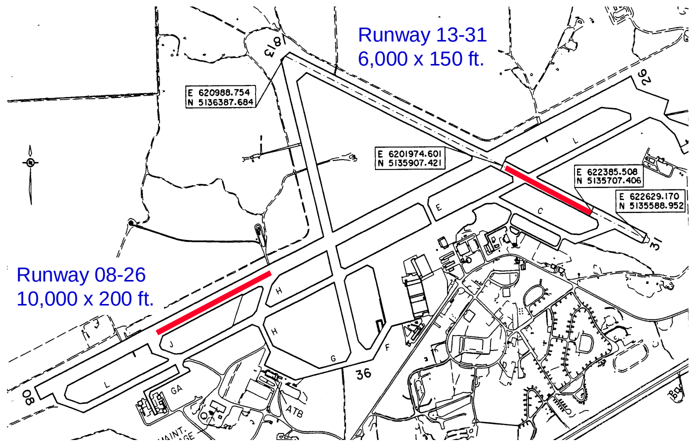
Test Site Description
North Bay Airport



Runway 08 Test Section: 2000 x 80 ft.
Runway 31 Test Section: 1200 x 80 ft.

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Test Procedures – Safety Considerations

- Test sections originally prepared by blowing snow “back onto” the runway, now NATURAL snow only
- Runway edges left and right of the test sections (40 ft. width) are kept bare and dry
- Maximum contaminant depth of 0.75 in. equivalent water depth

- Brake energy limits observed for cumulative test runs
- Ground Test Coordinator monitors test section and all aircraft runs

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Joint Winter Runway Friction Program
Falcon 20 Results to Date

- Four years of testing completed out of a five-year program
- Over 40 different runway surface conditions
- Over 240 test points:
  - braking coefficients (126 runs)
  - contaminant drag (115 runs)

- One instance of snow ingestion into the Falcon engines
- Two instances of aircraft lateral departure from the test section
- Observations:
  - Contaminant drag versus groundspeed in snow
  - Aircraft braking coefficients versus CRFI – Good correlation
  - CRFI Table of Recommended Landing Distances

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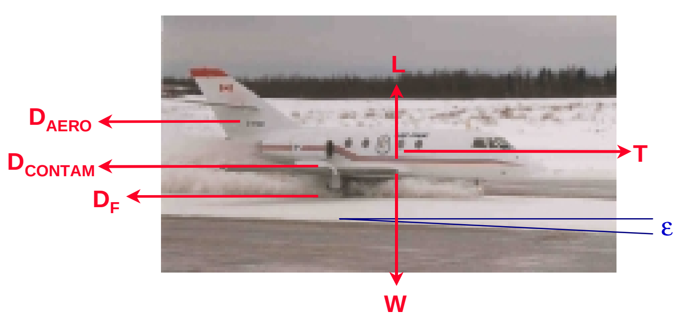
Falcon 20 Braking Performance and
Landing Distance Computation

Aircraft Braking Coefficient, or μ Braking (μ_B), is the basic measure of braking effectiveness on a contaminated runway

$$\mu_B = D_F / (W \cos \varepsilon - L) \text{, or} \qquad D_F \approx \mu_B \times (W - L)$$



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Falcon 20 Test Results – Braking Coefficients

Aircraft μ braking (μ_B) computed from flight test data:

$$\frac{1}{g}\frac{dV}{dt} = \frac{T}{W} - \frac{D_{AERO}}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \mu_B\left(1-\frac{L}{W}\right)$$

Three examples:

- **Case 1:** Moderate surface friction on compacted snow, CRFI = 0.25
- **Case 2:** High surface friction on 60% bare and dry, 40% loose snow, CRFI = 0.51
- **Case 3:** Low surface friction on smooth ice, CRFI = 0.17

For each case:

- Plot data for a single (representative) test run
- Show the μ braking vs groundspeed trend for several runs on each surface condition

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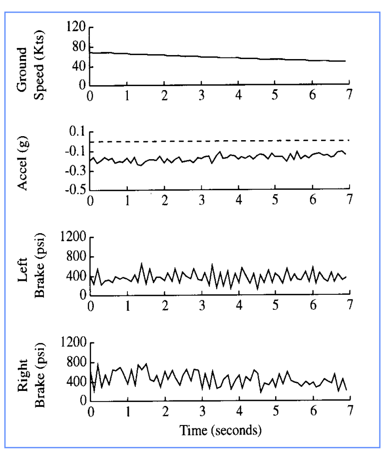
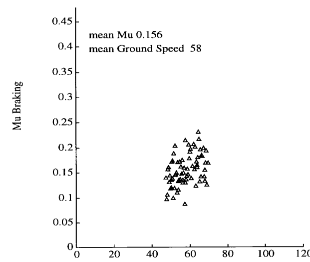
Falcon 20 μ Braking Computation
Case 1: "Moderate" Surface Friction

Runway surface 100% compacted snow with ice patches; CRFI = 0.25
Flight 98/08, Run 04





- Maximum anti-skid braking
- Landing configuration

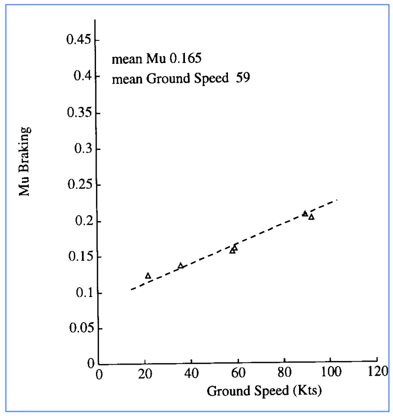
NRC · CNRC

Case 1 (cont'd)
Aircraft μ Braking vs Groundspeed

Flight 98/08, Runs 01 - 06

Moderate surface friction, CRFI = 0.25

μ decreases with decreasing groundspeed



- Maximum anti-skid braking
- Landing and RTO configurations

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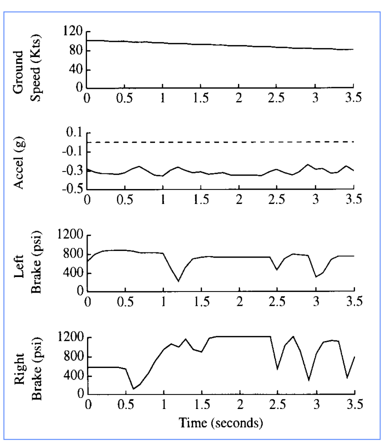
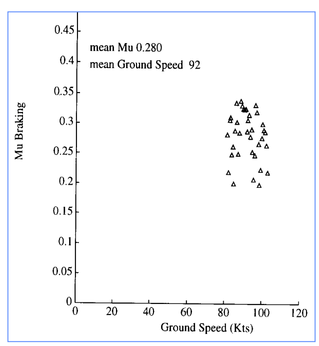
Falcon 20 μ Braking Computation
Case 2: "High" Surface Friction

Runway surface 60% bare and dry, 40% loose snow; CRFI = 0.51
Flight 98/01, Run 09





- Maximum anti-skid braking
- Landing configuration

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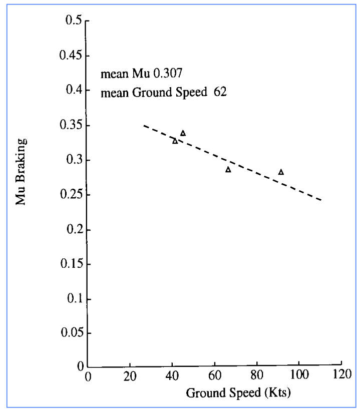
Case 2 (cont'd)
Aircraft µ Braking vs Groundspeed

Flight 98/01, Runs 06 - 09

High surface friction, CRFI = 0.51

µ increases with decreasing groundspeed

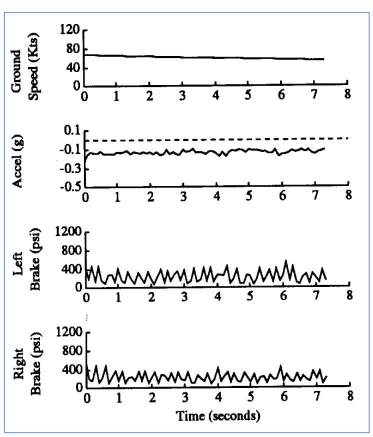


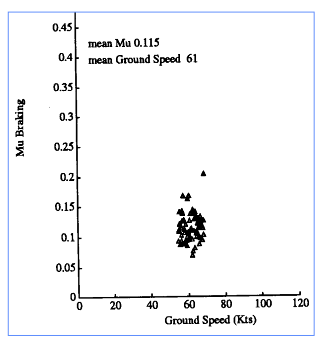
- Maximum anti-skid braking
- Landing and RTO configurations

NRC · CNRC

Falcon 20 µ Braking Computation
Case 3: "Low" Surface Friction

Runway surface 100% ice with one application of sand; CRFI = 0.17
Flight 99/06, Run 04





- Maximum anti-skid braking
- Landing configuration

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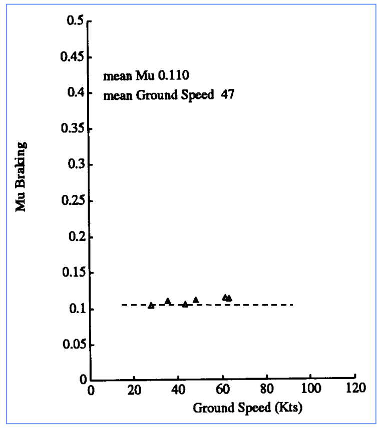
Case 3 (cont'd)
Aircraft μ Braking vs Groundspeed

Flight 99/06, Runs 01 - 06

Low surface friction, CRFI = 0.17

μ independent of groundspeed



- Maximum anti-skid braking
- Landing and RTO configurations

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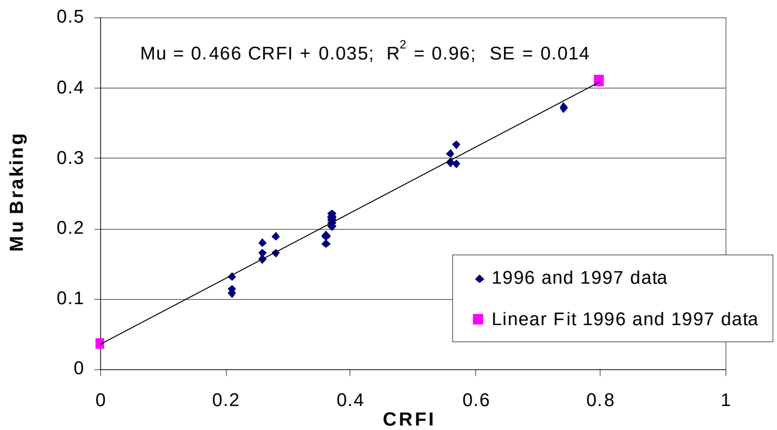
Falcon 20 μ Braking vs CRFI
1996 and 1997 Data



- Maximum anti-skid braking, idle thrust, landing configuration
- Runway surfaces (9) with uniform distribution of contaminant

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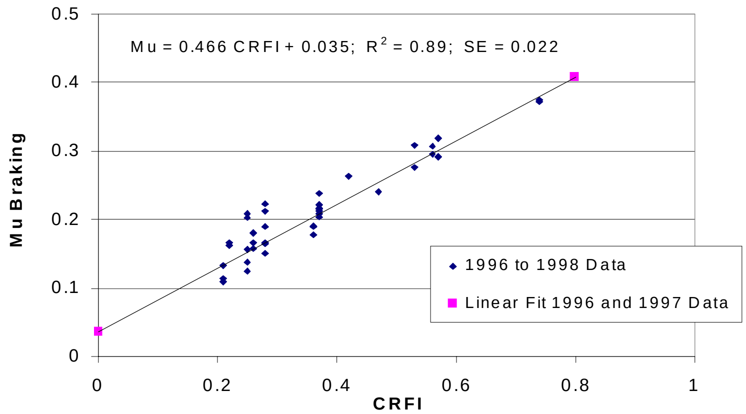
Falcon 20 µ Braking vs CRFI 1996 to 1998 Data



- Maximum anti-skid braking, idle thrust, landing configuration
- Runway surfaces (14) with uniform distribution of contaminant

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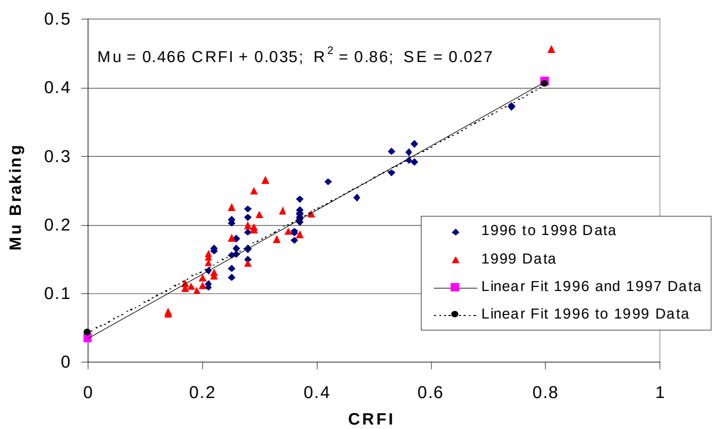
Falcon 20 µ Braking vs CRFI 1996 to 1999 Data



- Maximum anti-skid braking, idle thrust, landing configuration
- Runway surfaces (23) with uniform distribution of contaminant

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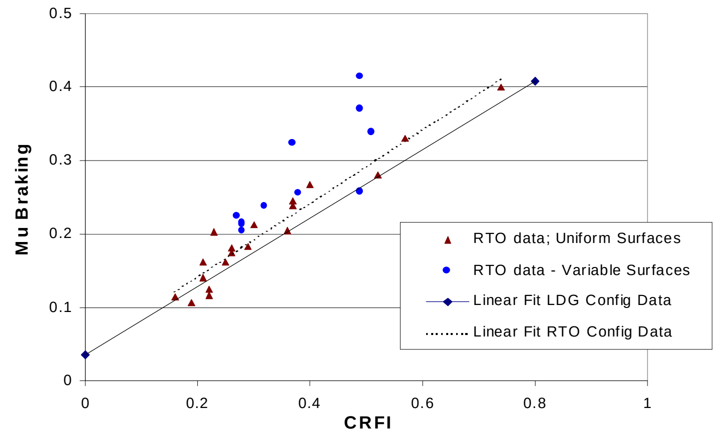
Falcon 20 µ Braking vs CRFI
RTO Configuration



- Maximum anti-skid braking, idle thrust, 1996 to 1999 data
- All runway surface conditions

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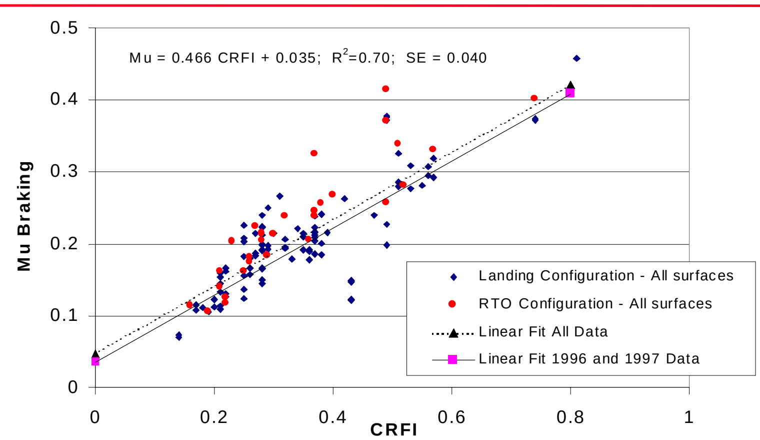
Falcon 20 µ Braking vs CRFI
All Test Points



- Maximum anti-skid braking, idle thrust, 1996 to 1999 data
- All runway surface conditions (35)

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Falcon 20 μ Braking versus CRFI
Statistical Summary

Test Years	Number of Surfaces (Uniform Contaminant)	Number of Data Points (Ldg Config)	Linear Fit R^2	Linear Fit SE
1996 – 1997	9	23	0.96	0.014
1996 – 1998	14	39	0.89	0.022
1996 – 1999	23	67	0.86	0.027
1996 – 1999	35*	127**	0.70	0.040

* Includes all surfaces, including non-uniform contaminant

** Includes data points for RTO configuration

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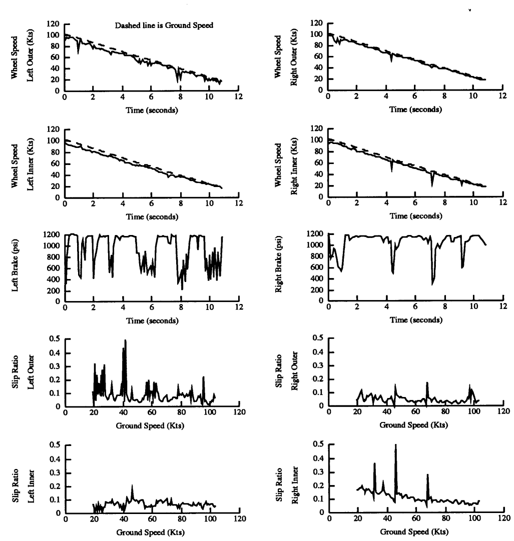
Falcon 20 Slip Ratios
High Surface Friction, CRFI = 0.81



Flight 9901
Run 06
Landing Configuration
Runway 100% B & D
CRFI = 0.81

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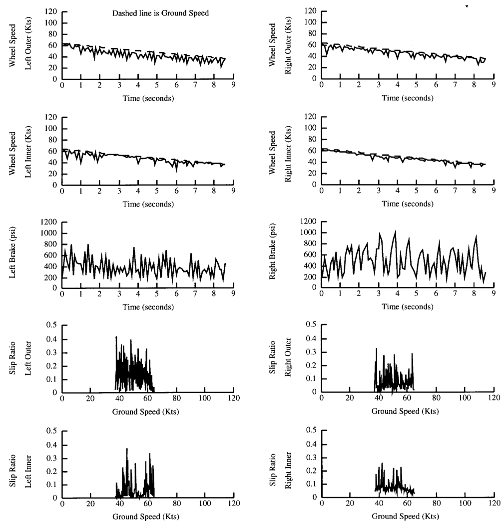
Falcon 20 Slip Ratios
Moderate Surface Friction, CRFI = 0.29



Flight 9802

Run 05

Landing Configuration

Runway 100% loose snow over 60% asphalt / 40% ice patches

CRFI = 0.29

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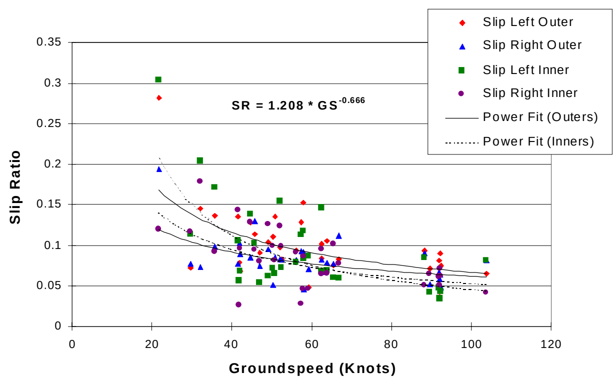
Falcon 20 Slip Ratio vs Groundspeed
Maximum Anti-skid Braking



- Data from all 1998 braking runs on various surface conditions
- Landing and RTO configurations

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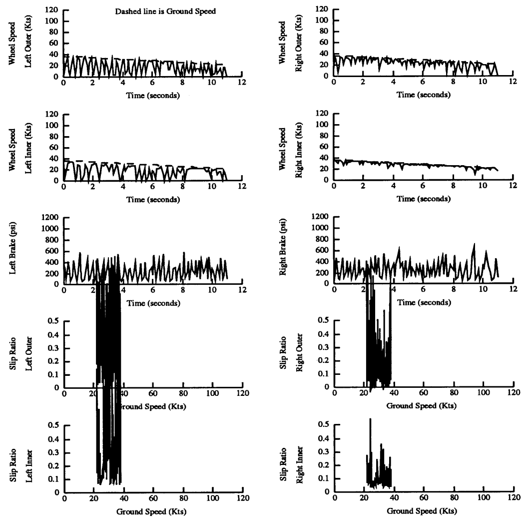
Falcon 20 Slip Ratios
Low Surface Friction, CRFI = 0.22



Flight 9907
Run 04
Landing Configuration
Runway 100% ice, sanded
CRFI = 0.22

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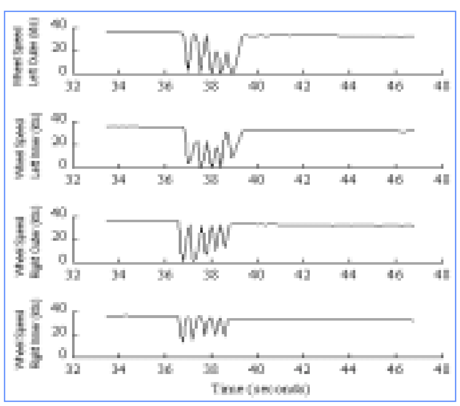
Directional Control Problems
on Low Friction Surfaces

- Surface condition: 100% smooth ice, no sand
- CRFI from 0.12 to 0.21, average CRFI = 0.17
- Full anti-skid braking – wheels cycling between 0 and 100% slip ratio



Flight 9907
Run 01
Runway 31 test section
4 knots crosswind component

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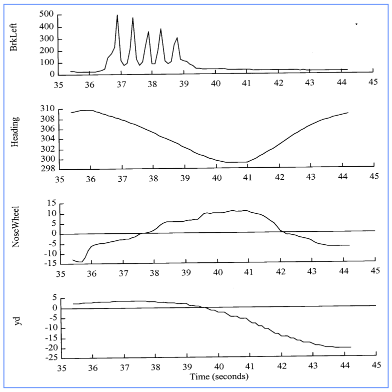
Directional Control Problems on Low Friction Surfaces (cont'd)

- Heading excursion > 10 degrees
- Runway C/L deviation of 25 feet
- Nosewheel steering and rudder ineffective



Full anti-skid braking on ice
↓
High mean slip ratios
↓
Low cornering friction
↓
Directional control poor at low to moderate speeds
↓
Crosswind makes it worse

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Falcon 20 Braking Performance Conclusions

- No consistent variation of aircraft braking coefficients with groundspeed, may depend on surface condition
- Good correlation between Falcon 20 braking coefficients and CRFI on runway surfaces with uniform contaminant distribution
- Increase in wheel slip ratios with decreasing groundspeed
- Reduction in directional control at lower speeds on ice-covered surfaces

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Recommendations and Future Testing

- Further investigation of the correlation between aircraft braking coefficients and runway friction indices for additional:
  - aircraft types
  - friction measuring devices + IRFI
  - runway surface conditions (slush, chemicals…)
- More active participation and advice is being sought from aircraft manufacturers and operators
- Additional Falcon 20 tests:
  - – contaminant drag
  - – slush, chemicals
  - – crosswind effect

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Dash 8 Aircraft Performance Testing on Contaminated Runway Surfaces

Ed Lim
Bombardier Aerospace
Downsview, Ontario

IMAPCR '99

Dash 8 Aircraft Performance Testing on Contaminated Runway Surfaces

2nd International Meeting on Aircraft Performance on Contaminated Runways - November 1999

Edward Lim

BOMBARDIER AEROSPACE

IMAPCR '99

Test Objectives

- To determine
  - Contaminant drag effects
  - Aircraft braking coefficients
- To contribute to the establishment of the Aircraft Runway Friction Index (ARFI)

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Test Site and Date

- Jack Garland Airport
  - North Bay, Ontario, Canada
- February 12 - 15, 1998

BOMBARDIER AEROSPACE

IMAPCR '99

Dash 8 Flight Test Aircraft

- A/C Serial # 002 configured as Model 202
- Two Pratt & Whitney PW123D engines
  - Fitted with four-bladed Hamilton Standard 14SF variable pitch propellers
- Anti-skid braking system
  - Mark III Hydroair

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Test Surface

- 1996-97
  - Loose snow between 1.0' and 1.5'
  - Hard-packed snow 1.5' in depth
  - Loose snow between 1.5' and 2.0' on top of hard-packed snow
- 1997-98
  - Rough ice
  - Moderately smooth ice
  - Sand on moderately smooth ice

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Test Procedure

- Ground vehicle brake friction test
- Aircraft tests
  - Rejected take-offs and landings
    - Brakeless
    - Braked
- Ground vehicle brake friction re-test

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Flight Test Data

- Aircraft Data Acquisition System
  - Aydin Vector Programmable Master Unit (PMU)
  - NovAtel RT-20 Differential Global Positioning System (DGPS)
- Test Parameters
  - Aircraft acceleration (Nx)
  - Aircraft airspeed (ASIP)
  - Engine torque (TQ)
  - Propeller rotation speed (Np)

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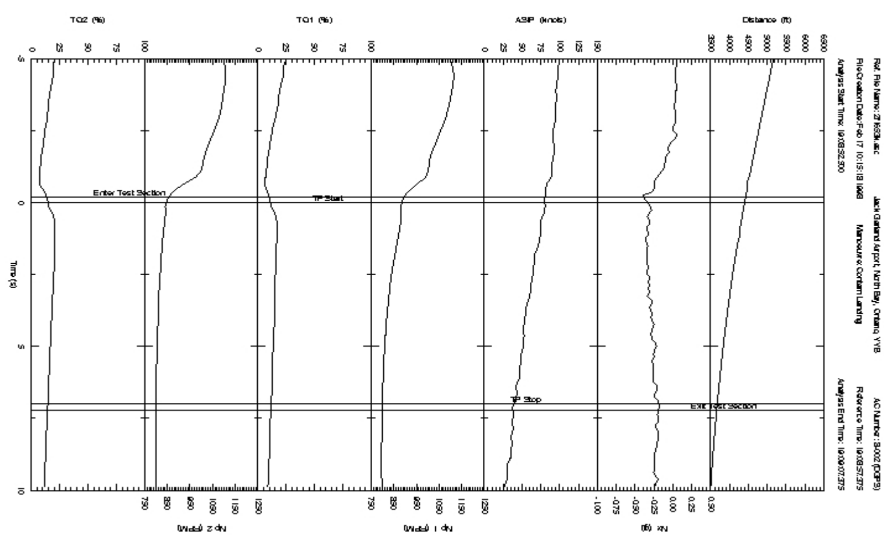
Typical braked run on rough ice



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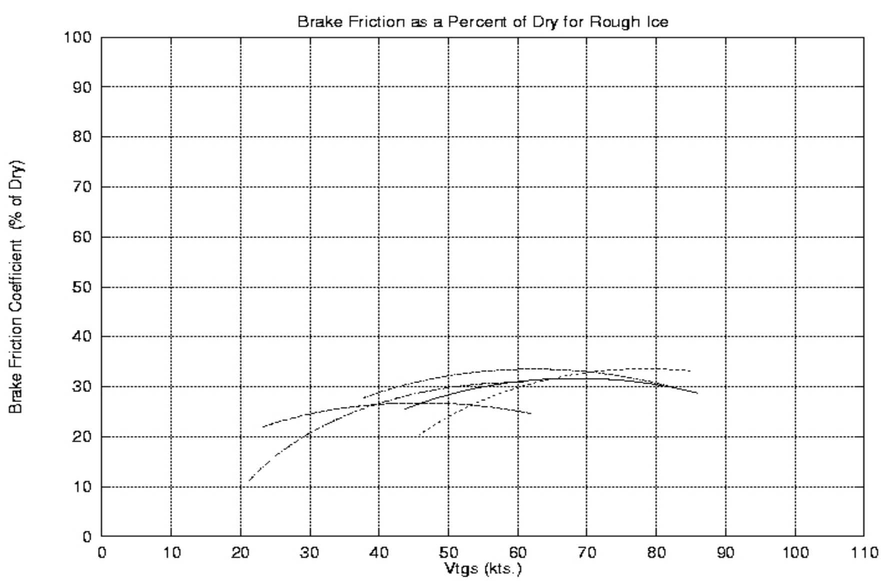
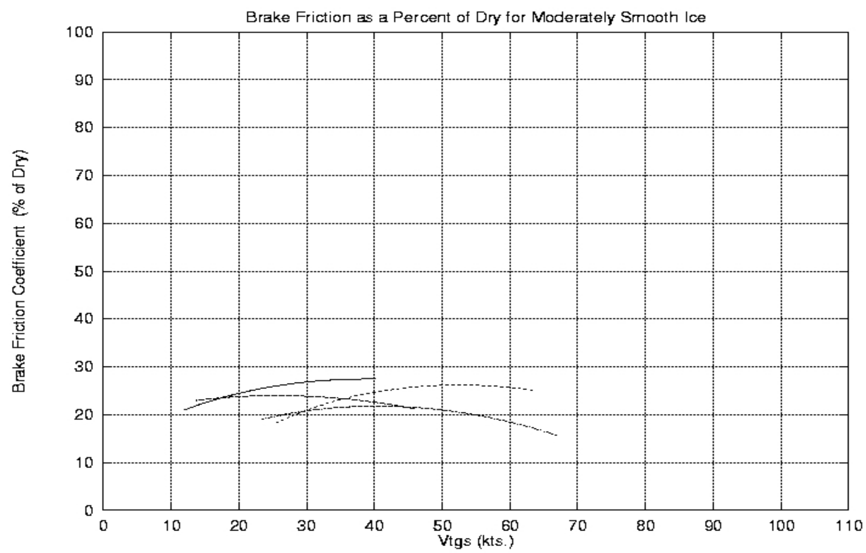
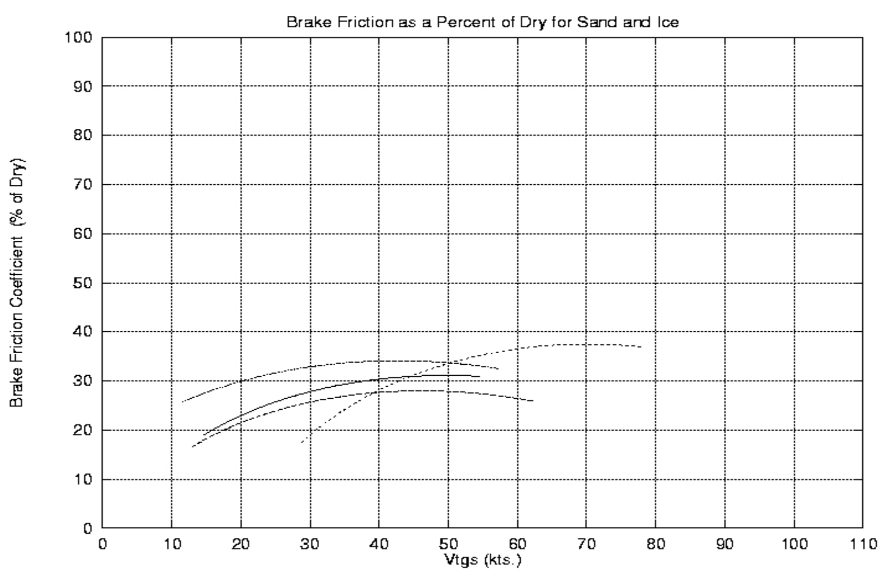
Test Results

- Contaminant Drag
  - No appreciable impingement or displacement drag
- Braking Friction Coefficient
  - Brake friction coefficient and true groundspeed were determined for the three contaminants

BOMBARDIER
AEROSPACE




Brake Friction as a Percent of Dry for Moderately Smooth Ice
Brake Friction Coefficient (% of Dry)
Vtgs (kts.)
0
10
20
30
40
50
60
70
80
90
100
110


Brake Friction as a Percent of Dry for Sand and Ice
Brake Friction Coefficient (% of Dry)
Vtgs (kts.)
0
10
20
30
40
50
60
70
80
90
100
110

Comparison of Aircraft Braking Performance on Contaminated Runways

Matthew Bastian
National Research Council Canada, Flight Research Laboratory
Ottawa, Ontario

National Research Council Canada | Conseil national de recherches Canada

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Comparison of Aircraft Braking Performance on Contaminated Runways

Matthew Bastian
National Research Council Canada

Canada

Aircraft Types Compared

- Falcon 20, NRC 1996-1999
- B 737, NASA 1996
- B 727, FAA 1997
- B 757, NASA 1999
- Dash 8, de Havilland 1996, 1998 and 1999

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Background

- Comparison of μ braking and CRFI
- CRFI = JBI as measured by ERD
- Uniform surfaces compared only
- No thrust reversers
- Computational methods used are outlined in Appendix A of NRC report LTR-FR-132

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Basic μ Braking Equation

$$\mu_B = \frac{\left(\frac{T}{W} - \frac{D}{W} - \varepsilon - \frac{1}{g}\frac{dV}{dt}\right)}{\left(1 - \frac{L}{W}\right)}$$

W = aircraft weight
T = engine thrust
D = aerodynamic drag
L = aerodynamic lift
e = runway slope
dV/dt = acceleration
g = gravity constant

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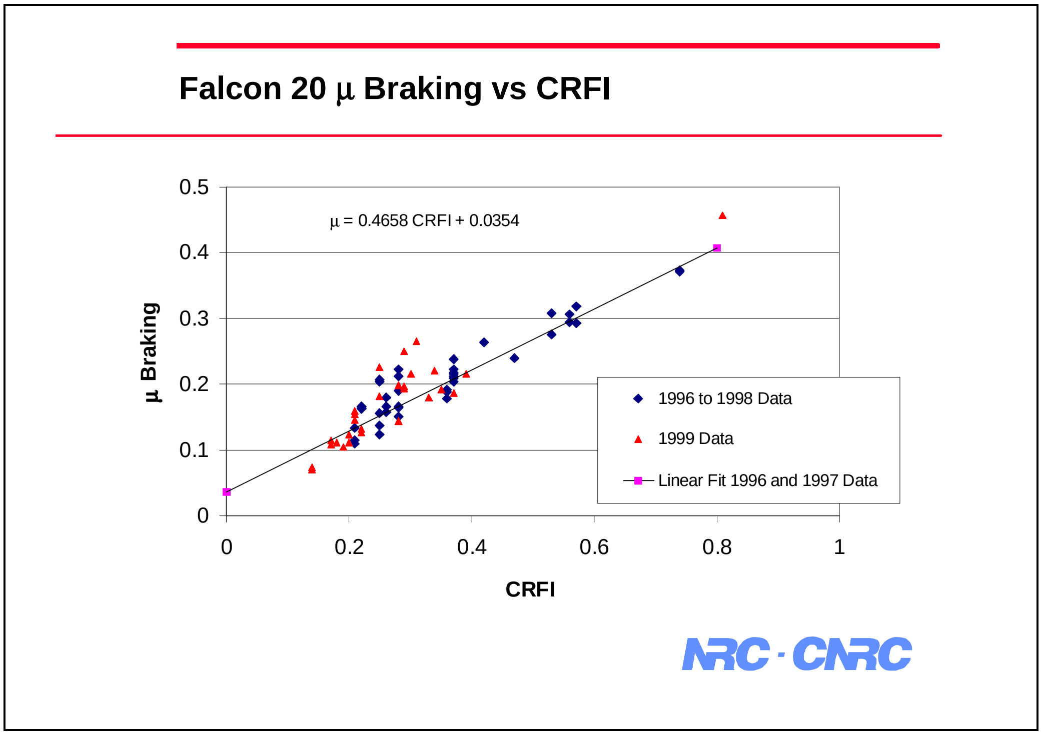
Falcon 20 µ Braking vs CRFI
µ = 0.4658 CRFI + 0.0354
µ Braking
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
CRFI
1996 to 1998 Data
1999 Data
Linear Fit 1996 and 1997 Data
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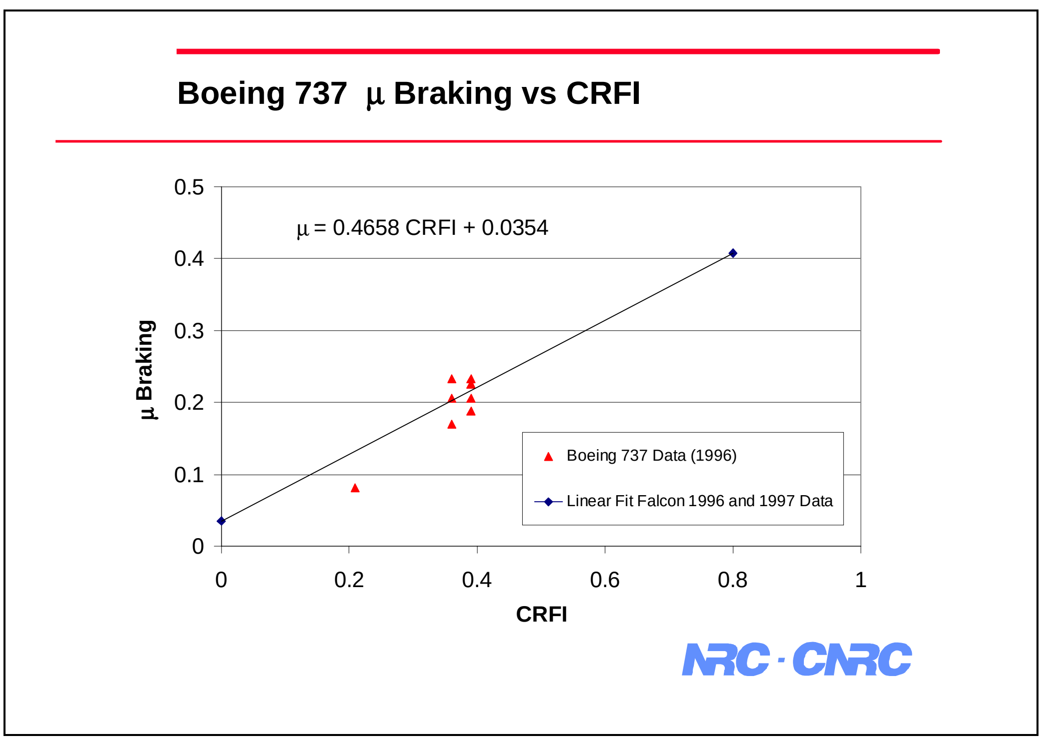
Boeing 737 µ Braking vs CRFI
µ = 0.4658 CRFI + 0.0354
µ Braking
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
CRFI
Boeing 737 Data (1996)
Linear Fit Falcon 1996 and 1997 Data
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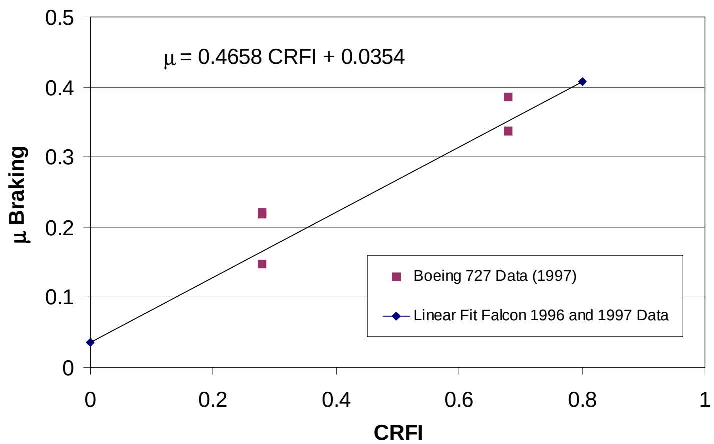
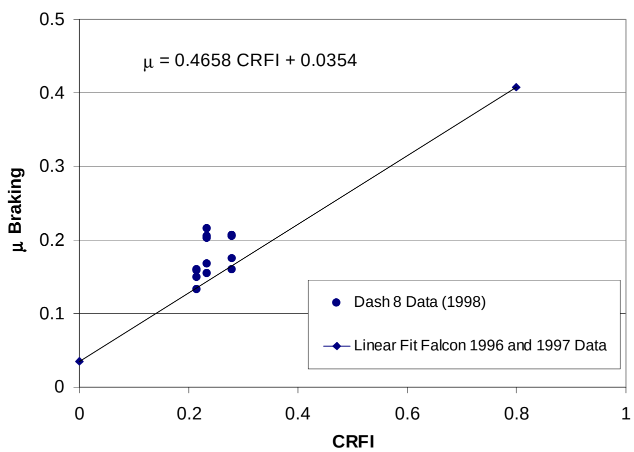
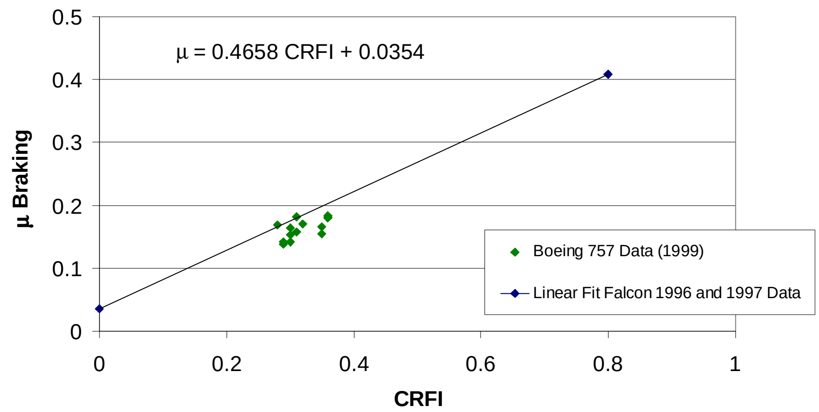
Boeing 727 μ Braking vs CRFI



de Havilland Dash 8 μ Braking vs CRFI



Boeing 757 μ Braking vs CRFI (preliminary)



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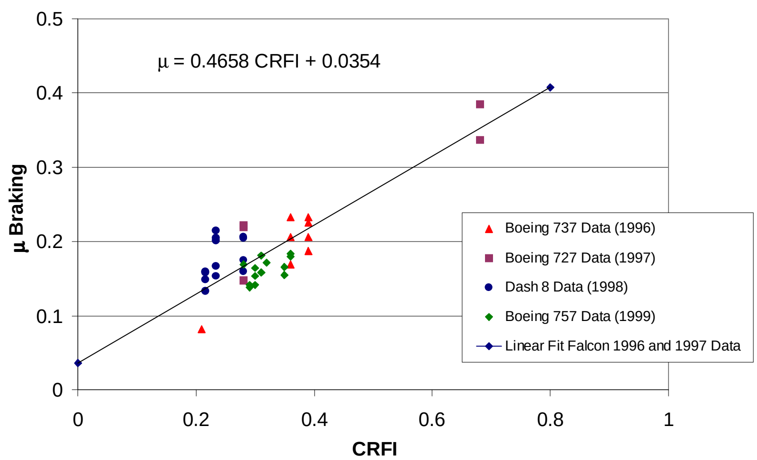
All Other Aircraft (not including Falcon) μ Braking vs CRFI



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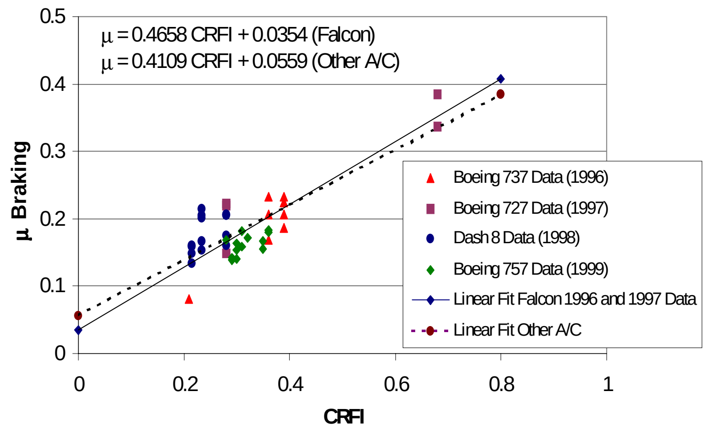
All Other Aircraft Results (not including Falcon) μ Braking vs CRFI



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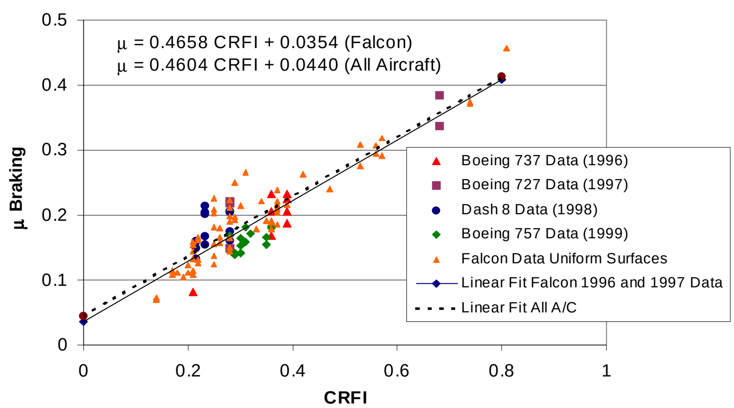
Combined Aircraft Results



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Conclusions

- All aircraft compared very well with one another
- Anti-skid systems of the five aircraft are all working at similar efficiencies
- Validation of the mathematical models used and their success at removing aircraft specific aerodynamic effects
- μ braking versus CRFI is independent of aircraft type for the aircraft tested (no thrust reversers)
- Data supports CRFI tables of recommended landing distances

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Aircraft Takeoff Performance on Contaminated Runways

J.C.T. Martin
Transport Canada, Aircraft Certification
Ottawa, Ontario

Transport Canada Aircraft Certification

AIRCRAFT TAKEOFF PERFORMANCE ON CONTAMINATED RUNWAYS

IMAPCR '99

2nd International Meeting on Aircraft Performance on Contaminated Runways

2-4 November 1999

J.C.T. Martin
Flight Test Engineer
Transport Canada

1

Transport Canada Aircraft Certification

Contents of Presentation

- Performance Program
  - Requirement
  - Development
  - Description
  - Runway Condition Options
- Use of Takeoff Performance Program
  - Examples of Balanced Field Lengths for different runway conditions
  - Examples of Field Lengths for fixed V1/VR
- Summary

2

Transport Canada Aircraft Certification

Requirement for Takeoff Performance Model

- Aircraft manufacturers develop takeoff performance models (computer programs) for certification and operational support
- Usually source code and configuration dependent data are proprietary
- Even if takeoff performance program is available, there may not be flexibilty to change runway conditions

3

Transport Canada Aircraft Certification

Requirement for Takeoff Performance Model (continued)

- In order to examine issues associated with wet and contaminated runway performance, a takeoff performance model that is capable of representing a wide range of transport category aircraft and runway conditions is required

4

Transport Canada Aircraft Certification

Development of Takeoff Performance Model

- The Transport Canada Takeoff Performance Program has been developed using industry standard performance methods
- Takeoff distances are calculated in accordance with current (Amendment 25-92) FAR 25 requirements
- The program accounts for all major variables, including aircraft characteristics and atmospheric conditions

5

Transport Canada Aircraft Certification

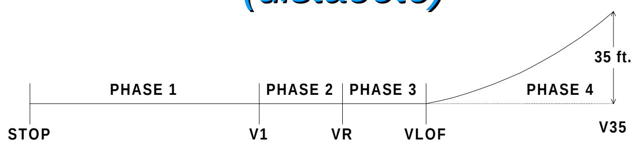
Description of Takeoff Performance Program

- The program uses both internally stored aircraft configuration data and user input takeoff condition data
- The program calculates four distances for each V1/VR:
  - All engines operating takeoff distance (distaeoto)
  - One engine inoperative takeoff distance (distoeito)
  - All engine operating rejected takeoff distance (distaeorto)
  - One engine inoperative rejected takeoff distance (distoeirto)
- Program calculates optimum V1/VR ratio and Balanced Field Length (BFL)

6

Transport Canada Aircraft Certification

All Engines Operating Takeoff Distance (distaeoto)

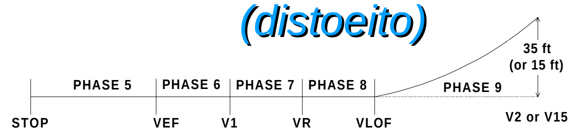


Phase 1	Accelerate from Stop to V1
Phase 2	Accelerate from V1 to rotation speed, VR
Phase 3	Accelerate from VR to liftoff speed, VLOF
Phase 4	Accelerate from VLOF to V35 and climb to 35 ft.
distaeoto	The AEO takeoff distance is the sum of the distances calculated above multiplied by a factor of 1.15

7

Transport Canada Aircraft Certification

One Engine Inoperative Takeoff Distance (distoeito)



Phase 5	Accelerate from Stop to engine fail speed, VEF
Phase 6	Accelerate from VEF to V1 with one engine inoperative
Phase 7	Accelerate from V1 to rotation speed VR with one engine inoperative
Phase 8	Accelerate from VR to liftoff VLOF with one engine inoperative
Phase 9	Accelerate from VLOF to V2 (or V15 if runway is wet or contaminated) and climb to 35 ft. (or 15 ft. if runway is wet or contaminated) with one engine inoperative
distoeito	The OEI takeoff distance is the sum of the distances calculated above

8

Transport Canada Aircraft Certification

All Engines Operating Rejected Takeoff Distance (distaeorto)

Phase 10 Accelerate from Stop to V1
This phase is identical to Phase 1

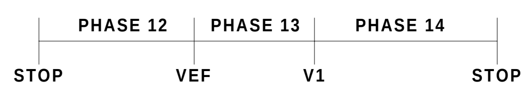
Phase 11 Decelerate to Stop from maximum speed obtained after first action taken to reject the takeoff at V1

distaeorto The AEO accelerate stop distance is the sum of the distances calculated above, plus a distance equivalent to two seconds at constant V1

9

Transport Canada Aircraft Certification

One Engine Inoperative Rejected Takeoff Distance (distoeirto)



Phase 12 Accelerate from Stop to engine fail speed, VEF
This phase is identical to Phase 5

Phase 13 Accelerate from VEF to V1 with one engine inoperative
This phase is identical to Phase 6

Phase 14 Decelerate to Stop from maximum speed obtained after first action taken to reject the takeoff at V1

distoeirto The OEI accelerate stop distance is the sum of the distances calculated above plus a distance equivalent to two seconds at constant V1

10

Transport Canada Aircraft Certification

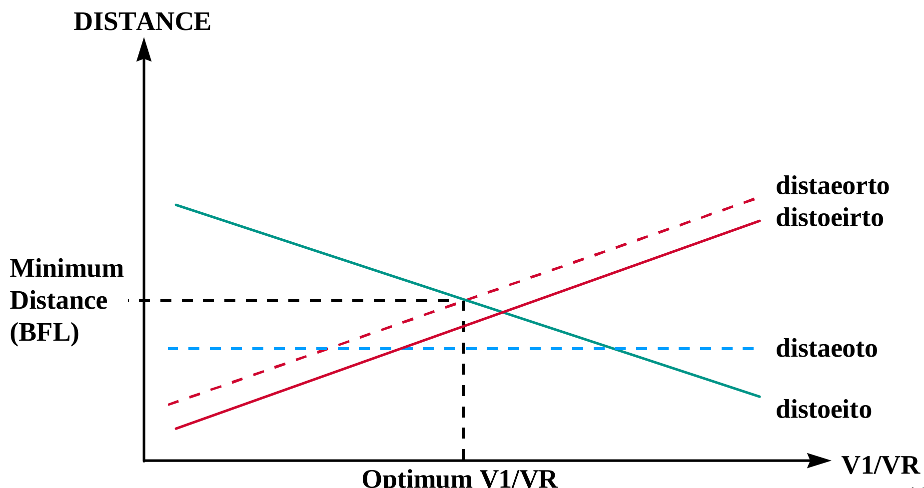
Takeoff Distance, Accelerate Stop Distance and Balanced Field Length

- The Takeoff Distance is the longer of:
  - All engines operating takeoff distance
  - One engine inoperative takeoff distance
- The Accelerate Stop Distance is the longer of:
  - All engines operating rejected takeoff distance
  - One engine inoperative rejected takeoff distance
- The Balanced Field Length:
  - Minimum distance required
  - Takeoff Distance = Accelerate Stop Distance
  - Optimum V1/VR ratio

11

Transport Canada Aircraft Certification

Illustration of Balanced Field Length



12

Transport Canada Aircraft Certification

Runway Condition Options Included in Program

- Dry Runway
  - 35 ft. screen height for both AEO and OEI takeoff distances
- Wet Runway
  - No contamination drag
  - Reduced braking friction (low μ)
  - 15 ft. screen height for OEI takeoff distance, 35 ft. for AEO

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Transport Canada Aircraft Certification

Runway Condition Options Included in Program (continued)

- Contaminated Runway, No Contamination Drag
  - No contamination drag
  - Reduced braking friction (low μ)
  - 15 ft. screen height for OEI takeoff distance, 35 ft. for AEO
- Contaminated Runway, Contamination Drag
  - Contamination drag
  - Reduced braking friction (low μ)
  - 15 ft. screen height for OEI takeoff distance, 35 ft. for AEO
- No reverse or reverse thrust credit, for all runway conditions

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Use of the Takeoff Performance Program

- The program may be used to examine the relative effects of the various parameters on the takeoff performance of sample aircraft
- However, the output data are not intended, and should not be used, to replace Aircraft Flight Manual (AFM) or other data provided by the manufacturer for a specific aircraft type

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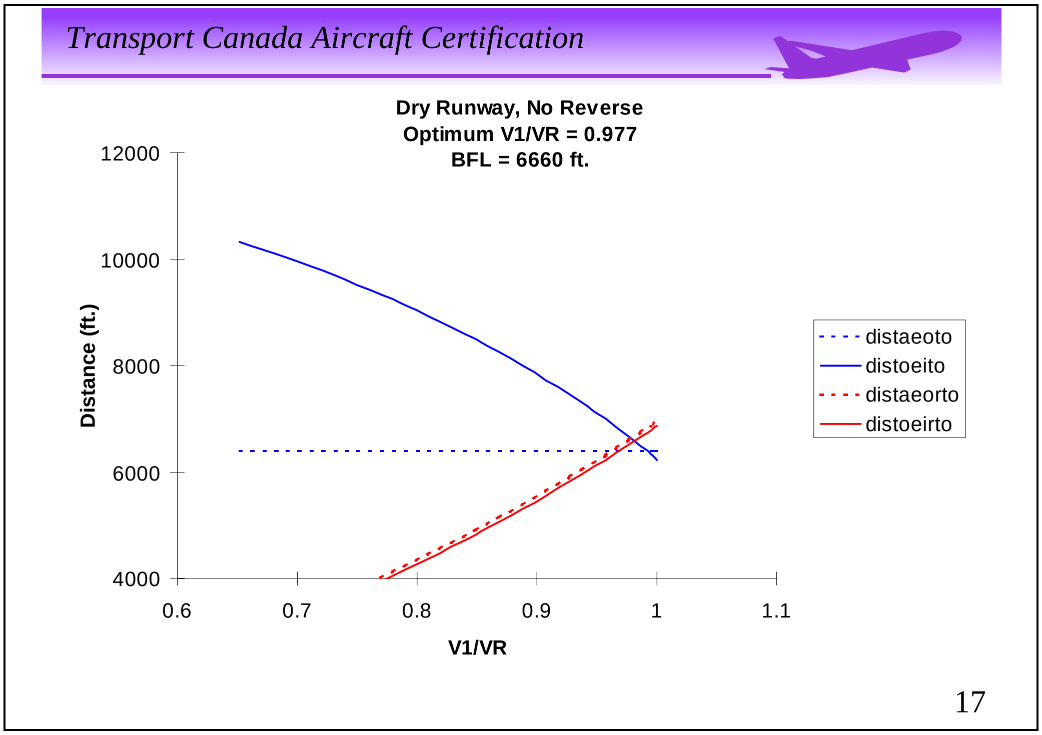
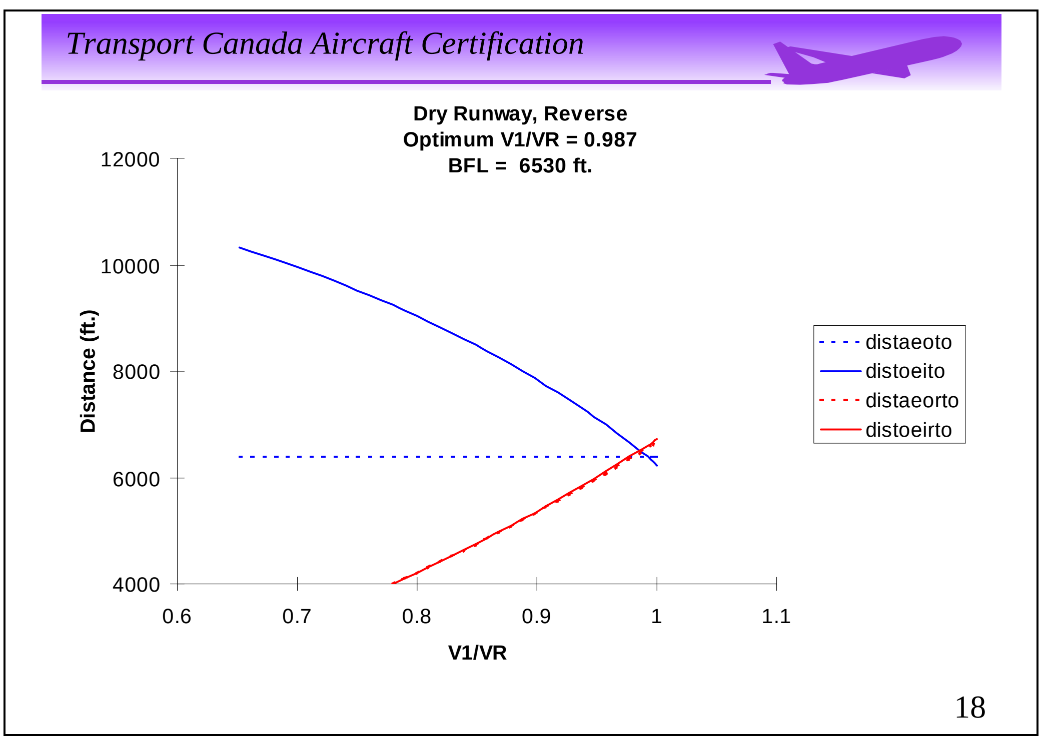
Example

- Generic two engine commuter jet
  - Maximum structural takeoff weight
  - Sea level, ISA temperature
  - Zero wind, zero runway slope
  - No clearway, no stopway
- Runway conditions
  - Dry
  - Wet
  - Contaminated, ice, $\mu = 0.1$
  - Contaminated, 0.25 inch standing water, $\mu = 0.25$
  - Contaminated, 1.0 inch loose snow, SG = 0.2, $\mu = 0.15$

16


Transport Canada Aircraft Certification
Dry Runway, No Reverse
Optimum V1/VR = 0.977
BFL = 6660 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
17


Transport Canada Aircraft Certification
Dry Runway, Reverse
Optimum V1/VR = 0.987
BFL = 6530 ft.
Distance (ft.)
12000
10000
8000
6000
4000
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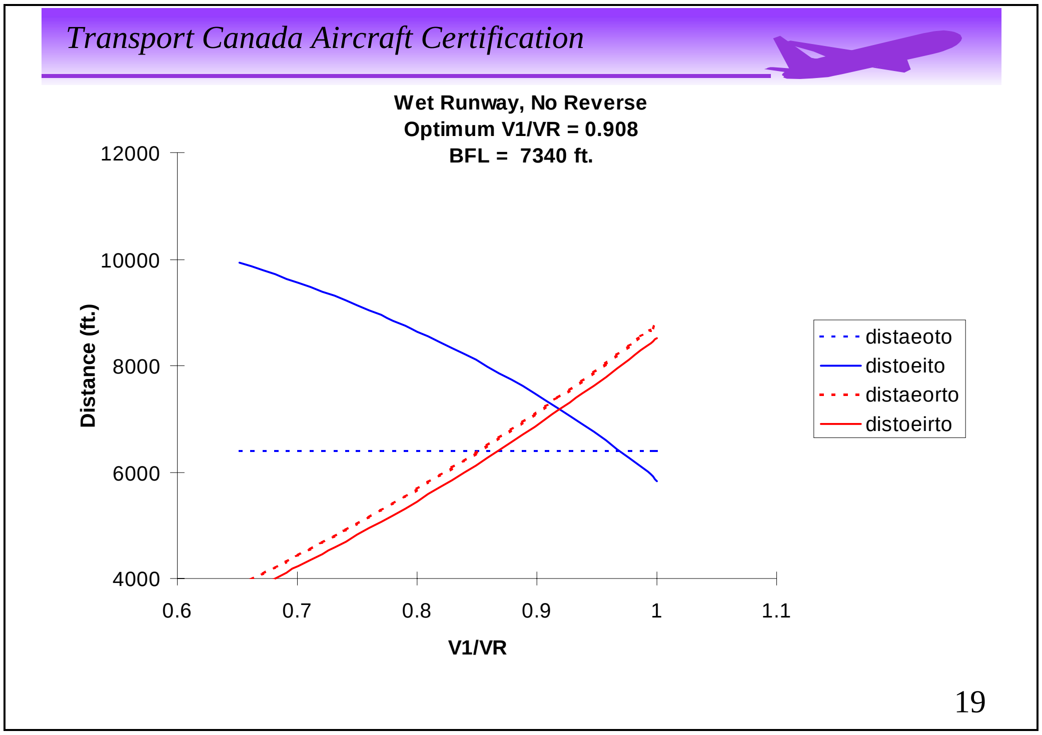
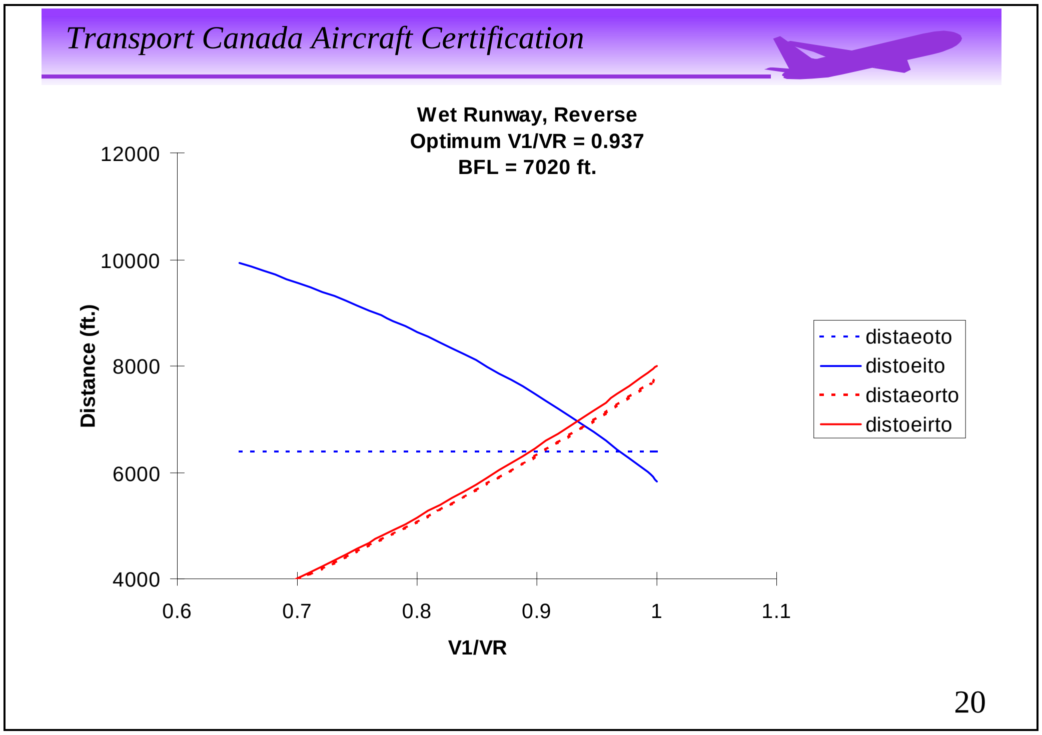
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
18


Transport Canada Aircraft Certification
Wet Runway, No Reverse
Optimum V1/VR = 0.908
BFL = 7340 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
19


Transport Canada Aircraft Certification
Wet Runway, Reverse
Optimum V1/VR = 0.937
BFL = 7020 ft.
Distance (ft.)
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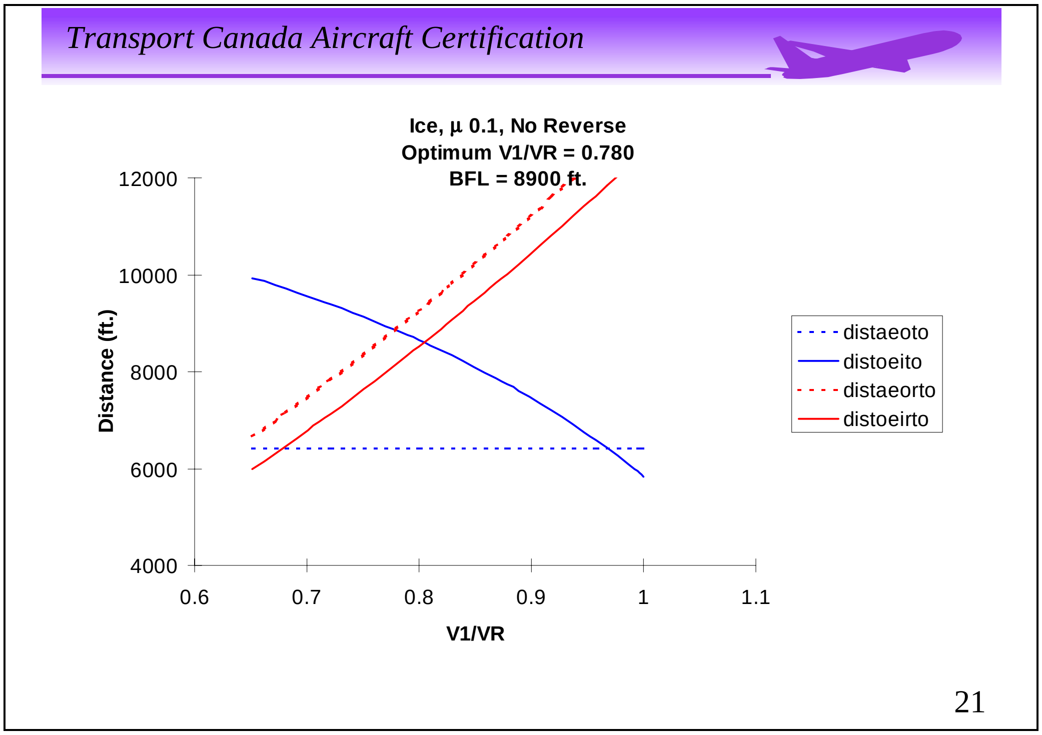
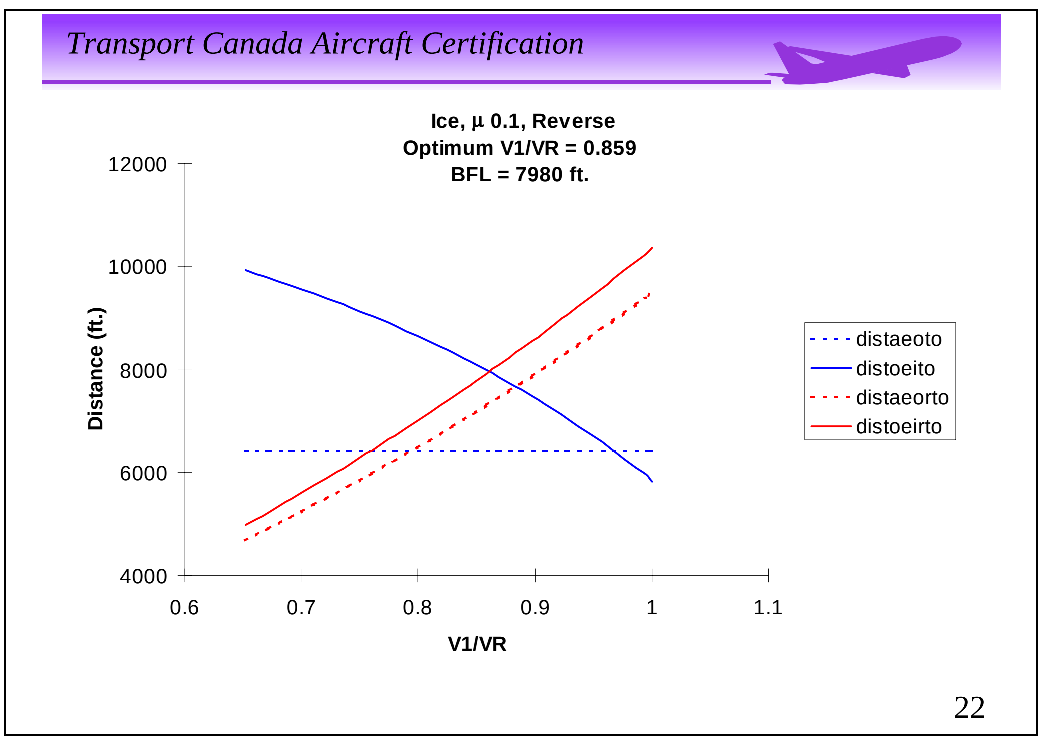
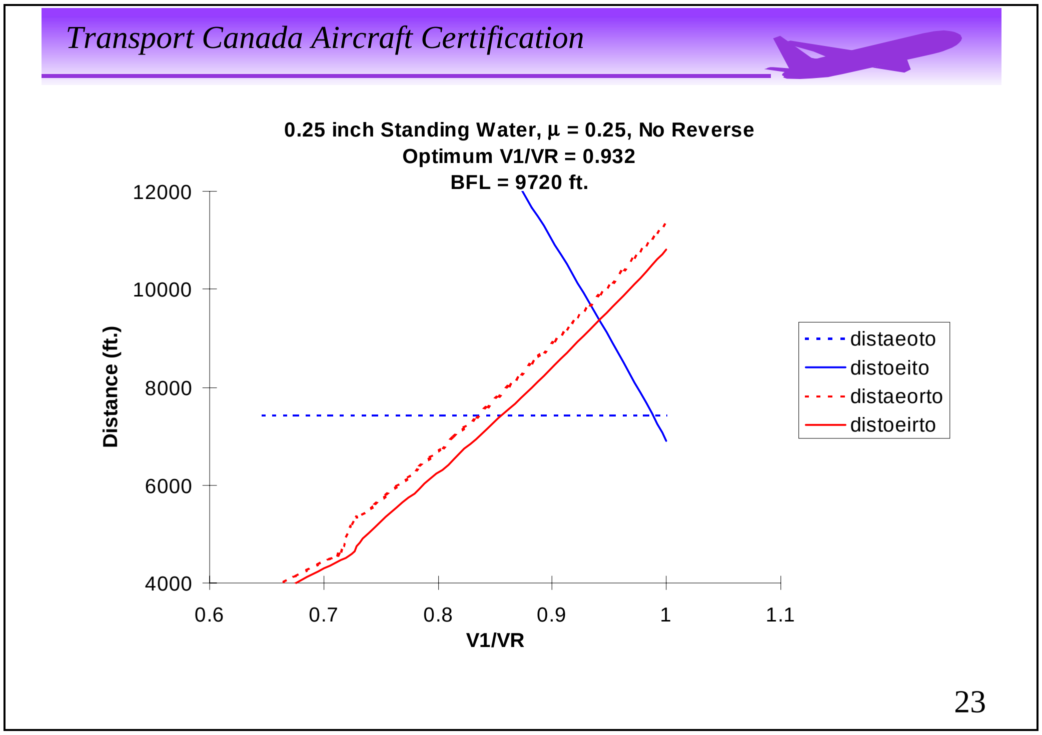
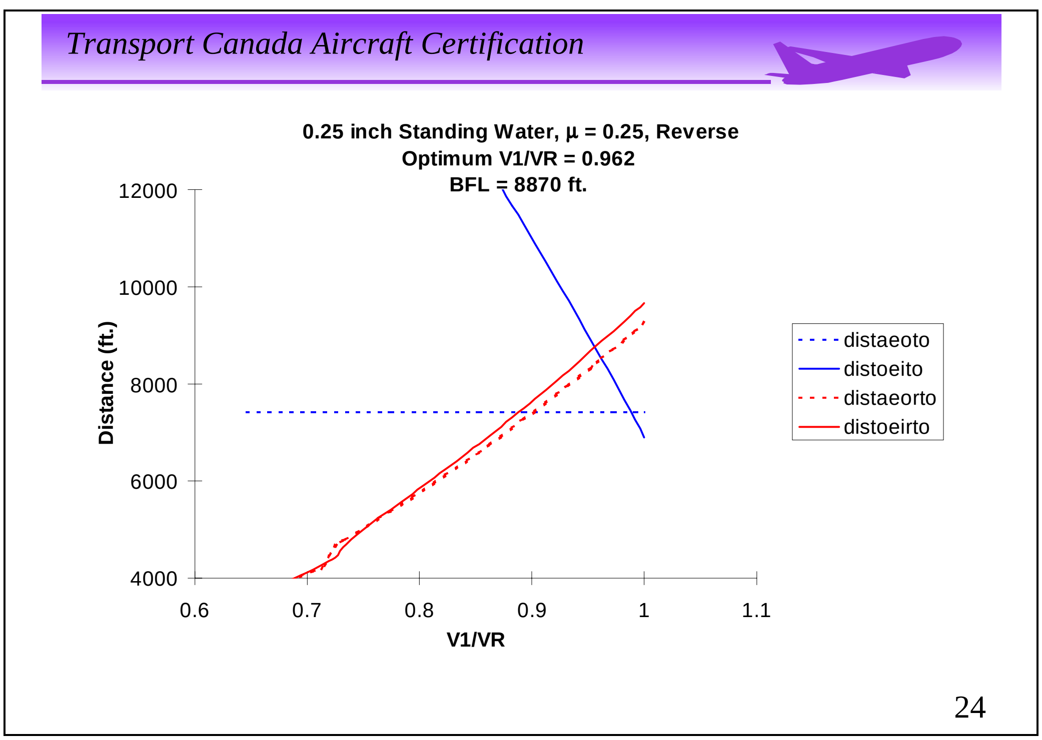
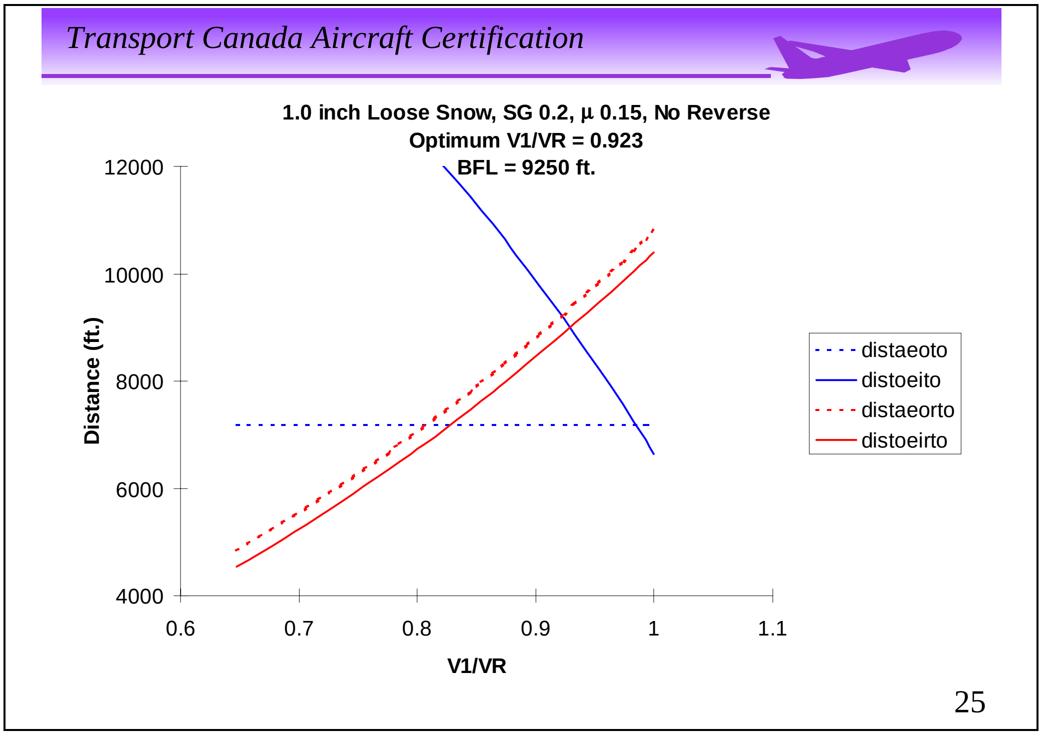
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
20

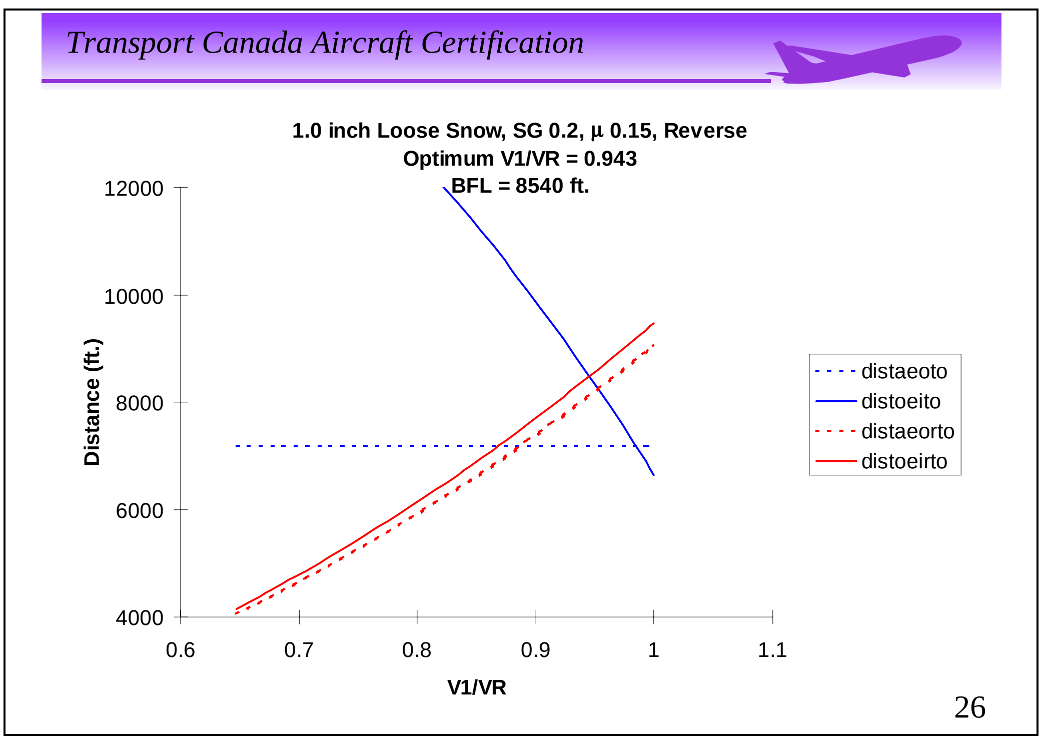

Transport Canada Aircraft Certification
Ice, µ 0.1, No Reverse
Optimum V1/VR = 0.780
BFL = 8900 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
21


Transport Canada Aircraft Certification
Ice, µ 0.1, Reverse
Optimum V1/VR = 0.859
BFL = 7980 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
22


Transport Canada Aircraft Certification
0.25 inch Standing Water, μ = 0.25, No Reverse
Optimum V1/VR = 0.932
BFL = 9720 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
23


Transport Canada Aircraft Certification
0.25 inch Standing Water, μ = 0.25, Reverse
Optimum V1/VR = 0.962
BFL = 8870 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
24


Transport Canada Aircraft Certification
1.0 inch Loose Snow, SG 0.2, µ 0.15, No Reverse
Optimum V1/VR = 0.923
BFL = 9250 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
25


Transport Canada Aircraft Certification
1.0 inch Loose Snow, SG 0.2, µ 0.15, Reverse
Optimum V1/VR = 0.943
BFL = 8540 ft.
Distance (ft.)
12000
10000
8000
6000
4000
0.6
0.7
0.8
0.9
1
1.1
V1/VR
distaeoto
distoeito
distaeorto
distoeirto
26

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Example
BFL Distances for Different Runway Conditions

	No Reverse		Reverse	
	Optimum V1/VR	**BFL (ft.)**	**Optimum V1/VR**	**BFL (ft.)**
Dry Runway	0.977	6660	(0.987)	(6530)
Wet Runway	0.908	7340	0.937	7020
Ice $\mu = 0.1$	0.780	8900	0.859	7980
0.25 Inch Standing Water $\mu = 0.25$	0.932	9720	0.962	8870
1.0 Inch Loose Snow, SG = 0.2 $\mu = 0.15$	0.923	9250	0.943	8540

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Example
Field Lengths using Dry Runway V1/VR

	BFL (ft.)	Field Length No Reverse (ft.)	Field Length Reverse (ft.)
Dry Runway	6660	-	-
Wet Runway	-	8370	7620
Ice $\mu = 0.1$	-	12850	9930
0.25 Inch Standing Water $\mu = 0.25$	-	10770	9170
1.0 Inch Loose Snow, SG = 0.2 $\mu = 0.15$		10310	9040

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Summary

- A Takeoff Performance Program has been developed using industry standard performance methods
- The program accounts for all major variables, including aircraft characteristics and atmospheric conditions
- The program is capable of representing a wide range of transport category aircraft

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Summary (continued)

- The program may be used to examine the relative effects of the various parameters on the takeoff performance of the sample aircraft
- However, the output data are not intended, and should not be used, to replace Aircraft Flight Manual (AFM) or other data provided by the manufacturer for a specific aircraft type

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Operations on Contaminated Runways
Harmonization of FAR/JAR Operating Rules

Don Stimson
U.S. Federal Aviation Administration, Transport Standards
Seattle, Washington

Operations on Contaminated Runways

Harmonization of FAR/JAR Operating Rules

Don Stimson
FAA Transport Standards Staff

2 November 1999

Airplane Performance Harmonization Working Group

- Chartered in November 1997
- Task: To harmonize the performance-related FAR/JAR operating rules
- Membership includes: Regulatory authorities, airplane manufacturers, pilot groups, and operators from the U.S., Europe, and Canada

JAA Contaminated Runway Requirements

- Takeoff: Engine failure accountability
- Landing: Takeoff weight limited by forecast/expected landing conditions

FAA Contaminated Runway Requirements

- No specific operational or airworthiness requirements
- AC 91-6A provides guidance for operations on contaminated runways

Harmonization Status

No Consensus Yet

- Majority support: JAR requirements for takeoff

  Rely on in-flight check for landing
- Stumbling Block: Economics (Payload offload)

Still Looking for Consensus

- Goal: Reduce payload penalty
- Two subgroups to address:
  - Runway reporting/clearing issues
  - Airplane data issues

Subgroup Issues

Runway Issues

Reporting
- Timeliness
- Responsibility
- Contaminant type
- Contaminant depth
- Friction level

Clearing
- Timeliness
- Quality
- Surface treatments

Data Issues

- Analysis methods
- Presentation
  - Simplification/conservatism
  - Contaminant types/depths
- AFM data range
- Data usage

Where To Go from Here?

- Subgroups to report at January meeting
- Significant economic issues likely to remain
- Working group recommendations due before end of year 2000
- Rulemaking will take time

How Can Winter Runway Program Help?

- Gaps in data potentially causing excess conservatism:
  - Flooded/slush-covered runways
  - Modern antiskid systems
  - Current airplane/wheel configurations
- Standardized reporting practices

Goal

Safer operations on contaminated runways

Determination of Aircraft Landing Distance on Winter Contaminated Runways

John Croll
National Research Council Canada
Ottawa, Ontario

National Research Council Canada   Conseil national de recherches Canada

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Determination of Aircraft Landing Distance on Winter Contaminated Runways

John Croll
Jim Martin
Paul Carson
Matthew Bastian

IMAPCR
November 1999

Canada

Landing Distance Determination on Contaminated Runways

1. Compute aircraft μ braking based on flight test data
2. Plot mean μ braking versus CRFI
3. Use the μ braking / CRFI relationship to develop a deceleration model for full anti-skid braking
4. Determine braking distance (D3)
5. Add equations for air distance (D1) and delay distance (D2) based on flight test data
6. Add safety factors to obtain "recommended landing distance"

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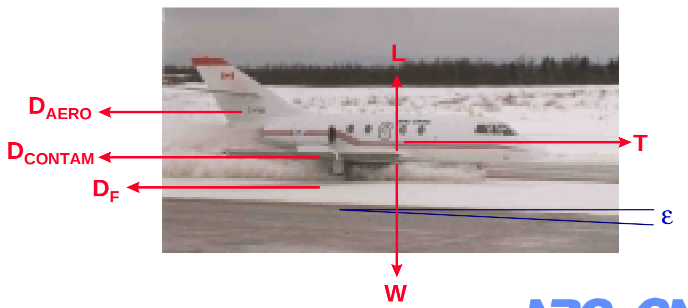
Aircraft Braking Coefficient Computation

μ braking (μ_B) computed from flight test data:

$$\frac{1}{g}\frac{dV}{dt} = \frac{T}{W} - \frac{D_{AERO}}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \mu_B(1-\frac{L}{W})$$



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Landing Distance Determination on Contaminated Runways

1. Compute aircraft μ braking based on flight test data
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4. Determine braking distance (D3)
5. Add equations for air distance (D1) and delay distance (D2) based on flight test data
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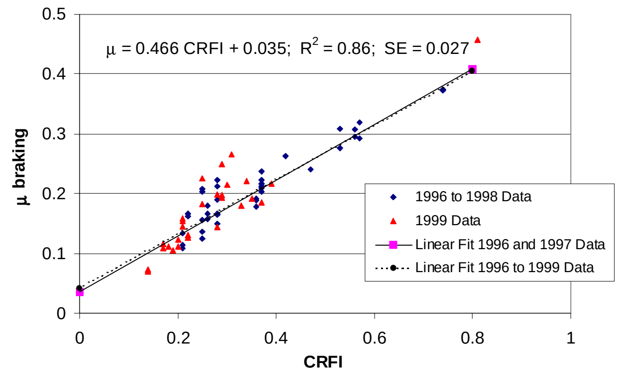
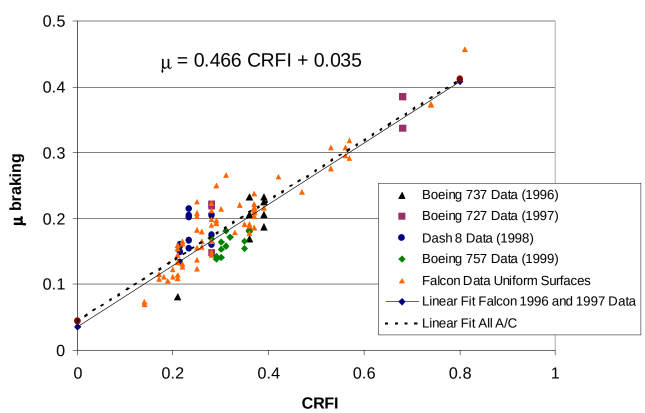
Falcon 20 µ Braking vs CRFI
1996 to 1999 Data



- Maximum anti-skid braking, idle thrust, landing configuration
- Runway surfaces (23) with uniform distribution of contaminant

Other Aircraft µ Braking vs CRFI
1996 to 1999 Data



- Maximum anti-skid braking, idle thrust, landing configuration
- Surfaces with uniform distribution of contaminant

Landing Distance Determination on Contaminated Runways

1. Compute aircraft μ braking based on flight test data
2. Plot mean μ braking versus CRFI
3. Use the μ braking / CRFI relationship to develop a deceleration model for full anti-skid braking
4. Determine braking distance (D3)
5. Add equations for air distance (D1) and delay distance (D2) based on flight test data
6. Add safety factors to obtain "recommended landing distance"

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Falcon 20 Deceleration Model Maximum Anti-skid Braking, Idle Thrust

$$\frac{1}{g}\frac{dV}{dt} = \frac{T}{W} - \frac{D_{AERO}}{W} - \frac{D_{CONTAM}}{W} - \varepsilon - \mu_B(1 - \frac{L}{W})$$

- Substitute $\mu_B = 0.035 + 0.466 \times \text{CRFI}$;
- Assume contaminant drag and ε are zero;
- Substitute idle thrust $T = f\ (V_{EAS})$;
- L, D equations with C_L and C_D in the landing configuration:

$$\frac{1}{g}\frac{dV}{dt} = f\,(W, CRFI, V_{EAS}, V_{EAS}^2)$$

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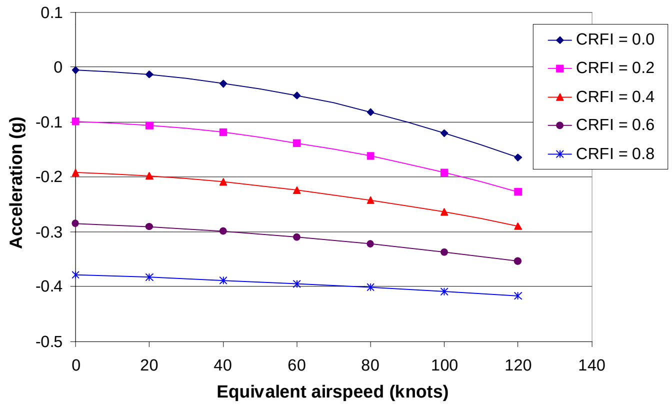
Falcon 20 Deceleration Model
Maximum Anti-skid Braking, Idle Thrust



- Aircraft gross weight = 20,000 lb.
- Landing configuration

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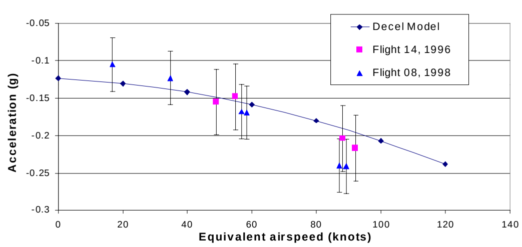
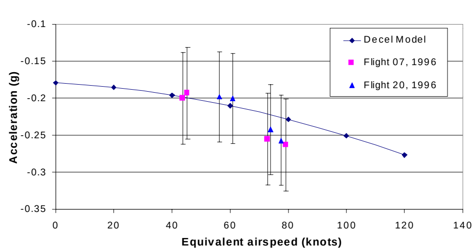
Falcon 20 Deceleration Model
Comparison with Actual Test Points

CRFI = 0.25
GW = 21,000 lb.





CRFI = 0.37
GW = 21,000 lb.

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Landing Distance Determination on Contaminated Runways

1. Compute aircraft μ braking based on flight test data
2. Plot mean μ braking versus CRFI
3. Use the μ braking / CRFI relationship to develop a deceleration model for full anti-skid braking
4. Determine braking distance (D3)
5. Add equations for air distance (D1) and delay distance (D2) based on flight test data
6. Add safety factors to obtain "recommended landing distance"

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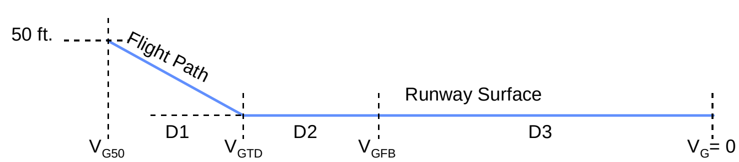
Landing Distance – Definition



- Landing distance (LD) is the total distance from 50 ft. above the runway to a full stop, and is the sum of:
  - Air distance **D1** = 50 ft. to touchdown
  - Delay distance **D2** = touchdown to application of full braking
  - Braking distance **D3** = application of full braking to a stop
- LD = D1 + D2 + D3

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Landing Distance – Terminology

- **AFM LD**
  - Aircraft Flight Manual LD based on the manufacturer's flight tests
  - Bare and dry runway (CRFI ≈ 0.8)
  - NO safety factors (unfactored)
- **Landing Field Length**
  - AFM LD with safety factors included (AFM LD / 0.6), also called "factored LD"
- **Predicted LD**
  - Based on Falcon 20 flight test data
  - Contaminated runways (CRFI = 0.16 to 0.8)
  - NO safety factors
- **Recommended LD**
  - Predicted LD with safety factors added (2 sigma)

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Falcon 20 Predicted Landing Distance Computation

$$D1 = 1.55 \times (V_{G50} - 80)^{1.35} + 964 \qquad (ft)$$

$$D2 = 2.96 \times (V_{G50} - 9.98) \times 1.688 \qquad (ft)$$

For D3, use an average deceleration from the model at the RMS of V_{EFB} :

$$ACC_{AV} = f\left(W, CRFI, \frac{V_{EFB}}{\sqrt{2}}, \frac{V_{EFB}^2}{2}\right)$$

$$D3 = (V_{GFB} \times 1.688)^2 \div (64.348 \times ACC_{AV}) \qquad (ft)$$

Predicted LD = D1 + D2 + D3

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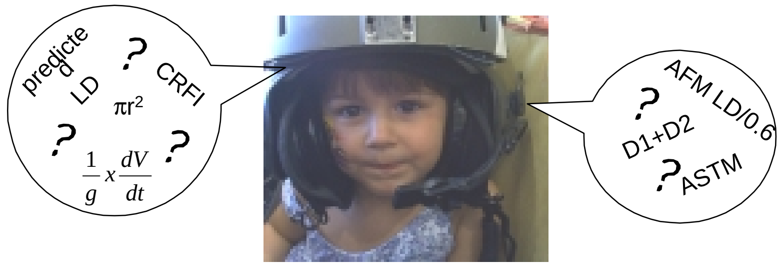
Presentation of the Data to the Pilot for Most Efficient Use



- Not practical to compute predicted LD for each landing from the various equations
- Instead, determine predicted LD from:
    1) AFM LD (available from the charts), and
    2) the reported CRFI
- Require a direct comparison between predicted LD and AFM LD

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Comparison of Falcon 20 Predicted LD vs (AFM LD, CRFI)

- Select a full range of Falcon 20 AFM LDs (1800 - 4000 ft.), and determine the associated approach parameters (W, PA, and wind)
- Compute predicted LDs from the same approach parameters (for each AFM LD) for CRFIs between 0.18 and 0.8

W (lb.)	CRFI	V_{E50} (kt)	PA (ft.)	V_{T50} (kt)	HW (kt)	V_{G50} (kt)	AFM LD (ft.)
17000	0.8	105.83	0	105.83	20	85.83	1800
18000	0.8	109.31	0	109.31	10	99.31	2000
18000	0.8	109.31	0	109.31	0	109.31	2200
20700	0.8	117.82	0	117.82	0	117.82	2400
23200	0.8	124.76	0	124.76	0	124.76	2600
25100	0.8	129.55	0	129.55	0	129.55	2800
25200	0.8	129.80	3000	135.64	0	135.64	3000
25200	0.8	129.80	6000	141.48	0	141.48	3200
25300	0.8	130.04	6000	141.74	-3	144.74	3400
25400	0.8	130.28	6000	142.00	-6	148.00	3600
25400	0.8	130.28	6000	142.00	-9	151.00	3800
25700	0.8	130.99	6000	142.78	-10.5	153.28	4000

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Predicted LD vs (AFM LD, CRFI)
AFM LD = 3600 ft.

- Extend table rows to include calculations for predicted LD (PLD)
- D3 and predicted LD increase with decreasing CRFI values
- AFM LD constant at 3600 ft.

W	V_{E50}	PA	V_{T50}	HW	V_{G50}	AFMLD	CRFI	V_{EFB}	V_{GFB}	ACC_{AV}	D3	D2	D1	PLD
(lb.)	(kt)	(ft.)	(kt)	(kt)	(kt)	(ft.)		(kt)	(kt)	("g")	(ft.)	(ft.)	(ft.)	(ft.)
25400	130.28	6000	142.00	-6	148.00	3600	0.8	117.13	134.85	-0.403	1996	685	1437	4117
25400	130.28	6000	142.00	-6	148.00	3600	0.7	117.13	134.85	-0.362	2222	685	1437	4343
25400	130.28	6000	142.00	-6	148.00	3600	0.6	117.13	134.85	-0.321	2505	685	1437	4626
25400	130.28	6000	142.00	-6	148.00	3600	0.5	117.13	134.85	-0.281	2870	685	1437	4992
25400	130.28	6000	142.00	-6	148.00	3600	0.4	117.13	134.85	-0.240	3361	685	1437	5482
25400	130.28	6000	142.00	-6	148.00	3600	0.35	117.13	134.85	-0.219	3675	685	1437	5796
25400	130.28	6000	142.00	-6	148.00	3600	0.3	117.13	134.85	-0.199	4054	685	1437	6175
25400	130.28	6000	142.00	-6	148.00	3600	0.25	117.13	134.85	-0.178	4520	685	1437	6641
25400	130.28	6000	142.00	-6	148.00	3600	0.2	117.13	134.85	-0.158	5106	685	1437	7227

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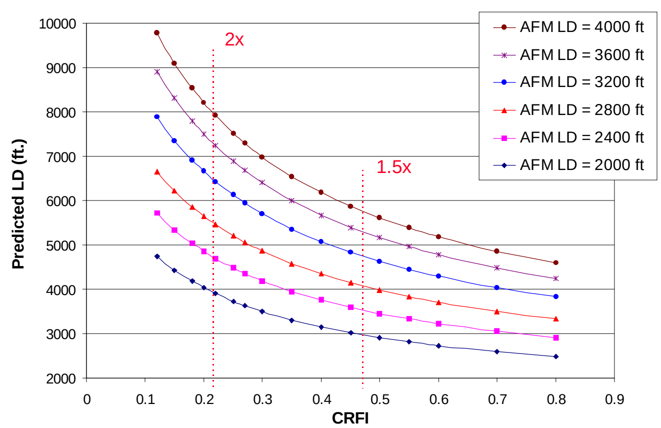
Falcon 20 Predicted LD vs CRFI
AFM LD from 2000 to 4000 ft.



- Full anti-skid braking, idle thrust, landing configuration
- Typical Falcon 20 GW, PA, and wind combinations

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Landing Distance Determination on Contaminated Runways

1. Compute aircraft μ braking based on flight test data
2. Plot mean μ braking versus CRFI
3. Use the μ braking / CRFI relationship to develop a deceleration model for full anti-skid braking
4. Determine braking distance (D3)
5. Add equations for air distance (D1) and delay distance (D2) based on flight test data
6. → Add safety factors to obtain "recommended landing distance"

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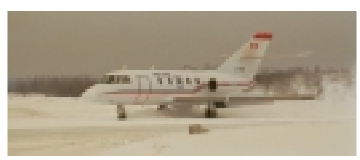
Recommended Landing Distance

- Recommended LD is predicted LD increased by safety factors accounting for variations in:
  - pilot technique
  - aircraft performance
  - runway condition (CRFI)



- Computations include the following adjustments:
  - D1 and D2:
    - Add twice the standard deviation to each (provides 95% level of confidence)
  - D3 computation:
    - Decrease linear fit of μ braking vs CRFI by about one standard deviation
    - Use 80% of the reported CRFI

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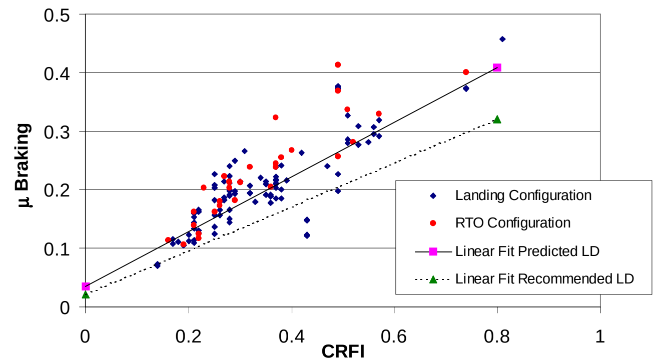
Falcon 20 µ Braking vs CRFI
All Surfaces Tested



- Maximum anti-skid braking, idle thrust
- 120 out of 126 data points above the line, or 95%

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Recommended
Landing Distance Computation

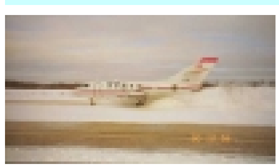
$$D1R = D1 + (V_{G50} - 6.52) \times 1.56 \times 1.688 \qquad (ft)$$

$$D2R = D2 + (V_{G50} - 13.44) \times 1.86 \times 1.688 \qquad (ft)$$

For D3R, average deceleration from the model, with safety factor adjustments, at RMS of V_{EFB}

$$ACCR_{AV} = f(W, 0.8 \times CRFI, \frac{V_{EFB}}{\sqrt{2}}, \frac{V_{EFB}^2}{2})$$

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



Recommended LD = D1R + D2R + D3R

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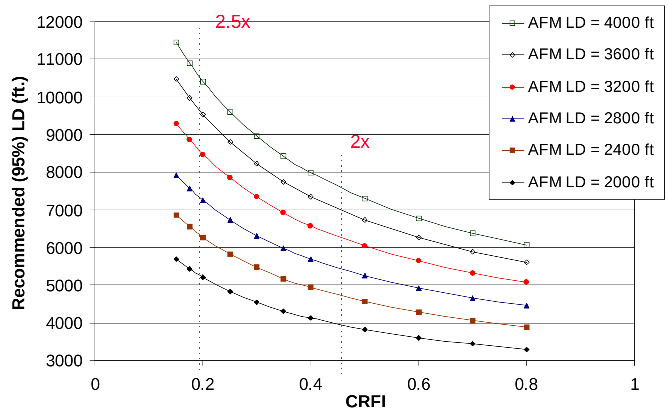
Recommended LD vs CRFI
AFM LD from 2000 to 4000 ft.



- Full anti-skid braking, landing configuration, idle thrust
- Typical Falcon 20 GW, PA, and wind combinations

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CRFI Table of Recommended Landing Distance
No Reverse Thrust

Landing Distance Bare and Dry (unfactored)	Recommended Landing Distance – No Reverse 95% Confidence Level											
	Reported Canadian Runway Friction Index (CRFI)											
	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.27	0.25	0.22	0.2	0.18
1800	3180	3260	3360	3480	3610	3780	3970	4120	4220	4400	4540	4690
2000	3550	3650	3770	3910	4070	4260	4490	4660	4780	4990	5150	5330
2200	3800	3910	4050	4200	4380	4590	4850	5030	5170	5410	5580	5780
2400	4190	4320	4470	4640	4840	5080	5370	5570	5730	5980	6180	6390
2600	4550	4700	4860	5050	5270	5530	5850	6080	6240	6520	6730	6970
2800	4830	4980	5160	5360	5600	5880	6220	6460	6630	6930	7150	7400
3000	5190	5360	5560	5780	6040	6360	6730	7000	7190	7520	7770	8040
3200	5580	5770	5980	6230	6520	6870	7280	7570	7790	8150	8430	8730
3400	5880	6090	6320	6590	6900	7270	7720	8030	8260	8650	8950	9270
3600	6200	6420	6660	6950	7290	7680	8160	8500	8750	9170	9480	9830
3800	6500	6740	7000	7310	7660	8090	8600	8960	9220	9670	10010	10380
4000	6710	6960	7230	7550	7920	8360	8890	9270	9540	10010	10360	10750

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Recommended Landing Distance
Effect of Reverse Thrust

Turbojet Aircraft (with reverse)		Turboprop Aircraft (prop discing)	
µB Ratio	**SDR**	**µB ratio**	**SDR**
1.0	0.94, 0.97	1.0	0.82, 0.87
0.7	0.89, 0.92	0.7	0.76, 0.82
0.5	0.82, 0.87	0.5	0.70, 0.77
0.3	0.72, 0.76	0.3	0.63, 0.68
0.1	0.48, 0.49	0.1	0.40, 0.45

$$\textbf{µB ratio} = \frac{\text{µB contaminated (CRFI)}}{\text{µB (dry)}}$$

$$\text{Stopping Distance Ratio } \textbf{(SDR)} = \frac{\text{SD with reverse (discing)}}{\text{SD without reverse (discing)}}$$

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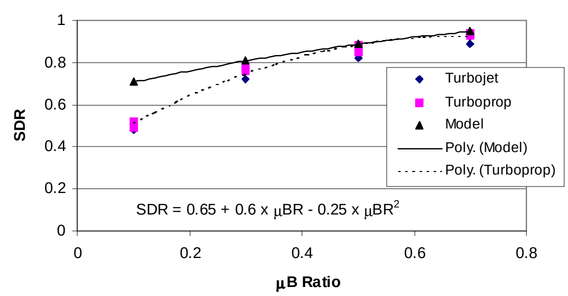
Recommended Landing Distance
Effect of Reverse Thrust



$D3R_{REVERSE} = D3R_{NO\ REVERSE} \times SDR$

SDR = ƒ (µB Ratio)

µB Ratio = ƒ (CRFI) $LDR_{REVERSE} = D1R + D2R + D3R_{REVERSE}$

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CRFI Table of Recommended Landing Distance Reverse Thrust

Landing Distance Bare and Dry (unfactored)	Recommended Landing Distance – Reverse Thrust 95% Confidence Level											
	Reported Canadian Runway Friction Index (CRFI)											
	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.27	0.25	0.22	0.2	0.18
1800	3130	3200	3270	3350	3450	3560	3690	3790	3860	3970	4060	4150
2000	3500	3580	3660	3760	3870	4000	4160	4270	4350	4480	4580	4700
2200	3740	3830	3930	4040	4160	4310	4480	4600	4690	4840	4950	5080
2400	4130	4220	4330	4460	4590	4760	4950	5080	5180	5340	5460	5600
2600	4480	4590	4710	4840	4990	5170	5380	5520	5630	5810	5940	6080
2800	4740	4860	4990	5130	5300	5490	5710	5860	5970	6160	6300	6450
3000	5100	5230	5370	5530	5710	5920	6170	6340	6460	6670	6820	6990
3200	5480	5620	5780	5960	6160	6390	6660	6840	6980	7210	7380	7560
3400	5780	5930	6100	6290	6510	6750	7040	7250	7390	7640	7820	8020
3600	6080	6250	6430	6630	6860	7130	7440	7660	7820	8080	8270	8490
3800	6380	6560	6750	6970	7210	7500	7830	8060	8230	8510	8720	8940
4000	6590	6770	6970	7200	7450	7750	8100	8330	8510	8800	9010	9250

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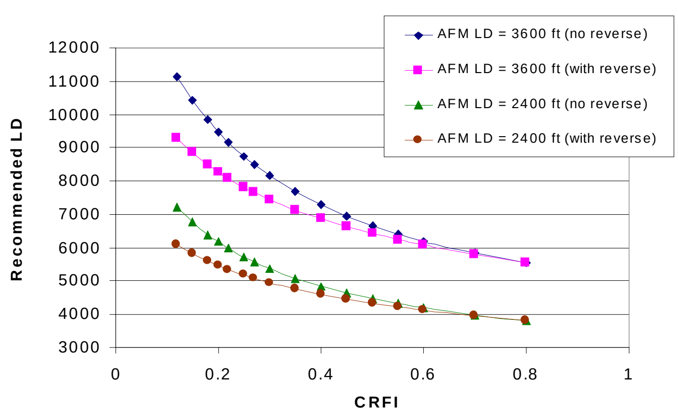
Recommended Landing Distance Comparison With and Without Reverse Thrust



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**Landing Distance Determination
Conclusions**

- Good correlation between Falcon 20 braking coefficients and CRFI on runway surfaces with uniform contaminant distribution
- Limited tests on other aircraft show trends of braking coefficient vs CRFI to be similar to that obtained on the Falcon 20
- A Falcon 20 deceleration model enables prediction of braking distance on contaminated runways
- Inclusion of safety factors provides a 95% confidence level, based on flight test data
- Effect of reverse thrust on stopping distance used to generate a CRFI table with credit for reverse thrust or prop discing

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**Landing Distance Determination
Conclusions** (cont'd)

- The CRFI tables provide recommended landing distances (landing field length) on contaminated runways, based on AFM LD on a bare and dry runway and the reported CRFI value
- Applicability of CRFI table to other aircraft due to:
  - use of aircraft specific AFM LD as a basis
  - proportional corrections applied to AFM LD, based on similar anti-skid system performance
  - safety factors applied

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Statistical Analysis of Stopping Performance on Wet Runways

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OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

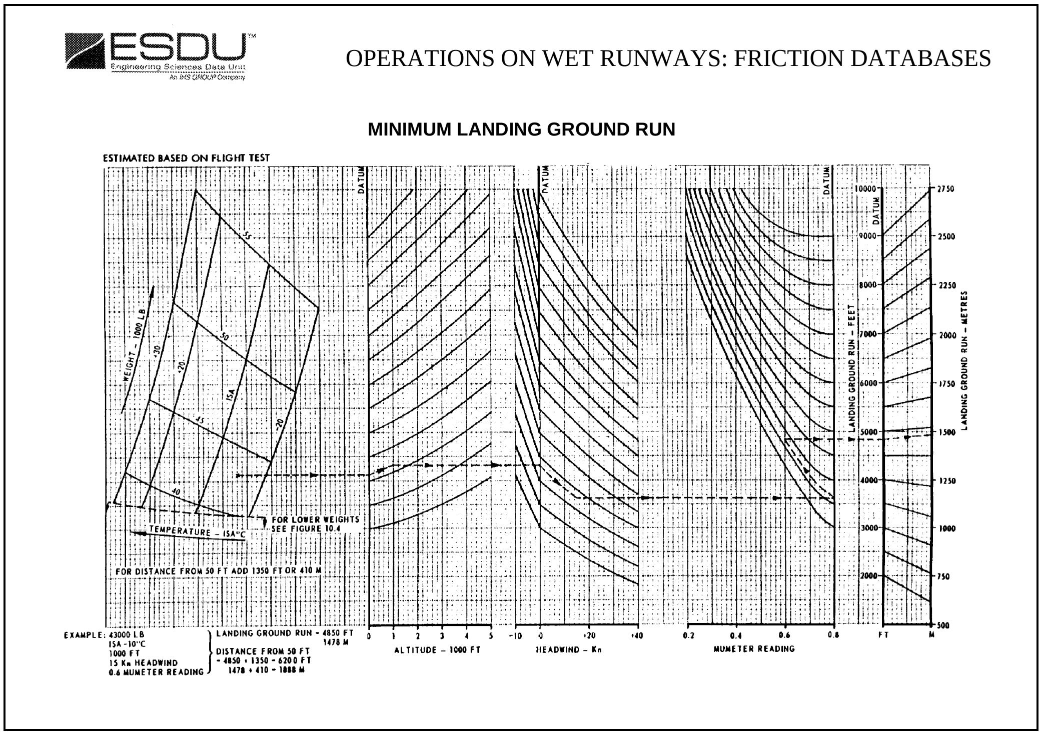
Statistical Analysis of Stopping Performance on Wet Runways

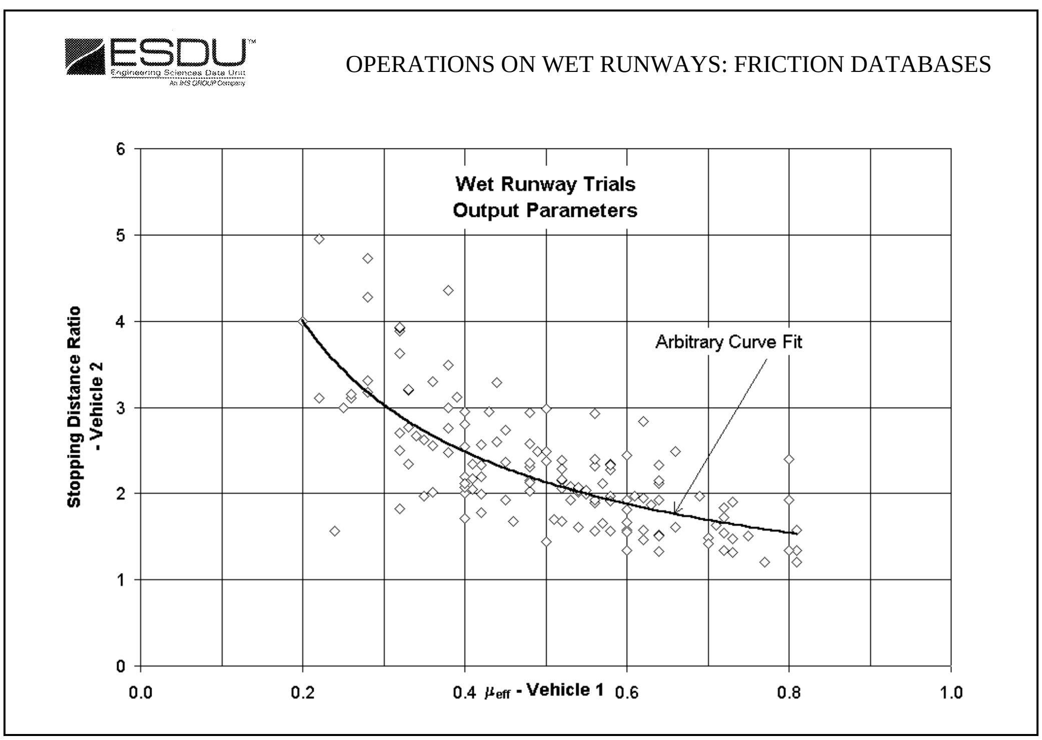
Ken Balkwill

Chairman
Performance Committee
ESDU International

OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

- ❑ Introduction
- ❑ Physical Model
- ❑ Statistical Model
- ❑ Friction Database
- ❑ Use of Existing Data


ESDU
Engineering Sciences Data Unit
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES
MINIMUM LANDING GROUND RUN
ESTIMATED BASED ON FLIGHT TEST
WEIGHT – 1000 LB
TEMPERATURE – ISA°C
FOR LOWER WEIGHTS SEE FIGURE 10.4
FOR DISTANCE FROM 50 FT ADD 1350 FT OR 410 M
EXAMPLE: 43000 LB
ISA -10°C
1000 FT
15 Kn HEADWIND
0.6 MUMETER READING
LANDING GROUND RUN – 4850 FT
1478 M
DISTANCE FROM 50 FT
= 4850 + 1350 = 6200 FT
1478 + 410 = 1888 M
DATUM
ALTITUDE – 1000 FT
HEADWIND – Kn
MUMETER READING
LANDING GROUND RUN – FEET
LANDING GROUND RUN – METRES
FT
M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OPERATIONS ON WET RUNWAYS: FRICTION DATABASES
Wet Runway Trials
Output Parameters
Arbitrary Curve Fit
Stopping Distance Ratio - Vehicle 2
μ_{eff} - Vehicle 1
0
1
2
3
4
5
6
0.0
0.2
0.4
0.6
0.8
1.0

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OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

Some of the factors affecting braking on wet runways

- ❑ Speed
- ❑ Macro- and micro-texture
- ❑ Water depth
- ❑ Tire pressure, temperature and state of wear
- ❑ Tire constituents, structure and tread pattern
- ❑ Braking system efficiency, torque capability and wheel slip ratio
- ❑ Braking effort and so on...

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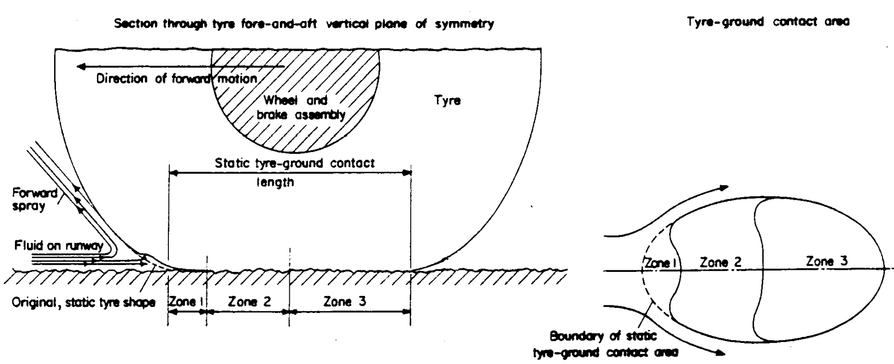
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES



- ❑ Three-zone model of tire-ground contact area

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OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

- Total normal force – sum of pressure forces in all three zones

$$Z = Z_1 + Z_2 + Z_3 = a_1p_1 + a_2p_2 + a_3p_3$$

- Braking force generated in Zone 3

$$G_B = \mu_{dry}a_3p_3$$

$$\mu = \frac{G_B}{Z} = \frac{\mu_{dry}a_3p_3}{a_1p_1 + a_2p_2 + a_3p_3}$$

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OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

Rearranging

$$\mu = \frac{\mu_{dry}}{1 + \frac{p_1}{p_3}\left[\frac{a_1}{a_3} + \frac{p_2\,a_2}{p_1\,a_3}\right]}$$

- Which is of the form

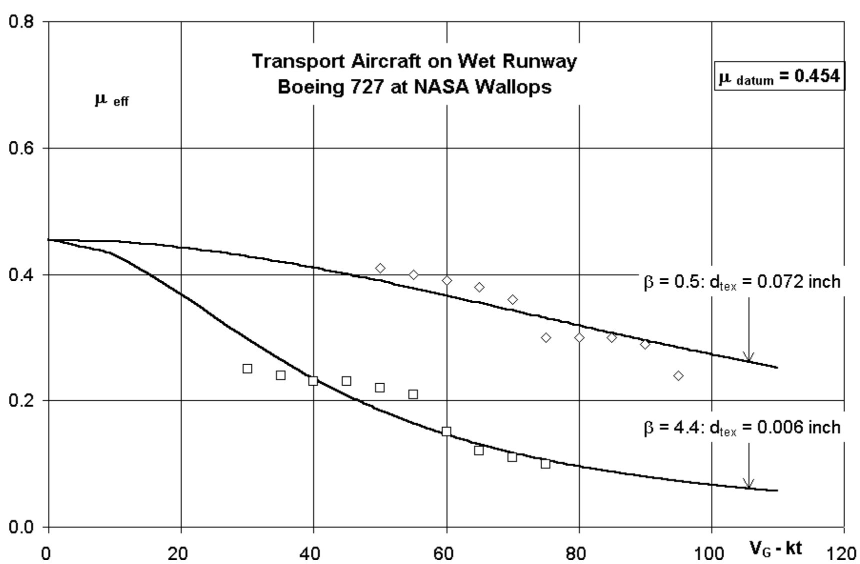
$$\mu = \frac{\mu_{dry}}{1 + ß\,\frac{q}{p}}$$

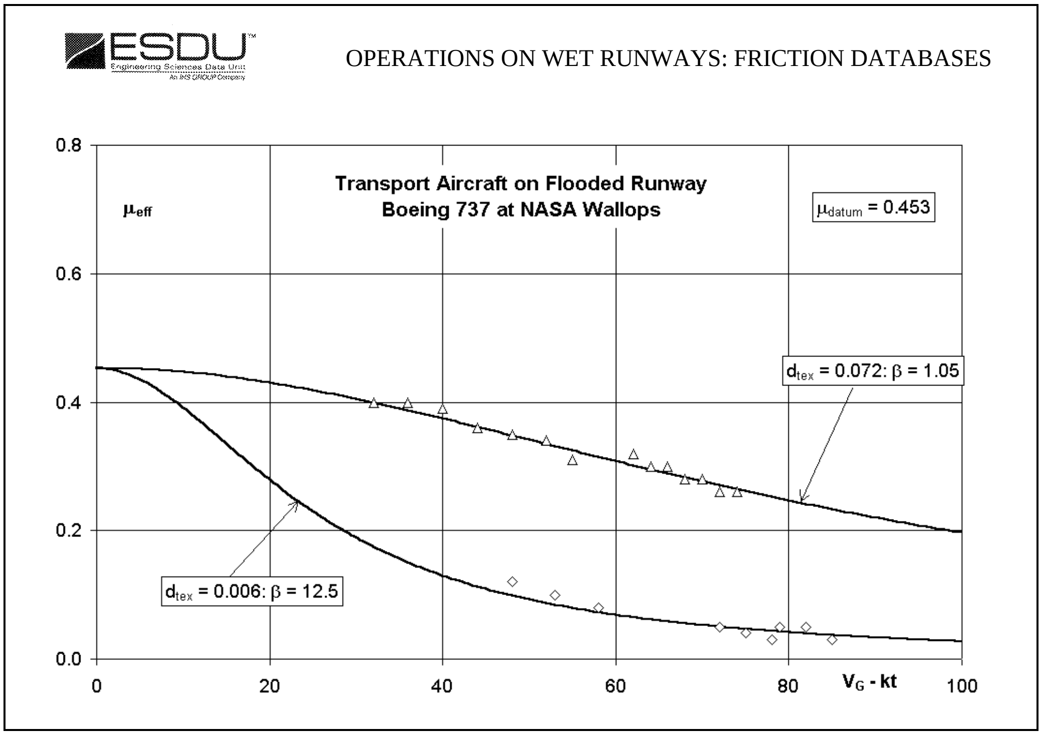
ESDU OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

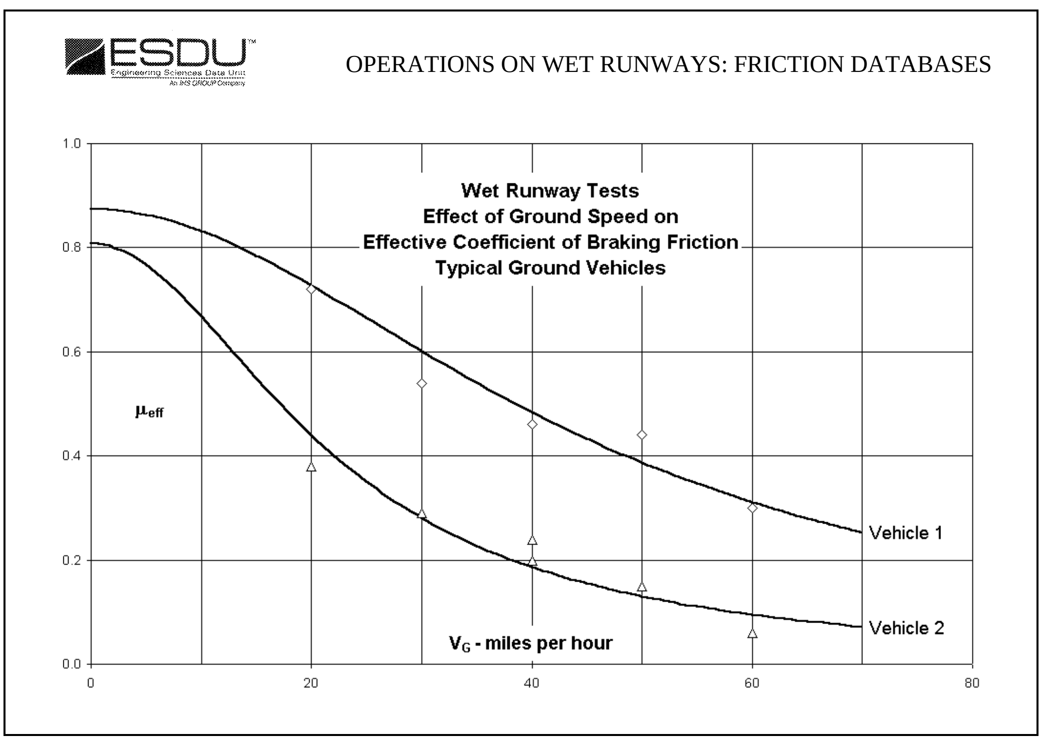
- Case 1: Solution of equation of motion

$$\mu = \frac{\text{[total longitudinal force]} - \text{[aerodynamic drag]}}{\text{[normal (to runway) reaction on braked wheel]}}$$

ESDU OPERATIONS ON WET RUNWAYS: FRICTION DATABASES




ESDU
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES
Transport Aircraft on Flooded Runway
Boeing 737 at NASA Wallops
μ_{eff}
μ_{datum} = 0.453
d_{tex} = 0.072: β = 1.05
d_{tex} = 0.006: β = 12.5
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
V_G - kt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OPERATIONS ON WET RUNWAYS: FRICTION DATABASES
Wet Runway Tests
Effect of Ground Speed on
Effective Coefficient of Braking Friction
Typical Ground Vehicles
μ_{eff}
Vehicle 1
Vehicle 2
V_G - miles per hour
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80

OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

❑ Case 2: Using stopping distance ratio

$$ß = \frac{p}{q}\left\{\frac{S_{wet}/S_{dry}}{1 - \dfrac{D_G\,[\,(S_{wet}/S_{dry}) - 1\,]}{\mu_{datum}\overline{R}_{braked}}} - 1\right\}$$

OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

❑ Characteristic equation

$$\mu_{wet} = \frac{\mu_{datum}}{\left(1 + ß\,\dfrac{q}{p}\right)}$$

❑ Auxiliary equation

$$\kappa = \sqrt{ßd_{tex}}$$

❑ ê is system-runway interaction parameter

ESDU — OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

Constituents of friction database

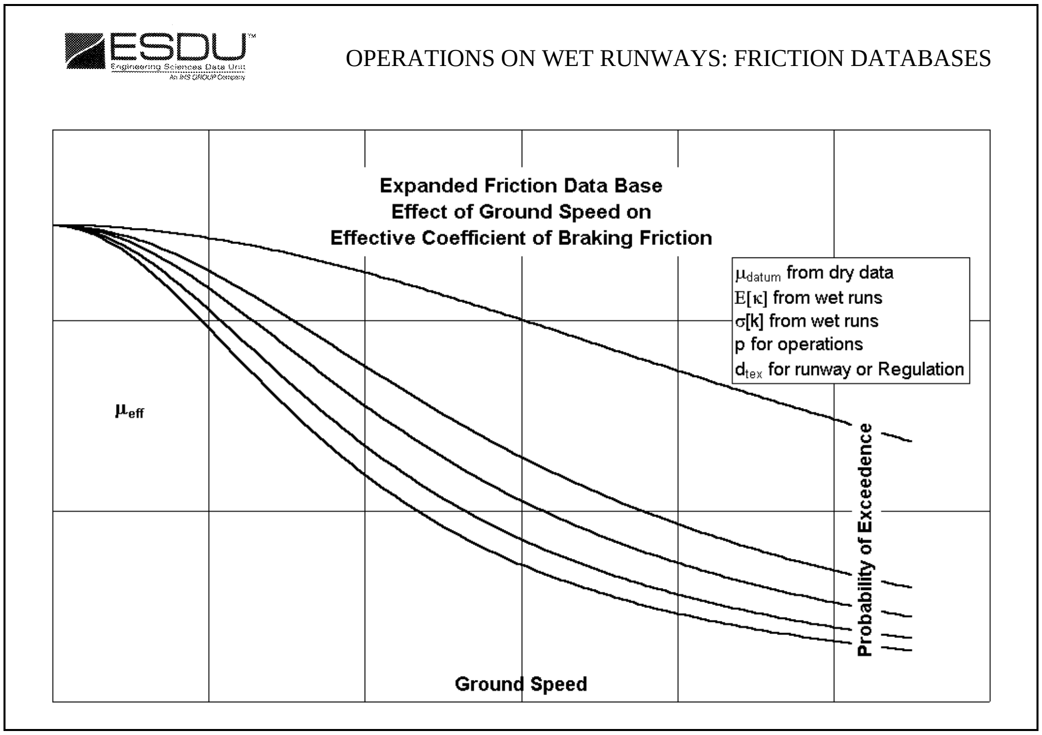
- Datum friction coefficient – μ_{datum}
- Mean value of system-runway interaction parameter – $\bar{\kappa}$
- Standard deviation of system-runway interaction parameter – $\sigma[\kappa]$

ESDU — OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

Combine characteristic and auxiliary equations

$$\mu_{wet} = \frac{\mu_{datum}}{\left(1 + \frac{(\bar{\kappa} + z\sigma[\kappa])^2}{d_{tex}} \frac{q}{p}\right)}$$

- Value of z determined by choice of probability of exceedence
- Macro-texture depth for given runway or set by Regulations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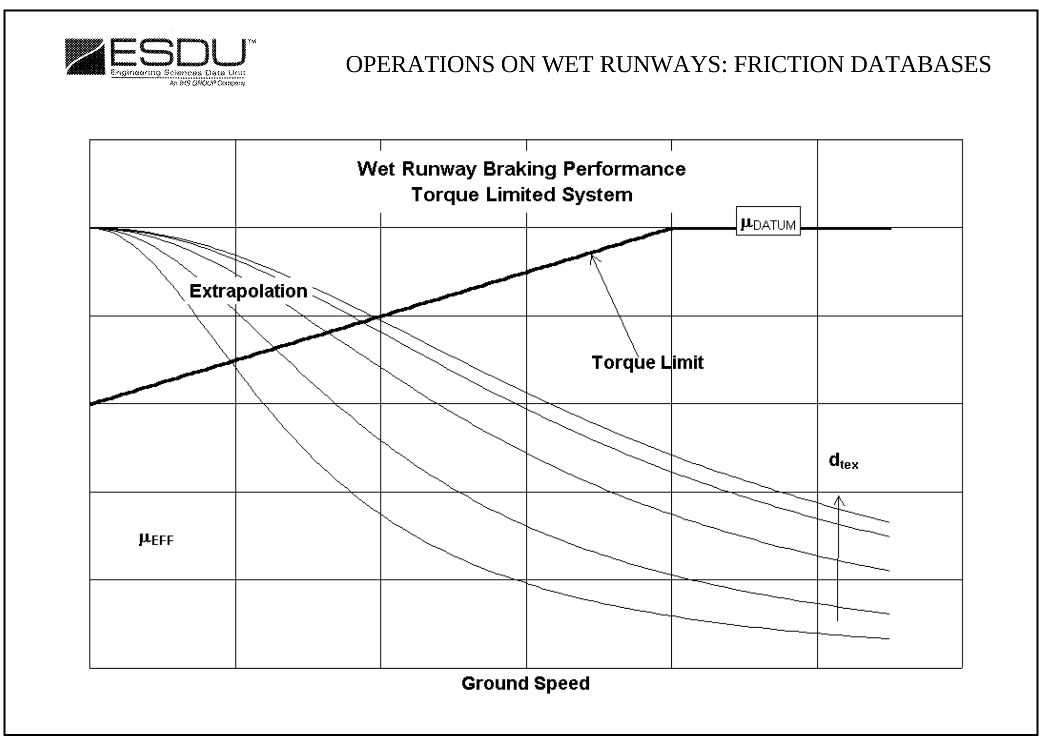
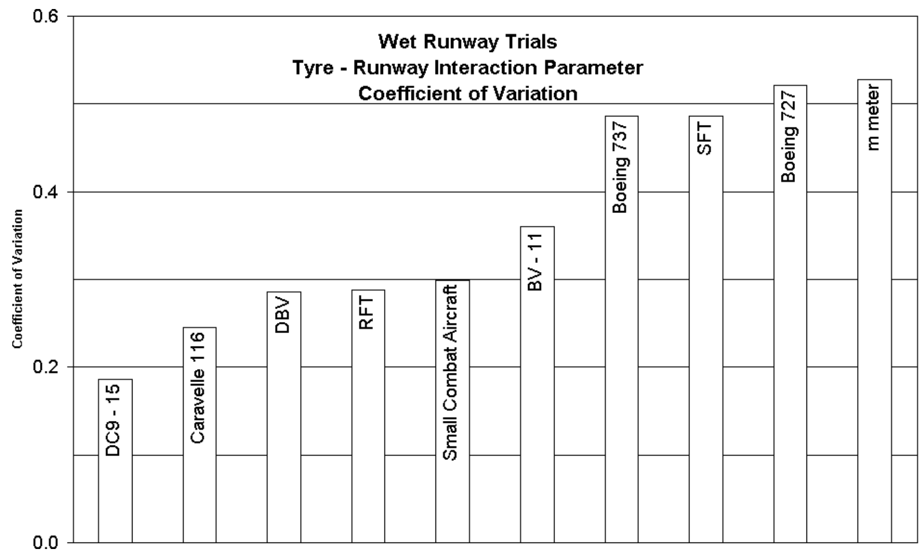
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES
Expanded Friction Data Base
Effect of Ground Speed on
Effective Coefficient of Braking Friction
μ_{datum} from dry data
E[κ] from wet runs
σ[k] from wet runs
p for operations
d_{tex} for runway or Regulation
μ_{eff}
Probability of Exceedence
Ground Speed


ESDU
Engineering Sciences Data Unit
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES
Wet Runway Braking Performance
Torque Limited System
μ_{DATUM}
Extrapolation
Torque Limit
d_{tex}
μ_{EFF}
Ground Speed

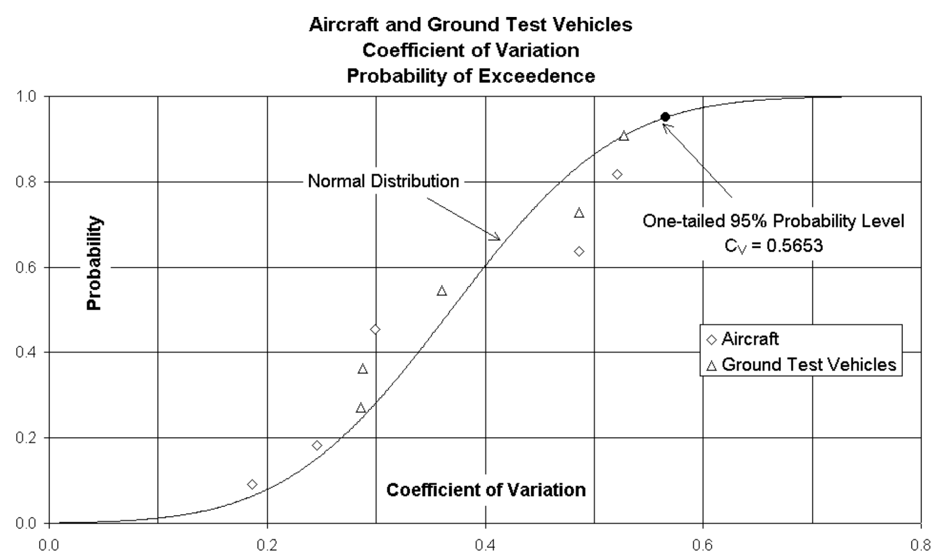
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES



OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

- Coefficient of variation of κ – consistency

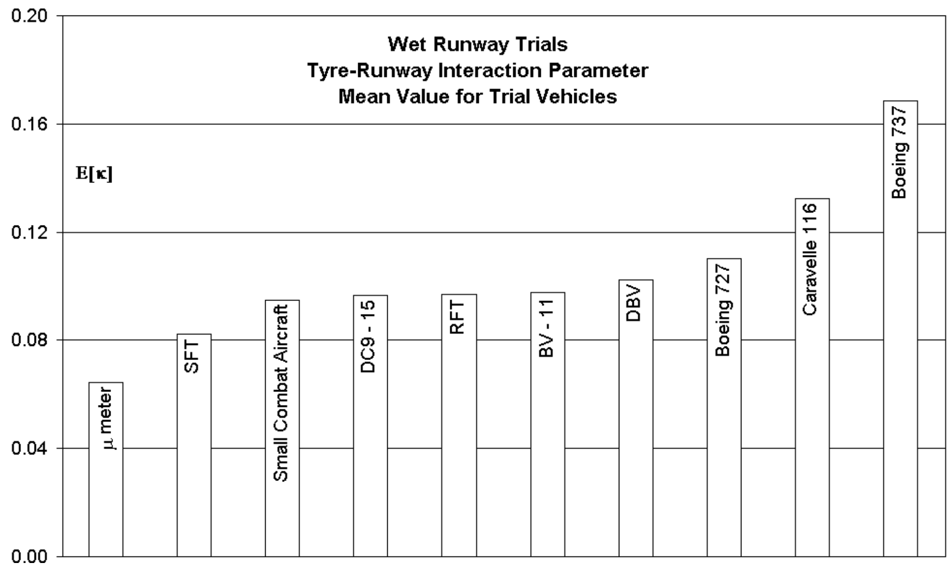
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES



OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

- Coefficient of variation of κ – distribution

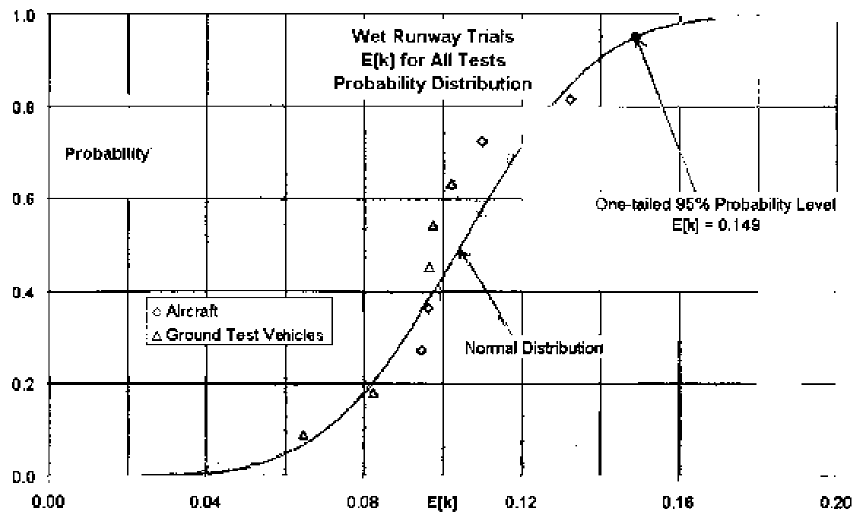
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES



OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

- Mean value of κ – consistency

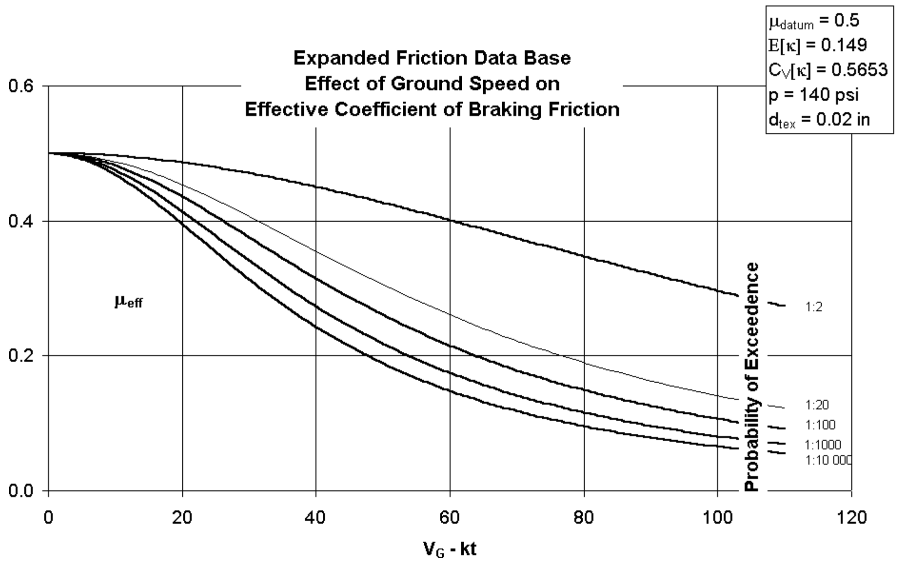
OPERATIONS ON WET RUNWAYS: FRICTION DATABASES



OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

- Mean value of κ – distribution

OPERATIONS ON WET RUNWAYS: FRICTION DATABASES



OPERATIONS ON WET RUNWAYS: FRICTION DATABASES

Statistical model based on simple physical model

- ❑ Water depth limited?
- ❑ Braking system limited only by friction?
- ❑ Comprehensive testing of new systems?
- ❑ Extension of methods to other kinds of contamination?

Summary of Falcon 20 Contamination Drag Results, 1996 to 1999

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Transport Canada, Aircraft Certification
Ottawa, Ontario

Transport Canada Aircraft Certification

Summary of Falcon 20 Contamination Drag Results, 1996 to 1999

IMAPCR '99

2nd International Meeting on Aircraft Performance on Contaminated Runways

2-4 November 1999

J.C.T. Martin
Flight Test Engineer
Transport Canada

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Contents of Presentation

- Definition of Contamination Drag and Equivalent Water Depth
- Test Conditions
- Test Configurations
- Analysis Method for Contamination Drag
- Results for Contamination Drag
- Analysis Method for Aircraft Braking Coefficient
- Results for Aircraft Braking Coefficient
- Concluding Remarks

2

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Contamination Drag and Equivalent Water Depth

- During takeoff on a contaminated runway, aircraft acceleration is reduced and takeoff distance is increased due to:
  - displacement of contaminant
  - impingement of contaminant on aircraft
- Contamination drag is the sum of the displacement drag and the impingement drag
- Equivalent Water Depth (EWD) = Depth * Specific Gravity (SG)

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Test Conditions for Contamination Drag

- Winter of 1995-96
  - Flt 96/07, 0.2 inch loose snow, SG = 0.53
  - Flt 96/08, 1.1 inch loose snow, SG = 0.53
  - Flt 96/09, 1.9 inch loose snow, SG = 0.53
  - Flt 96/12, 1.1 inch loose/medium compacted snow, SG = 0.55
  - Flt 96/13, medium/hard compacted snow, SG = 0.57
  - Flt 96/20, 0.2 inch loose snow, SG = 0.44
  - Flt 96/21, 2.0 inch loose snow, SG = 0.52
  - Flt 96/22, 3.0 inch loose snow, SG = 0.53

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Test Conditions for Contamination Drag (continued)

- Winter of 1996-97
  - Flt 97/07, 1.5 inch loose snow taken from runway shoulders, SG = 0.67
  - Flt 97/08, 0.8 inch loose snow taken from runway shoulders, SG = 0.35
  - Flt 97/09, 2.5 inch loose snow taken from runway shoulders, SG = 0.51

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Test Conditions for Contamination Drag (continued)

- Winter of 1997-98
  - Flt 98/02, 0.4 inch loose snow, SG = 0.11
  - Flt 98/03, 1.6 inch loose snow, SG = 0.13
  - Flt 98/05, 2.3 inch loose snow, SG = 0.28
  - Flt 98/06, 1.2 inch loose snow, SG = 0.31
  - Flt 98/07, 1.7 inch loose snow, SG = 0.27
  - Flt 98/09, mixed bare and wet/standing water/slush/snow, average (weighted) depth = 0.25 inch, SG = 0.54
- Winter of 1998-99
  - Flt 99/03, mixed bare and dry/loose snow in drifts, average (weighted) depth = 0.6 inch, SG = 0.12

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Aircraft Configurations

- Three aircraft configurations were tested:
  - Continued takeoff (flap 15, airbrakes in) for contamination drag only
  - Rejected takeoff (flap 15, airbrakes out), contamination drag and aircraft braking coefficient
  - Landing (flap 40, airbrakes out), contamination drag and aircraft braking coefficient

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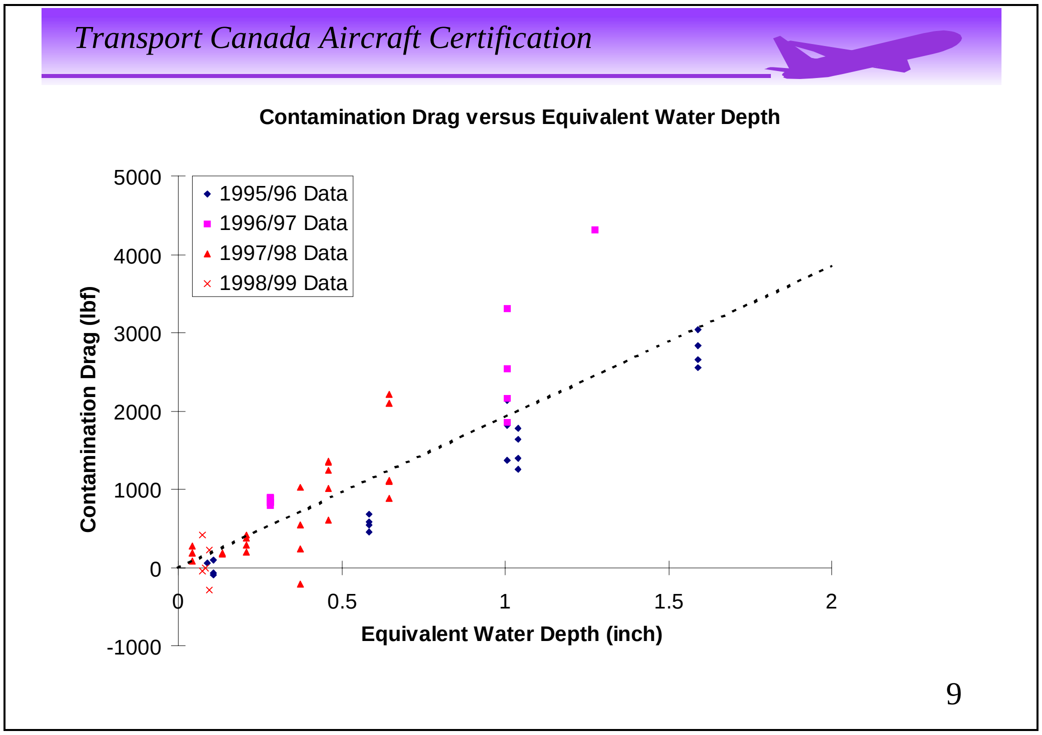
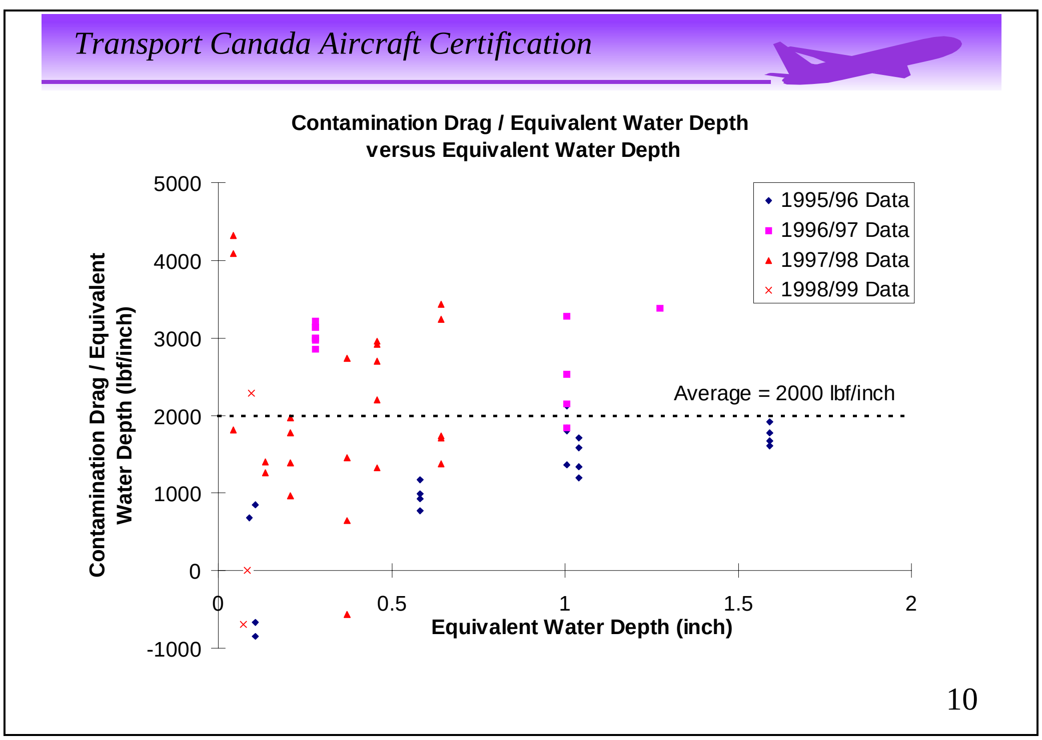
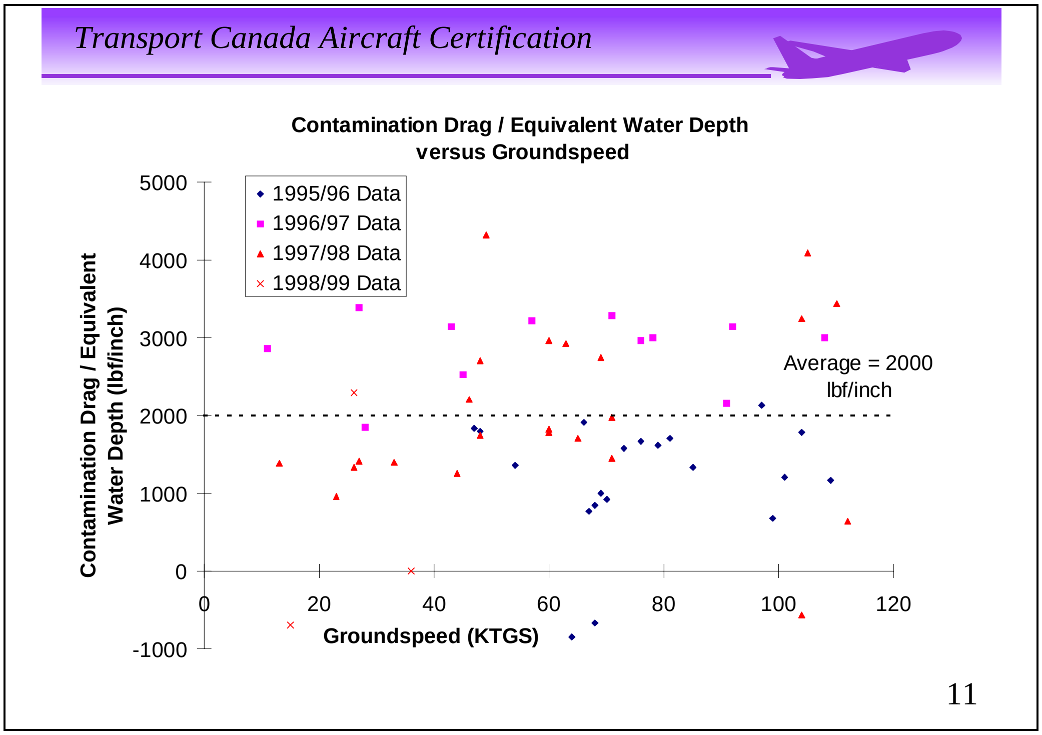
Analysis Method for Contamination Drag

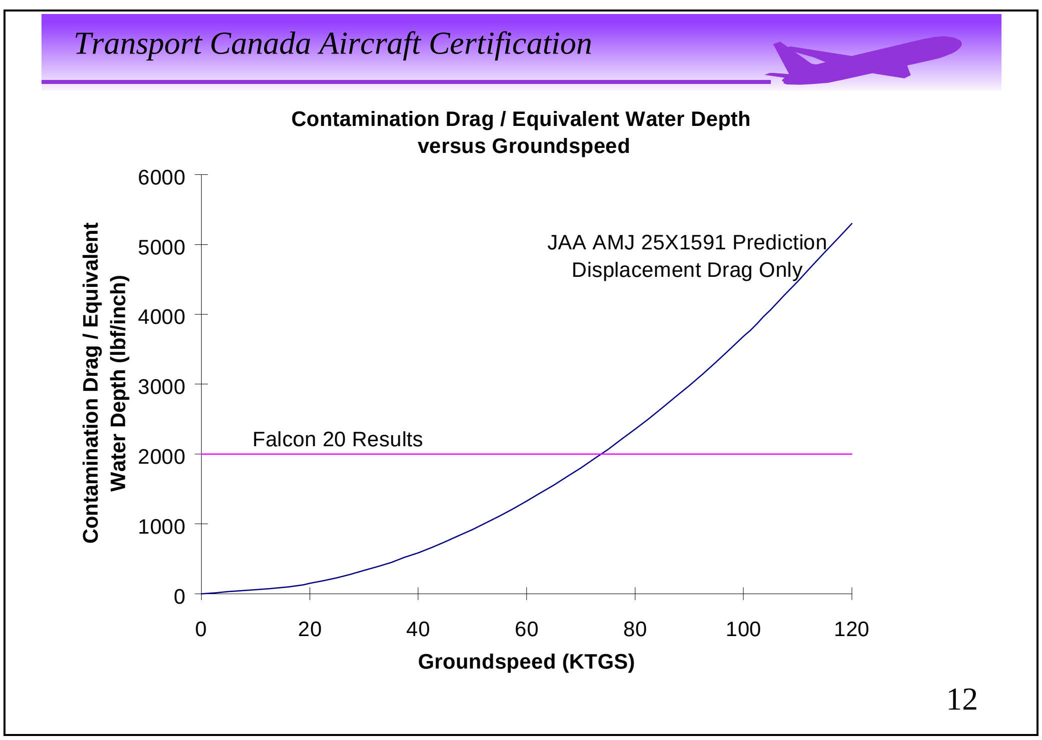
- Aircraft acceleration was calculated from DGPS data
- Contamination drag is derived from acceleration taking into account idle thrust, aerodynamic drag, runway slope, rolling friction coefficient on a bare runway, aerodynamic lift and aircraft weight

8


Transport Canada Aircraft Certification
Contamination Drag versus Equivalent Water Depth
Contamination Drag (lbf)
Equivalent Water Depth (inch)
1995/96 Data
1996/97 Data
1997/98 Data
1998/99 Data
5000
4000
3000
2000
1000
0
-1000
0
0.5
1
1.5
2
9


Transport Canada Aircraft Certification
Contamination Drag / Equivalent Water Depth
versus Equivalent Water Depth
Contamination Drag / Equivalent Water Depth (lbf/inch)
Equivalent Water Depth (inch)
1995/96 Data
1996/97 Data
1997/98 Data
1998/99 Data
Average = 2000 lbf/inch
5000
4000
3000
2000
1000
0
-1000
0
0.5
1
1.5
2
10


Transport Canada Aircraft Certification
Contamination Drag / Equivalent Water Depth
versus Groundspeed
1995/96 Data
1996/97 Data
1997/98 Data
1998/99 Data
Average = 2000
lbf/inch
Contamination Drag / Equivalent
Water Depth (lbf/inch)
5000
4000
3000
2000
1000
0
-1000
0
20
40
60
80
100
120
Groundspeed (KTGS)
11


Transport Canada Aircraft Certification
Contamination Drag / Equivalent Water Depth
versus Groundspeed
JAA AMJ 25X1591 Prediction
Displacement Drag Only
Falcon 20 Results
Contamination Drag / Equivalent
Water Depth (lbf/inch)
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
Groundspeed (KTGS)
12

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Summary of Aircraft Contamination Drag Results

- Sixty-one data points have been collected on 18 different loose snow conditions
- Results are highly variable but show a clear trend
- Contamination drag is a function of Equivalent Water Depth (EWD)
- For the Falcon 20, D_{CONTAM} is negligible below 0.1 inch EWD (approximately 3 mm)

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Summary of Aircraft Contamination Drag Results (continued)

- Results can be quantified using a Contamination Drag/ Equivalent Water Depth (D_{CONTAM}/EWD) parameter D_{CONTAM}/EWD is constant with EWD
- D_{CONTAM}/EWD is constant with groundspeed
- For the Falcon 20, D_{CONTAM}/EWD = 2000 lbf/inch
- JAA AMJ 25X1591 methodology for estimating contamination drag (based on water/slush test) does not appear to be valid for loose snow

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Aircraft Braking Coefficient on Loose Snow

- Aircraft Braking Coefficient (μ_B) is the total braking force / weight on wheels
- μ_B is derived from acceleration taking into account idle thrust, aerodynamic drag, runway slope, aerodynamic lift, aircraft weight, *and contamination drag*

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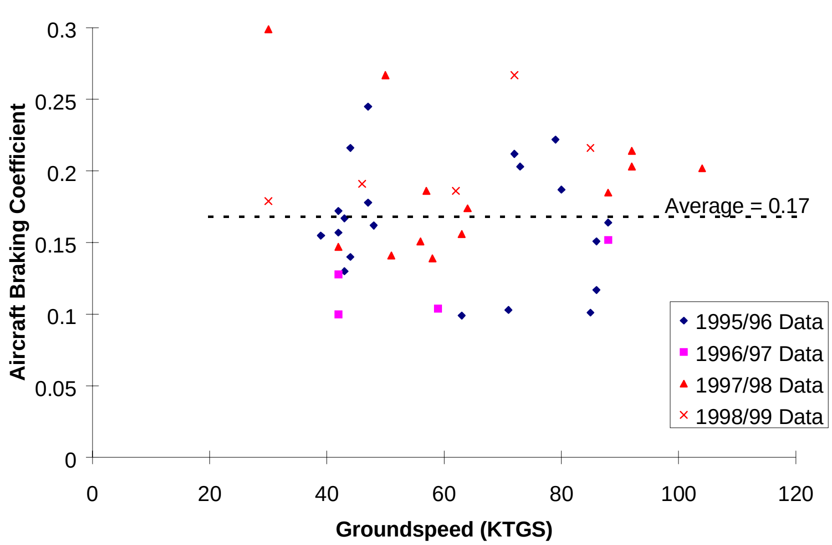
Aircraft Braking Coefficient versus Groundspeed



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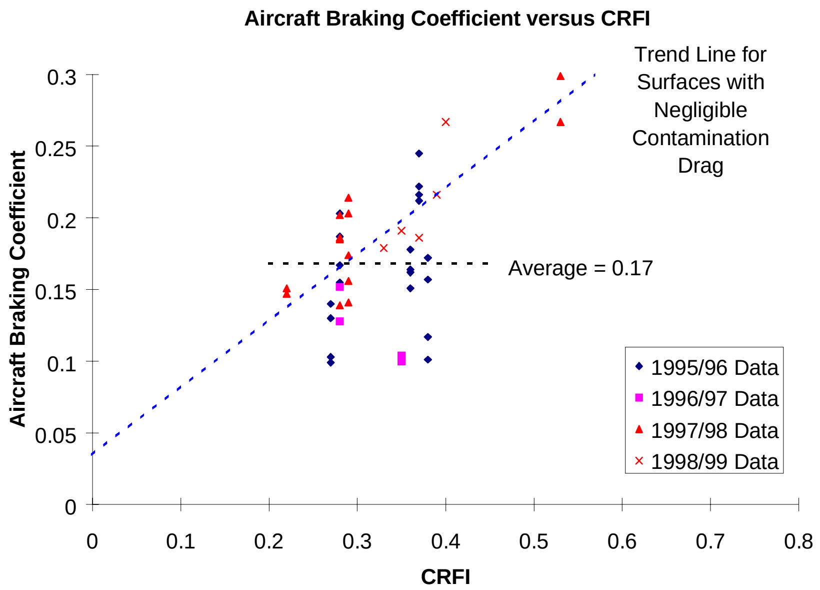

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Summary of Aircraft Braking Coefficient Results

- Forty-two data points have been collected on 12 different loose snow conditions
- Aircraft Braking Coefficient (μ_B) is constant with groundspeed
- μ_B may be dependent on CRFI but for loose snow conditions, the range of CRFI variation is small
- Average CRFI for loose snow = 0.32
- Average μ_B for loose snow = 0.17

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Concluding Remarks

- The Falcon 20 test results indicate that contamination drag can be represented by a D_{CONTAM}/EWD parameter which is constant with EWD and groundspeed
- The Falcon 20 test results indicate that μ_B on loose snow, although dependent on CRFI, can be represented as a constant because of the relatively small variation of CRFI
- μ_B on loose snow is constant with groundspeed

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Concluding Remarks (continued)

- Performance measurement on contaminated runway surfaces is not an exact science
- The Falcon 20 test program includes a significant number of data points on different runway conditions
- Although there is significant scatter in the data, this is in part due to the nature of contaminated runway surfaces
- Care should be taken with interpreting results from a limited number of test points and test conditions

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Takeoff and Landing on Runways Contaminated by Standing Water, Slush, or Snow

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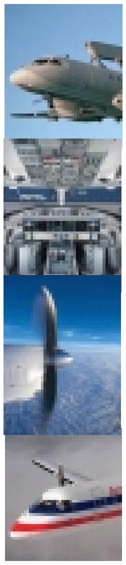
Saab Aircraft Customer Support

CONTAMRUNWAY



Take-Off and Landing on Runways Contaminated by Standing Water, Slush or Snow

- Project funded by the European Commission under the Transport RTD programme of the 4th Framework Programme
- Coordinator: Dassault Aviation (FR)
- Partners: NLR (NL)
  Saab AB (SE)

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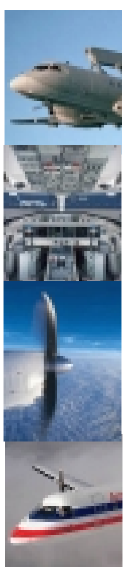

Objectives

- JAR requirements to provide information for take-off and landing taking into account runway surface condition. JAR OPS 1: Single V1 requirement.
- Review validity of AMJ 25X1591 (Supplementary Performance Information for Take-off from Wet Runways and for Operation on Runways Contaminated by Standing Water, Slush, Loose Snow, Compacted Snow or Ice) for small and commuter aircraft.
- Investigate precipitation drag encountered by an aircraft on contaminated runways with wheels free to roll (no braking).

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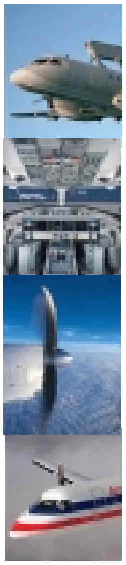

Approach and Methodology

AMJ 25X1591

- Displacement drag
- Impingement drag
- Aquaplaning speed
- Equivalent water depth

Methodology based on large transport aircraft and specific tire testings at beginning of 1960s, confirmed around 1990 on large transport aircraft.

Need to improve database for small and commuter aircraft

- Theoretical model for spray impingement
- Existing data analysis
- Specific testing

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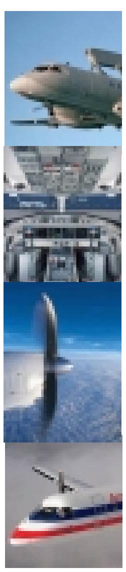

Work Packages

	Responsible
1. Theoretical study of spray impingement	NLR
2. Existing data analysis	Dassault, Saab
3. Citation II tests	NLR
4. Intermediate synthesis	All partners
5. Complementary tests	All partners
6. Final synthesis	All partners

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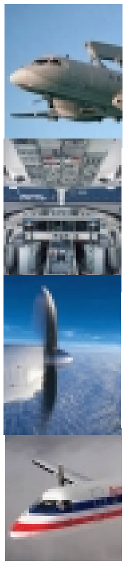

Existing Data Analysis – Dassault

Falcon 10, 20, 50, 900, 2000, and Mercure

- Drag calculated according to AMJ underestimates drag produced at speeds below 100 kts.
- For the Mercure the agreement between measured flight test drag and drag calculated according to FWP 478 was good.
- The speed corresponding to max drag is approximately 20-30% lower then the V_p calculated according to the AMJ.
- Drag is a linear function of water depth (Falcon 900).

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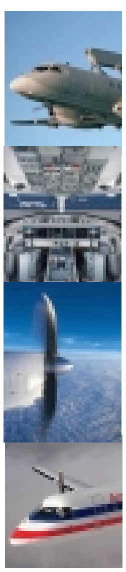

Existing Data Analysis – Saab

Saab 340 and 2000

- Flight tested drag was 10-30% higher than the drag calculated according to the AMJ formulae.
- Propeller efficiency is not influenced by spray plume from the nose wheels.
- Acceleration and deceleration have no significant effect on hydrodynamic drag.
- The speed corresponding to max drag is approximately 10% lower than the V_p calculated according to the AMJ.
- Hydrodynamic drag is not a linear function of water depth.
- Observation of the videotape footage showed a higher spray plume angle compared to the theoretical formulae used in AMJ.

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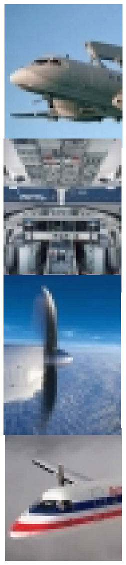

Citation II Tests – NLR

- Flight tested hydrodynamic drag was 15-40% higher than the drag calculated according to the AMJ formulae.
- Flap setting has no significant effect on hydrodynamic drag.
- Open or closed wheel wells have no significant effect on hydrodynamic drag.
- The speed corresponding to max drag is approximately 20% lower than the V_p calculated according to the AMJ.
- Video analysis showed a considerable amount of vertical spray at both main and nose gear.

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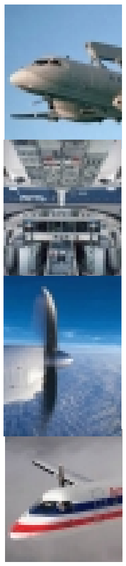

Intermediate Synthesis

- All flight tests show higher hydrodynamic drag than the drag calculated according to the AMJ formulae.
- The maximum spray plume angle seems to be twice that determined by the ESDU data item referenced in the AMJ.
- The speed corresponding to maximum hydrodynamic drag is lower than the V_p calculated according to the AMJ.
- All test data collected are communicated to ESDU in order to improve the validity of ESDU data items referenced in the AMJ.

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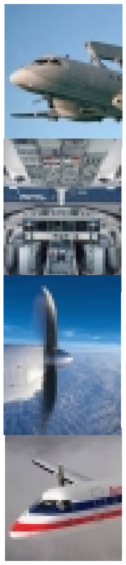

Intermediate Synthesis (cont'd)

HYDRODYNAMIC DRAG (N)

80 kts - 10 mm water depth

	AMJ 25X1591			Flight tests	
	Nose Gear	Main Gear	Total	Total	Ratio to AMJ
FALCON 10	1245 32%	2664 68%	3909		
FALCON 20	2214 42%	3061 58%	5275	11500	2.18
FALCON 50	2489 45%	3061 55%	5550	14000	2.52
FALCON 900	2430 41%	3420 59%	5850	12500 (2)	2.14
FALCON 2000	2501 45%	3078 55%	5579	10000 (2)	1.79
MERCURE	5936 44%	7420 56%	13356	19900	1.49
SAAB 340 (1)	2670 45%	3312 55%	5982	8973	1.50
SAAB 2000	4206 49%	4365 51%	8571	12660	1.48
CITATION II (3)	1215 33%	2465 67%	3680	4800 (2)	1.30

(1) Assuming aquaplaning speed (nose wheel) = 66 kts, theoretical drag calculated by AMJ = 5195 N and ratio to AMJ = 1.73.

(2) Contribution of main gear in test drag is 76% for FALCON 900, 70% for FALCON 2000 and 81% for CITATION II.

(3) Nose gear drag 920 N and main gear drag 3880 N in separate tests.

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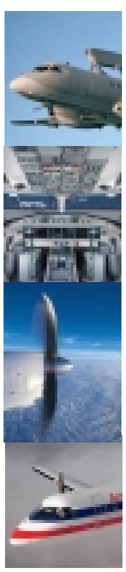

Complementary Tests Definition

Tests on Standing Water

- Separate tests with nose and main gear for drag determination.
- Evaluate the V_p formulae in AMJ (tire pressure).
- Evaluate speed for maximum drag.

Tests on Natural Snow

- Runway conditions which correspond to operational conditions.
- Determine contaminated drag with wheels free to roll (no braking).
- Evaluate the "equivalent water depth concept" used in the AMJ.

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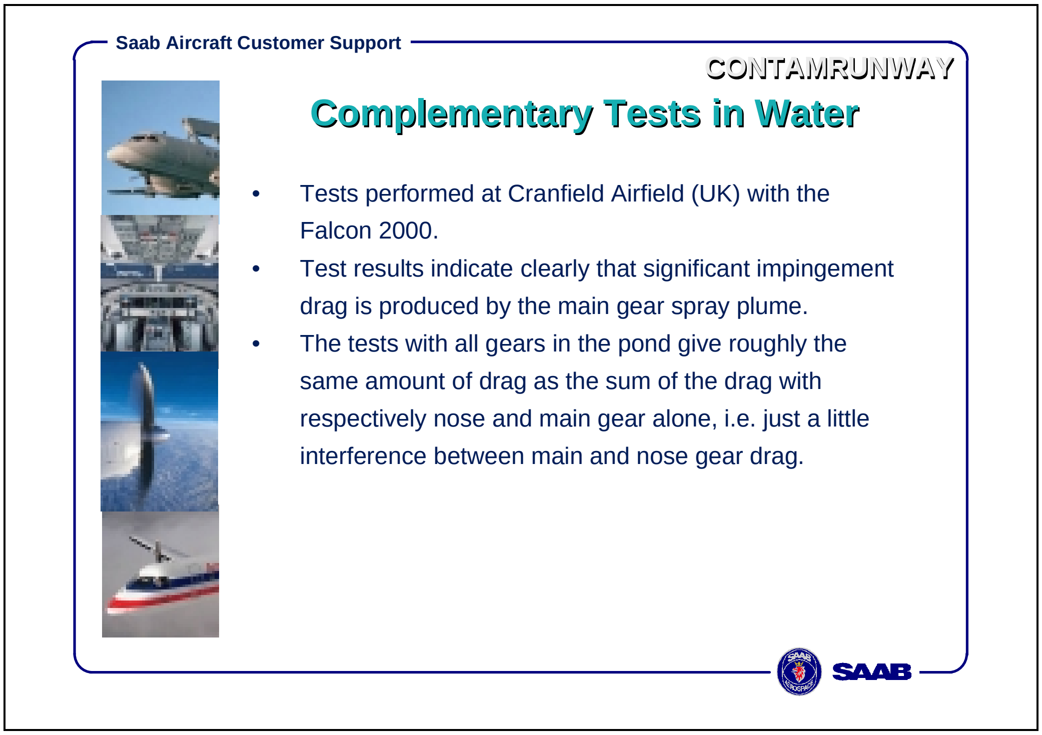
Saab Aircraft Customer Support
CONTAMRUNWAY
Complementary Tests in Water
• Tests performed at Cranfield Airfield (UK) with the Falcon 2000.
• Test results indicate clearly that significant impingement drag is produced by the main gear spray plume.
• The tests with all gears in the pond give roughly the same amount of drag as the sum of the drag with respectively nose and main gear alone, i.e. just a little interference between main and nose gear drag.
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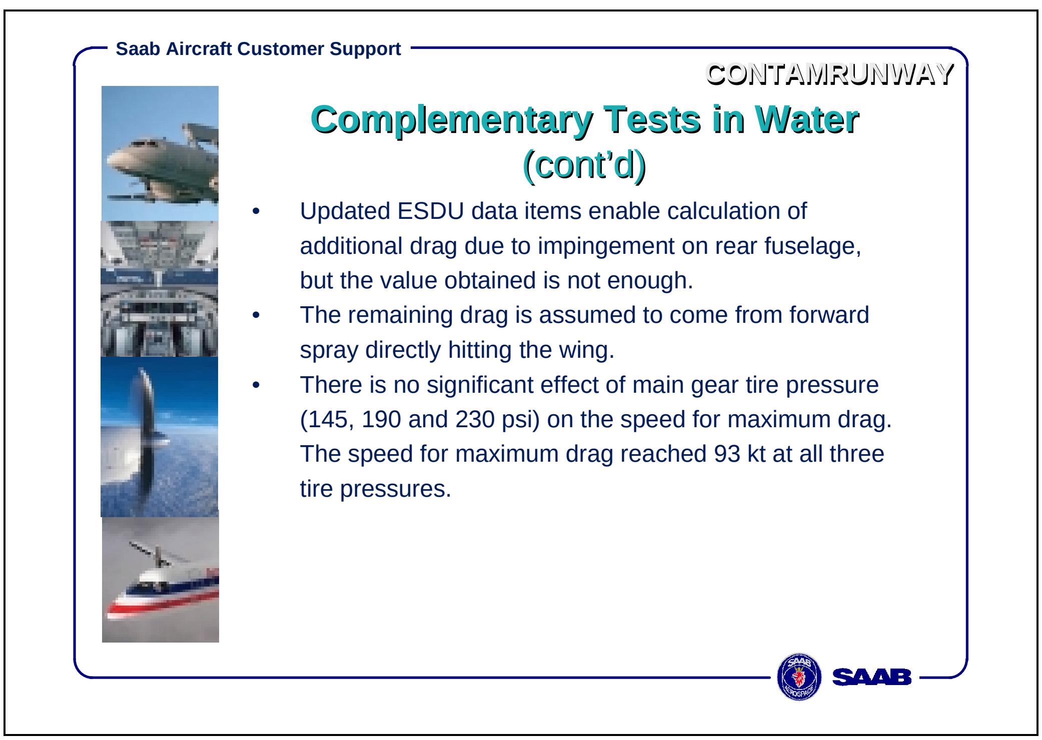
Saab Aircraft Customer Support
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Complementary Tests in Water (cont'd)
• Updated ESDU data items enable calculation of additional drag due to impingement on rear fuselage, but the value obtained is not enough.
• The remaining drag is assumed to come from forward spray directly hitting the wing.
• There is no significant effect of main gear tire pressure (145, 190 and 230 psi) on the speed for maximum drag. The speed for maximum drag reached 93 kt at all three tire pressures.
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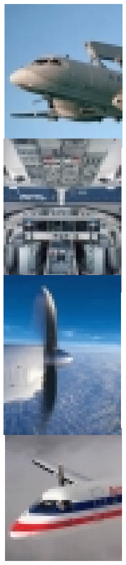

Complementary Tests in Wet Snow/Slush

- Tests performed at Malmen Airforce base (SE) with the Saab 2000.
- Specific gravity during the tests was between 0.5 and 0.8.
- The results verify that the “equivalent water depth concept” used in the AMJ is valid down to 0.5 in specific gravity.
- There is no effect of specific gravity in speed for maximum drag. Speed for maximum drag is 103 kt for the Saab 2000, independent of specific gravity.

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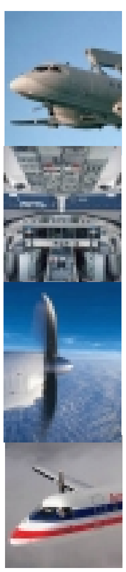

Final Synthesis

- The flight tested hydrodynamic drag is different from that obtained with current AMJ formulae.
- At low speed current AMJ underestimates the drag, but at high speed the AMJ overestimates the drag.
- The overestimation at high speed is caused by the fact that the theoretical calculation of aquaplaning speed does not correspond clearly to the peaking of hydrodynamic drag.
- Updated ESDU data items seem to provide a reasonably good estimation of the hydrodynamic drag for the Saab 2000, although it is very sensitive to the implementation of the geometry.

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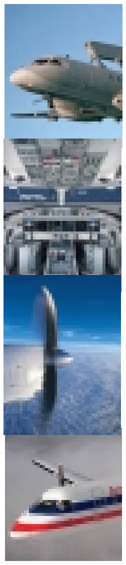

Final Synthesis (cont'd)

- This methodology applied to Citation II and Falcon 2000 shows that at low speed the drag is underpredicted, probably because of an extra drag produced by the main gear bow wave.
- The "equivalent water depth concept" used in the AMJ is valid down to 0.5 in specific gravity.
- The speed for maximum hydrodynamic drag was not affected by the specific gravity of wet snow/slush down to 0.5.

SAAB

Contamrunway Snow Tests

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NLR

CONTAMRUNWAY
Snow Tests

by

M. Giesberts

1

NLR

Background

- Current regulation:
  - JAR AMJ 25X1591
  - Advisory
  - Water precipitation drag not correct for smaller types of aircraft
  - Simple models for snow based on equivalent water depth theory

2

European Project

- Project funded by the European Commission DGVII
- Partners:
  - Dassault Aviation
  - Saab AB
  - NLR
- Consulting partners:
  - CAA UK
  - ESDU

3

Objectives

- To improve the current AMJ models concerning:
  - precipitation drag of smaller aircraft when operating from runways covered with water, slush or dry natural snow
  - evaluation of the hydroplaning speed and associated effects

4

Main Activities of CONTAMRUNWAY

- Analysis of existing data from ingestion tests
- Performance of runway tests in both water and snow
- Development of a theoretical model for the prediction of the spray pattern and the precipitation drag caused by standing water

5

Testing in Snow

6

AMJ on Snow

- AMJ suggests using an equivalent water depth theory (where the calculation of the precipitation drag for 100 mm snow with specific density (SD) 0.1 corresponds to the results found for 10 mm standing water (SD = 1))
- Because of the physical differences between snow and water, this assumption is basically wrong
- AMJ suggests hydroplaning is possible on snow

7

Basic Snow Characteristics

- Porous, permeable aggregate of ice grains
- Variety of possible forms of existence (with different densities)
- Thermodynamically unstable
- Compressible
- Metamorphic

8

Snow Types

- Dry new snow (0.05 - 0.2)
- Snow (0.2 - 0.45)
- Compacted snow (0.45 - 0.7)
- Wet snow (0.3 - 0.7)

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Dry Natural Snow

- Specific Gravity: 0.05 to 0.2
- No water between crystals
- Bearing capacity very low
- Highly compressible
- Environmental changes will influence characteristics

10

Typical Snow Test Run

- Use test runway cleared of snow except for test area of 100 m length
- Test aircraft aligns at beginning of runway
- Acceleration to 5-10 kt above design test speed
- Throttle idle as A/C rolls through snow test area
- A/C passes test area with idle thrust

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Determination of Drag

- The precipitation drag is determined using the difference in deceleration before, in, and after the test area
- Average values for the deceleration and thrust are used before, in, and after the test area

12

Snow Test Safety Analysis

- Airfield has to provide one testing and one operational runway
- Test runway cleared of snow except for snow pond (100 m length)
- Simulator tests showed: if remaining runway after pond has less than good braking action then continue test into takeoff at test speeds above 40 kt
- Crosswind limit of 7 kt

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Instrumentation On Board

- INS System (a(xyz), GS, angles, etc.)
- Wheel speed sensors (nose, main)
- Engine parameters (N1, N2, fuel, etc.)
- Air data (IAS)
- Aircraft (position control surfaces, nose strut extension, etc.)

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Quality of the Parameters

- All signals (including: wheel speeds, acceleration and ground speed) are successfully recorded
- Important parameters 50 Hz
- Parameters linear fitted to a uniform time base of 50 Hz

15

Standard Test Configuration

- T/O configuration of A/C
- Speeds from 20 kt up to 90 kt in 10 kt increments
- Wheel wells open

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Snow/Slush Tests

- Saab:
  - Saab 2000
  - Malmen Airport (Sweden)
  - 100 mm fresh snow SD= 0.1
  - 30 mm slush SD = 0.56
- NLR:
  - Citation II
  - Skavsta Airport (Sweden)
  - 40 mm fresh snow SD= 0.125
- Dassault:
  - Falcon 2000
  - Ivalo Airport (Finland)
  - 100 mm fresh snow SD= 0.11

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NLR Citation 40 kt

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NLR Citation 70 kt

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NLR Citation 90 kt

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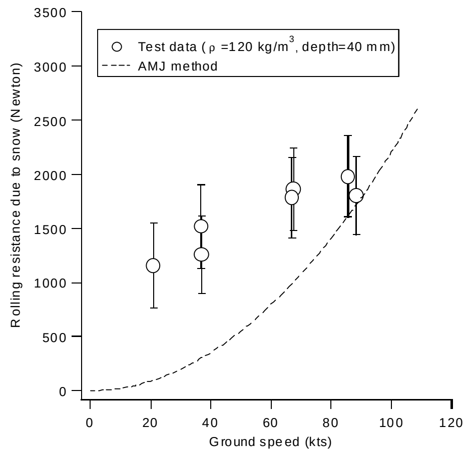
Citation II Test Results



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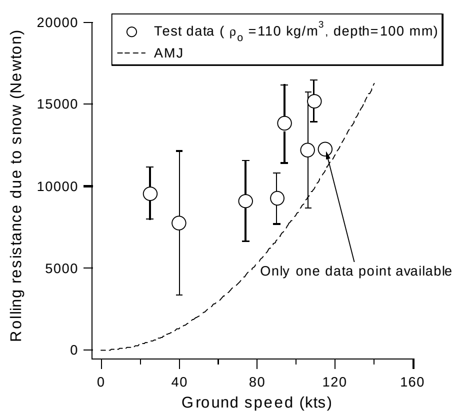
Falcon 2000 Test Results



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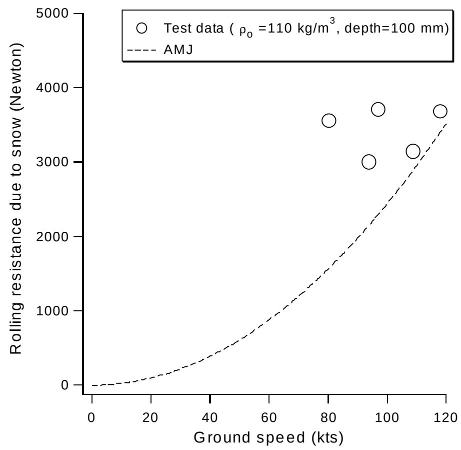
Falcon 2000 Nose Wheel



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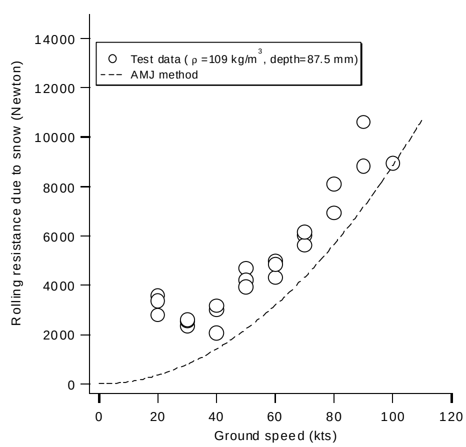
SAAB 2000 Test Results



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Conclusions on Snow

- Precipitation drag in natural dry snow at low speeds is substantial because of compression drag
- No hydroplaning on dry snow
- Snow drag increases with speed, but less than AMJ prediction
- For SD > 0.5 (slush) precipitation behaves like a fluid
- Dry snow has no impingement with wings or fuselage

25

Contamrunway Results and Models

- New theoretical method for predicting spray patterns and impingement drag (NLR)
- New method for predicting drag due to dry snow (NLR)
- Update of the ESDU spray patterns method (Item 83042)
- Improvement of drag calculation due to impingement model by ESDU (Item 98001)

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Conclusions

- Current AMJ 25X1591 underestimates the drag due to water/slush for smaller aircraft
- Drag due to dry snow is incorrectly predicted by current AMJ 25X1591
- New NLR model for dry snow drag looks promising
- NLR theoretical model for spray prediction and precipitation drag looks promising

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Recommendations

- Comparison of NLR method with tests conducted with large aircraft on dry snow-covered runways
- Research needed on friction of aircraft tires on wet and contaminated runways

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A Model for Predicting Rolling Resistance of Aircraft Tires in Dry Snow

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1 INTRODUCTION

When taking off from a runway covered with slush, standing water or snow, the required take-off ground-run distance will be longer than on a dry runway. This is the result of the fact that slush, standing water and snow on the runway will generate a rolling resistance that increases the total resistance on the aircraft during the ground-run. For this reason the Joint Aviation Authorities (JAA) have established aircraft certification and operational rules accounting for runway surface conditions (see JAR 25X1591). In addition to the rules, the JAA have issued Advisory Material Joint AMJ 25X1591, a document providing information, guidelines, recommendations and acceptable means of compliance concerning take-offs and landings on wet and contaminated runways. A study conducted by the National Aerospace Laboratory NLR (Ref. 1), has shown that there is a four-fold increase in the probability of an accident for aircraft operating on wet and contaminated runways. This indicates the importance of certification and operational rules for wet and contaminated runway operations.

AMJ 25X1591 considers a number of contaminates like water, slush, ice, wet snow and dry snow. The current version of AMJ 25X1591 (Change 14, 27 May 1994) assumes that the rolling resistance caused by dry snow on the runway, can be calculated using the models originally developed for water and slush covered runways. Since snow is compressible and water and slush are not, this assumption is incorrect from a physical point of view. This is also clearly illustrated in Ref. 2, where experimentally determined rolling resistance in dry snow for a Falcon 20 aircraft shows quite different results from rolling resistance calculated according to AMJ 25X1591.

Currently a number of models are available to calculate the rolling resistance of tires in dry snow (See Ref. 3). Many of these models have been developed to analyse the mobility of military vehicles. These mobility models vary from purely empirical to analytical. From the study presented in Ref. 3 it becomes clear that these mobility models are not suited for aircraft tires. A more suitable model is developed by Lidstrom (Ref. 4). This model gives better results for aeronautical use than the mobility models (See Ref. 3). However, Lidstrom's model can only be used for low snow densities and high tire pressures. Furthermore, a number of approximations and assumptions are made which reduce the accuracy of the model.

The objective of this paper is to present an accurate method for predicting the rolling resistance of aircraft tires in dry snow which can be used for all practical snow densities. This method should be considered instead of the current method recommended by the JAA. The paper is organised as follows. Basic snow characteristics are outlined first. A theoretical method for predicting the rolling resistance of a tire in dry snow is then described. The presented method is then compared with experimental data from tests employing single tires and full-scale aircraft.

2 BASIC SNOW CHARACTERISTICS

Snow is a porous, permeable aggregate of ice grains, which can be single crystals, or close groupings of several crystals. Air and water vapor surround the crystals. Snow is a complicated material because of the variety of forms it can take and because it is thermodynamically unstable, which means that the physical properties of the snow can change with time (known as snow metamorphism). A large number of different types of snow are known. A possible classification of these types including typical densities, is given as follows:

- New snow (50-200 kg/m^3)
- Powder snow (200-450 kg/m^3)
- Compacted snow (450-700 kg/m^3)
- Wet snow (300-700 kg/m^3)

All these types of snow are compressible. This means that the volume changes when the snow is loaded. This volume change becomes evident as surface compaction. Density is probably the most useful single parameter of snow properties because e.g. structural characteristics show some correlation with density. The compression strength of snow, and thus its bearing capacity, also appears to be strongly influenced by its density. Below a density of 400 kg/m^3 the bearing capacity of snow is usually very low resulting in large volume changes of the snow when it is loaded. At higher densities higher loads are required to compress the snow. Whenever snow is subjected to loads e.g. by moving the snow with a bulldozer or running a tire over it, the snow becomes stronger than natural snow of the same density. This is a result of bond growth between the ice crystals. As already pointed out, snow is metamorphic. Environmental influences like wind, temperature fluctuations, and rain can change the characteristics of snow within days and even within hours.

The behaviour of undisturbed snow under loading has been studied by the US ARMY Cold Regions Research and Engineering Laboratory CRREL (See e.g. Ref. 5 and 6). Results of such studies show that the tire pressure has a significant influence on the final snow density after loading. Table 1 gives an overview of the final snow densities used in the CRREL snow mobility models as a function of the tire pressure. Note that the values listed in table 1 refer to undisturbed snow. An adjustment to the original table was made for tires having a pressure of less than 150 kPa, based on experimental data for these tires. Most aircraft tires have pressures in the range of 560-1400 kPa. For such tire pressures the final snow density will be 600 or 650 kg/m^3 according to table 1.

3 DESCRIPTION OF THE METHOD

3.1 Introduction

When a tire moves over a surface covered with dry snow, it will deform the snow. The work needed for this deformation results in forces acting on the tire opposite to the direction of motion. In general the resistance of dry snow results from two forces (Ref. 3):

- compression resistance D_c
- vertical displacement resistance D_d

Theoretical methods for predicting both these forces will be discussed.

3.2 Resistance due to compression

When a tire rolls over a snow-covered surface, compaction of the snow occurs. The work needed to compact the snow layer from an initial snow volume V_1 to a final snow volume V_2 is given by (Ref. 3):

$$W = \int_{V_2}^{V_1} p\, dV \tag{1}$$

With p the pressure exerted on the snow. Because the rolling resistance in snow due to compression is the work needed to compress the snow per distance covered, Eq.1 can be rewritten into (using the relation dV=b.ds.dh, with ds distance travelled)[3,4]:

$$D_c = \int_{h_f}^{h_o} b\,\sigma\, dh \tag{2}$$

In which σ is the unconfined compressive strength of snow, b is the effective tire width at the point of contact between tire and snow surface, h_o is the initial snow depth, and h_f is the snow depth after compression. The effective tire width can be obtained through a geometrical analysis of the tire section in combination with the snow surface. This width is given by (Ref. 3):

$$b = 2w\sqrt{\frac{\delta + h_o}{w} - \left(\frac{\delta + h_o}{w}\right)^2} \tag{3}$$

With. δ = vertical tire deflection (static load)
w = maximum tire width

For $(\delta + h_o)/w \geq 0.5$ the effective tire width can be regarded as equal to the maximum tire width w.

The bearing capacity of natural snow is usually very low, especially for snow with a density of less than 400 kg/m^3. This results in large snow deformations in the form of compaction. This deformation continues until there is equilibrium between the snow's bearing capacity and the load placed on the tire. Strength studies of snow have shown that a relation exists between the initial snow density and its unconfined compressive strength. Ref. 8 gives the following empirical equation for the unconfined compressive strength of snow:

$$\sigma = \sigma_i e^{-\lambda r^2} \tag{4}$$

Where σ_i is the compressive strength of ice (=1.10^6 N/m^2), λ is a grain structure index, and r is the void ratio defined as the ratio of void volume to the volume of solid ice grains. The void ratio is given by:

$$r = \frac{\rho_i}{\rho} - 1 \tag{5}$$

In which ρ_i is the density of ice (=920 kg/m^3) and ρ the actual snow density. The grain structure index λ is an empirical constant, which varies between 1 and 2 (Ref. 8). For natural snow this index is equal to 1.5 (Ref. 3).

Combining Eq. 2 and 4 results in:

$$D_c = b\sigma_i \int_{h_f}^{h_o} e^{-\lambda r^2} dh \tag{6}$$

By introducing the relation u = $\sqrt{\lambda}$ (h/h$_i$ - 1) = $\sqrt{\lambda}$ (ρ_i/ρ - 1), Eq. 6 can be written as:

$$D_c = \frac{b\sigma_i \rho_o h_o}{\rho_i \sqrt{\lambda}} \int^{u_o} e^{-u^2} du \tag{7}$$

In which:

$$u_o = \sqrt{\lambda}\left(\frac{\rho_i}{\rho_o} - 1\right) \quad \text{and}$$

$$u_f = \sqrt{\lambda}\left(\frac{\rho_i}{\rho_f} - 1\right)$$

Note that ρ_o is the initial snow density and ρ_f is the final snow density after compression by the tire. The integral in Eq. 7 is equal to the standard error function except for the missing term $2/\sqrt{\pi}$. Numerical solutions of the integral in Eq. 7 are presented in figure 1 for the five final snow densities of table 1. The resistance due to snow compression can be obtained from Eq. 7 in combination with figure 1.

Figure 2 gives an example of the resistance due to compression of a single tire of type VII with a diameter of 0.37 m, a width of 0.14 m, tire pressure of 937 kPa, and with a normal load of 4400 Newton. Up to a snow density of about 350 kg/m^3 the resistance due to compression increases linearly with increasing initial snow density. Around a snow density of 420 kg/m^3 a maximum occurs in the resistance due to compression. For higher snow densities the resistance decreases because the bearing capacity of the snow increases, resulting in less deformation of the snow. For the same tire the variation of the grain structure index λ is analysed. For a snow depth of 80 mm, D_c is calculated as function of initial snow density for three values of λ. The results are shown in figure 3.

A higher grain structure index indicates stronger snow which results in a lower rolling resistance due to compression. Furthermore, the maximum drag due to compression occurs at a higher initial snow density when the grain structure index is increased.

3.3 Resistance due to motion

When a tire moves over a surface covered with snow, the snow particles that are being compressed have to be given enough dynamic energy to move them in vertical direction. The energy needed for this will result in a force acting on the tire opposing the forward movement of the tire. This force can be obtained by considering the kinetic energy of a snow particle being compressed. The resulting force acting on the tire opposite to the direction of motion is given by (Ref. 3 and 4):

$$D_d = \frac{b}{2} \int_{h_f}^{h_o} \rho V_g^2 \sin^2 \alpha \, dh \tag{8}$$

Where V_g is the ground speed and α is defined in figure 4.

With the help of figure 4 and standard trigonometric relations Eq. 8 can be solved. The result is:

$$D_d = \frac{b}{2} h_o \rho_o V_g^2 \quad \left(1 - \cos^2 \alpha_1 - \frac{2}{R} h_f \cos \alpha_1 - \frac{h_f^2}{R^2}\right) \ell n \left(\frac{h_o}{h_f}\right) + \\ + \left(h_o - h_f\right) \left(\frac{2}{R} \cos \alpha_1 + \frac{2h_f}{R^2} \quad \frac{1}{2R^2} \left(h_o^2 - h_f^2\right)\right. \tag{9}$$

Where R is the tire radius. The final snow depth is given by the relation $h_f = h_o \, \rho_o / \rho_f$ (preservation of mass) assuming that all compacting in front of the tire occurs in the vertical direction only.

The dynamic resistance D_d appears to be directly influenced by the final snow depth and therefore by the initial snow density according to the relation $h_f = h_o \, \rho_o / \rho_f$. To illustrate this effect the dynamic snow resistance is defined by $D_d = k \, V_g^2$. Figure 5 gives an example of k as a function of initial snow density and snow depth for a single tire of type VII, with a diameter of 0.37 m, a tire width of 0.14 m, tire pressure of 937 kPa, and a normal load of 4400 Newton. It becomes clear that k in this example has a maximum around an initial snow density ρ_o of 200 kg/m^3. Below this density the influence of the low density of the snow becomes a dominant factor (see Eq. 9). Above 200 kg/m^3 the effect of the reduced sinkage ($= h_o - h_f$) becomes the dominant factor (see Eq. 9). This example shows that at low densities of approximately 150-300 kg/m^3 , the ground speed has a strong influence on the rolling resistance. In general the maximum dynamic resistance is a complex function of tire radius, final snow depth, tire foot print length, and initial snow depth. An analysis of a number of aircraft configurations showed that in general the maximum dynamic resistance occurs at a snow density of around 200 kg/m^3.

4 CALCULATION OF THE ROLLING RESISTANCE OF A COMPLETE AIRCRAFT ROLLING IN DRY SNOW

4.1 Basic approach

The total rolling resistance of an aircraft rolling along a snow-covered runway is given by:

$$D_{rolling} = D_r + D_c + D_d \quad (10)$$

In which D_r is the rolling resistance on a dry hard surface. The equations presented in this paper for D_c and D_d are for single tires. A complete aircraft has at least 3 tires, one on each main landing gear and one on the nose landing gear. To obtain the total aircraft rolling resistance due to snow, the resistance D_c and D_d for each single tire have to be calculated and summed.

The rolling resistance on dual tire landing gears (found on both nose and main gears) is simply the resistance of both single tires added together. The interference effects between both tires as found on dual tire configurations running through slush or water, is not likely to be present when rolling over a snow covered surface. The rolling resistance originates from the vertical compaction of the snow layer. Although there is some deformation perpendicular to the tire motion direction present, this deformation occurs mainly at or below the bottom of the rut (Ref. 9) and therefore does not affect the deformation in front of the adjacent tire. Hence interference effects can be ignored.

Another multiple-tire configuration is the bogie landing gear. After the initial compression of the snow by the leading tires, the snow in the rut becomes stronger and a higher pressure must be applied to compress the snow further (Ref. 4). Therefore, the trailing tires will have a lower rolling resistance than the leading tires. Experimental data presented in Ref. 10 for tires with an inflation pressure of 179 kPa, show that the resistance of the trailing tire can be around 20% of the resistance of the leading tire. However, as shown in Ref. 6, aircraft tires which have an inflation pressure in the range of 560-1400 kPa, compact the snow such that further compaction of a significant level is only possible if the pressure of the trailing tire is at least more than 2100 kPa. The compaction of the snow in the rut by the trailing tires, which have an inflation pressure of 560-1400 kPa, will be minimal (Ref. 6). Therefore the rolling resistance of the trailing tires can be neglected when compared to the rolling resistance of the leading tires. Hence, the resistance on a bogie landing gear is equal to that of a dual tire configuration.

All other multiple-tire configurations can be treated in the same manner as described above.

Unpublished experimental results have shown that the snow sprays coming from the tires are limited to small portions, which hardly strike the airframe. The speed and the density of the snow spray are much less than for instance water spray. Therefore, the resistance due to snow impingement on the airframe can be neglected.

In order to calculate the rolling resistance the static tire deflection d and tire footprint length have to be known. In the absence of experimental data empirical equations presented in Ref. 11 and 12 can be used.

4.2 Limitations of the presented method

For all calculations the following limitations apply:

- The snow depth must not exceed the tire radius. If so, there will be additional resistance due to "bulldozing" which is not considered in the presented method.
- Great care must be taken when comparing the results of the presented method with results obtained on surfaces with processed snow (e.g. snow that has been blown back onto the runway by snow removal equipment). It is known that processed snow behaves in a significantly different manner than natural snow (Ref. 13). This will result in different values for the final snow densities than the snow densities presented in table 1. Also the grain structure index λ for processed snow will be different than for natural snow.
- The method only applies to dry snow.

5 COMPARISON WITH TEST DATA

5.1 Single tire test data

Test data of single aircraft tires rolling in dry snow are scarce. A literature search revealed only a very limited number of sources which could be used. Unfortunately, most data cannot be used for analysis due to the fact that processed snow was used during the tests and no natural snow. Two data sources were found which could be used. First single tire test data from Ref. 14 are used for comparison with the presented method. Ref. 14 provides test data obtained from a modified BV friction test vehicle. Tests were conducted with two different tires (radius 0.35 m, width between 0.12-0.254 m and inflation pressures between 165-550 kPa) at a limited number of ground speeds which varied between 27-43 kts. The natural snow used in these tests had a low density which did not exceed 130 kg/m^3. The snow depth varied between 10 and 90 mm. Ref. 14 also presents data of several runs made on a dry, snow-free surface. These results are subtracted from the resistance values measured on a snow-covered surface to obtain the rolling resistance due to snow. These results are compared with the present method and the AMJ method. The method of JAA AMJ 25X1591 is presented in an appendix to this paper. The results are shown in figure 6. The theoretical and experimental results for the presented method correlate better than the AMJ method. The standard deviation for the presented method is 31% compared to 50% of the AMJ method.

In addition to the data obtained from Ref. 14, resistance data for single tires rolling in natural snow presented in Ref. 10 are used. The tires used had a diameter of around 0.74 m, a width of 0.27 m, and an inflation pressure of 179 kPa. All tests reported in Ref. 10 were conducted at ground speeds of less than 6 kts. The natural snow used in these tests was of low density and did not exceed 250 kg/m^3. The snow depth varied between 100 and 360 mm. The comparison between experimental results and theory is shown in figure 7. The theoretical and experimental results for the presented method appear to correlate much better than the AMJ method. The standard deviation for the presented method is 36% compared to 98% of the AMJ method. The AMJ method completely underestimates the resistance.

Although in these two cases the presented method has a reasonable high standard deviation, it can still be regarded as accurate when considering the number of variables involved and the inaccuracies of e.g. the measurements of snow depth, snow density and the resistance itself.

5.2 Full scale test data

Full scale test data of aircraft rolling on snow covered runways are available for a number of aircraft. Most of these tests were conducted in combination with braking friction tests. Unfortunately, a large number of the tests were not conducted in natural snow. Snow was either blown onto the runway or processed in another way before it was put on the runway surface. Examples of tests conducted in processed snow are given in references 15, 16 and 17. These test results cannot be used to validate the presented method. Fortunately, there are tests conducted in natural snow. Tests in natural snow have been conducted by the National Aerospace Laboratory NLR, SAAB AB, and Dassault Aviation using a Citation II, a SAAB 2000 and a Falcon 2000 respectively. These tests were conducted as part of a project known as “CONTAMRUNWAY”. This project was funded by the European Commission under the transport RTD programme, 4th framework. The National Research Council Canada NRC has conducted tests in natural snow using a Falcon 20. This work is part of the international Joint Winter Runway Friction Measurement Program.

The test results obtained in the “CONTAMRUNWAY” project and the Joint Winter Runway Friction Measurement Program will be compared with theoretical results of the method presented in this paper and with the method of JAA AMJ 25X1591 in the following sections.

5.2.1 Comparison with the Citation II test data

The National Aerospace Laboratory NLR has conducted tests with a Citation II on a snow-covered runway of Skavsta airport, in Sweden (See Ref. 18 for details). The results of these tests will be compared with the method presented in this paper. Figure 8 shows the comparison between experimental results, the JAR AMJ 25X1591 method (noted as AMJ), and with the presented method. Correlation between the experimental data and presented method appears to be good. The differences all lie within the overall accuracy of the experimental data. Note that the error bars in figure 8 were calculated considering the data reduction method and inaccuracies of the measured variables. The AMJ method does not correlate well with the experimental data. At low speeds the AMJ method gives almost no resistance whereas the experimental data and the present method do show a considerable amount of resistance at these low speeds.

5.2.2 Comparison with the SAAB 2000 test data

SAAB AG has conducted tests with a SAAB 2000 on a snow-covered runway of Linköping airport, in Sweden (See Ref. 19 for details). The results of these tests will be compared with the method presented in this paper. Figure 9 shows the comparison between experimental results, the JAR AMJ 25X1591 method, and with the presented method. The present method predicts a higher rolling resistance than measured. The resistance due to compression D_c is overestimated whereas the variation of rolling resistance with ground speed is similar to the experimental found variation. The snow in the tests was very homogenous and constant in depth. It is therefore unlikely that the difference between present method and experimental data is caused by variations in snow depth and/or density. During the tests the acceleration was measured. This acceleration was then compared to the calculated acceleration on a dry runway. The difference between both accelerations is then multiplied with the mass of the aircraft to obtain the rolling resistance due to snow. Ref. 19 does not provide details about the accuracy of this approach. In general the AMJ method underestimates the rolling resistance due to snow. At low speeds the AMJ method gives almost no resistance whereas the experimental data and the present method do show a considerable amount of resistance at these low speeds.

5.2.3 Comparison with the Falcon 2000 test data

Dassault Aviation has conducted tests with a Falcon 2000 on a snow-covered runway of Ivalo airport, in Finland (See Ref. 20 for details). The results of these tests will be compared with the method presented in this paper. Figure 10 shows the comparison between experimental results, the JAR AMJ 25X1591 method, and with the presented method. In figure 10 the average rolling resistance due to snow for each test run is presented. To indicate the variation in the experimental derived rolling resistance, the standard deviation of each data point is also plotted in figure 10. Correlation between the experimental data and presented method appears to be good. However, the two data points at low ground speeds are above the present method. The standard deviation of one data point at these low ground speeds is significant, which indicates some uncertainty for this result. The standard deviation of the other data point is much less, so for this result it is unclear why the present method underestimates the rolling resistance at low speeds. The AMJ method does not correlate well with the experimental data. At low speeds the AMJ method gives almost no resistance whereas the experimental data and the present method do show a considerable amount of resistance at these low speeds.

Besides results for all tires in the snow also results for the nose gear only in snow are presented in Ref. 20. Figure 11 shows the results of these tests compared with results of the present method and the AMJ method. Only results at high ground speeds are available. The present method correlates reasonable well with the experimental data. This confirms that the interference effects between both tires can be ignored and that the rolling resistance due to snow of a dual tire configuration is simply the resistance of both tires added together. The AMJ method underestimates the rolling resistance of the nose gear only.

5.2.4 Comparison with the Falcon 20 test data

The Falcon 20 of the Canadian Institute for Aerospace Research (IAR-NRC) was tested on a number of contaminated runways, including snow-covered runways. Some results of these tests are presented in Ref. 2, 15 and 19. Most of the tests were conducted in snow that was obtained by blowing snow from the runway infields onto the test sections. Only a limited number of tests were conducted in natural snow (See Ref. 21). The results of the tests conducted in natural snow will be compared with the method presented in this report.

Figure 12 and figure 13 show the comparison between experimental results, the JAR AMJ 25X1591 method, and the presented method. In Ref. 21 the average rolling resistance for each run is presented. To indicate the variation in the experimental derived rolling resistance, the standard deviation of each data point is also plotted in figure 12 and figure 13. There is a similar variation of the rolling resistance with ground speed as for the Citation II tests. At low ground speeds a considerable amount of resistance is present as for the Citation II results. The presented method tends to overestimate the rolling resistance. This difference between test data and the results of the presented method can be explained as follows. During the tests conducted by IAR-NRC, no engine parameters were recorded. It is assumed that all tests are conducted with idle thrust. In Ref. 21 Newton's second law is applied to an aircraft moving on the runway. The measured accelerations and ground speeds are combined with the data for the lift, drag, thrust and other basic characteristics of the aircraft, to calculate the rolling resistance due to snow. A simple equation is used to calculate the idle thrust as a function of air speed only. This simple approach for calculating the idle thrust can introduce inaccuracies in the derived rolling resistance. For instance if there was actually more thrust than in the idle setting during the tests, the derived rolling resistance would be too low. Tests conducted with idle thrust settings can also be influenced by considerable effective lags in the engine cycle during the transition from full take-off thrust to idle thrust. Bias will be introduced into the thrust calculation when these lags are not accounted for. If these lags in engine cycle were present in the IAR-NRC tests, the derived rolling resistance due to snow would be too low. Note that the lags in engine cycle were accounted for when analysing the data of the tests with the Citation II, which were also conducted with idle thrust settings (Ref. 18). The tests presented in figure 13 were conducted with almost identical snow conditions (snow density and depth) as the Citation II tests presented in figure 8. The nose and main gear tires of the Falcon 20 and the Citation II are similar in size. The Falcon 20 has a dual tire configuration on both nose and main gear whereas the Citation II has single tires on both the nose and main gear. The rolling resistance due to snow compression for the Falcon under the conditions noted in figure 13 should therefore be roughly twice as high as the rolling resistance of the Citation II presented in figure 8. However, the rolling resistance of the Falcon 20 is of the same order as that of the Citation II. The present method does predict a rolling resistance that is almost twice as high as that for the Citation II. During the tests with the Citation II engine parameters, needed to calculate the thrust using an engine database, were recorded. This approach results in a much more accurate and reliable estimation of the thrust during the tests than the simple method used by IAR-NRC. With the assumption that the results obtained with Citation II are accurate, it can be concluded that the rolling resistance due to snow obtained by IAR-NRC with the Falcon 20 is likely to be too low.

However, a more detailed analysis of the IAR-NRC results should be conducted to confirm these conclusions.

The AMJ method does not correlate well with the experimental data obtained with the Falcon 20. At low speeds the AMJ method gives almost no resistance whereas the experimental data and the present method do show a considerable amount of resistance at these low speeds. The AMJ method also shows a stronger variation of the rolling resistance with the ground speed than the experimental data.

6 CONCLUSIONS AND RECOMMENDATIONS

A new method for predicting the rolling resistance of a complete aircraft in dry snow is presented in this paper. It is concluded from a comparison with test data that the presented method is better than the method suggested in the current JAA AMJ 25X1591 (Change 14, 27 May 1994), which is used for certification. It is therefore recommended to consider the use of the presented method for the prediction of the rolling resistance due to dry snow, instead of the JAA AMJ 25X1591 method. However, further validation of the presented method is recommended. Especially larger aircraft with bogie landing gears should be analysed.

7 ACKNOWLEDGEMENTS

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A model for predicting rolling resistance of aircraft tires in dry snow

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Overview of the presentation

- **Model for predicting the rolling resistance in dry snow**
- **Theoretical results**
- **Comparison model with some test data**

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NLR model for snow

Total snow drag = $D_c + D_d$

D_c ⇨ work needed to compress a snow layer

D_d ⇨ work needed to move the snow particles in vertical direction, varies with ground speed

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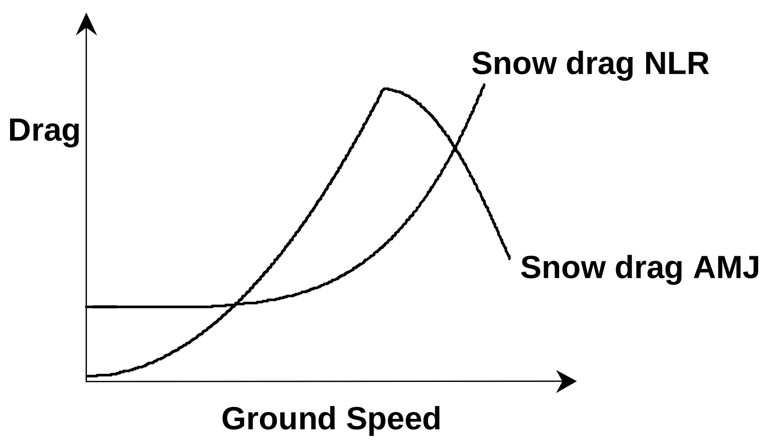
NLR versus AMJ method



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Model variables

Snow drag is a function of:

- **Snow density**
- **Snow depth**
- **Tire parameters (size, pressure)**
- **Ground speed**

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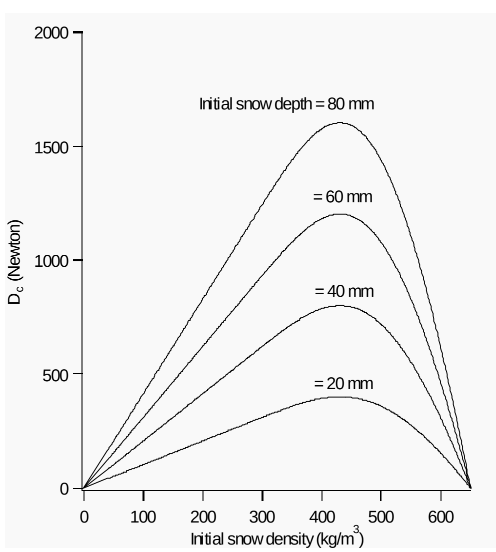
Drag due to compression

Single tire:

•Type VII
•D= 370 mm
•W= 140 mm
•P= 937 kPa



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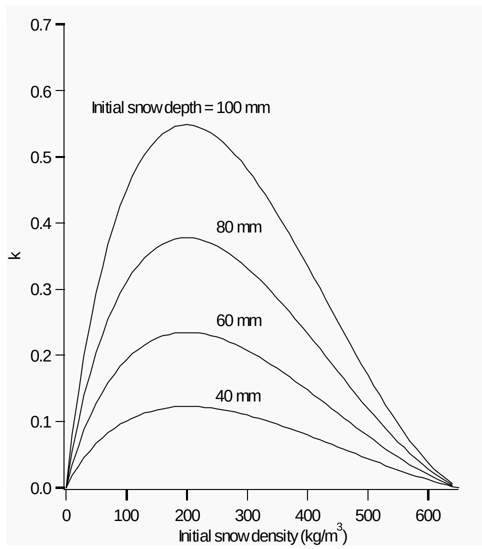
Drag due to motion

Single tire:

- **Type VII**
- **D= 370 mm**
- **W= 140 mm**
- **P= 937 kPa**
- **D_d=k V_g^2**



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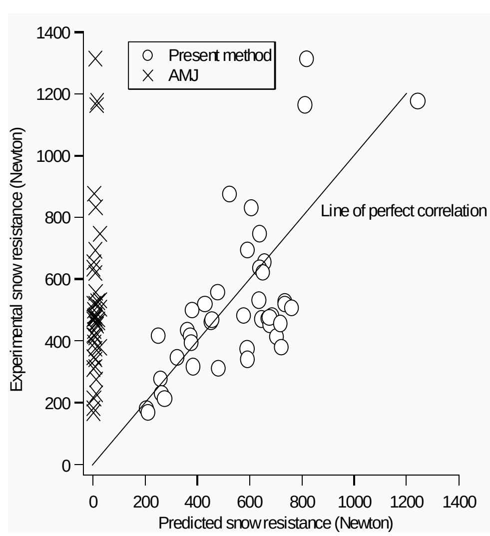
Comparison with single tire

Ground speed < 10 kt



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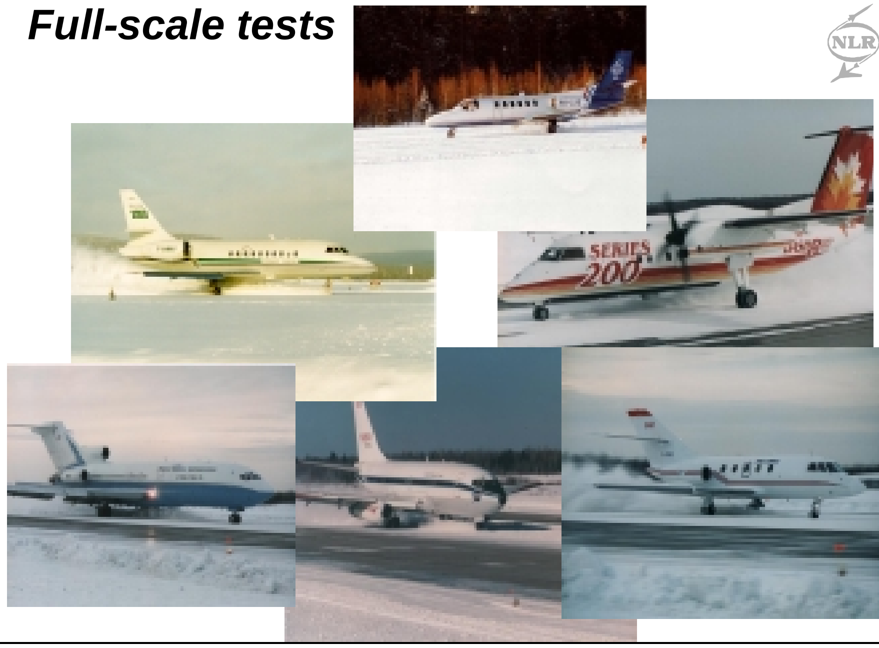
Full-scale tests



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Test area

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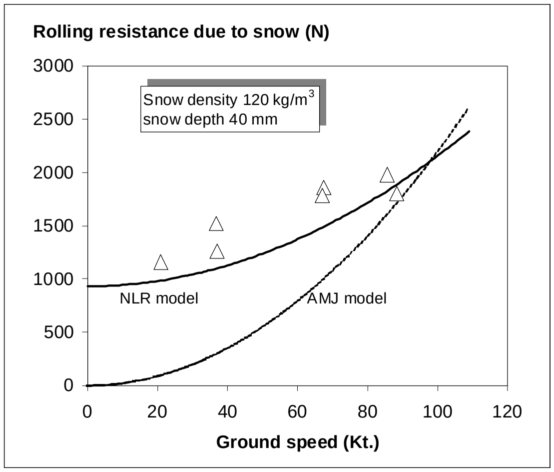
Citation II test results



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Conclusions

- **Drag due to dry snow is incorrectly predicted by current AMJ 25X1591**
- **New NLR model for dry snow drag looks promising**

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Recommendations

- **Comparison of NLR model with tests conducted with large aircraft on dry snow covered runways**

Hydroplaning of Modern Aircraft Tires

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1 INTRODUCTION

Hydroplaning of aircraft tires is often a contributing factor in overrun and veeroff accidents. Therefore hydroplaning of aircraft tires has been studied for many years. The majority of the current knowledge on hydroplaning was obtained in the 60s mainly by NASA studies (see e.g. Ref. 1). Since then new tire types like radial tires were introduced for civil aircraft. This paper will discuss the hydroplaning characteristics of these modern tires. Simple theoretical models in combination with empirical data will be used to analyse the hydroplaning characteristics.

2 THEORY OF HYDROPLANING

When a tire rolls along a wet surface, it is squeezing water from under the footprint. This squeezing process generates water pressures on the surface of the tire footprint. At a critical speed the tire will be completely separated from the ground surface by a film of water. This speed is called the hydroplaning speed. The water pressure build-up under the tire originates from the effects of fluid density and fluid viscosity. Two types of hydroplaning can be distinguished:

- Dynamic hydroplaning
- Viscous hydroplaning

In general both types of hydroplaning can occur at the same time. This paper will focus on dynamic hydroplaning because this is the most dominant one.

Dynamic hydroplaning is the result of the hydrodynamic forces developed when a tire rolls on a water covered surface. This is a direct consequence of the tire impact with the water that overcomes the fluid inertia. The magnitude of the hydrodynamic force varies with the square of the tire forward ground speed and with the density of the fluid. Dynamic hydroplaning is influenced by tire tread, water layer thickness and runway macrotexture. Macrotexture is the runway roughness formed by the large stones and grooves in the surface of the runway. When there is sufficient macrotexture on the surface and / or the tire has proper tread, total dynamic hydroplaning will usually not occur. However, hydroplaning can occur when the water depth is high enough so that both tire tread and runway macro texture cannot drain the water sufficiently quickly.

The hydrodynamic dynamic lift generated under a tire rolling along a water-covered surface is given by (Ref. 1)

$$L = \tfrac{1}{2}\rho V^2 S C_{Lh} \tag{1}$$

with ρ density of the fluid, S the tire footprint area, V the ground speed and C_{Lh} the hydrodynamic lift coefficient. When total dynamic hydroplaning occurs, L/S is equal to the tire bearing pressure that can be approximated by the tire inflation pressure (p). Hence, the total dynamic hydroplaning speed is given as

$$V_p = \sqrt{\frac{2}{C_{Lh}}}\sqrt{\frac{p}{\rho}} \tag{2}$$

For a free rolling tire C_{Lh} is about 0.7. However, for a sliding tire (e.g. a tire that has to spin-up just after touchdown) C_{Lh} is about 0.95. It appears that it is more difficult for a fluid to escape from a sliding tire than from a rolling tire. The value of 0.95 is based on ad hoc tests conducted by NASA Langley (Ref. 2) using bias-ply tires. The value of 0.7 is based on a large number of tests including full-scale aircraft equipped with bias-ply tires.

Using a hydrodynamic lift coefficient of 0.7 and the density for water, Eq. 2 simplifies to

$$V_p = 9\sqrt{p} \tag{3}$$

with p in psi and V_p in Kt. This equation is simply known as Horne's equation for dynamic hydroplaning. For many years Eq. 3 has been used to predict the hydroplaning speed of aircraft tires.

Eq. 3 is presented in most of the literature on hydroplaning. An alternative approach to analysing dynamic hydroplaning will be discussed now. Assume that a state of total hydroplaning has been reached. The tire footprint is now completely supported by a water film over a length L_f (footprint length). Consider a tread element on the surface of the tire. The time (t) which the tread element needs to penetrate the water film completely, is given by (ref 3)

$$t = \frac{L_f}{V_p} \tag{4}$$

It can be shown that t is a function of tire pressure p, fluid density r and footprint width W_f (See Ref. 3)

$$t \cong W_f\sqrt{\frac{\rho}{p}} \tag{5}$$

Combining Eq. 4 and 5 results in a relation for the hydroplaning speed

$$V_p = \lambda\frac{L_f}{W_f}\sqrt{\frac{p}{\rho}} \tag{6}$$

where λ is a constant, which depends on surface texture, tread of the tire and water depth (See Ref. 3 for details). It follows directly from Eq. 6 that the longer and the more narrow the footprint is, the higher the hydroplaning speed becomes. In both Eq. 6 and Eq. 2 the influence of tire pressure and fluid density is presented in a similar way. It follows from Eq. 6 that the hydrodynamic lift coefficient (C_{Lh}) is a function of tire footprint width and length, surface texture, tread of the tire and water depth.

$$C_{Lh} = \frac{2}{\lambda^2}\left(\frac{W_f}{L_f}\right)^2 \tag{7}$$

The value of 0.7 for the lift coefficient of a rolling tire given in for instance Ref. 1 is based on experiments where the water depth was greater than the tire grooves and surface texture (flooded runways). For such conditions λ can be considered as an overall constant (Ref. 3). Therefore, for flooded runways the lift coefficient is a function of the tire footprint aspect ratio (W_f / L_f) only. Harrin in Ref. 4 suggests a value for λ of 1 based on some limited experimental data. Similar values are found from theoretical calculations (See Ref. 3). Using this value for λ (=1) and typical tire footprint aspect ratio's for aircraft tires in the range of 0.58 - 0.65, C_{Lh} varies between 0.67 and 0.85. These values compare well with a theoretical value of 0.8 given by Martin in Ref. 5 and also with the experimental value determined by NASA (0.7). So for flooded runways the hydroplaning speed is determined by tire inflation pressure, fluid density and tire footprint aspect ratio.

For a tire that needs to spin-up after touchdown, the constant λ is assumed to be equal to 0.85 based on the results presented in Ref. 2. However, detailed full-scale experiments are necessary to confirm this. Note that experiments conducted by the Davidson Laboratory using an open cell polyurethane model tire, suggest a λ of 0.8 (See Ref. 6). This value is similar to the one presented by Pinsker in Ref. 7.

The influence of tire footprint aspect ratio was initially not considered in the NASA studies conducted on hydroplaning. However, in 1984 Horne published a paper in which he analysed the effect of tire footprint aspect ratio (Ref. 8). He points out that tire footprint aspect ratio has a significant influence on the hydroplaning speed.

3 HYDROPLANING SPEEDS OF MODERN AIRCRAFT TIRES

3.1 Predicted hydroplaning speeds

With help of equation 6 it is possible to analyse the hydroplaning characteristics of aircraft tires. The following three tire types are considered for this: bias-ply tire, type-H tire and a radial-belted tire. These tires have different footprint dimensions for the same tire pressure, tire size and load. The tire footprint length and width are calculated using empirical equations presented in Ref. 9. These empirical equations are developed using the results from static tests with the three tire types. In Figure 1 the theoretical hydroplaning speed as function of tire pressure is presented for a 40x14 tire with a vertical load of 40,000 Newton. Equation 3 is also included in Figure 1. Figure 1 clearly shows that for a given tire pressure the hydroplaning speeds of all three tire types is lower than the hydroplaning speed predicted by equation 3. The radial-belted and H-type tires have significantly lower hydroplaning speeds than the bias-ply tire. This is caused by the difference in tire footprint dimensions of these tires. Note that the approximations for the hydroplaning speeds for the three tires, given in the brackets in Figure 1, should be used with caution. For different tire sizes and vertical loads these approximations will be slightly different. However the results can be used as a first approximation.

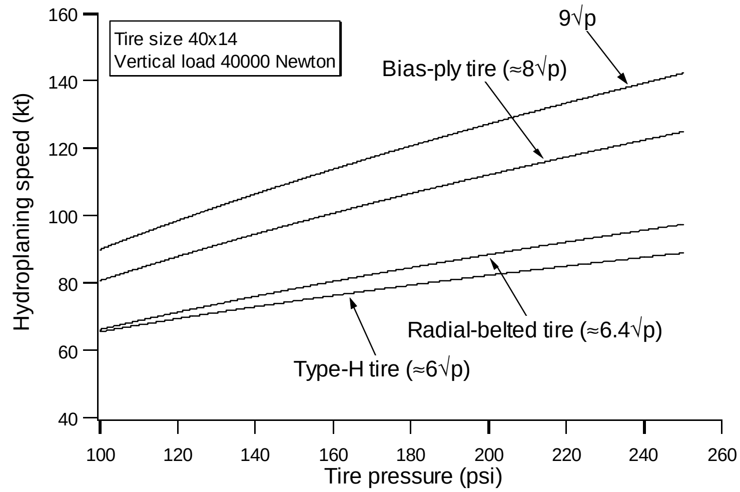

Figure 1: Theoretical hydroplaning speeds for three tire types.

3.2 Experimental hydroplaning speeds

To support the findings of section 3.1 some experimental data on hydroplaning speeds of modern aircraft tires will be presented. Results of full-scale hydroplaning tests are shown in Figure 2. From Figure 2 it can be seen that the older bias-ply tires correlate reasonable well with Horne's equation (Eq. 3). However, newer bias-ply tires, type-H tires and radial-belted tires have lower hydroplaning speeds than predicted by equation 3. Unfortunately, obtaining accurate hydroplaning speeds from full-scale aircraft tests is difficult. For instance the vertical load on the tires will be fluctuating, tire pressure can fluctuate due to heating of the brakes, fluid depth is not constant etc. This will introduce scatter in the experimental derived hydroplaning speeds shown in Figure 2. Furthermore there is no common method to derive the hydroplaning speed from full-scale tests. All this suggests that further systematic tests on single tires should be conducted with a common definition for determining the hydroplaning speed.

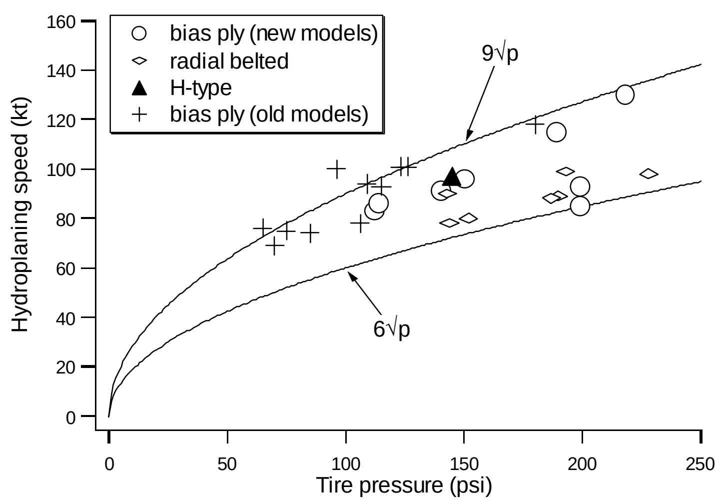

Figure 2: Experimental hydroplaning speeds as function of tire pressure for different tire types.

4 CONCLUSION

It is concluded from the results presented in this paper that modern aircraft tires have lower hydroplaning speeds than predicted by the well-known and commonly accepted equation developed by Horne from NASA. This is caused by the difference in tire footprint dimensions of these modern tires compared to the older bias-ply tires.

5 RECOMMENDATION

To further confirm the results found in this paper, it is recommended that systematic tests should be conducted on the footprint characteristics of modern aircraft tires in combination with hydroplaning tests. The facilities at NASA Langley Research Centre could be considered to conduct such tests (NASA's Aircraft Landing Dynamics Facility).

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Hydroplaning of modern aircraft tires

Gerard W.H. van Es

National Aerospace Laboratory NLR

The Netherlands

NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM
NATIONAL AEROSPACE LABORATORY NLR

Overview of the presentation

- **Models for predicting the hydroplaning speed**

- **Theoretical & experimental results for modern aircraft tires**

NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM
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Example hydroplaning accident

- **Qantas, Bangkok, 23 September 1999**

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Example hydroplaning accident II

Britannia Airways, Spain, 15 September 1999

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What is hydroplaning?

- Tire is fully separated from the runway by a film of water
- Low tire braking friction

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Hydroplaning speed

Horne's equation for hydroplaning speed (spin-down):

$$V_p = 9\sqrt{p}$$

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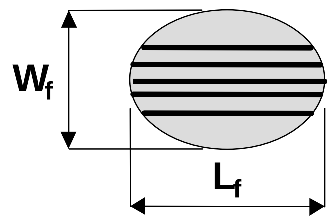
Alternative equation

$$V_p = \lambda \frac{L_f}{W_f} \sqrt{\frac{p}{\rho}}$$



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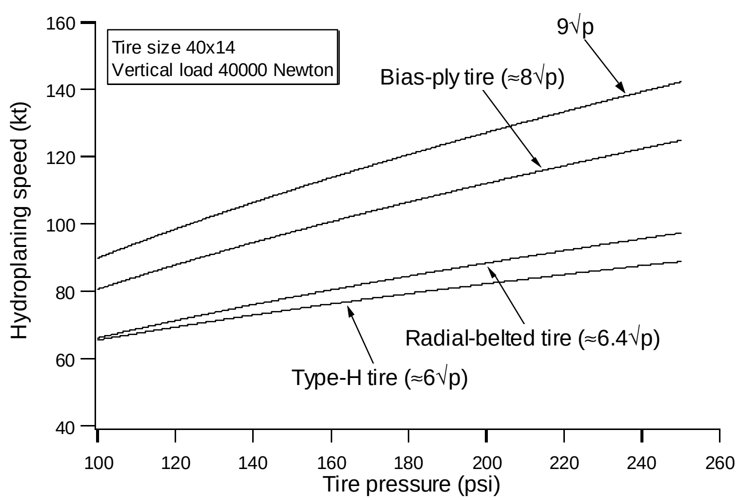
Theoretical results



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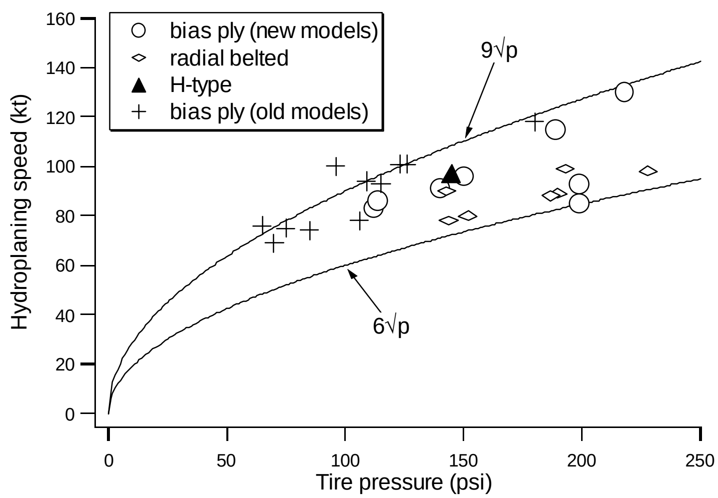
Experimental results



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Conclusions & Recommendations

- **Modern aircraft tires appear to have lower hydroplaning speeds than predicted by 9√p**

- **Conduct systematic tests on the footprint dimensions of modern aircraft tires in combination with hydroplaning tests**

What Do We Know about Snow and Ice?

Nirmal K. Sinha
National Research Council Canada, Institute for Aerospace Research
Ottawa, Ontario

Introduction

A number of presentations have been made at this meeting on the performance of aircraft and ground-vehicle based friction measuring devices on winter contaminated runways by our researchers at the National Research Council (See the presentations of Croll et al. 1999a). These tests could lead to the development of the Canadian Runway Friction Index (CRFI) and the International Runway Friction Index (IRFI). Braking performance of NRC's Falcon 20 jet aircraft on winter contaminated runways in North Bay Airport, Ontario from field tests during the period 1996 to 1999 was presented along with the performances of the devices mounted on ground vehicles. Methods of determining aircraft landing distance on winter contaminated runways were also discussed in detail (Croll et al. 1999b). In support of all those measurements a number of other investigations were also carried out, including data collections on the characteristics of snow and ice. For our colleagues from all over the world who were not participants in the North Bay, Ontario, field testing and other field activities, a report (Sinha, 1998) describing how the properties of snow and ice on runways and taxiways were measured during field tests is available at the front desk. It might give you an idea as to how we approach the measurement of the winter contaminants on the traveled surfaces.

I've decided to speak to you about something very different from what we have been hearing about the runway winter contaminants so far. I hope it will give you some everlasting memories and food for thought.

Past and present

18 000 years ago Canada, Greenland, and much of United States were under hundreds of metres of snow and ice that was collected previously for over 10,000 years. This is illustrated in Figure 1.

Today almost all of the snow and ice on the mainland is gone and what is left over looks like the illustration in Figure 2. Most of Greenland land is still covered with fields of ice. However, only remnants of ice can be seen in other places – Arctic islands, the Rockies, and near the west coast. A similar scenario also applies to many other continents. The disappearance of all that snow and ice on the land mass during these 18 000 years of global warming has slowly raised the sea level by about one hundred metres.

If the leftover ice (mostly in Greenland and Antarctica) disappears from the world, the sea level will rise again by about 100 m. What would that mean to us? This is difficult to visualize. I have tried to illustrate the possible consequences in Figure 3. So you see, if we wait long enough and if the general trend in global warming continues, there will be no problem with snow and ice on the runways. However, we will have to wait another few thousand years. Until then we must try something else.

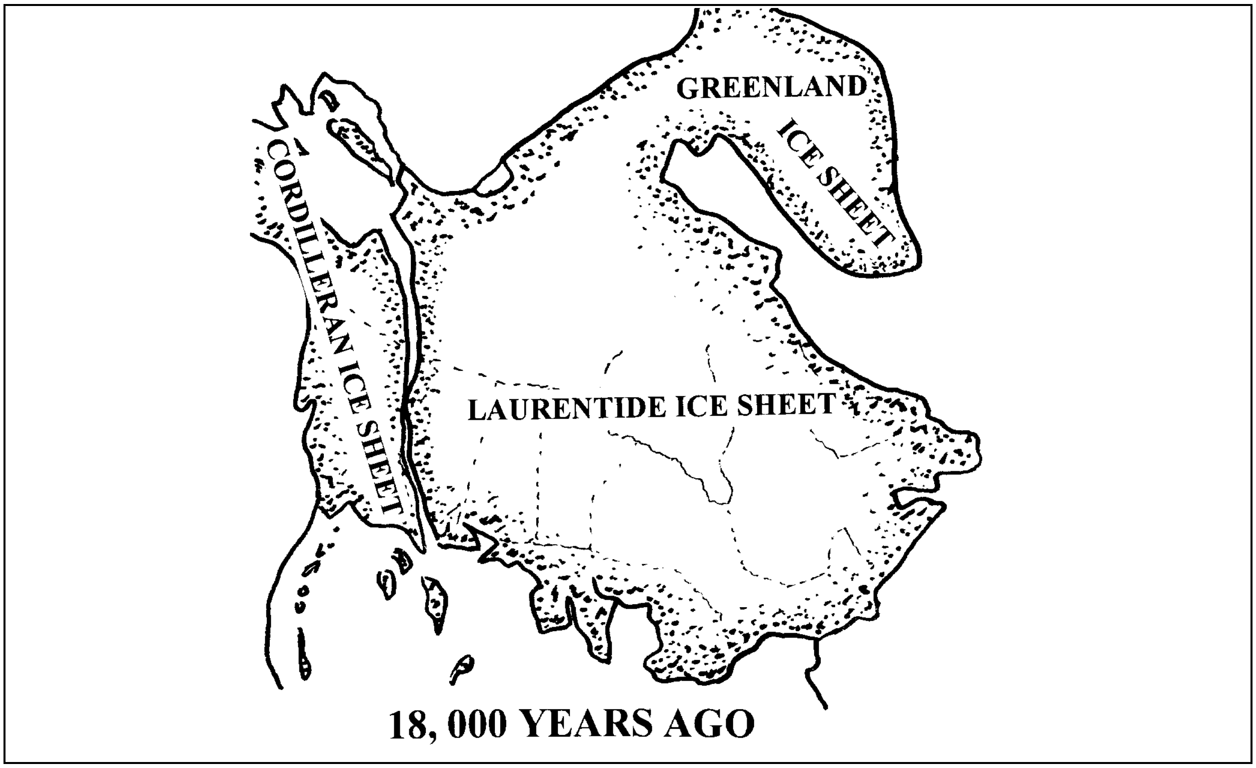

Figure 1 North America under solid ice 18 000 years ago

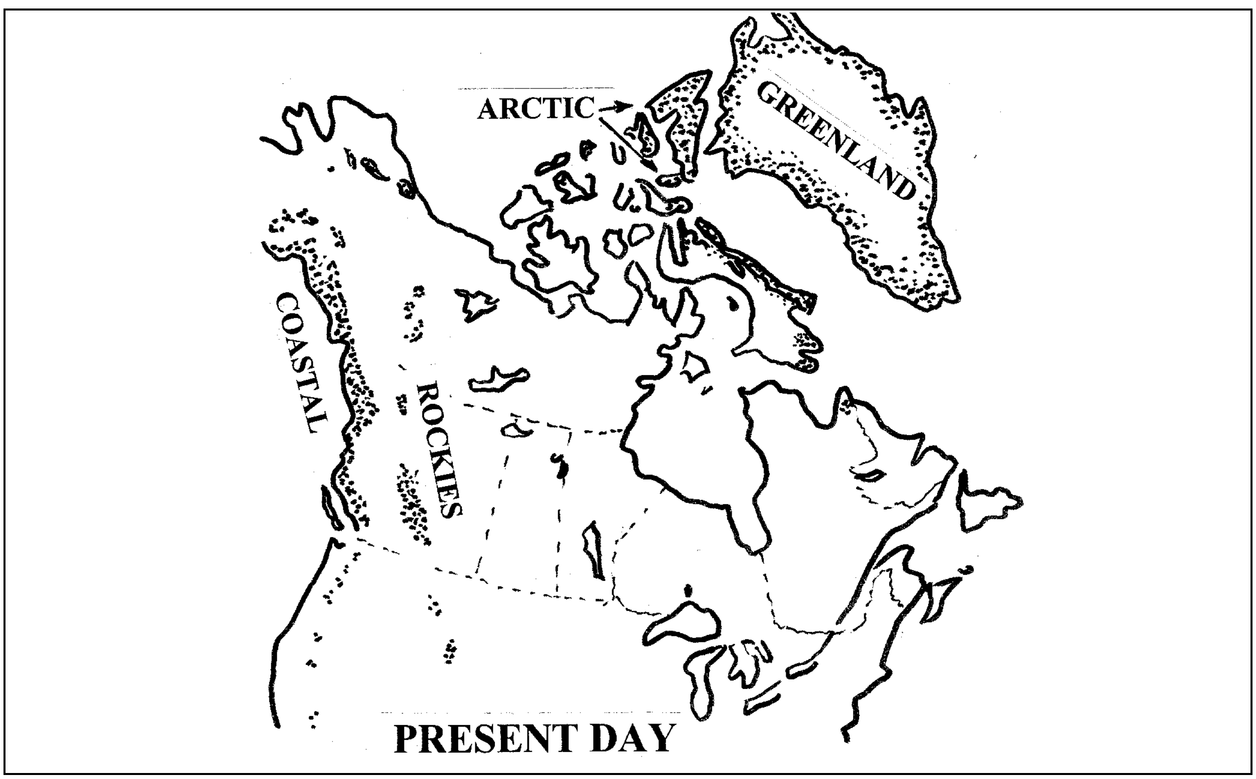

Figure 2 Remnants of ice-covered areas in North America

Figure 3 Rise in sea level if all the continental ice of the world melts

Snow and ice – cold stuffs?

In 1975 I joined the National Research Council Canada to work on snow and ice, and soon after this I started scratching my head asking myself, “Why did I join this field with no background whatsoever?”. I asked myself, “What is snow? What is ice?”. Well, we talked about snow but a particle of snow is really an ice particle, it’s a particle of frozen water. From the chemical point of view, there is no difference between snow and ice. From the crystallographic point of view, snow or ice particles belong to the hexagonal system very similar to α (alpha) phase in titanium-based alloys used extensively in aerospace industry. Historically, the term snow referred to faceted solid particles falling from the sky – snow particles develop by solidification processes from the vapour phase. Ice usually refers to the material formed by the solidification of water from the liquid phase. Again, historically compacted snow often refers to ice with a density higher than about 83 percent of the density of pure water. At this density, the compacted snow mass is usually impermeable.

Pure ice melts at a temperature of about 273 Kelvin. This is a low temperature if one compares the melting point of most of the materials used in the aerospace industry (see Figure 4) such as aircraft engine materials and other metals or alloys used in general. So, when we talk about the melting point of snow or ice, we are near the bottom of the totem pole as far as the temperature column is concerned. Naturally we think of snow or ice as a very, very cold material. Well, I’m going to change that perspective.

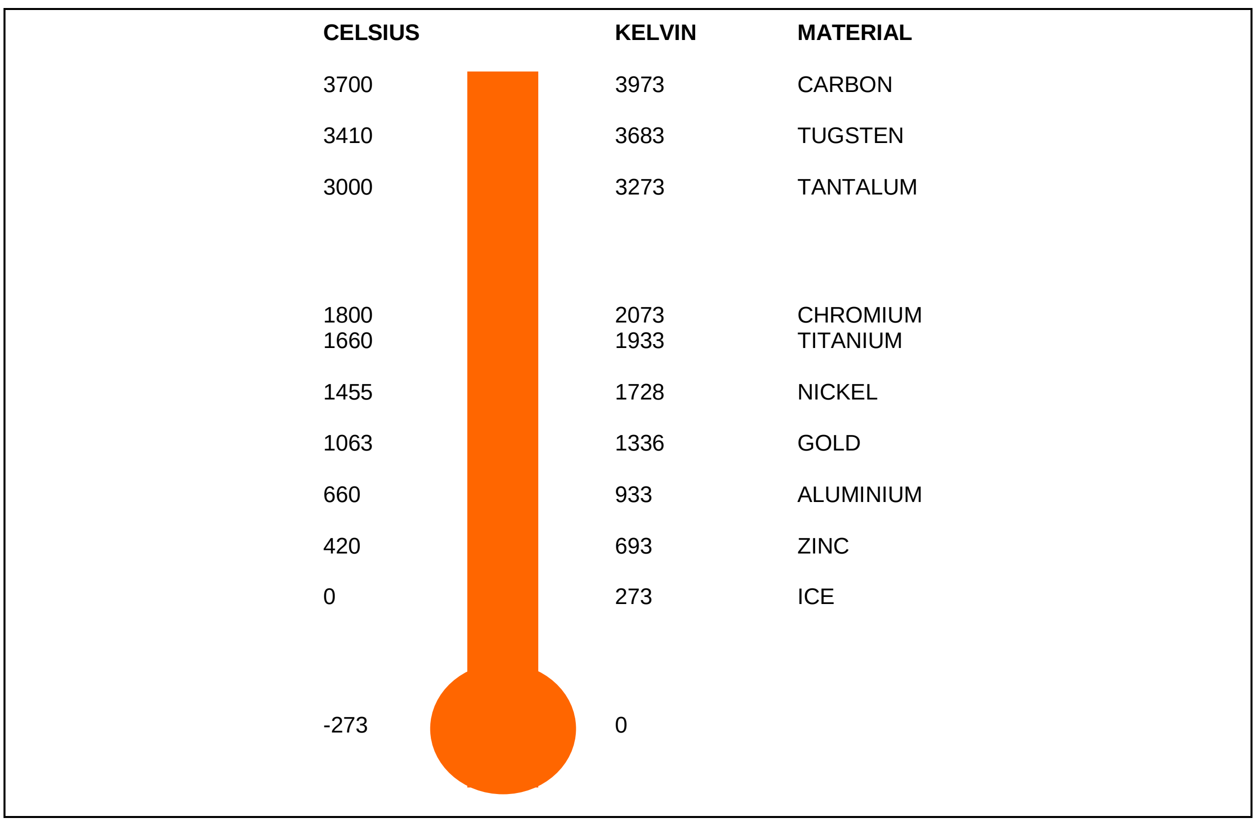

Figure 4 Melting point of some materials in two different temperatures scales

Snow and ice are actually very hot materials

When we discuss temperatures, we find that the Celsius (C) scale is not really a good scientific scale. A better scale is Kelvin (K). Consider a working temperature of –27°C. It is really extremely cold for humans. We have seen this temperature in North Bay, Ontario, during our runway friction tests. This temperature is equivalent to 246 K. If we take a ratio of this working temperature, T, of 246 K with the melting point, T_m of snow or ice, 273K, then this working temperature is actually 0.90 of the melting point (T/ T_m). This is, therefore, only 10 percent below the melting point. So, a temperature of -27°C is not really cold for snow or ice as materials in solid state, but it is only 10 percent below the melting point of this material. The normalized scale, given in terms of T/ T_m , is known as the Homologous scale.

The Homologous scale provides a rational method of comparing the thermal state of different materials at different temperatures. Consider, for example, 316 stainless steel, a common high-temperature stainless steel, with a melting point of 2000 K (or 1727°C), used in nuclear power stations and the first stages of gas turbine land-base or aeroengines. For this material, a temperature of 0.90 T_m is equivalent to 1800 K (or 1527°C), as illustrated in Figure 5. This is certainly an extremely high temperature for human touch. Thermodynamically speaking, 316 stainless steel at 1800 K (1527°C) is equivalent to snow or ice at 246 K (–27°C). Because of this thermodynamic equivalency, many physical properties, such as mechanical properties of snow and ice, can be compared with those of other materials at extremely high Homologous temperatures.

Let me clarify some of the points.

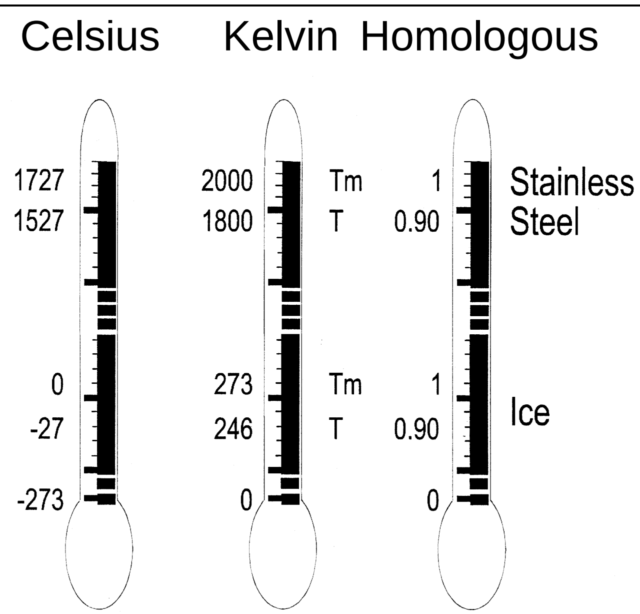

Figure 5 Comparison of temperatures in Celsius, Kelvin, and Homologous scales

Pressures involved during tire/pavement interactions

Air pressure of one Megapascal (1 MPa) is often used for tire pressures of aircraft operating on runways and taxiways. The winter contaminants, such as snow or ice on runway pavements, are subjected to this pressure during the operation of aircraft in winter. If we normalize this tire pressure, P, with the Young's Modulus, E, of ice (about 10 GPa), then the ratio, P/E, is $1x10^{-4}$. This pressure is then equivalent to a pressure of 20 MPa for a metal with a Young's modulus of 200 GPa. A pressure of 20 MPa in case of a metal is, therefore, equivalent to a pressure of 1 MPa for aircraft tires operating on runways contaminated with snow and ice at high Homologous temperatures. At Homologous temperatures greater than about 0.35 T_m , any pressures (stress) greater than 1×10^{-5} E are considered to be high pressures. At these pressures, cracks form in between grains in polycrystalline materials. This is known as high-temperature embrittlement and these types of cracks are known as intergranular cracks. For this reason, temperatures greater than about 0.35 T_m are known as high temperatures. Thus, aircraft tires induce materially speaking high stresses on winter contaminants.

Consequently aircraft tire/pavement interaction processes are 'high-temperature' and 'high-pressure' phenomena if the pavement surfaces are covered with winter contaminants.

Missing corn on a corncob

I'm sure you have eaten corn on the cob. Have you looked at what it consists of? Often you might see a structure shown in Fig. 6. This is a photograph of a corncob I grew in my garden one summer.

Figure 6 Corncob showing ordered and disordered structure

Note the ordered structure at the top half and the bottom half (unfortunately, I punctured one kernel accidentally) of this corncob. The central area is certainly disturbed and defective. Careful examination shows that the disturbance is caused by one extra kernel. One unwanted kernel actually distorted all the arrangements here. This extra kernel (or sometimes a missing kernel) acts like a point defect. This is common to natural crystals also.

The ordered structures of atoms in crystals are known as perfect lattice structure. However, perfect crystals do not exist in nature. The defects are known as the imperfections in crystals and there can be point defects as well as line defects (called lattice dislocations), as shown in Figure 7. Like any crystalline metal or nonmetal, ice and snow are no exceptions. Each crystal of snow and ice contains both point and line defects. Each flake of snow or crystal in ice may contain millions of these defects.

These defects move when subjected to external forces. This leads to time dependent viscous (or plastic) deformations. Since the entire lattice structure of a crystal could distort elastically, the material deforms elastically as well as plastically. This leads to two different kinds of deformations at the same time. One is the deformation of the lattice, which is elastic or instantly recoverable deformation, and the second is viscous or permanent deformation due to the movement of defects. These are the two basic deformation mechanisms in most materials at low temperatures. The materials science literature is full of visco-elastic and/or elasto-plastic analysis.

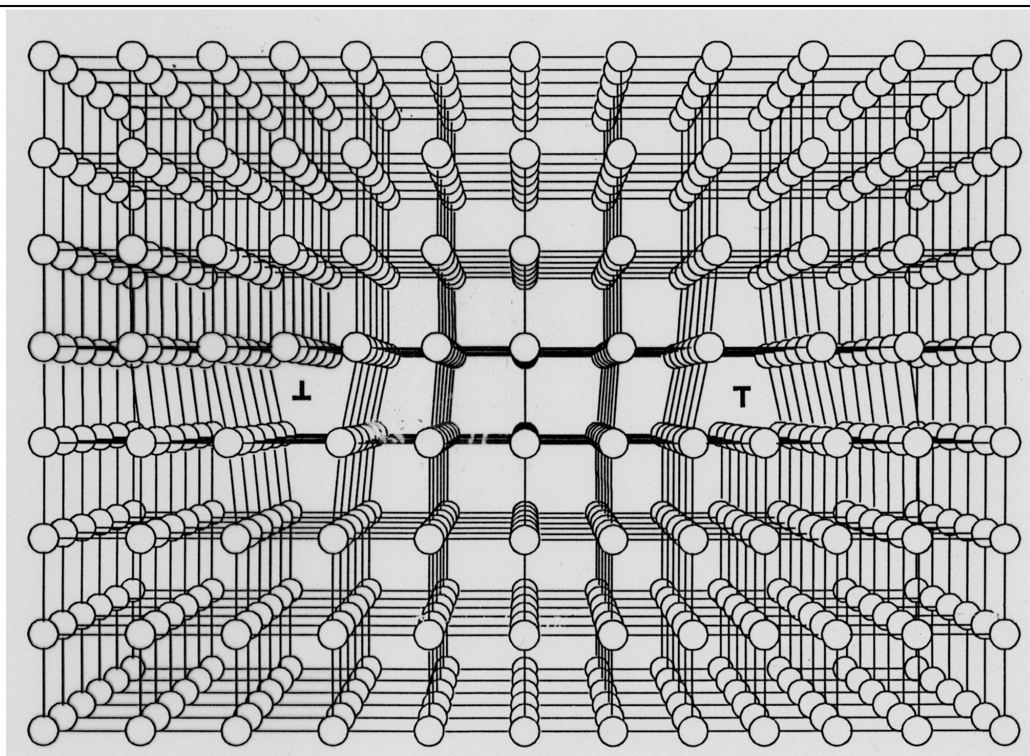

Figure 7 A pair of dislocations or line defects in a crystal

At temperatures greater than about 0.35 T_m, another mechanism, shearing between the crystal boundaries, takes place. This leads to a high temperature mechanism of time-dependent elastic deformation that rebounds when you remove the load. So micromechanisms dealing with snow and ice include not only elasto-plastic deformations, but also delayed elastic phenomena. This applies to all metals, alloys, and ceramics at high temperatures.

Delayed elasticity in snow and ice – a high temperature phenomenon

What is a delayed elastic phenomenon? How one can examine this?

If you apply a load to a body of snow or ice and then remove the load after some time, the material deforms delayed elastically, with time during the loading time, in addition to the instantaneous pure elastic deformation of the lattice and time dependent viscous (or plastic) deformation due to the mobility of the defects. When the load is removed, the elastic deformation recovers instantaneously. The viscous deformation stays as permanent deformation. The delayed elastic strain recovers with time. So really it is not the loading part that gives us information about delayed elasticity, it is the unloading part that gives us information. Only then we can define the total deformation in terms of elastic deformation, delayed elastic deformation, and viscous (or plastic) deformation. I won't go into any more detail on this and the mathematics that describe these components.

Figure 8 illustrates experimental results carried out on slightly compacted Himalayan snow. These were different samples of snow that were deformed and unloaded, a few times, to see whether the theoretical aspect that we are talking about would actually work on snow. These experiments were carried out at the Snow and Avalanche Study Establishment (SASE) in Manali, India. The density of the snow samples used in these experiments was comparable to that of snow compacted by NASA's Boeing B-757 aircraft during taxiing on freshly fallen, previously undisturbed snow, during winter friction tests at K.I. Sawyer Air Base in Michigan in February 1998 (Figure 9).

For interaction processes between aircraft tires and contaminated pavement surfaces, we talk about tribological processes between the interfaces of the tire (s) and the pavement, in the presence of lubricating materials like snow/ice/slush in between. As discussed earlier, this interface material can be looked at as a material undergoing deformation at high temperatures and high stresses.

Figure 8 exemplifies the response of snow on cyclic loading and unloading very similar to the field tests involving friction measuring ground devices going back and forth on snow-covered runways. Often one vehicle followed the other one. To simulate these conditions we loaded and unloaded, loaded and unloaded the same snow samples to see how their behaviour changes. Note the progressive increase in the amount of permanent deformation in Fig. 8. This means that the structure of snow changes with time and from one cycle of loading to the next cycle. Some of these measurements can be mathematically expressed in general terms as,

$$\varepsilon = \varepsilon_e + \varepsilon_d + \varepsilon_v \quad (1)$$

In short, mathematical developments can be made in terms of a total deformation, ε, consisting of elastic strain, ε_e, delayed elastic strain, ε_d, and the viscous (plastic) strain, ε_v. All these quantities depend on the functional relationship between a number of material and interaction parameters, such as temperature, density, bond characteristics, crystal size, surface characteristics of interacting bodies, and speed. Interactive processes can take account of energy input, changes in temperature, damage initiation, crack opening, crack sliding, crack closure, compactions, and all kinds of complexities.

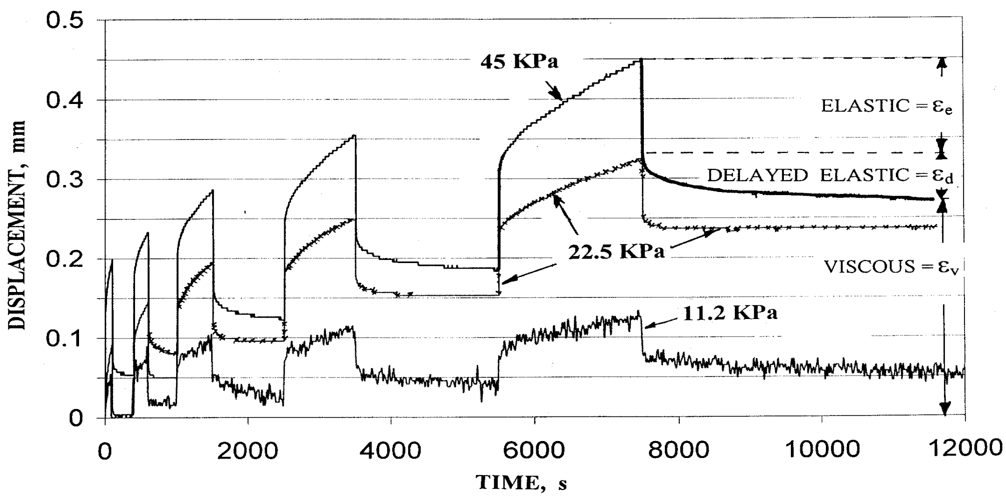

Figure 8 Elastic, delayed elastic, and viscous deformation in compacted snow during several load/unload experiments under three different load levels at 263 K or –10°C (Courtesy: Snow and Avalanche Study Establishment (SASE), Manali, India)

Figure 9 NASA's Boeing B-757 aircraft (a) during taxiing on freshly fallen, previously undisturbed snow, at K.I. Sawyer Airforce base in Michigan in February 1998, and the compacted snow (b) under the tire of the main gear

Some characteristics of snow on runway and taxiway surfaces

Snow on a pavement is a mixture of ice particles, air, and free water, depending on its temperature and atmospheric conditions. Freshly fallen snow can have densities in the range of 30 $kg.m^{-3}$ to 100 $kg.m^{-3}$. Free spaces between the particles are known as pores. In addition to morphological processes inducing changes in the densities, a snow cover in an airport movement area could be mechanically compacted due to vehicular movements. Snow is a compressible material, as may be seen in Figures 8 and 9, and the compaction processes in snow are similar to high-temperature sintering processes used in the field of ceramics and powder metallurgy. Making snow-balls is like making hot isostatically pressed superalloys used in hot sections of aeroengines.

Snow consists of ice particles that form in the atmosphere by complex joining processes of water molecules. These particles encompass a large variety of crystal habits and sizes. After the deposition of snow on the runway pavements, a process known as metamorphism modifies the geometrical features of the particles. The rate of change of these features depends on the temperatures of the air and the pavement, and the atmospheric conditions, including solar radiation. The metamorphic processes that cause these changes in shape and size are still poorly understood. However, thermally activated microstructural changes can be reduced to three basic types: a) equi-temperature (ET) metamorphism, b) temperature-gradient (TG) metamorphism, and c) melt-freeze (MF) metamorphism. Examples of these three metamorphic changes are shown in Figures 10, 11, and 12.

Snow when it gets warm melts and can refreeze. We have seen this melt-freeze (MF) metamorphism many, many times in North Bay and other places during our field tests. Figure 12 illustrates the microstructures of natural snow after melt-freeze situations.

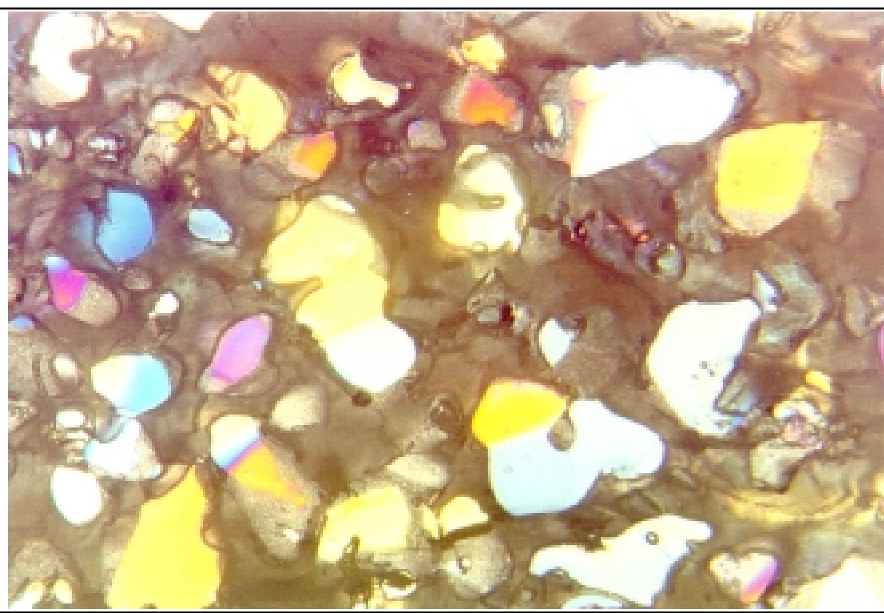

Figure 10 Microstructure of snow that has been mechanically compacted to a density of 400 $kg.m^{-3}$, comparable to the density of snow compacted by NASA's B 757 shown in Figure 9b, and subjected to equi-temperature (ET) metamorphism

Figure 11 Microstructure of snow that has been mechanically compacted and subjected to temperature-gradient (TG) metamorphism

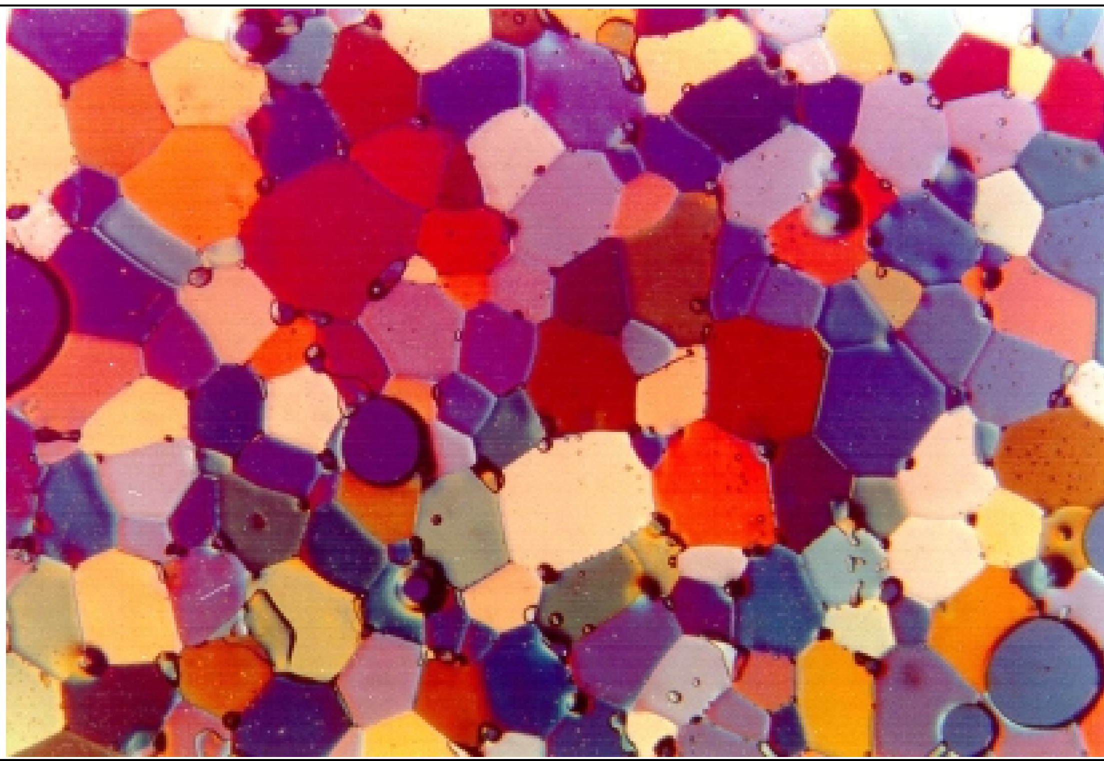

Figure 12 Microstructure of snow that has been subjected to melt-freeze (MF) metamorphism

Concluding remarks

We have now developed techniques by which we can examine the macroscopic mechanisms and the micro-mechanisms that govern the mechanical response of snow and ice on runway movement areas. These high-temperature and high-stress mechanisms can be formulated and applied to specific tribological interaction processes between aircraft tires and the surfaces of pavement contaminated with snow and ice as interface materials. A pragmatic approach is needed in relating the runway friction numbers obtained with different vehicles, aircraft, and other ground devices for short-term goals. Ultimately we have to look into the mechanisms that actually operate during interaction processes. Until then we have no hope of solving these problems for universal applications.

Acknowledgements

The author would like to convey his thanks to Barry Myers and Angelo Boccanfuso of the Transportation Development Centre of Transport Canada and Al Mazur of the Aerodrome Safety Branch of Transport Canada for supporting this work. He is indebted to S.S. Sharma, Director of the Snow and Avalanche Study Establishment (SASE), Manali, India for his permission to use the snow deformation data of Figure 8, obtained with the assistance of R. Kausik, and the micrographs used in Figures 10 – 12, provided by P. Satyawali.

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JAR Regulations on Contaminated Runways
Update – November 1999

G.J.R. Skillen
Civil Aviation Authority
Surrey, U.K.

JAR Regulations on Contaminated Runways

Update – November 1999

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Main Work Areas Are

- Basic aircraft dispatch
- Advice on braking action for landing

Dispatch – 1

We use AFM data (read across to Operational Data)

AFM data is by
- Test or calculation
- Standardised contaminants

It includes assumptions

Dispatch – 2

To use AFM data, *actual* contaminant conditions must be identified

- Type (per AFM list)
- Depth
- Friction quality

Problems – 1

Sensitivity of contaminant data

- How fine a slice you use
- How accurately you can define it
- How quickly you can define it

Problems – 2

Sliding scale of
- effort/result
- cost/benefit

Leads to the conclusion
- Sensitivity analysis necessary
- Factors, either direct or inbuilt

Operational Problems – 1

As JAR-OPS is written at present

- Penalties can be large
- Predictive element

Solutions might be

- Increased number of alternates
- Rely on in-flight check

How Are JAA Dealing With These Issues?

- Rewrite AMJ 25X1591 (Airworthiness Regulation)
- Contributor to Performance Harmonisation Working Group (ARAC)
- Supporting European test work

AMJ 25X1591 – Items Largely Complete

- Contaminants limited to realistic ones
- Uniform contaminants only
- Split – solids/liquids, drag/no drag, reduced braking or not
- Revised aquaplaning philosophy for low SG
- Upgraded ESDU standards for drag, etc.

AMJ 25X1591 – Open Items

- V_{MCG}
- Use of Reverse Thrust

AMJ 25X1591 – Open Item – Braking – 1

Shortage of data

- very wet or flooded – minimal data
- snow – reasonable quantity of data
- icy – some data

(does it correlate with wet at low texture depth?)

AMJ 25X1591 – Open Item – Braking – 2

- ESDU wet statistical method can be extended to contaminated
- Low speed flooded testing (<50 kt) helpful
- Controllability is dominant, so high data accuracy not necessary

Braking Reports for Landing – 1

- ESDU statistical methods can be used
- Vehicles have to split drag and friction for them to be fully useful
- Accuracy, banding of values

Braking Reports for Landing – 2

- Operational flexibility required
- Speed and accuracy of measurement
- Pragmatism, *please!*

Summary

Yes, we can calculate effects

Operational aspects are dominant and must not be neglected at the expense of technical purity

Knowing the distance accurately doesn't help if the crosswind caused the pilot to lose control

Safety Oversight – ICAO Documents

Armann Norheim
Norwegian Civil Aviation Administration
Oslo, Norway

Introduction

Safety oversight is defined as a function by means of which States ensure effective implementation of the safety-related Standards and Recommended Practices and associated procedures contained in the Annexes to the Convention on International Civil Aviation and related ICAO documents.

Let us define our problem and have a look at the related ICAO documents. Annex 15 describes it as significant changes in hazardous conditions due to snow, slush, ice, or water on the movement area. Visualised in a tribological system it will look like this (See Slide 1).

And what is a tribological system? (See Slide 2)

Tribo is derived from Greek, and means to rub. A tribological system has four main components:

1. Triboelement 1	The tire (tribometer, aircraft)
2. Triboelement 2	The surface
3. Interfacial medium	Contamination (water, snow, ice, sand, chemicals)
4. Environment	Atmospheric conditions

The friction measuring devices we use are thus different tribometers. Each tribometer is a tribosystem of its own with its own parameters.

The related science is the science of tribology and is defined as:

The science of interacting surfaces in relative motion and of the practices related thereto.

It follows that friction or a friction-coefficient is not a property of any single element. The friction-coefficient is a quotient arising from the measurement of forces between interacting surfaces in relative motion. Research has shown that the classical friction formula describing the linear relationship between the normal load and the horizontal force is not valid for pneumatic tires. The relationship is a more complicated exponential function.

We have now defined our problem: presence of snow, slush, ice, or water. We have described the system where the problem arises: the tribological system. To understand the system we have to deal with the uncertainties associated with the specific system and express the uncertainty in measurements.

Let us now return to the ICAO documentation dealing with snow, slush, ice, and water on the movement area. For the rest of my presentation I will use the term "safety barrier" when addressing issues and discrepancies in the ICAO documentation.

What are hazardous conditions? The ICAO documents do not describe the envelope for such conditions. And a hazardous condition for one aircraft is not necessarily a hazardous condition for another. This brings us to the subject of certification and airworthiness of aircraft.

Safety Barrier 1

Annex 8, Airworthiness of Aircraft, includes no standards or recommended practices related to snow, slush, ice, and water.

However, a standard referring to Annex 6, Operation of Aircraft, states that performance shall be determined and scheduled in the aircraft flight manual, so that the operating rules by which the aircraft is to be operated will provide a safe relation between the performance of the aircraft and the aerodromes and routes on which it is capable of being operated.

It adds that account must be taken of factors that significantly affect the performance of the aircraft, such as the presence of slush, water, and/or ice on the runway. Such factors shall be taken into account directly as operational parameters or indirectly by means of allowances or margins.

In the Airworthiness Technical Manual we find guidance on the variables to be considered in calculations. Four different tribosystems related to snow, slush, ice, or water are addressed (See Slide 3):

- Runway covered with wet loose contaminants, depth less than 0.5 mm
  - Friction varying with speed
- Runway covered with wet loose contaminants, depth more than 0.5 mm
  - Depth
  - Density
  - Tire pressure
- Runway covered with ice or compacted snow
  - Friction, fixed max value
- Runway covered with dry snow
  - Friction, fixed max value

The variables to be considered in these systems (See Slide 4) are:

- Friction varying with speed
- Depth, density, tire pressure
- Friction, fixed max value
- Friction, fixed max value

Calculations should be made for the following conditions:

- Smooth runway (not grooved) of typical construction
- Tires giving performance no better than 80 percent worn tires with five-groove tread

Safety Barrier 2

The smooth runway of typical construction is not defined.

To establish a relationship between friction measured by a tribometer (ground friction measuring device) and friction experienced by an aircraft tire, a narrower definition is needed.

Safety Barrier 3

No guidance is available on how to measure tire wear and how to incorporate this into performance calculations.

Safety Barrier 4

The lower depth limit for contaminants in calculations differs from those for assessment and reporting purposes.

The Airworthiness Technical Manual defines the lower contaminant depth for slush, wet snow, or water to be 0.5 mm. Annexes 14 and 15 recommend that an assessment of the mean depth of each third of the runway should be made to an accuracy of approximately 1 cm for dry snow and 0.3 cm for slush.

Safety Barrier 5

The Airworthiness Technical Manual and Annex 14 do not have the same definition for slush.

In the Airworthiness Technical Manual the term "slush" is used to cover the whole range of precipitation densities from that of dry snow to that of free-standing water. In Annex 14 slush is defined as water-saturated snow that, with a heel-and-toe slapdown motion against the ground, will be displaced with a splatter; specific gravity: 0.5 up to 0.8.

Safety Barrier 6

Preparation of an Operations Manual gives examples of a direct relationship between aircraft performance and friction measurements. Annex 14 and the Airport Service Manual – Pavement Surface Conditions states that as yet there is no general agreement that such a relationship exists.

If we look at the operation of aircraft, we find from Annex 6 that the operator shall establish aerodrome operating minima approved by the State, and that the State shall require that in establishing the aerodrome operating minima, full account shall be taken of the dimensions and characteristics of the runways that may be selected for use.

Examples of such information are given in the Preparation of an Operations Manual. The manual gives example of guidance on operations from contaminated runways in Attachment H. This guidance describes a direct relationship between the friction coefficient measured by ground friction measurement devices and aircraft performance for takeoff or landing and crosswind.

Attachment H gives guidance for specific tribometers and friction readings in wet loose contaminants (standing water, slush, and wet snow). The Airworthiness Technical Manual states that, for such conditions, depth, density, and tire pressure should be the variables. Under such conditions significant drag forces are present.

Safety Barrier 7

Preparation of an Operations Manual gives examples of a relationship between aircraft performance and friction measurements taken in wet loose contaminants. The Airworthiness Technical Manual does not list friction as a variable under such conditions.

Annex 14 tells us as a standard to remove snow, slush, ice, standing water, and other contaminants as rapidly and completely as possible to minimize accumulation. However, conditions of slush, snow, or ice cannot always be avoided. Annex 14 then recommends that the condition of the runway should be assessed, the friction coefficient measured, and the readings of the tribometer should adequately correlate with the readings of one other such device. However, the method of measuring friction contains a lot of noise because of the number of variables involved. The very reason for this is that friction is a process and not a property of any of the single elements involved.

Safety Barrier 8

The acceptable error ±6μ = 12μ represents almost the whole reporting band of 15μ between Good and Poor.

The Airport Service Manual, Pavement Surface Conditions, describes the acceptable error for repeatability to be ±6μ for the equipment at a confidence level of 95.5 per cent.

The Airport Service Manual does not describe the uncertainty of reproducibility between different equipment of the same brand and type. Nor does it describe the acceptable uncertainty for one single measurement according to the method used.

Results from JWRFMP show that the accuracy indicated (narrow bands) in the table in Annexes 14 and 15 (SNOWTAM) cannot be met by one single measurement according to the state-of the-art of the method described. Results from the JWRFMP will be presented by others at this conference. Tests from the Kollerud Calibration Test Track at Gardermoen, Norway, have shown that variance in repeatability and reproducibility for various tribometers is significant. This adds to the uncertainty.

Safety Barrier 9

The total acceptable uncertainty for a single measurement is not described.

The table used in the SNOWTAM format and described in the green pages of Annex 14 was developed in the early 50s using a piston driven aircraft and subjective reports from pilots. It has survived up to the present (See Slide 5). This table indicates an accuracy that cannot be possible, because of the uncertainty of the measuring method used. The reporting band is too narrow. A division into five cannot be justified.

Safety Barrier 10

The accuracy indicated in the table in 6.6 – green pages – in Annex 14 cannot be met by the measuring method used.

For water on the runway, Annex 14 states as a standard that information shall be made available that a runway or portion thereof may be slippery when wet. It further states as a standard that a continuous friction measuring device should be used and gives guidance that friction values according to a Table A-1 in the green pages should be treated as absolute values. The method to be used to attain the absolute values is not described. It must be stressed that the accuracy does not only rely on the equipment, but on the influence and variation of all the tribological elements involved, and as such pertains to the process and not only to the equipment.

An important variable is thus the texture of the surface. Annex 14 describes, as a recommendation, that the average surface texture depth of a new surface should be not less than 1.0 mm. New technology (laser) has been introduced. Researchers have found that a relationship exists between texture and friction (PIARC 1995 and others). This relationship is not reflected by the ICAO documents. If this relationship is applied to the values in Table A-1, mismatch is experienced.

Safety Barrier 11

The acceptable uncertainty of the measuring method to be used for wet friction measurements is not described.

Safety Barrier 12

Due to the uncertainties regarding repeatability and reproducibility of the tribometers and the measuring method, the measured values cannot be treated as absolute values as stated in Annex 14 – green pages.

In the standards in Annex 14 related to snow, slush, ice, or water, the focus is mostly on the friction characteristics and friction measurements and not to the same degree on the presence of snow and ice and water. A lot of effort has been spent on controlling and understanding the tribometers and relating them to our problem. Less effort has been spent on understanding the physical and mechanical properties of snow.

A lot has been gained in the knowledge and understanding of the mechanical behaviour and processes of snow and ice in recent decades. Temperature is one of the most important parameters and liquid water content another. The mechanical aspects of snow important to mobility are the ability to support vertical loads and its resistance to horizontal shear displacement. More focus should be on research of the properties of snow and ice related to our problem, including the influence of chemicals (glycols, formates, and acetates).

Safety Barrier 13

The NOTAM Code according to Doc 8400 does not distinguish between wet snow and slush.

Annex 14 has definitions for snow (on the ground), dry snow, wet snow, compacted snow, and slush. These correspond with the terms used when deciding variables to be considered in calculations according to the Airworthiness Technical Manual. If we look in Annex 15 and at the terms used in the NOTAM and SNOWTAM format we find in the NOTAM format the same terms with the addition of frozen ruts and ridges. We also find that the NOTAM format does not distinguish between wet snow and slush.

Safety Barrier 14

The operational significance and relation to aircraft performance is not addressed for the all the terms used in the NOTAM and SNOWTAM, such as damp, rime or frost covered, frozen rut, and ridges.

In the SNOWTAM format the following additional conditions are reported: damp, rime, or frost covered.

Safety Barrier 15

The ICAO documentation does not include or categorize all common contamination types relative to airworthiness and operation of aircraft, as well as reporting of surface conditions.

The NOTAM and SNOWTAM format does not address some common types of contamination (See Slide 6):

- Wet ice
- Sanded wet ice
- Sanded dry ice
- Sanded wet compacted snow
- Sanded dry compacted snow

- Use of solid chemicals
- Use of liquid chemicals

The wet conditions appear at the melting point of the contaminant. Use of chemicals can depress this.

Safety Barrier 16

The SNOWTAM Format and the MOTNE Code do not use the same scale.

Another reporting format described in the ICAO documentation (Doc 8755/13) is the non-meteorological eight-figure MOTNE Code which is added to the METAR. It complies with the SNOWTAM format except when it comes to reporting depth of deposits. It uses a more accurate reporting scale.

Summary

- For certification and airworthiness of aircraft, Annex 8 includes no standards related to snow, slush, ice, or standing water on the movement area.

- For operation of aircraft, the acceptable uncertainties related to measuring the variables used in calculations related to the different tribosystems are not described.

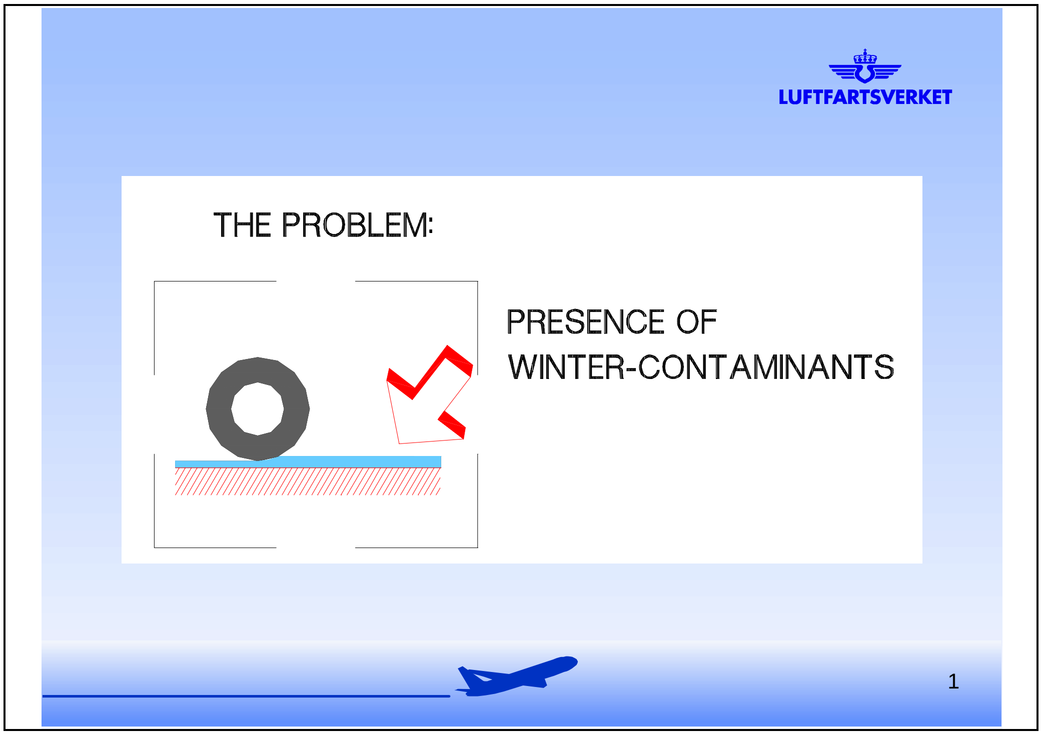
- The ICAO documentation indicates an accuracy for reporting of friction characteristics (wet friction, compacted snow, and ice) that cannot be met, because of the uncertainties of the measuring methods used.

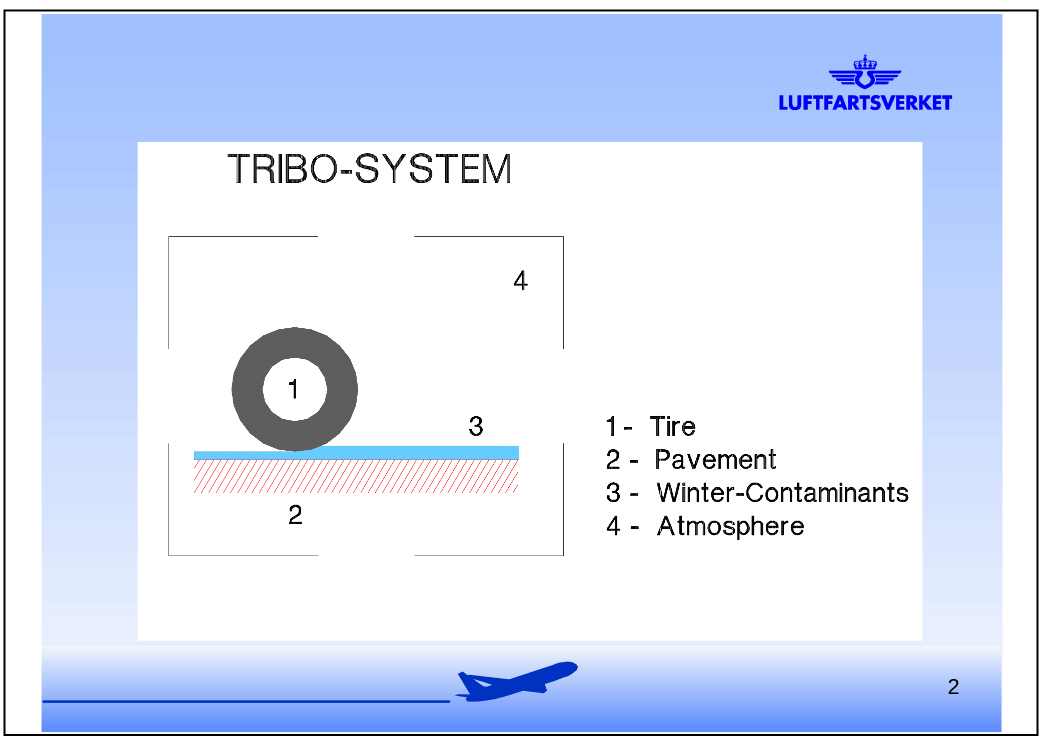
- The language used in the ICAO documents dealing with snow, slush, ice, and water on the movement area is not consistent and does not reflect all types of operational surfaces.

My recommendation is that ICAO address these discrepancies in their documentation and at the same time update their documentation to include current knowledge of the different scientific disciplines involved. This is important for the process in which States ensure effective implementation of the safety-related Standards and Recommended Practices and associated procedures contained in the Annexes to the Convention on International Civil Aviation and related ICAO documents.

ICAO Documents

Annex 6	Operation of Aircraft
Annex 8	Airworthiness of Aircraft
Annex 14	Aerodromes
Annex 15	Aeronautical Information Services
Doc 8126-An/872	Aeronautical Information Services Manual
Doc 8400/4	ICAO Abbreviations and Codes
Doc 8755/13	Air Navigation Plan – North Atlantic, North American, and Pacific Regions
Doc 9051-An/896	Airworthiness Technical Manual
Doc 9137-An/898 Pt 2	Airport Service Manual – Pavement Surface Conditions
Doc 9137-An/898 Pt 8	Airport Service Manual – Airport Operational Services
Doc 9137-An/898 Pt 9	Airport Service Manual – Airport Maintenance Practices
Doc 9376-An/914	Preparation of an Operations Manual
Doc 9734-An/959	Safety Oversight Manual


LUFTFARTSVERKET
THE PROBLEM:
PRESENCE OF
WINTER-CONTAMINANTS
1


LUFTFARTSVERKET
TRIBO-SYSTEM
4
1
3
2
1 - Tire
2 - Pavement
3 - Winter-Contaminants
4 - Atmosphere
2

LUFTFARTSVERKET

TRIBO-SYSTEMS

- 1 — loose contaminants less than 0.5 mm
- 2 — loose contaminants more than 0.5 mm
- 3 — compacted snow and ice
- 4 — dry snow

3

LUFTFARTSVERKET

VARIABLES

- 1 — Friction varying with speed
- 2 — Depth, density, tire pressure
- 3 — Friction, fixed max value
- 4 — Friction, fixed max value

4

LUFTFARTSVERKET

EARLY 1950s

FRICTION MEASUREMENTS ON EACH THIRD OF TOTAL RUNWAY LENGTH

MEASURED OR CALCULATED COEFFICIENT or ESTIMATED BRAKING ACTION

0.40 and above	GOOD	- 5	
0.39 to 0.36	MEDIUM/GOOD	- 4	
0.35 to 0.30	MEDIUM	- 3	
0.29 to 0.26	MEDIUM/POOR	- 2	
0.25 and below	POOR	- 1	
9 – unreliable	UNRELIABLE	- 9	(from 1982)

(When quoting a measured coefficient use the observed two figures; when quoting an estimate use single digits.)

TODAY'S AIRCRAFT

5

LUFTFARTSVERKET

CONTAMINATION

- Wet ice
- Sanded wet ice
- Sanded dry ice
- Sanded wet compacted snow
- Sanded dry compacted snow
- Use of solid chemicals
- Use of liquid chemicals

6

Statistical Methodology for International Runway Friction Index (IRFI)

James C. Wambold
CDRM, Inc.
State College, Pennsylvania

Statistical Methodology for International Runway Friction Index (IRFI)

2nd International Meeting on Aircraft Performance on Contaminated Runways

Sponsored by

Transport Canada (TC)
Transportation Development Centre (TDC)

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Objectives

Compile a database containing all data available from winter and summer runway friction measurements using different devices and tires and aircraft tire braking performance.

Correlate the data to determine a harmonized runway friction index, the International Runway Friction Index (IRFI).

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Reference Device

- Ideal: Design and build a set of devices.
- Virtual reference: Average of all participating devices (used in IFI).
- Virtual reference: Average of limited number of devices.
- Arbitrary device.

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Statistical Model

IRFI = a + b DEV

Where a & b are calibrated from regressing:

REF DEV = a + b DEV

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1998 Data – IRFI

	Model	IRFI = a+ b x device Ref.=(SFT79 + IMAG)/2 1998 data		
Device	**a**	**St. Error a**	**b**	**St. Error b**
ASFT	0.0055	0.0147	0.6232	0.0574
BV-11	0.0395	0.0104	0.6424	0.0472
ERD	0.0417	0.0269	0.8705	0.1211
GT-STD	-0.0147	0.0066	0.9923	0.0442
GT-SC	0.0285	0.0102	0.7523	0.0497
IMAG	-0.0577	0.0105	1.291	0.0558
OSCAR	0.0146	0.0193	1.0205	0.1307
RUNAR	-0.1405	0.0338	1.348	0.1471
SFT97	0.0413	0.0039	0.7875	0.0203

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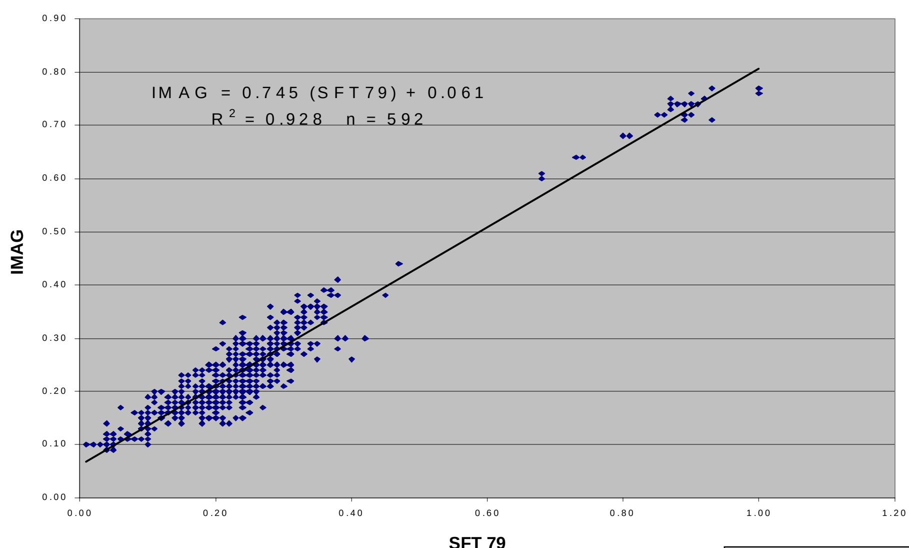
IMAG vs SFT79 All Data



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Surfaces Classes

Class	Base	Condition
• IB	Ice	Bare
• ID	Ice	Drifting snow
• IF	Ice	Frost/Damp
• IS	Ice	Slush
• IW	Ice	Wet
• PB	Pavement	Bare
• PD	Pavement	Drifting snow
• PF	Pavement	Frost/Damp
• PS	Pavement	Slush
• PW	Pavement	Wet
• SB	Snow	Bare
• SD	Snow	Drifting snow
• SS	Snow	Slush
• SW	Snow	Wet

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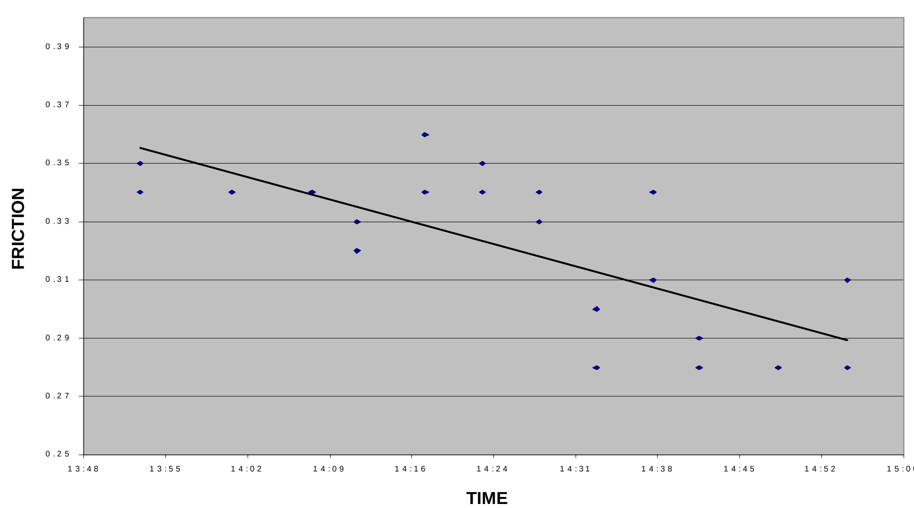
IMAG on Drifting Snow



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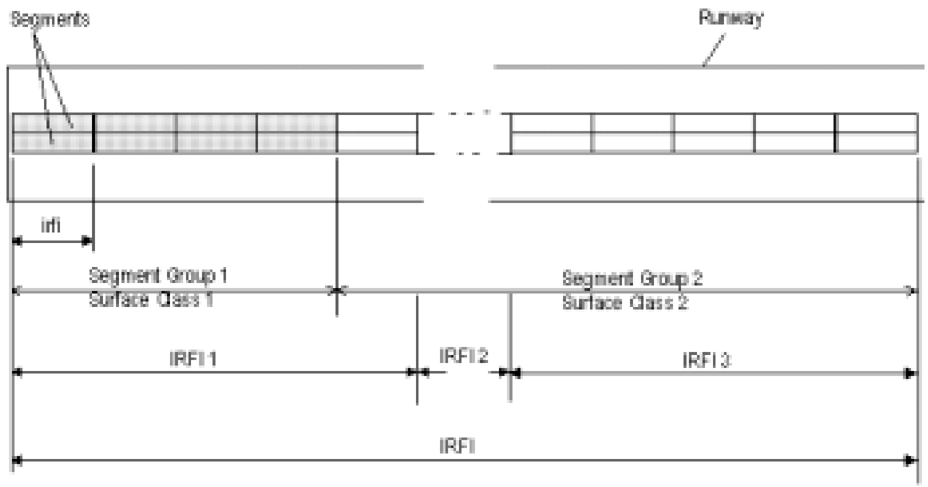
Surface Segments



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IRFI for Mixed Surface Classes

$$IRFI = \frac{1}{L} \Sigma(l_i \bullet irfi_i)$$

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IFI

$$S_p = a + b\,TX$$
$$F60 = A + B\ DEV\ \exp[-(60 - S)/S_p)]$$
$$IFI = \{F60; S_P\}$$

Where S_P is the Speed Constant
TX is a texture measurement
S is the Slip Speed
  S = Vehicle velocity (V) for locked wheel testers
  S = V percent slip for fixed slip testers
  S = V sin(Y) for sideforce testers, where Y = yaw angle
DEV is the device measurement at the slip speed S
a, b, A and B are determined for a device by regression with a virtual reference

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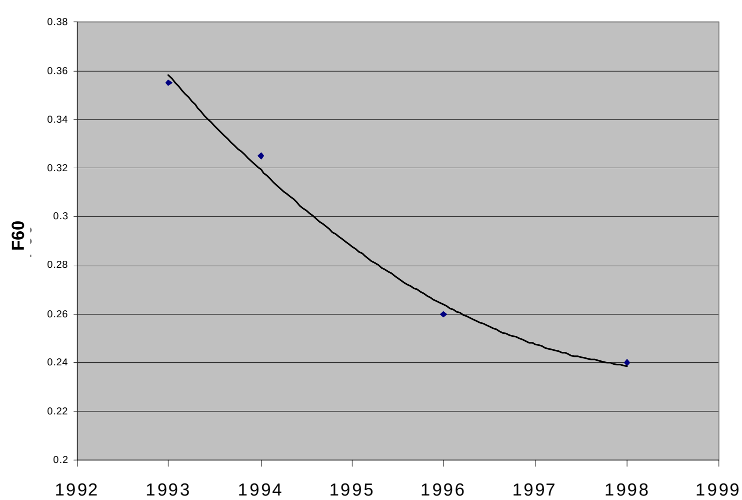
IFI History – F60



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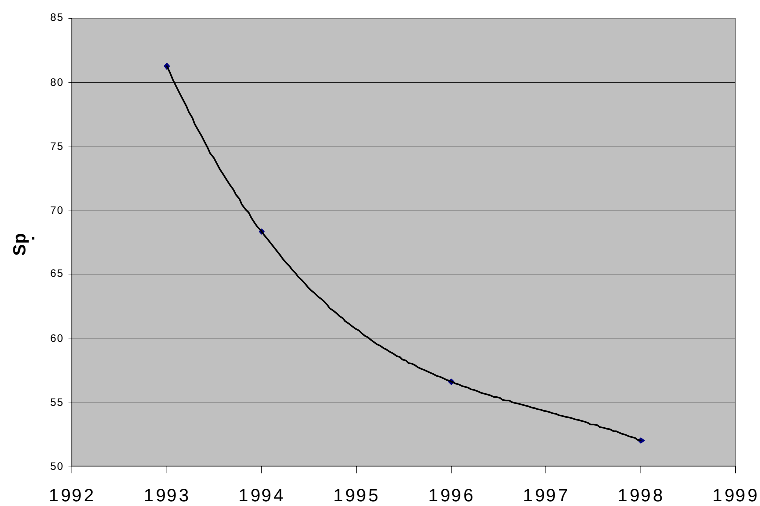
IFI History – S_p



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ASTM Standard

Proposed Standard Test Method for Calculating International Runway Friction Index for Operational Use

Scope

This test method covers the calculation of the International Runway Friction Index, IRFI, from measurements by ground friction measurement devices on runways and taxiways. The assessment of surface conditions is necessary to implement this calculation.

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Conclusions

- A reference device for the IRFI is needed.
- The Statistical IRFI has being developed.
- An ASTM Standard has been drafted.

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International Runway Friction Index (IRFI) – Validation vs Sensitivity

James C. Wambold
CDRM, Inc.
State College, Pennsylvania

International Runway Friction Index (IRFI) Validation vs Sensitivity

Second International Meeting on Aircraft Performance on Contaminated Runways

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Validation Method for IRFI

The validation procedure to be used is a four-step process, which is as follows:

1. All of the new data are collected in pairs.
2. The IRFI constants from the previous year are applied for each paired 100 m and compared to the reference for standard deviation, coefficient of variation, and the root mean square error.
3. The data for the present year are then used to calculate the IRFI constants for comparison with the previous IRFI constants.
4. The paired data for the current year are combined with all previous paired data, and the IRFI constants are recalculated.

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Statistical Model

IRFI = a + b DEV

Where a & b are calibrated from regressing:

REF DEV = a + b DEV

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Validation of IRFI in 1998

In the first effort to validate the harmonization of the statistical IRFI, the IRFI constants (determined from 1998 Oslo data only) were applied to an independent data set: the 1998 North Bay data.

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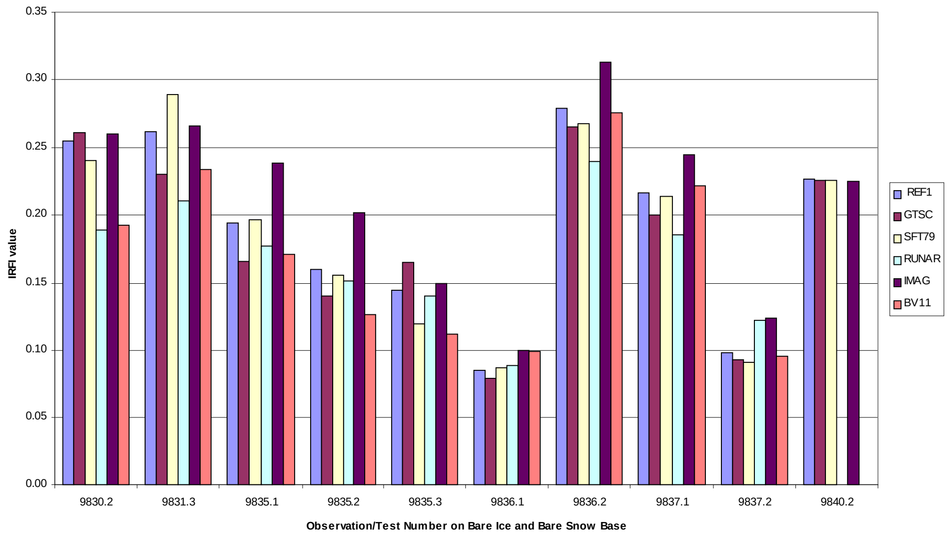
Harmonization on Result Sample:
North Bay Adjusted by Gardemoen IRFI Calibration Constants



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Difference of Correlations with all 1998 Data from Oslo Correlations

	Model		**IRFI = a + b x μ_{device}**		
		Difference between correlation values using all the 1998 data minus the values from Oslo only data			
Device	**a**	**St. Error a**	**b**	**St. Error b**	**R^2**
ASFT[1]	0	0	0	0	0
BV-11	0.0037	0.0018	0.0318	0.0075	-0.052
ERD[2]	0.0466	0.0121	-0.1129	0.0351	-0.359
GT-STD[1]	0	0	0	0	0
GT-SC	0.0031	0.0039	0.0193	0.0175	-0.0396
IMAG	-0.0002	-0.0035	-0.0333	-0.0285	-0.0008
OSCAR[1]	0	0	0	0	0
RUNAR	-0.0397	-0.0057	0.2292	-0.0291	-0.0027
SFT97	0.0026	-0.0009	0.0103	-0.008	-0.0013
Average	0.0018	0.0009	0.016	-0.0006	-0.0506

Notes:
1. The device was only in Oslo, thus NB adds no new data.
2. The data are with one vehicle in Oslo and a different one in NB.

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1998 Data – IRFI

	Model	IRFI = a + b x device Ref.=(SFT79 + IMAG)/2 1998 data		
Device	**a**	**St. Error a**	**b**	**St. Error b**
ASFT	0.0055	0.0147	0.6232	0.0574
BV-11	0.0395	0.0104	0.6424	0.0472
ERD	0.0417	0.0269	0.8705	0.1211
GT-STD	-0.0147	0.0066	0.9923	0.0442
GT-SC	0.0285	0.0102	0.7523	0.0497
IMAG	-0.0577	0.0105	1.291	0.0558
OSCAR	0.0146	0.0193	1.0205	0.1307
RUNAR	-0.1405	0.0338	1.348	0.1471
SFT97	0.0413	0.0039	0.7875	0.0203

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Standard Error of Estimate and Sensitivity 1998

Device	Sensitivity	Standard error of estimate
ASFT1	0.012028	0.0193
BV-11	0.013426	0.0209
ERD[2]	0.039085	0.0449
ERDNissan[1]	0.018095	0.0184
GT-STD[1]	0.005061	0.0051
GT-SC	0.007147	0.0095
IMAG	0.018074	0.014
OSCAR[1]	0.026533	0.026
RUNAR	0.038688	0.0287
SFT97	0.006615	0.0084
Average	0.018475	0.01952

Notes:
1. The device was only in Oslo, thus NB adds no new data.
2. The data are with one vehicle in Oslo and a different one in NB.

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Conclusions

- A reference device for the IRFI is needed.
- Devices must be calibrated periodically against the reference.
- Annual calibration is recommended.
- With a fixed reference the IRFI is stable.
- The statistical IRFI has acceptable error.

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International Runway Friction Index (IRFI) – Virtual Reference vs Real Reference

James C. Wambold
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State College, Pennsylvania

International Runway Friction Index (IRFI) Virtual Reference vs Real Reference

Second International Meeting on Aircraft Performance on Contaminated Runways

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Reference Device

- Ideal: Design and build a set of devices.
- Virtual reference: Average of all participating devices (used in IFI).
- Virtual reference: Average of limited number of devices (used in1998-99).
- Arbitrary device: STBA – offered on loan as an interim reference (2000).

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(Virtual) IRFI Reference Selection 1998

- In order to perform a linear regression a virtual device made up of combinations of devices was constructed.
- All feasible combinations of devices were investigated.
- A single device would be adequate; however, if that device gave an erroneous reading, everything would be harmonized incorrectly.

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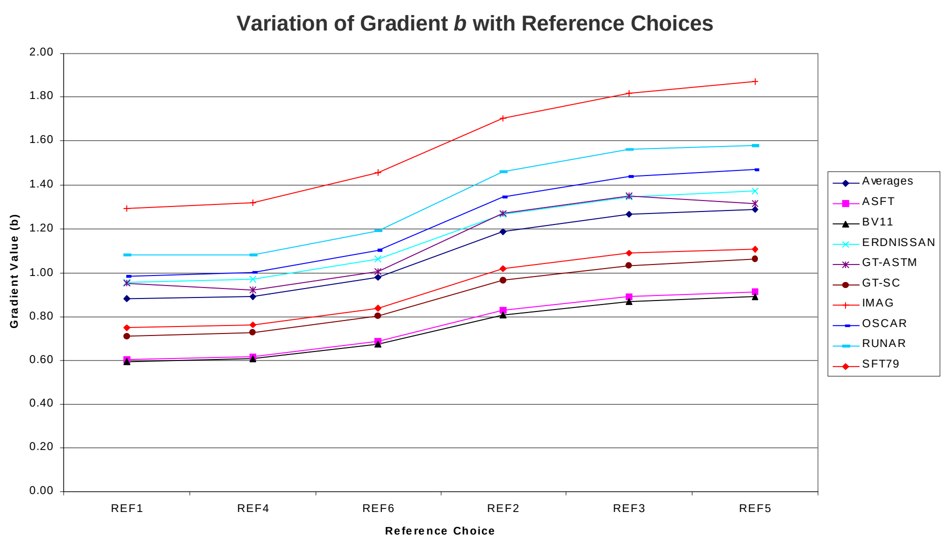
Effect of Gradient by Reference Choice



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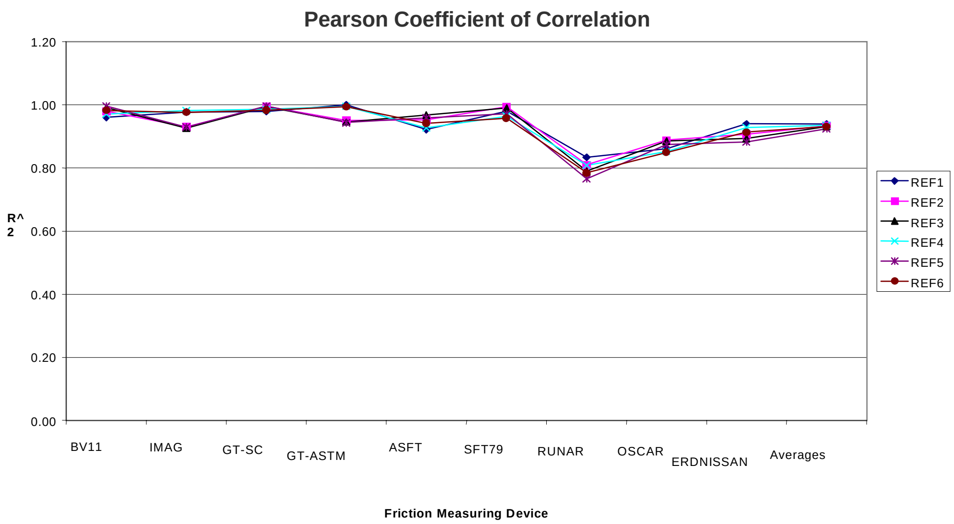
Coefficient of Correlation by References



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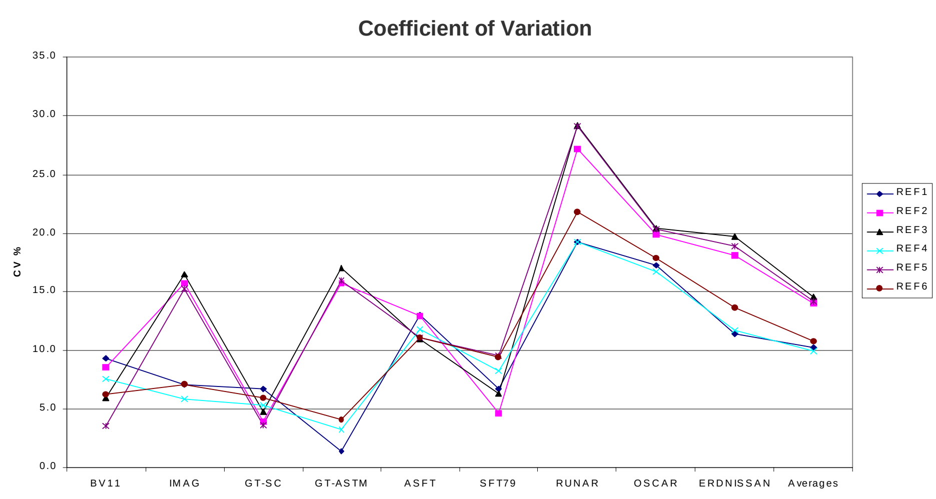
Coefficient of Variation by Device for Different References



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Reference 1, the Average of the SFT-TC79 and the IMAG

- They tested at Gardermoen and North Bay.
- They produced equivalent or better correlations, R^2 and CV, and the average friction of the ground testers.
- They measure both force and torque.
- They will be at the three sites in the coming years.

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Statistical Model

IRFI = a + b DEV

Where a & b are calibrated from regressing:

REF DEV = a + b DEV

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CDRM, Inc.

1998 Data –IRFI

	Model	IRFI = a + b x device Ref.=(SFT79 + IMAG)/2 1998 data		
Device	**a**	**St. Error a**	**b**	**St. Error b**
ASFT	0.0055	0.0147	0.6232	0.0574
BV-11	0.0395	0.0104	0.6424	0.0472
ERD	0.0417	0.0269	0.8705	0.1211
GT-STD	-0.0147	0.0066	0.9923	0.0442
GT-SC	0.0285	0.0102	0.7523	0.0497
IMAG	-0.0577	0.0105	1.291	0.0558
OSCAR	0.0146	0.0193	1.0205	0.1307
RUNAR	-0.1405	0.0338	1.348	0.1471
SFT97	0.0413	0.0039	0.7875	0.0203

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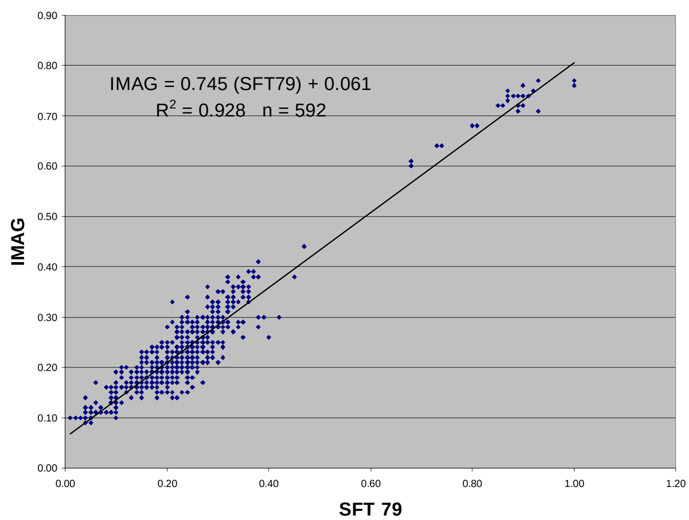
IMAG vs SFT79 All Data



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Conclusions

- A reference device for the IRFI is needed.
- An STBA device has been offered as an interim reference.
- Devices must be calibrated periodically against the reference.
- Annual calibration is recommended.

IMAPCR '99

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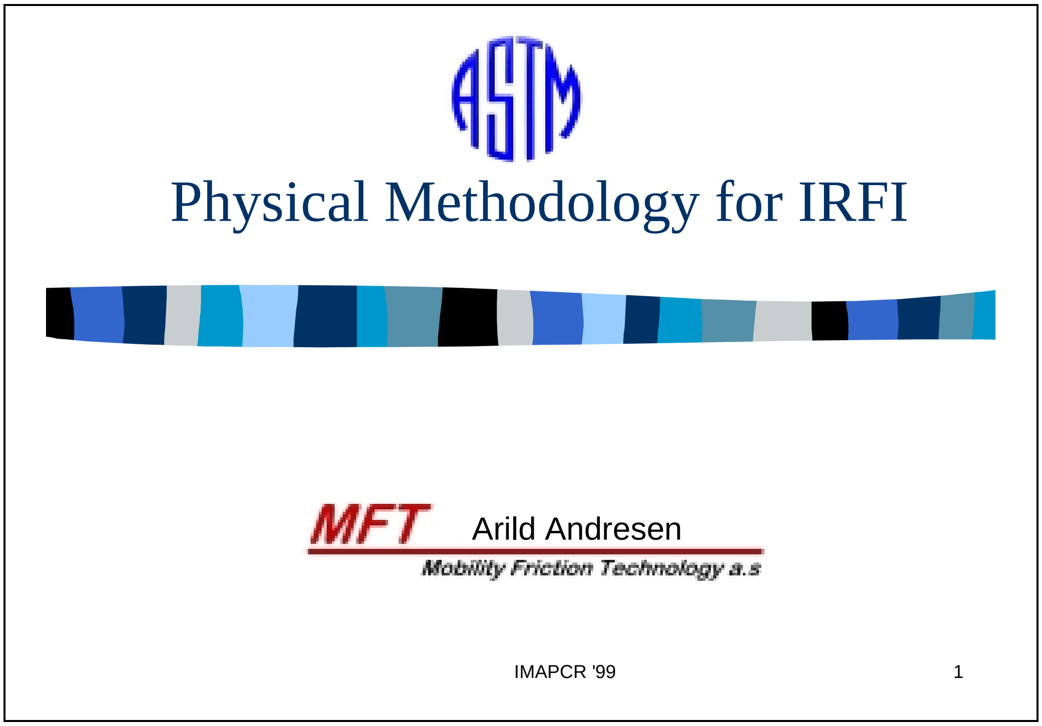
Physical Methodology for IRFI

Arild Andresen
MFT Mobility Friction Technology
Oslo, Norway

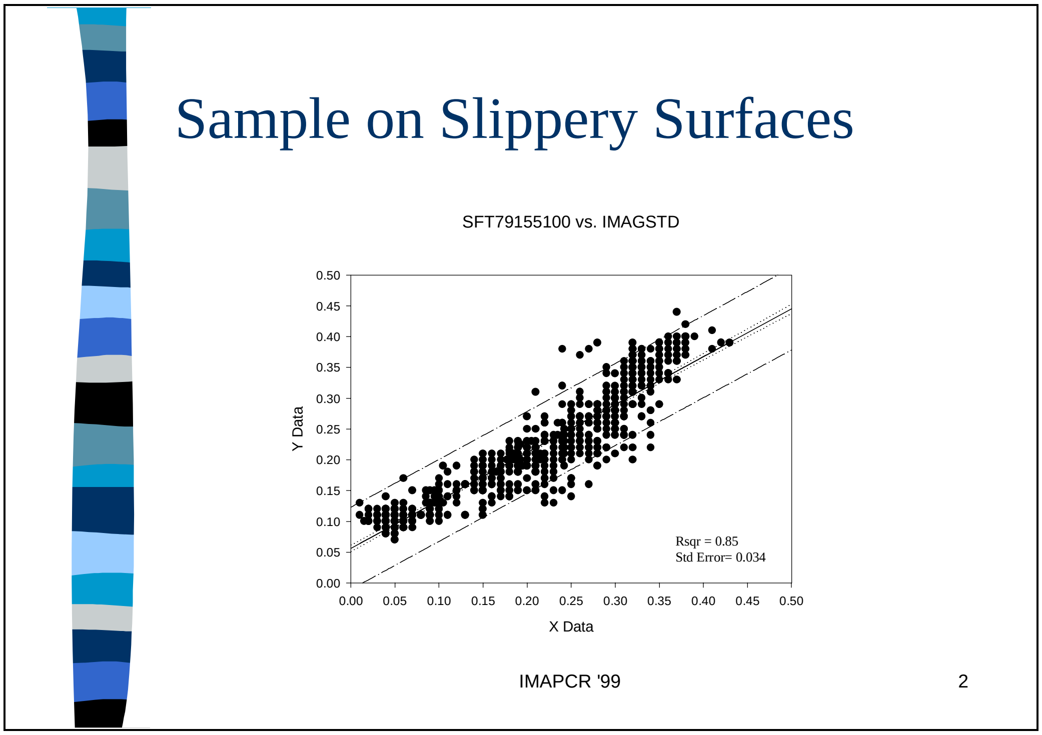


Arild Andresen is chairman of the ASTM Subcommittee E 17.22 on Friction Measurement of Traveled Surfaces Under Winter Conditions.

The International Runway Friction Index (IRFI) standard is being developed in task group E17.22/96.1 chaired by Al Mazur, Transport Canada.

The standards development is ongoing. A first step standard utilizing statistical methodology is currently on ballot with a note that a physical model is being developed.

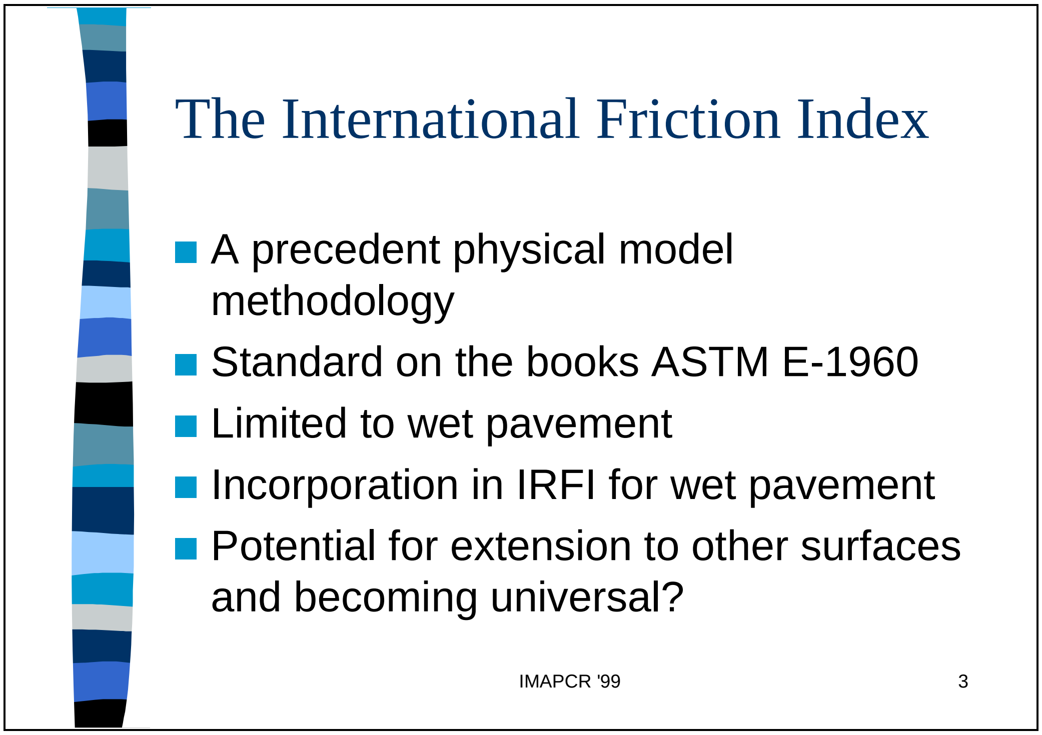
This presentation does not reflect the views of the IRFI task group or the subcommittee, but is an outline of development work funded by NASA and other constituents of the Joint Winter Runway Friction Measurement Program for consideration as ASTM standards material.



Doing a classical linear regression when comparing two ground friction measuring devices for ice and snow surfaces the plot typically looks like the one shown for SFT and IMAG on the basis of combined data for 1998 and 1999.

The spread of the data is a concern. A rule of thumb is that the surface and environmental variability is in a range of plus/minus 0.05 friction units about the average friction.

To investigate whether some of the variance is due to effects like temperature, measuring speed, surface material or the friction testers themselves, it can be useful to develop and try out physical models.



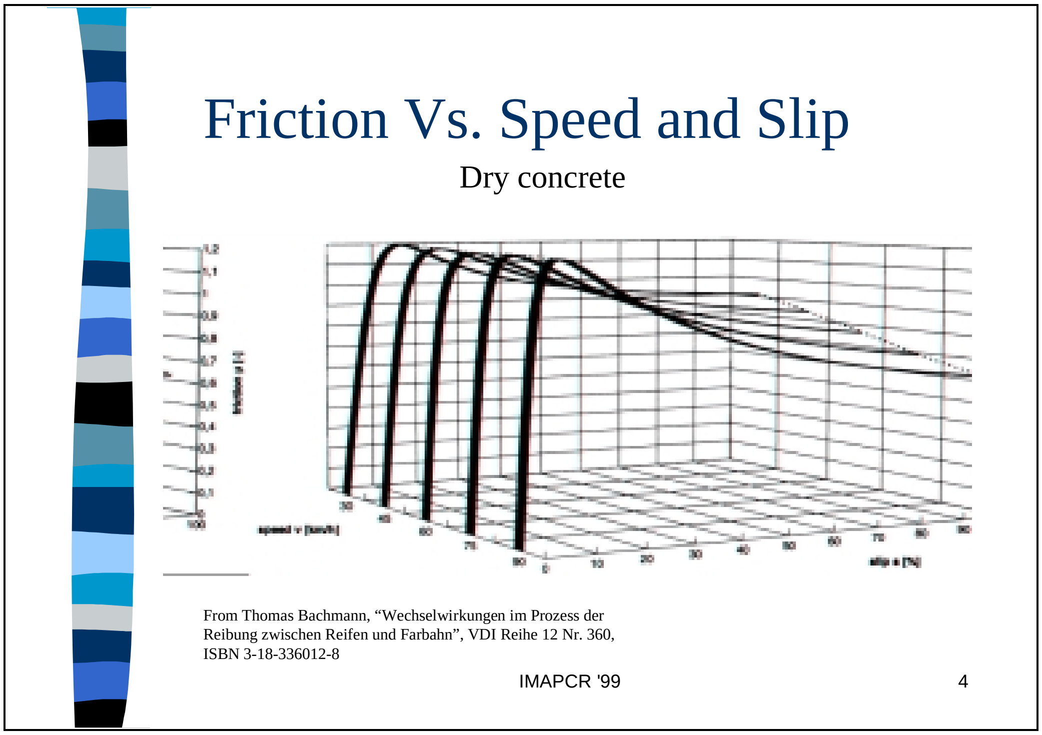
The International Friction Index became an ASTM standard in 1998 after it had been developed by the World Roads Association in 1992-95.

The IFI is a two parameter index including a friction value and a speed number. The index is device independent and therefore well suited for regulatory purposes or for users with a need to transform a friction measure from a reported value of one device to another.

The scope of the development was limited to wetted pavement as it is a common practice to monitor pavement frictional characteristics with a controlled water supply before the measuring wheel.

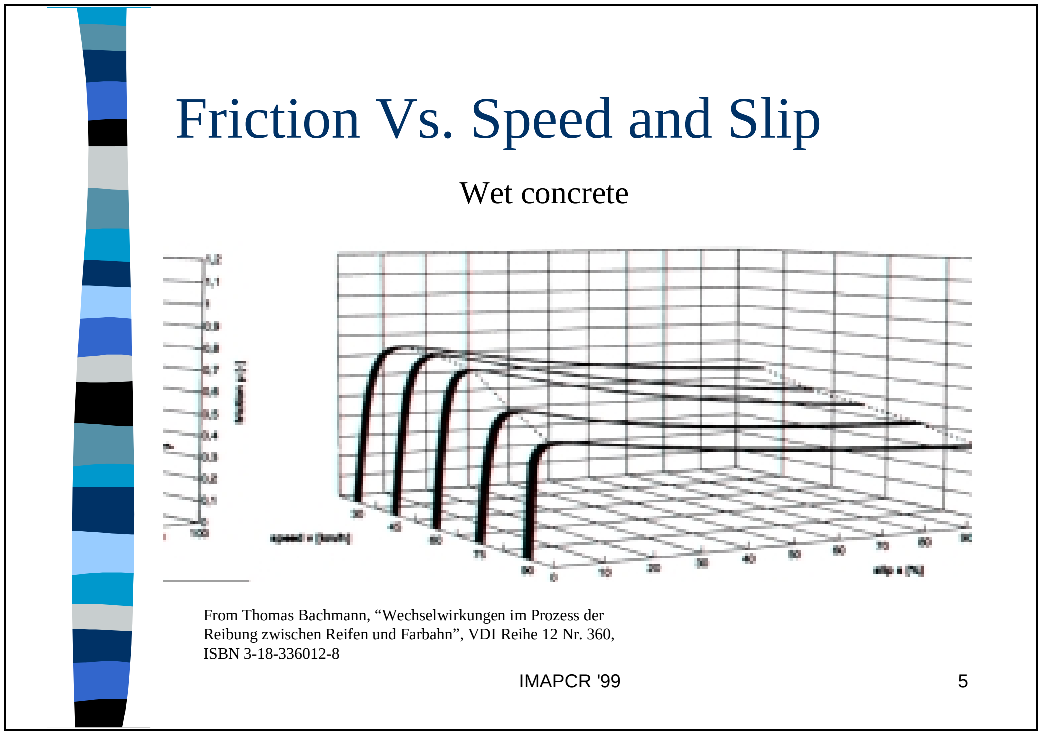
To fill the needs of operational friction measures of airport runways this index concept would have to be extended to many other base surfaces and conditions. Base surfaces, being the surface material on which a braked tire slips to generate frictional forces, come in three major classes: pavement of high mechanical strength; ice with an intermediate strength; and compacted snow that has a lower mechanical strength than pavement. These three base surfaces may be dry, damp, frosty, wet and often have a layer of liquid or loose snow particles.

In the context of the JWRFMP field research and ASTM standards development we are exploring the possibilities of extending the concept and methodology of the IFI to an International Runway Friction Index, IRFI.

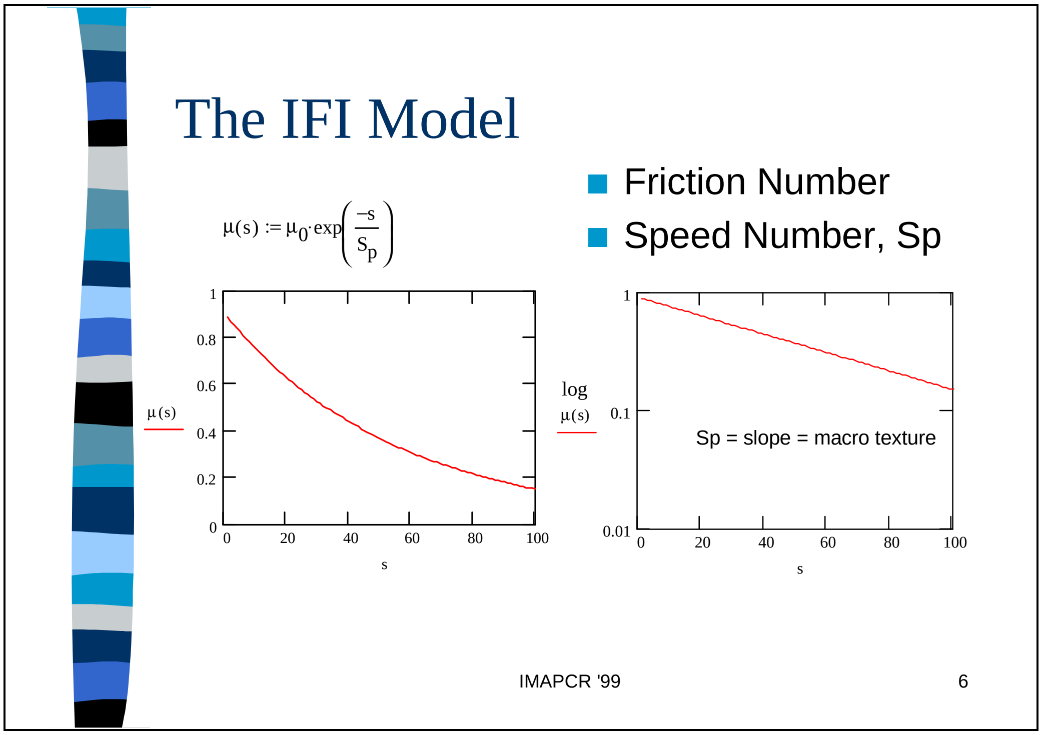


The physical modelling that will be looked at is a family of curves running parallel to the speed axis of the general type of friction vs. speed and slip ratio plot shown.

For ground friction devices the curves would typically run around 15% slip. For braking vehicles like aircraft the curves may typically run on the rising part of the μ-slip curves depending on how hard the braking is.



The physical model has to include non-linear relationships as shown by the fall in friction with increasing speed on this plot.



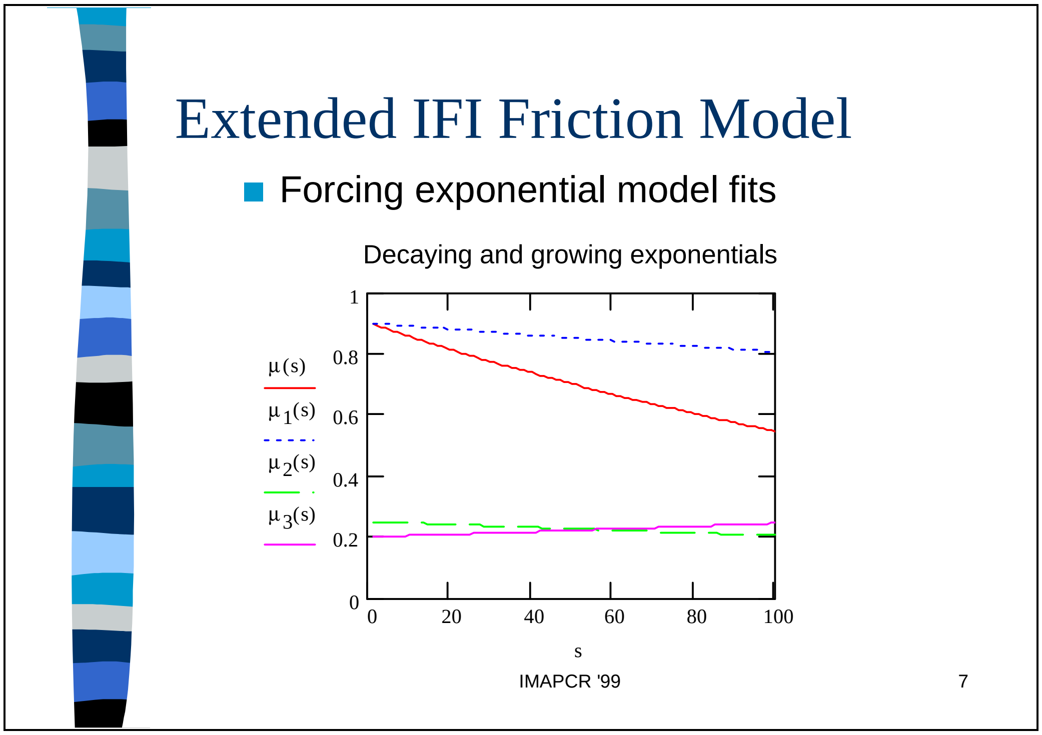
The IFI rests on a physical model, a decaying exponential function of friction with slip speed as independent variable and a texture measure of the surface as a parameter. The slip speed is the difference between the braked rotation speed of the wheel and the free rolling speed of the wheel. Friction devices typically measure with a fixed ratio of reduced rotation of the braked measuring wheel relative to free rolling. Hence, slip speed at the time of measurement can be calculated as the measuring speed times a fixed slip ratio.

The measure is of so-called macro texture that has been proven to correlate well with the slope of the model when it is put on a log normal form.

So when a pavement surface is wet we have a means of estimating how much the friction will be reduced with increasing slip speed.

Texture is not a feasible parameter for winter surfaces. There are no known means to measure texture on winter surfaces.

Rather than getting assistance from a texture measure, an alternative method is to measure at several speeds and derive the slope from friction-speed data.



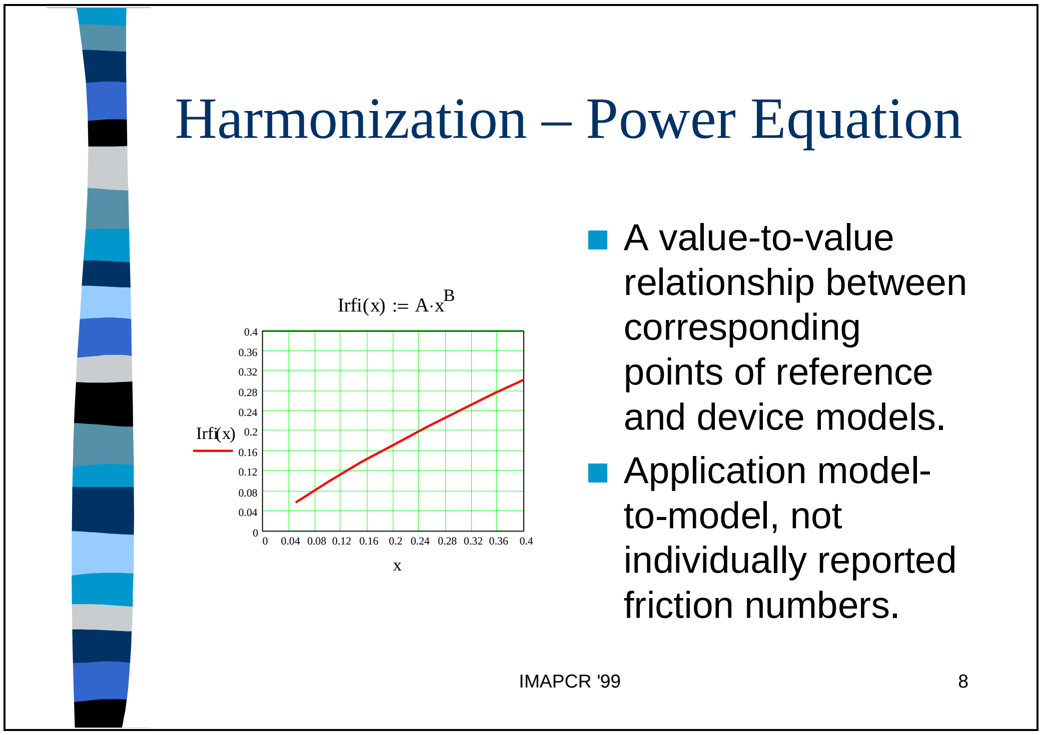
The extended IFI friction model would therefore still use exponential models, but one has to allow for flat horizontal lines or even growing exponentials to cover other surface types and conditions.

Dry pavement exhibits little change of braking slip friction with increasing speed. So do most ice and compacted snow surfaces, but at a fraction of the friction level of most dry pavement cases.

The speed dependencies exhibited on bare compacted snow and bare ice surfaces as observed by field tests in the JWRFMP differ between different friction measuring devices.

The presence of a loose snow particle layer or liquid adds speed effects into the reported friction measure, but they are believed to represent displacement drag forces and compacting forces together with a reduction of slip friction contact area due to planing. These speed effects represent errors introduced in the reported braking slip friction values.

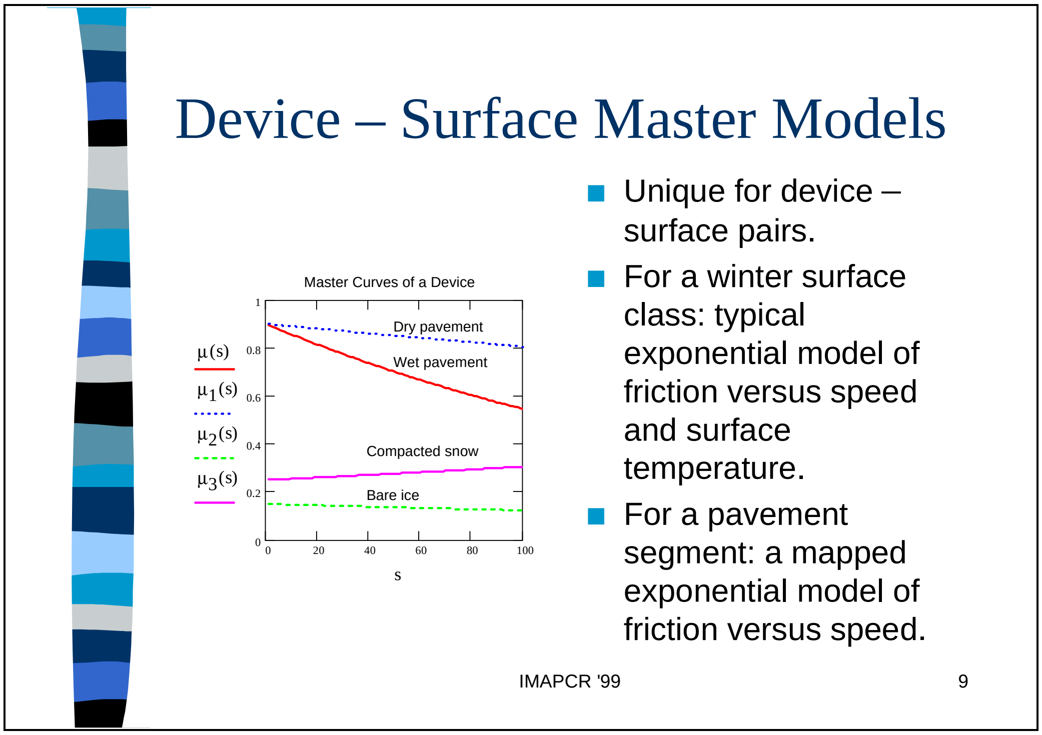
At the higher speeds there may be macro textural effects from rough ice in cold weather that produces hysteresis slip friction, which is related to speed.



The strong interest in a general exponential physical model is motivated by engineering convenience. A universal model is fine, but as it turns out, the ease of harmonization is also a significant pro. If we are to harmonize a physical exponential model with another, the relationship between the two models is a power equation.

A value in one model corresponds to a unique value in the other model. In order to perform a harmonization we need to use fitted models of measured data.

This sounds theoretically promising, but can we obtain and use models in real-life operational measurement situations?



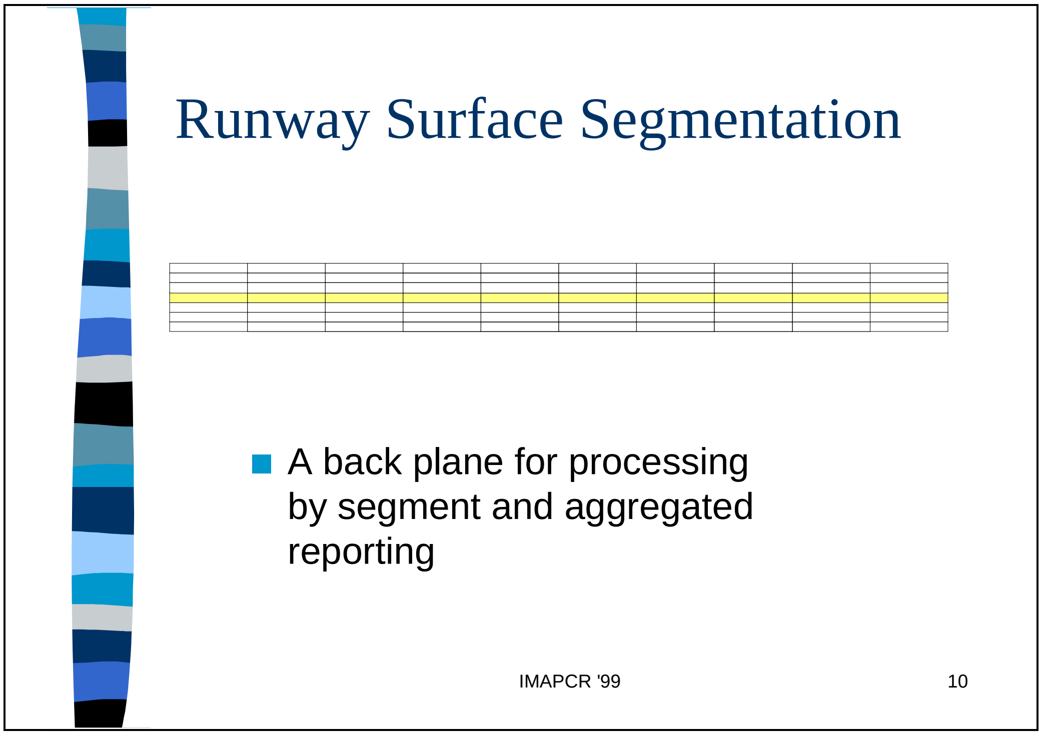
If a ground friction measuring device measures smooth ice with the same material temperature and the same environmental conditions at different locations, can we expect the reported results to be almost the same?

Our gut feeling is yes. Unlike pavements that can be made of many different mixtures of stone material and cement or other binder, ice is the same material, frozen water. If ice and snow have lesser material strength than the measuring tire, the friction measure is mainly a measure of surface material strength.

We can fit exponential models for a device working with bare ice and bare compacted snow that are typical for those surfaces, maybe with the inclusion of environmental variables such as surface temperature or humidity.

The JWRFMP database has data for different surface classes and a fitted exponential model for all the data of a surface class may represent what a device typically measures. The typical models can be called Master Models for the device on a base surface class. Speed, surface temperature and humidity can be the variables.

For the transient winter surface materials like ice and snow we may have a basis to catalogue master models founded on surface material mechanical strength. For pavements the approach can be previous friction history. Since pavements change less over time than the winter materials, previous recorded friction characteristics may adequately represent the actual characteristics. That links any pavement model to a particular piece of a runway.



When a runway geometry is segmented it becomes a convenient back plane for harmonization processing. Each segment may represent different surface classes that have different physical models that are used for harmonization.

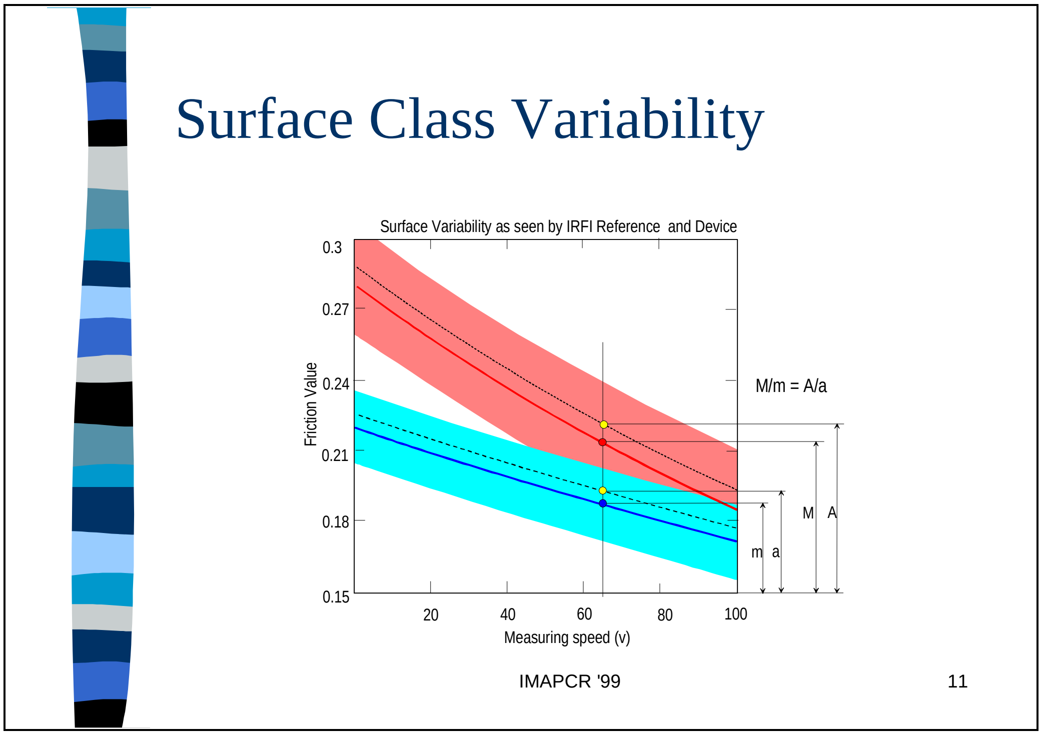
A segmentation is a moderate complexity easily handled by digital computers, even the smallest and most inexpensive.

The harmonization process would go hand-in-hand with runway condition reporting.

The previous friction history of segments may be recorded, kept available and called in to facilitate the processing segment-by-segment before reports are produced on aggregated levels like thirds or full length of a runway. Exceptions like the segments with lowest friction would be available.

It may be that an IRFI runway map as part of a runway condition report is a good base for enhanced integrated reporting.

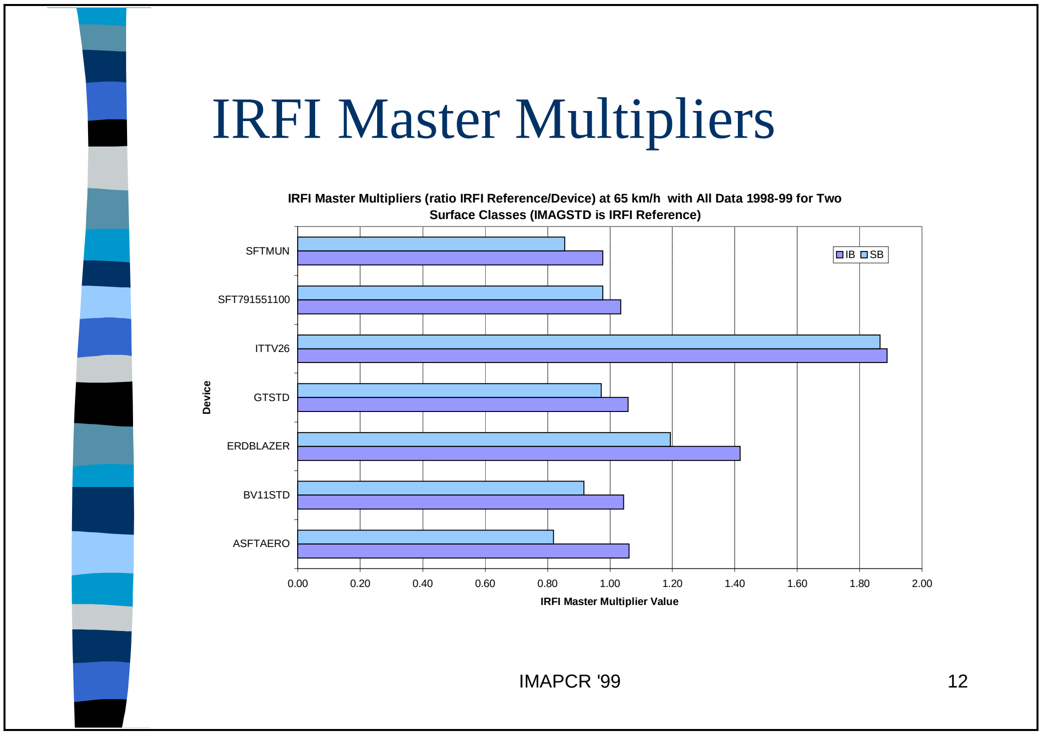
Equipped with exponential models, device-surface master models, previous runway pavement friction records, runway segmentation and runway condition reporting, we have the principal tools required to create a working methodology.



Models are general and we need techniques to make them applicable to actual situations. In this illustration we picture the allowable variance as colored bands for two models within a surface class for a non-harmonized device and a reference device. The master models are represented by the thick colored lines in the centre of the bands. The reference device band is red. The device band is blue.

Having assessed which surface class is measured we can calculate the master friction values, the typical expected value for the device on this surface class at the actual measuring speed. The master values are shown as red dots and have values m and M. The actual value measured by the device, which may be an average for a runway segment, is shown as a yellow dot in the blue band. The higher value is a. We assume that the reference also would have measured a higher value A, if it had been running on the surface at the same time. The ratio of the reference master friction value to the device master friction value is assumed to be constant for small surface class variances. This ratio is a key element and deserves its own name for easy reference. A suggested name is IRFI Master Multiplier (IMM).

Having the IMM determined at the measuring speed (65 km/h shown) we can either calculate or select the actual set of models for use in harmonization, knowing how much the actual friction value differs from the master value.

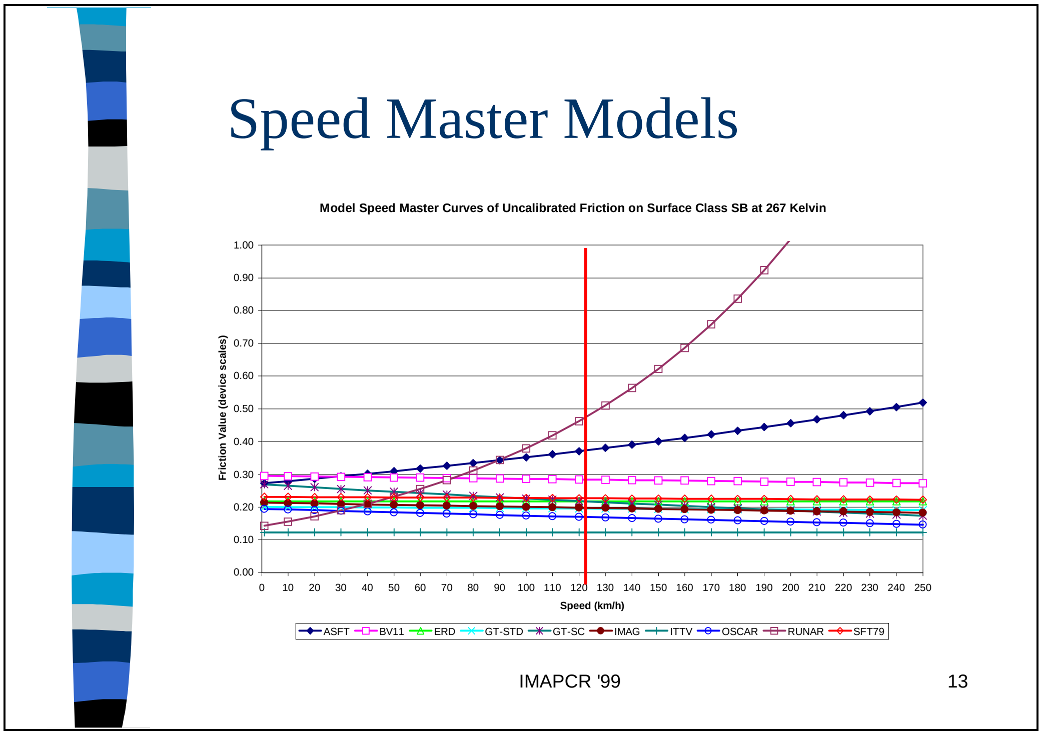


A derivation of IRFI Master Multipliers from the JWRFMP database is shown here for bare ice and bare compacted snow.

From this bar chart we see that different devices measure friction using different proprietary scales of friction. For instance, the friction measures of the NASA instrumented truck equipped with an 26 inch aircraft tire, coded as ITTV26, must be multiplied by 1.9 to report the same as the IMAG. The ITTV has practically the same IMM for ice and snow, whereas other devices have different values for the different surface classes.

These are indications that higher precision in predicted friction values is possible when differentiating between surface classes.

For all devices shown the IMM is smaller for snow than for ice.

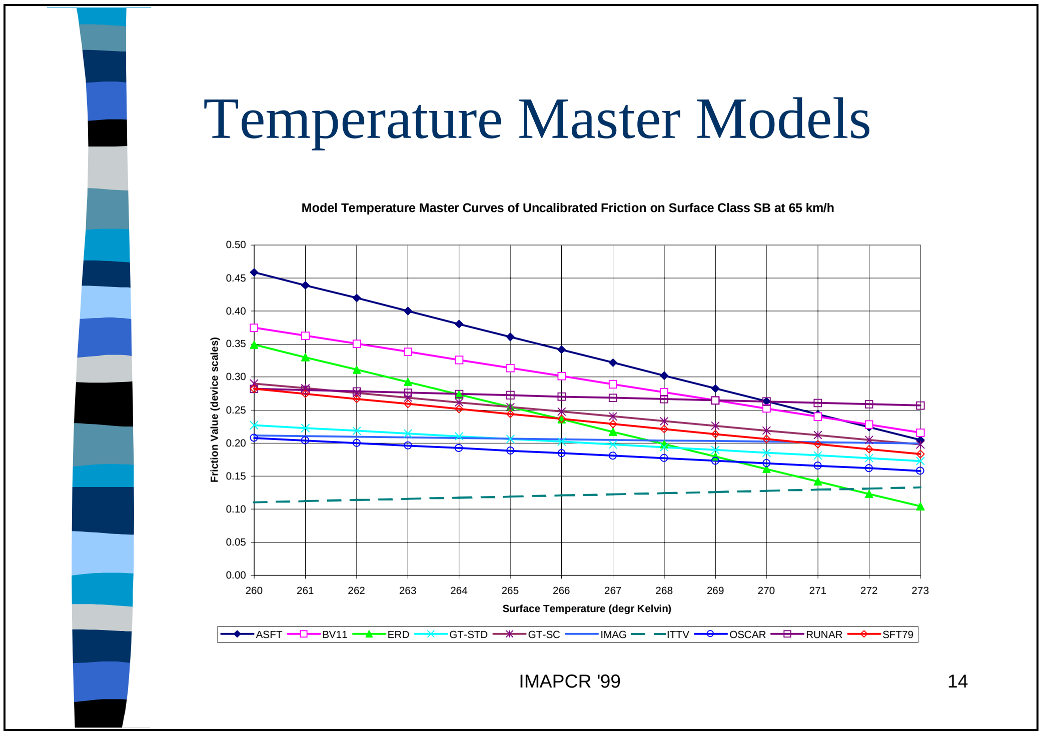


This is a sample of fitted exponentials encompassing all data points of the ground friction measuring devices from the 1998 test season taken on bare compacted snow. The model curves are generated for a surface temperature of minus 6 degrees Celsius or 267 Kelvin.

The majority of the devices exhibit the flat curves to be expected, but two devices indicate a stronger speed dependence. The speed scale of this plot is extended way beyond the measuring speed range of the devices. The maximum measuring speed is indicated by the red line.

The purpose of this extension was to point to the need for a speed independent harmonization scheme, as one cannot rule out speed dependencies, and if one wishes to compare aircraft with a ground friction tester the comparison may yield different results for a high and a low speed.

One benefit of harmonizing on the basis of exponential models is that speed is not part of the harmonization equation. It implies that an extension into the higher speed ranges for comparing aircraft and friction testers is built into the harmonization model.

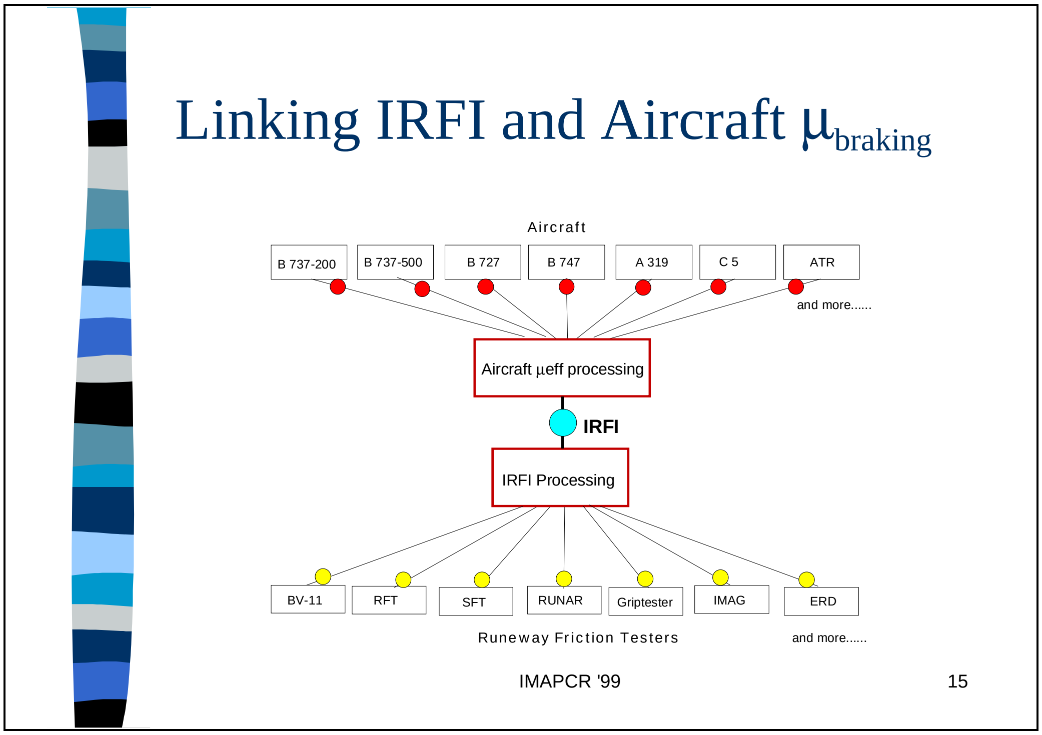


This plot is a sample of fitted exponential models with a temperature gain factor on the 1998 data of bare compacted snow. The data is generated for a measuring speed of 65 km/h.

The temperature dependency varies with friction tester type.

The significance of a Temperature Master Model is that friction of a device on snow can be predicted from surface temperature measurements. Of course the quality of that prediction depends on the device having a distinct temperature dependency. Some devices seem to exhibit that property and therefore lend themselves to this technique more than others.

We note that the IMAG device exhibits no temperature dependency, which may be a good feature for a reference device.



Our first mission has been to achieve an IRFI. All the yellow dots representing proprietary reported friction values can be transformed to an IRFI.

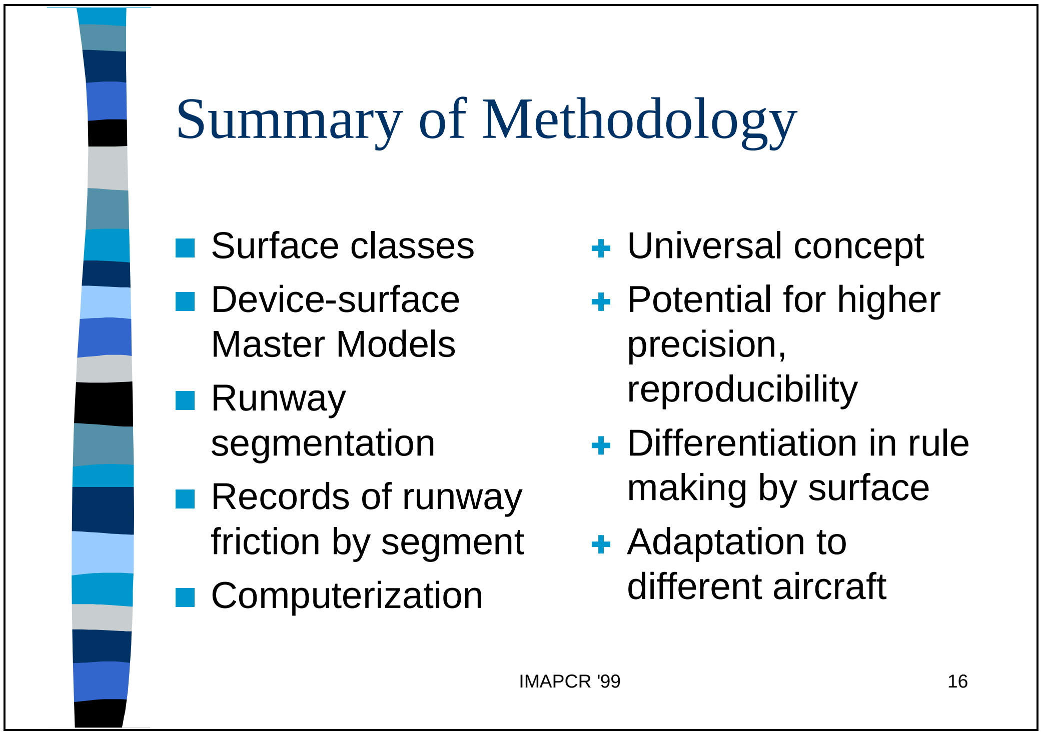
Just as friction devices differ in performance, wheel-braking slip friction for aircraft also differs. To go from IRFI to a predicted effective wheel-braking friction value the same methodology can be applied. The adaptation to each aircraft type then requires master models for each type. With the same harmonization between exponential models we solve for the unknown x in the relationship

$$\mathrm{IRFI} = A \cdot x^{B}$$

where A and B now are the harmonization constants for the aircraft type to IRFI.

Surface variability would be treated in the same manner as for ground friction devices.

This methodology would bring about quantitative information to replace the qualitative indices (like good, medium, poor, etc.) that are used by many today.



In summary, the methodology comprises a number of fixed surface classes, a library of master models for each friction measuring device or aircraft type, an accounting of runway pavement friction by segment, and computer programs to process IRFI by segment for reporting at aggregated runway distances.

The gains are a universal concept and a potential for higher precision and reproducibility.

Identifying friction characteristics by surface classes facilitates more flexible and comprehensive rule making.

Prediction of aircraft wheel-braking can be quantified and adapted to different types of aircraft.

IRFI Reference Device

J.-Cl. Deffieux
Service technique des bases aériennes
Bonneuil-sur-Marne, France

Joint Winter Runway Friction Measurement Program

IRFI Reference Device

DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

Objectives

- *Data base improvement*
- *Completion of devices harmonization*
- *IRFI validation*

DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

NEED for IRFI development and approbation

Acquisition and analysis of new data:

- **under surface conditions as defined in IRFI concepts**
- **with all the devices used previously**
- ***with a reference device***

DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

Reference Friction Device

The choice:
- **Among devices used on the JWRFMP**
- **Base on statistical correlations results**
- **Proper technical requirements**

DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

Reference Friction Device

Technical requirements

- **Mode of measurement**
- **Mode of braking**
- **Stability – vibrations**
- **Test tire**
- **Calibration maintenance**
- **Acceptable error measurements**
- **Results measurements presentation**

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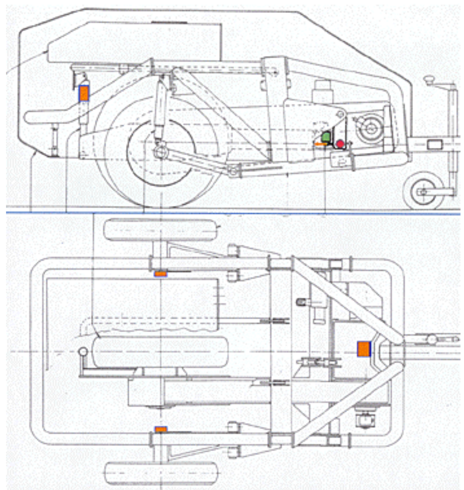
STBA Reference Device

DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

Reference Device – Description



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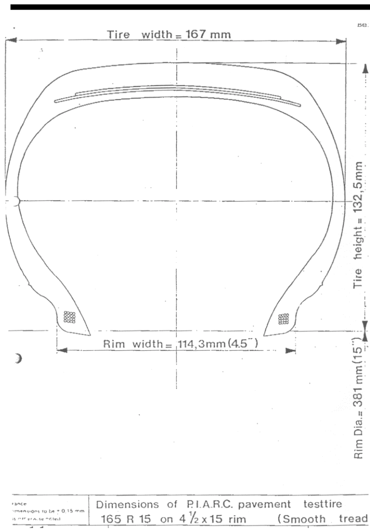
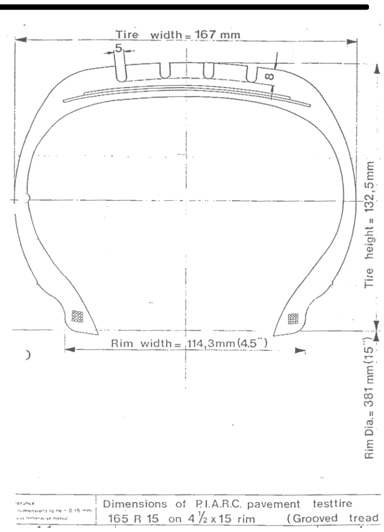
Reference Device – Tires





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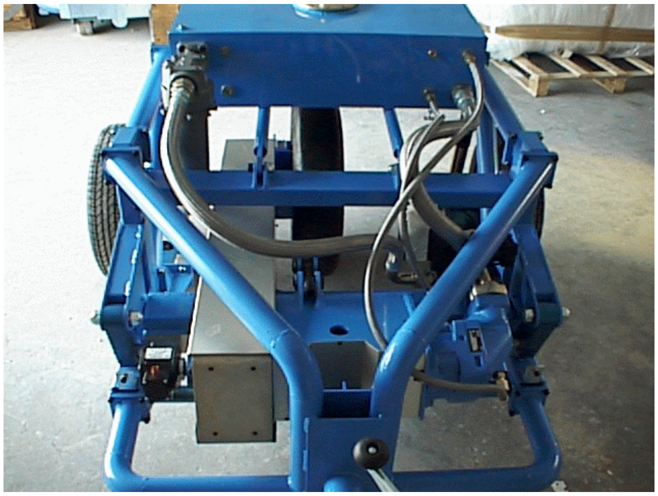
Reference Device – Description



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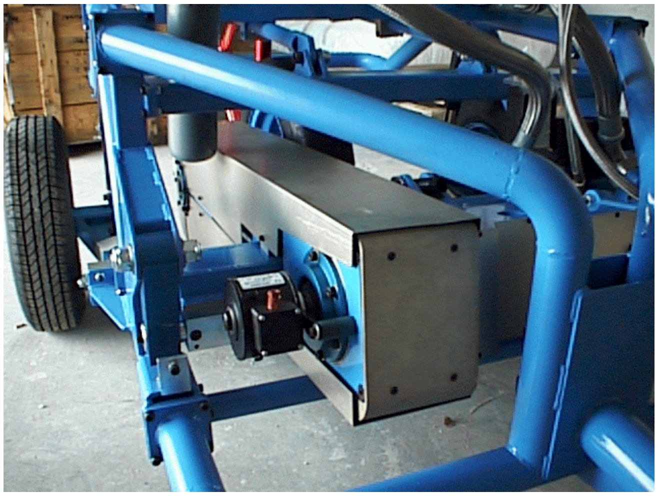
Reference Device – Description



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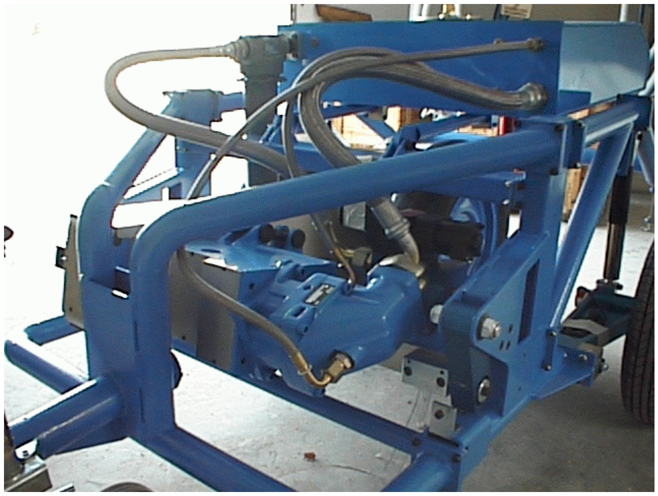

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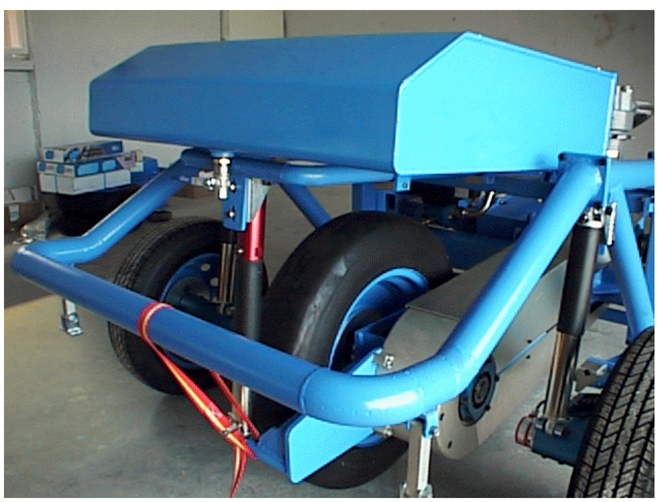
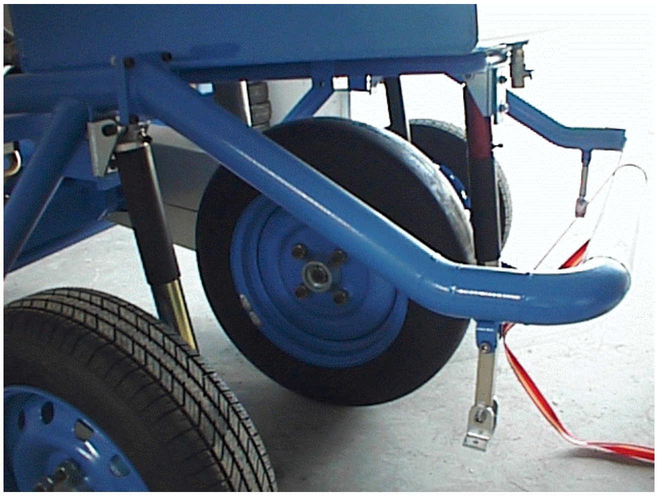
Reference Device – Description



DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

Reference Device – Description



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JWRFMP Tests at GWINN

DGAC-FRANCE - Service Technique des Bases Aériennes J.Cl.DEFFIEUX

JWRFMP Tests at WALLOPS

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Measurements

- **Operational flexibility**
- **Immediate set-up**
- **Automatic process**
- **Real-time visualisation measurements**
- **Instant results**

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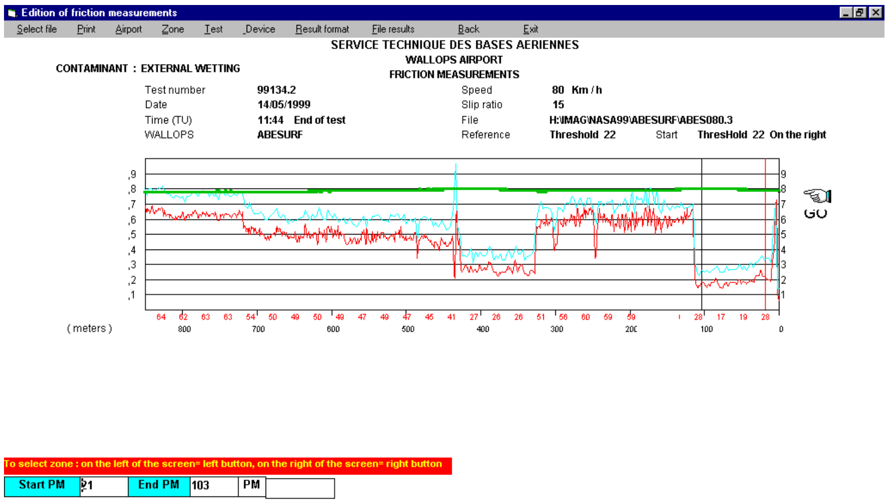
Measurements



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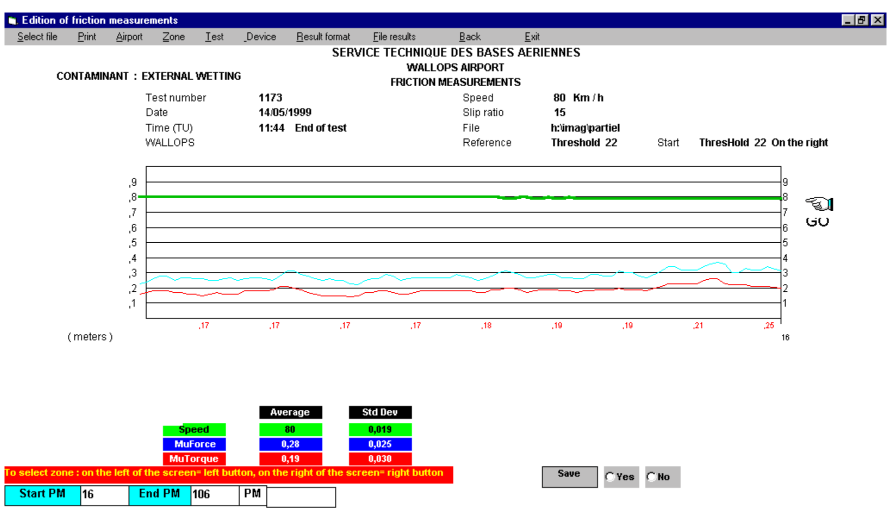
Measurements



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Thank you for your attention!

Next IRFI Reference Device will be ...

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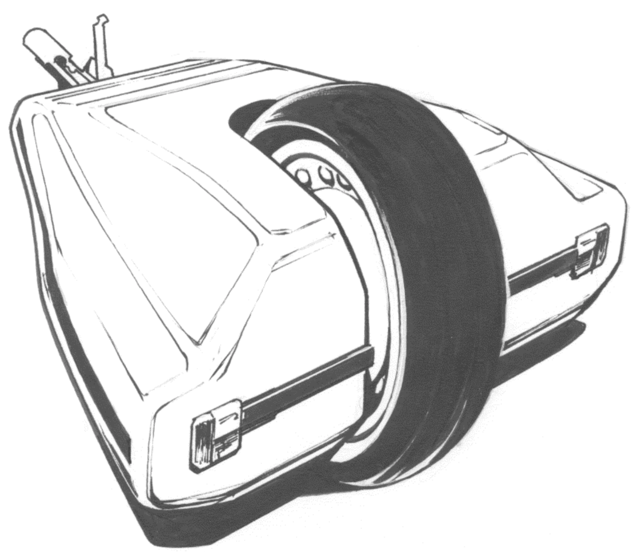

DEF 99

Joint Winter Runway Friction Test Program Database

George Comfort
Fleet Technology, Cold Regions Technology Centre
Kanata, Ontario

Joint Winter Runway Friction Test Program Database

1999
IMAPCR
Montreal

- **Objective:**
  - ❊to store and organize: the ground vehicle data
    reduced aircraft data
    the environmental data
  - ❊to contain search routines and to write the search results to external files
- **Acknowledgements:**
  - ❊Transport Canada (Aerodrome Safety)
  - ❊Transport Canada (Transportation Development Centre)
  - ❊National Research Council Canada

FLEET TECHNOLOGY LTD

Joint Winter Runway Friction Test Program Database

1999
IMAPCR
Montreal

- **Software: Access 97**
- **Current Size: 12 MB**
- **Operating System: Windows 95/98/NT**

- **Minimum Hardware:**
  - ❊Memory: 32 MB (Windows 95)
    64 MB (Windows NT)
  - ❊CPU: Pentium 150 MHz (Windows 95)
    Pentium II 200 MHz (Windows NT)
  - ❊Free Hard Drive Space: 100 MB

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Joint Winter Runway Friction Test Program Database: Contents

1999
IMAPCR

Montreal

- Ground Vehicle Data:
  - ❊North Bay Tests – 1996; 1997; 1998; 1999
  - ❊Norway Tests – 1998; 1999
  - ❊Sawyer Field Tests – 1999
- Aircraft Data:
  - ❊Falcon 20 – in database
  - ❊727 – to come
  - ❊737 – to come
  - ❊757 – to come
  - ❊Dash 8 – to come

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Joint Winter Runway Friction Test Program Database: Aircraft Data Format

1999
IMAPCR

Montreal

- Manoeuvre: Taxi
  Accelerate-Stop
  Landing
- Configuration: Continued Take-Off
  Accelerate-Stop
  Landing
- Braking: None
  Maximum

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Joint Winter Runway Friction Test Program Database: Configurations for Falcon 20

1999
IMAPCR

Montreal

- **Continued Take-Off:** Flaps: 15° Airbrake: In
- **Accelerate – Stop:** Flaps: 15° Airbrake: Out
- **Landing:** Flaps: 40° Airbrake: Out

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Joint Winter Runway Friction Test Program Database: Aircraft Data Search

1999
IMAPCR

Montreal

- **Data Source: Test Year and Site;**
  Test Number or Date
- **Aircraft Parameters:**
  - ❊Type of Aircraft
  - ❊ Manoeuvre; Configuration; Braking Action
- **Speed Range**
- **Surface Condition:**
  - ❊Base Type (5 Cases); Surface Condition (10 Cases)
  - ❊Maintenance Action (4 Cases); Depth of Contaminant

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Joint Winter Runway Friction Test Program Database: Aircraft Data Search Output

1999
IMAPCR

Montreal

- 3 Files: Aircraft Data
  Associated Ground Vehicle Data
  Associated Environmental Data
- Aircraft Data File:
  - ❊"Header": Date; Test No. & Loc'n.; Surface Descr.; Aircraft Type
  - ❊Test Information :
    - – Manoeuvre; Configuration
    - – Braking Action; Speed – Range & Mean
    - – Mean Contaminant Drag/Weight
    - – Mean Braking Coefficient

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Joint Winter Runway Friction Test Program Database: Aircraft Data Search Output

1999
IMAPCR

Montreal

- Associated Environmental Data Output File
  - ❊"Header": Date; Test No. & Loc'n.; Surface Descr.; Aircraft Type
  - ❊Air Temperature & Time of Measurement
  - ❊Surface Temperature & Time of Measurement
  - ❊Snow Density & Time of Measurement
  - ❊Snow Thickness

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Joint Winter Runway Friction Test Program Database: Ground Vehicle Data Search Routines

1999
IMAPCR

Montreal

- By Wizard
- By Test Number or Test Date

- <u>Search Routine</u>:
  - ❉1. By Test Location and Date
  - ❉2. By Test Type (Correlation vs Special Study)
  - ❉3. By Surface Condition
  - ❉4. By Test Vehicle
  - ❉5. By Test Speed
  - ❉6. By Time Interval

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Joint Winter Runway Friction Test Program Database: Ground Vehicle Data Contents

1999
IMAPCR

Montreal

- "Header" Information: Date and Time; Test No.; Location; Track Length
- Environmental Data: Surface Description; Air & Surface Temperatures
- Friction Data: Time of Measurement
  Speed
  Friction Factor
  Vehicle Configuration (inflation pressure; slip ratio & fixed vs variable slip?; tire type & tread; vertical load)

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Joint Winter Runway Friction Test Program Database: Ground Vehicle Data Output Options

1999
IMAPCR

Montreal

- "Header" – Standard
- Friction – Average for whole track
  Average for each 100 m section
  Average for all runs made at same target speed for that test
- Tire/Vehicle Configuration – 4 selections
- Statistical – Standard Deviation
- Surface Description – 6 selections

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Joint Winter Runway Friction Test Program Database: Status

1999
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Montreal

- Database Has Been Produced and Tested
- <u>Inputs</u>:
  - ❉Ground Vehicle Data
    - – 99% Complete
    - – Missing Some Environmental Data
  - ❉Aircraft Data
    - – Only Falcon 20 Data Included Now

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Surface Friction and Index Development

Thomas Torsten-Meyer
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The subject of winter services is one of my favorite topics. In my view it is one of the last really major safety problems in aviation.

As everyone has known for some time, up to 75 percent of air accidents occur at airports or in their direct vicinity. A large share of these accidents are, if Boeing studies are correct, caused by wintry conditions on areas of operation.

ACI-Europe and Munich Airport want to help in reducing the annual accident rate, which has been almost constant for around 20 years. You can therefore understand our great interest in improving winter services in Europe and, in particular, at Munich Airport. For that reason, I would like to express my thanks that this subject has been accorded a high level of importance after such a long time.

The JWRFMP was essential, especially since our airport colleagues in Canada and the USA have had this subject at the top of their list of priorities for the past 4 years. As regards Europe, the CAA in Norway is particularly familiar with the subject of friction.

I believe that the introduction of a globally standardized International Runway Friction Index and Aircraft Friction Index is of outstanding importance. It will give aircraft pilots and airport operators an important tool. Air traffic safety, particularly at the take-off and landing phases, can be decisively improved.

The pilot has to know what the people on the ground are doing on manoeuvring areas affected by snow and ice. Pilots must be given every assistance by ground services to complete their flight safely. The communicated condition data, our beloved braking coefficients, must be understood and above all believed. And I dare not mention the wide range of ground measurement technologies and interpretations by aircraft pilots. Sometimes it seems to me that we want to “square the circle”, so problematical is the entire subject.

The days of the American “lunchbox-tests” belong to the past. The magic word “unreliable” that is frequently used in Europe should also only be allowed in SNOWTAMS for surface conditions that really cannot be measured.

What has already been achieved? In the course of a five-year program, financed by Transport Canada, NASA, the FAA, and Norway’s CAA, measurement results between a wide range of ground measurement technologies have been compared. These measurements were conducted at airports in Canada, the USA, and Norway. Unfortunately, only insufficient braking actions for some aircraft have been determined up to now. As a result, comparisons between the ground and aircraft measurements have been very unsatisfactory – but these problems must now be tackled urgently. Considerable differences also remain in determination and communication of values between countries with intensive winter service activities.

Two weeks ago, a conference on the friction problem was held at Munich Airport parallel to an Operational Safety Subcommittee meeting. Representatives from organizations, companies, and authorities – TC, FAA, NASA, Airbus Industrie, Boeing, DLH, Condor, the Ministry of Transport, and ATC – were invited.

It was decided that with the aid of aircraft, we could conduct friction comparisons and calculations between the ground vehicles and aircraft on a runway at Munich in the winter months 1999-2000. I hope everything goes well, and the weather plays along. Condor has promised that they will provide the required equipment and the friction data from the black box.

I hear that the European Commission has already made a first contact between FAA and the EU research department. EU is interested in close transatlantic aeronautical safety cooperation and sponsoring. So I think that this could lead to a new start for the important development of the IRFI.

Winter Service Activities and Review

The problems of the future will be in the field of environmental protection. Here I am thinking in particular of the problematic aircraft de-icing agent, glycol. For some time now, the winter service activities of airports have not been regarded from the aspect of flight operation safety alone. Environmental protection is increasingly being accorded maximum priority. As you all know, official decrees were imposed on the new airport in OSL after its commissioning.

The airport water resources authorities are alarmed. It seems that authorities are aiming to outdo each other with water law stipulations. Considerable differences also exist between the various nations. For example: airport X diverts contaminated fluids into the nearby creek; airport Y takes the contaminated fluids and conducts them to the local sewage plant, constructed with airport money, to recycle the fluids. The distortion of competition between the commercial airports is thus considerable and, in my view, unacceptable.

Of very great interest here are developments in the field of surface de-icing agents. Water law provisions are observed for the most part. Of particular interest are developments in potassium formats. This agent was recently awarded the “blue environmental safety angel” in Germany. Admittedly, I would not drink the brew, but examinations revealed that this agent is particularly environmentally friendly. We should keep a close eye on developments in aircraft de-icing agents. The standard aircraft de-icing agent, glycol, can pollute the environment if it penetrates the soil.

Mr. Helgeson from NCAA will notify ACI-Europe of the latest findings on this subject on 24 November 99. You are all invited to this ACI Winter Service Workshop in Warsaw.

Future of Testing Program

Thomas J. Yager
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FUTURE OF TESTING PROGRAM

By
Thomas J. Yager
NASA Program Manager

At

IMAPCR '99
2nd International Meeting on Aircraft Performance on
Contaminated Runways
2-4 November 1999
Montreal, Quebec, Canada

OUTLINE

- Original objectives/scope
- Future near-term priorities
- Future organization overview
- Future scope
- Future program activities

JOINT WINTER RUNWAY FRICTION MEASUREMENT PROGRAM

PARTICIPANTS: NASA, Transport Canada, FAA, USAF, Joint Aviation Authority, and other aviation organizations

OBJECTIVES/SCOPE:

- Evaluate instrumented aircraft and ground vehicle friction harmonization
- Assess effects of both aircraft and runway anti- and de-icing chemicals
- Configure test run matrices to optimize information useful to pilots, airport operators, equipment manufacturers, and airframe companies
- Implement many of the recommendations from White Paper prepared by Government/Industry Winter Runway Friction Measurement and Reporting Working Group

SCHEDULE: Five (5) years

FUTURE SCOPE

- **Test Aircraft** – Wide body (commercial and military), commuter and military jets
- **Ground Test Vehicles** – Reference and masters
- **Runway Test Conditions** – Slush, solid ice and chemical/grit coatings on contaminant
- **Research and Development**
  - Better tools for airports
  - Improved aircraft brake systems
  - Enhanced ground friction measurements
  - Runway perimeter containment systems
  - “Bare & dry” runways for all aircraft operations

NEAR-TERM PRIORITIES

- More funding and additional partnerships
- Establish International Runway Friction Index (IRFI)
- Complete development/checkout of reference vehicle
- Prepare vehicle calibration procedures document
- Determine relationship of IRFI to aircraft braking performance
- Obtain ICAO's direct involvement in evaluation and implementation of test findings

DIRECTIONS FOR NEW MILLENIUM

- New partnerships including CAA, AIA, ACI, IATA, IFALPA and others
- Expanded test procedures, new test equipment and test sites
- Additional standards prepared to cover reference vehicle design and calibration procedures
- Guidelines provided for additional airline/airport involvement in collecting needed data

FUTURE PLANS

- Conduct NASA B-757 aircraft braking tests at Wallops Flight Facility, VA
- Get International Runway Friction Index (IRFI) standard approved by ASTM E17 Committee
- Conduct wide-body aircraft tests at Munich, Germany (Tentative)
- New Orleans ASTM E17 Committee mtg, Dec 5-8
- Perform additional aircraft/ground vehicle tests at North Bay, Ontario, and Sawyer Airbase, MI
- NASA Tire/Runway Friction Workshop, May 15-19