TP 14002E

Wet Runway Friction: Literature and Information Review

Prepared for
Transportation Development Centre

On behalf of Aerodrome Safety Branch
Transport Canada

August 2001

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 14002E	2. Project No. 5098	3. Recipient's Catalogue No.
4. Title and Subtitle Wet Runway Friction: Literature and Information Review		5. Publication Date August 2001
		6. Performing Organization Document No.
7. Author(s) G. Comfort		8. Transport Canada File No. ZCD2450-B-14
9. Performing Organization Name and Address BMT Fleet Technology Limited 311 Legget Drive Kanata, Ontario K2K 1Z8		10. PWGSC File No. MTB-1-00356
		11. PWGSC or Transport Canada Contract No. T8200-1-1505/001/MTB
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer A. Boccanfuso

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

Co-sponsored by the Aerodrome Safety Branch of Transport Canada

16. Abstract

Aircraft landings and take-offs regularly occur on damp and wet runways. The frictional forces between the aircraft tires and the runway have an important effect on the safety of these operations. Wet runway friction has been studied for many years, and a significant information base has been produced; however, it is fragmented. This work was aimed at reviewing the available information and assessing the current state-of-knowledge and the most critical information gaps. The review was focused on two basic questions:

1) How much water is likely to build up on the runway?
2) What is the resulting friction level experienced by an aircraft operating on the runway?

Item (1) is better understood than item (2), although important gaps still remain regarding water buildup on the runway.

With respect to item (2), the most significant uncertainties are considered to be the relationships among:

(a) the friction factors experienced by an aircraft;
(b) the friction factors measured by ground vehicles; and
(c) basic pavement parameters, such as texture, and water film depth.

These uncertainties make it difficult to evaluate operations outside the range of current experience, and leave detailed testing as the most reliable approach for evaluating them.

17. Key Words Wet runway friction, ground vehicle, pavement parameters, aircraft braking coefficient		18. Distribution Statement Limited number of copies available from the Transportation Development Centre		
19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xx, 92	23. Price Shipping/ Handling

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 14002E	2. N° de l'étude 5098	3. N° de catalogue du destinataire
4. Titre et sous-titre Wet Runway Friction: Literature and Information Review		5. Date de la publication Août 2001
		6. N° de document de l'organisme exécutant
7. Auteur(s) G. Comfort		8. N° de dossier - Transports Canada ZCD2450-B-14
9. Nom et adresse de l'organisme exécutant BMT Fleet Technology Limited 311 Legget Drive Kanata, Ontario K2K 1Z8		10. N° de dossier - TPSGC MTB-0-00356
		11. N° de contrat - TPSGC ou Transports Canada T8200-1-1505/001/MTB
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final
		14. Agent de projet A. Boccanfuso

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

Coparrainé par la Direction de la sécurité des aérodromes de Transports Canada

16. Résumé

Il arrive régulièrement aux avions de décoller et d'atterrir sur des pistes humides et mouillées. La force de frottement entre les pneus de l'avion et la piste influence de façon importante la sûreté de ces opérations. De nombreuses années de recherche sur le frottement sur piste mouillée ont permis la collecte d'une imposante base de données sur le sujet. Mais ces données sont éparses. Le but des présents travaux était de passer en revue cette information afin d'évaluer l'état actuel des connaissances et d'en cerner les lacunes les plus graves. La revue portait sur deux questions fondamentales :

1) Combien d'eau peut s'accumuler sur la piste?
2) Quel effet la présence d'eau sur la piste a-t-elle sur le coefficient de frottement réel pneu-chaussée?

La première question est mieux comprise que la deuxième, bien qu'il subsiste des interrogations importantes concernant l'accumulation d'eau sur la piste.

En ce qui a trait à la deuxième question, on considère que la lacune la plus urgente à combler est l'établissement de liens entre les variables suivantes :

(a) les coefficients de frottement mis en évidence en situation réelle;
(b) les coefficients de frottement mesurés par des véhicules au sol;
(c) les paramètres du revêtement, comme la rugosité et l'épaisseur de la pellicule d'eau.

Faute de connaître ces liens, il est difficile d'évaluer les opérations aéroportuaires (décollages et atterrissages) autrement que par l'expérience. La conduite d'essais exhaustifs demeure donc la façon plus fiable de procéder à cette évaluation.

17. Mots clés Frottement sur piste mouillée, véhicule au sol, paramètres du revêtement, coefficient de freinage d'un avion		18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.		
19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages xx, 92	23. Prix Port et manutention

ACKNOWLEDGEMENTS

The project was monitored by Dominic Morra, of the Aerodrome Safety Branch of Transport Canada. He is thanked for his suggestions that were made throughout the project.

EXECUTIVE SUMMARY

Introduction - Aircraft landings and take-offs regularly occur on damp and wet runways. The frictional forces developed between the aircraft tires and the runway have an important effect on the safety of these operations. Wet runway friction has been studied for many years with the result that a significant information base has been built up. However, it is fragmented. This work was aimed at reviewing the available information, and assessing the current state-of-knowledge and the most critical information gaps. In its simplest terms, the issue of wet runway friction, and its effect on aircraft operations, can be formulated by the following two basic questions, which were both considered in this project:

1) How much water is likely to build up on the runway?
2) What is the resulting friction level experienced by an aircraft operating on the runway?

In practice, of course, the problem is more complex as it is affected by many factors, as follows.

Water Buildup on the Runway - Of the two major questions posed above, the current state-of-knowledge is considered to be further advanced regarding the issue of water buildup on the runway. The current state-of-knowledge is summarized below.

(a) Environmental mechanisms causing water buildup – Although moisture can be produced on the runway by a variety of mechanisms (e.g., rain, fog, dew, frost), only rain has been studied to any significant extent. Most likely, the other environmental conditions would only cause damp runway conditions as opposed to wet or flooded ones.
(b) Amount of water built up during steady-state rainfall conditions – This has been studied extensively and several predictor equations have been developed. Although information gaps still exist, this subject area is relatively well understood.
(c) Transient effects, such as winds, variations in rainfall rates during a rain storm, or time lags for water runoff – These are not well understood although the current state-of-knowledge is sufficient to allow preliminary assessments.
(d) Pavement recovery from a wet or damp surface, to a dry condition – Some information is available from studies done on highways in the United States. No information was found relating to airport runways in Canada.

There are important information gaps for each of the above issues, with the result that:

(a) the current state-of-knowledge is useful for general studies and evaluations;
(b) it is inadequate to predict or evaluate water buildup on the runway in a real-time, operational mode; and
(c) regular monitoring of friction levels is required for real-time assessments in an operational mode.

Wet Runway Friction and Its Effect on Aircraft Operations - This topic encompasses two important issues as follows:

(a) the friction level of a damp, wet, or flooded runway, and the factors controlling it, such as (i) measurement technique (e.g., slip ratio, speed, tire pressure and type); (ii) hydroplaning; (iii) water film depth; (iv) pavement texture, and the presence of contaminants; and (v) long-term and short term variations in friction level.
(b) the relationships between the friction factors experienced by an aircraft; those recorded on aircraft tires tested under laboratory conditions (which did not include simulation of the aircraft's braking system); and those recorded by ground vehicles used to measure friction at airports.

A relatively large database of information is available which provides an understanding of the basic processes and trends. However, the state-of-knowledge is primarily empirical. The current state-of-knowledge is summarized below, in relation to the key issues.

(a) Friction level variations with time – Friction levels vary on long-term time scales (of months to years) and also in the short term in response to pavement rejuvenation actions, the buildup of contaminants, and rains which wash the contaminants off. The short-term variations are larger than the long-term ones.
(b) Factors controlling wet runway friction levels – The important factors include (i) speed; (ii) slip ratio; (iii) whether hydroplaning occurs; (iv) water film depth; (v) pavement texture; (vi) tire pressure; and (vi) the presence of contaminants.
(c) Hydroplaning – Hydroplaning has been studied extensively, and the general conditions causing hydroplaning have been identified. However, only general quantitative criteria are available to define the onset of hydroplaning. Predictor equations have been developed by NASA which have been generally corroborated with field data for aircraft and large trucks. Recent observations have brought into question whether the NASA equations can be extended to friction-measuring ground vehicles.
(d) Overall evaluation methods – Only a small number of approaches are available for undertaking an overall evaluation, such as relating the friction level experienced by an aircraft to either ground vehicle measurements or to basic pavement data, such as texture. They all suffer from a number of serious drawbacks. No universal, widely accepted, proven method is available for doing evaluations of this type.

The most significant limitation in the current information base is considered to be the relationships among (a) the friction factors experienced by an aircraft; (b) the friction factors measured by ground vehicles; and (c) basic pavement parameters, such as texture, and water film depth. This gap makes it difficult to evaluate operations outside the range of current experience, and leaves detailed testing as the most reliable approach for evaluating them.

Recommendations - Efforts should be focussed on developing an overall understanding among (a) the friction factors experienced by an aircraft; (b) the friction factors measured by ground vehicles; and (c) basic pavement parameters such as water film depth and pavement texture.

Because the state-of-knowledge regarding wet runway friction is primarily empirical, it is our opinion that the most reasonable method for evaluating it for operational conditions is on a case-by-case basis, with site-specific, and case-specific, measurements and monitoring.

SOMMAIRE

Introduction - Il arrive régulièrement aux avions de décoller et d'atterrir sur des pistes humides et mouillées. La force de frottement entre les pneus de l'avion et la piste influence de façon importante la sûreté de ces opérations. De nombreuses années de recherche sur le frottement sur piste mouillée ont permis la constitution d'une imposante base de données sur le sujet. Mais ces données sont éparses. Le but des présents travaux était de passer en revue cette information afin d'évaluer l'état actuel des connaissances et d'en cerner les lacunes les plus graves. Pour aller au plus simple, on peut ramener le frottement sur piste mouillée et ses effets sur le décollage et l'atterrissage d'un avion à deux questions fondamentales, qui ont guidé les présents travaux :

1) Combien d'eau peut s'accumuler sur la piste?
2) Quel effet la présence d'eau sur la piste a-t-elle sur le coefficient de frottement réel pneus-chaussée?

Bien sûr, dans la pratique, les choses ne sont pas si simples. Car de nombreux facteurs sont en cause, comme on le verra.

Accumulation d'eau sur la piste - Des deux grandes questions posées ci-dessus, c'est celle de l'accumulation d'eau sur la piste qui a été le plus étudiée. Voici où en est l'état des connaissances sur cette question :

(a) Mécanismes environnementaux à l'origine de l'accumulation d'eau – Divers mécanismes environnementaux peuvent entraîner la présence d'eau sur la piste (p. ex., pluie, brouillard, rosée, givre), mais seule la pluie a été étudiée dans une mesure appréciable. Il est raisonnable de penser que les autres phénomènes ne feront qu'humidifier la piste, sans la mouiller ni l'inonder.
(b) Importance de l'accumulation d'eau pendant une pluie persistante – Ce sujet a été amplement étudié et plusieurs équations de prédiction ont été élaborées. Il existe encore des trous dans les données, mais la question est relativement bien comprise.
(c) Effets intermittents causés par les vents, la variation de l'intensité de la pluie durant un orage, le temps de drainage de l'eau – Ces effets ne sont pas très bien compris, même si l'état actuel des connaissances permettrait des évaluations préliminaires.
(d) Transition entre une chaussée humide ou mouillée et une chaussée sèche – On dispose de certaines données sur cette question, grâce à des études sur les routes effectuées aux États-Unis. Aucune recherche analogue se rapportant aux pistes d'aéroports ne semble avoir a été menée au Canada.

Il existe donc des lacunes importantes dans l'information touchant chacun des sujets ci-dessus. Il s'ensuit que :

(a) l'état actuel des connaissances permet des études et des évaluations générales;
(b) les données disponibles ne permettent pas de prévoir ou d'évaluer l'accumulation d'eau sur la piste en temps réel et en situation opérationnelle;
(c) des mesures régulières des coefficients de frottement sont nécessaires pour des évaluations en temps réel et en situation opérationnelle.

Le frottement sur piste mouillée et ses effets sur le décollage et l'atterrissage - Ce sujet englobe deux grands thèmes :

a. le coefficient de frottement sur une piste humide, mouillée ou inondée, et les facteurs qui influent sur celui-ci, comme (i) la technique de mesure (p. ex., taux de glissement, vitesse de l'avion, pression des pneus et type de pneus); (ii) aquaplanage; (iii) épaisseur de la pellicule d'eau; (iv) rugosité du revêtement et présence de contaminants; (v) variations à long terme et à court terme du coefficient de frottement;
b. les liens entre : les coefficients de frottement mis en évidence en situation réelle; les coefficients de frottement enregistrés au cours d'essais en laboratoire de pneus d'avion (sans simulation du système de freinage de l'avion); et les coefficients de frottement mesurés par les véhicules au sol utilisés par les aéroports.

Il existe une base de données assez bien fournie, qui permet de comprendre les grandes tendances. Mais ces données sont surtout empiriques. Voici un résumé de l'état des connaissances sur quatre grandes questions :

i. Variation du coefficient de frottement avec le temps – Le coefficient de frottement varie sur de longues échelles de temps (mois et années) ainsi qu'à plus court terme, sous l'effet de divers facteurs : renouvellement de la chaussée, accumulation de contaminants, pluies qui chassent les contaminants. Les variations à court terme sont plus importantes que les variations à long terme.
ii. Facteurs influant sur le coefficient de frottement sur une piste mouillée – Voici les facteurs les plus importants : (i) vitesse de l'avion; (ii) taux de glissement; (iii) s'il y a aquaplanage ou non; (iv) épaisseur de la pellicule d'eau; (v) rugosité du revêtement; (vi) pression des pneus; (vi) présence de contaminants.
iii. Aquaplanage – L'aquaplanage a été étudié en profondeur, ce qui a permis de cerner les conditions générales qui causent ce phénomène. On ne dispose toutefois que de critères quantitatifs généraux pour le prévoir. Des équations de prédiction ont été élaborées par la NASA et celles-ci sont généralement corroborées par les données obtenues sur le terrain à l'aide d'avions et de camions lourds. Mais des observations récentes ont jeté un doute quant à l'applicabilité des équations de la NASA aux véhicules de mesure du frottement.
iv. Méthodes d'évaluation globale – Il n'existe que quelques méthodes pour effectuer une évaluation globale du frottement sur piste mouillée. Par exemple, mettre en rapport le coefficient de frottement mis en évidence en situation réelle, d'une part, et les mesures prises par un véhicule au sol ou les paramètres du revêtement, comme la rugosité, d'autre part. Ces méthodes présentent toutefois de graves inconvénients. Il n'existe aucune méthode universelle, largement reconnue et éprouvée pour faire des évaluations de ce type.

On considère que la lacune la plus urgente à combler dans la base de données actuelle est l’établissement de liens entre (a) les coefficients de frottement mis en évidence en situation réelle; (b) les coefficients de frottement mesurés par les véhicules au sol; et (c) les paramètres du revêtement de la piste, comme la rugosité et l’épaisseur de la pellicule d’eau. Faute de connaître ces liens, il est difficile d’évaluer les opérations aéroportuaires (décollages et atterrissages) autrement que par l’expérience. La conduite d’essais exhaustifs demeure donc la façon plus fiable de procéder à cette évaluation.

Recommandations - Des efforts devraient être faits pour comprendre les liens entre (a) les coefficients de frottement mis en évidence en situation réelle; (b) les coefficients de frottement mesurés par les véhicules au sol; et (c) les caractéristiques du revêtement, comme l’épaisseur de la pellicule d’eau et la rugosité.

Comme les connaissances sur le frottement sur piste mouillée sont surtout empiriques, nous sommes d’avis que la meilleure façon d’évaluer cette variable aux fins de prévoir les conditions opérationnelles est de procéder au cas par cas, en adaptant les moyens de mesure et de surveillance à chaque aéroport et à chaque cas.

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GLOSSARY

ABS	Antilock Braking System
ASTM	American Society for Testing and Materials
DBV	Diagonal Braked Vehicle
FAA	Federal Aviation Administration
LLTT	Landing Loads Test Track
MAPCON	Methodology for Analyzing Pavement Condition Data
NASA	National Aeronautics and Space Administration
PIARC	Acronym for the World Road Association
PTI	Pennsylvania Transportation Institute
SAE	Society of Automotive Engineers
SDR	Stopping Distance Ratio
SFT	Surface Friction Tester
SN	Skid Number
TTI	Texas Transportation Institute

1.0 INTRODUCTION AND PURPOSE

1.1 Introduction and Project Objectives

Aircraft landings and take-offs regularly occur on damp and wet runways. The frictional forces developed between the aircraft tires and the runway have an important effect on the safety of these operations. Wet runway friction has been studied for many years, and as a result, a significant information base has been built up. However, it is fragmented.

The general purpose of this report is to provide background information regarding wet runway friction and information relating to the assessment of aircraft operations on wet runways.

The specific objectives of this project were to:

(a) review the available information that is relevant to this technical area
(b) assess the current state of knowledge regarding key issues
(c) identify the most critical information gaps
(d) make recommendations regarding methods for filling the information gaps

1.2 General Overview: The Factors Affecting Wet Runway Friction

It is well known that the friction level of a wet pavement, as well as the tractive forces developed between aircraft tires and the pavement, depend on many factors (Figure 1.1), such as:

(a) speed – the friction factor decreases as the speed is increased up to the hydroplaning speed (Figures 1.2 to 1.4).

When the hydroplaning speed is reached, the friction factor at the tire-pavement interface drops to nil, or to a very low value (depending on the definition used for hydroplaning – discussed further in subsequent sections).

(b) slip ratio – the relationship between slip ratio and friction factor varies depending on the type of surface (i.e., bare and dry, bare and wet, wet ice, etc). See Figures 1.5 and 1.6. Figure 1.6 shows that the various contaminants affect the friction in two ways:

a. the magnitude of the peak friction varies with the contaminant type, and
b. the slip ratio at which the peak occurs differs with the contaminant type

For wet surfaces, the friction factor increases from virtually nil at the free-rolling condition (i.e., 0% slip) to a maximum in the range of 10 - 20% slip (depending on factors such as the surface and tire type). As the slip ratio is further increased towards 100% (i.e., locked wheel), the friction factor decreases on wet pavements.

Most of the friction data presented in this report, and the trends inferred from them, were collected in the 10% to 20% slip range. This was done because:

(a) aircraft braking systems are designed to operate in this general range to provide maximum braking efficiency, and

(b) most of the ground vehicles typically used to measure wet runway friction on airport runways are also designed to operate in this range of slip ratios.

Results obtained in accordance with ASTM E274 (which specifies testing with a locked wheel, i.e., 100% slip) are also presented in this report. This was done because a large information base is available from tests done on highways using this method, and this information is useful for verifying trends.

(c) tire inflation pressure – although this parameter is important, it is difficult to make general statements because its effect on friction is affected by other factors as well.
(d) pavement texture – the same comments made above apply to pavement texture.
(e) water film depth – the same comments made above apply to water film depth as well.

Because the above factors may all influence the friction significantly (depending on the case being considered), it is necessary to discuss all of the above variables together in presenting a summary of wet runway friction.

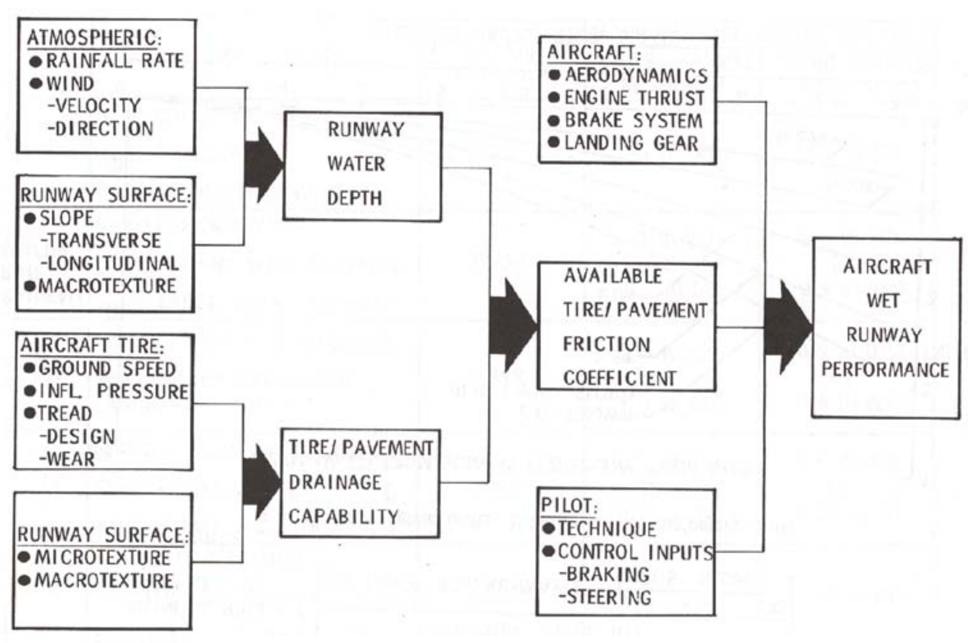


Figure 1.1: Factors Affecting Aircraft Wet Runway Performance (after Yager, 1983)

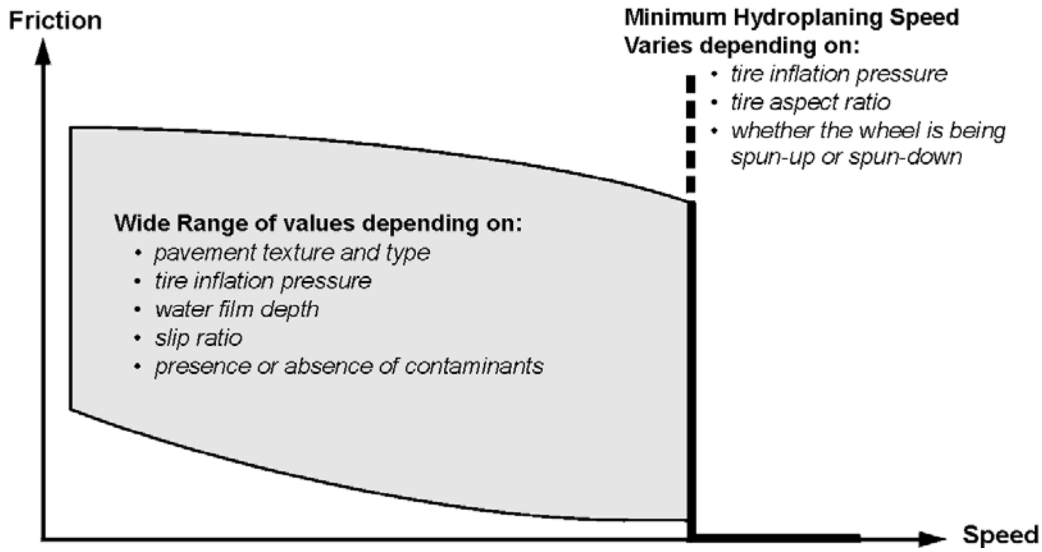


Figure 1.2: General Overall Trend: Wet Pavement Friction Versus Speed

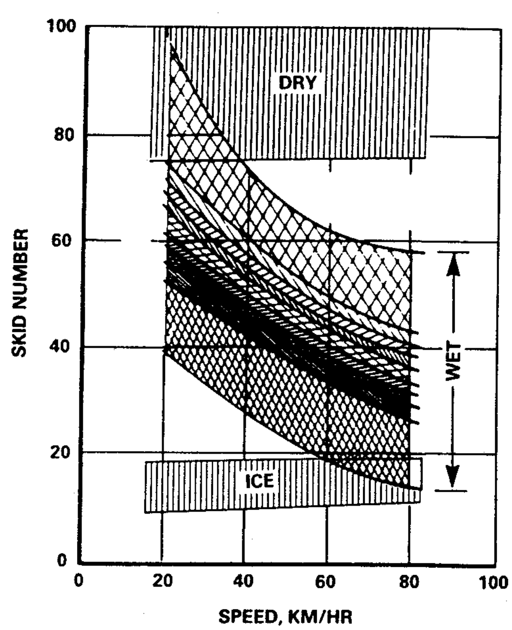
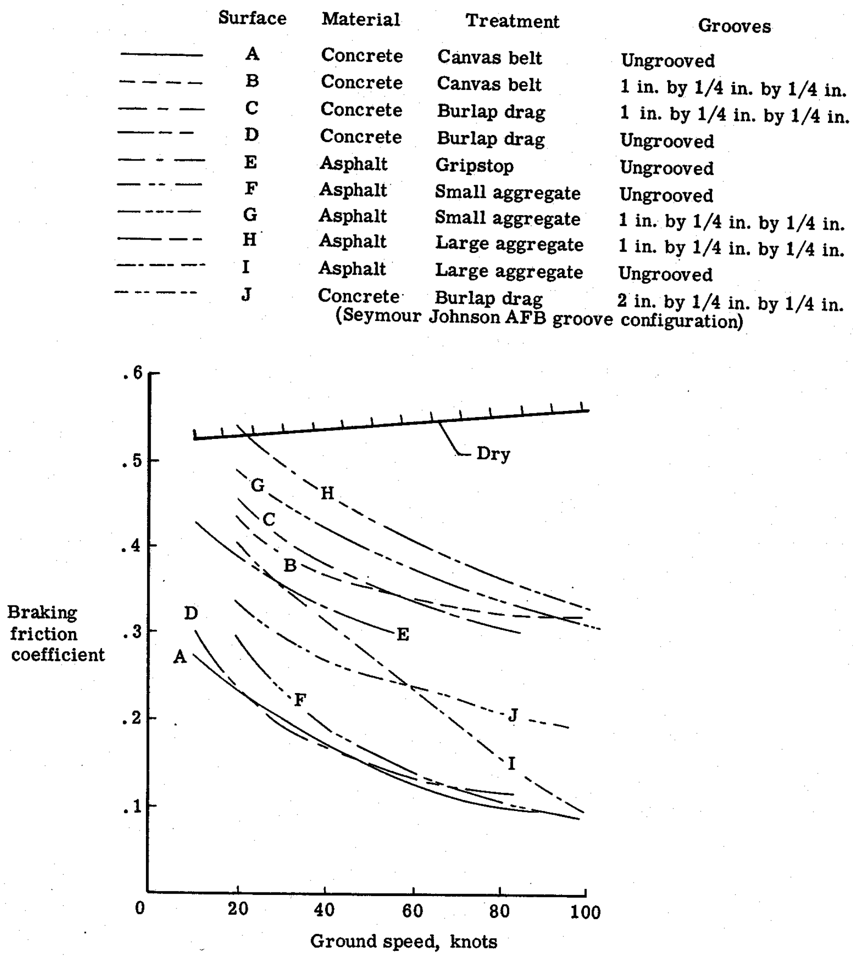


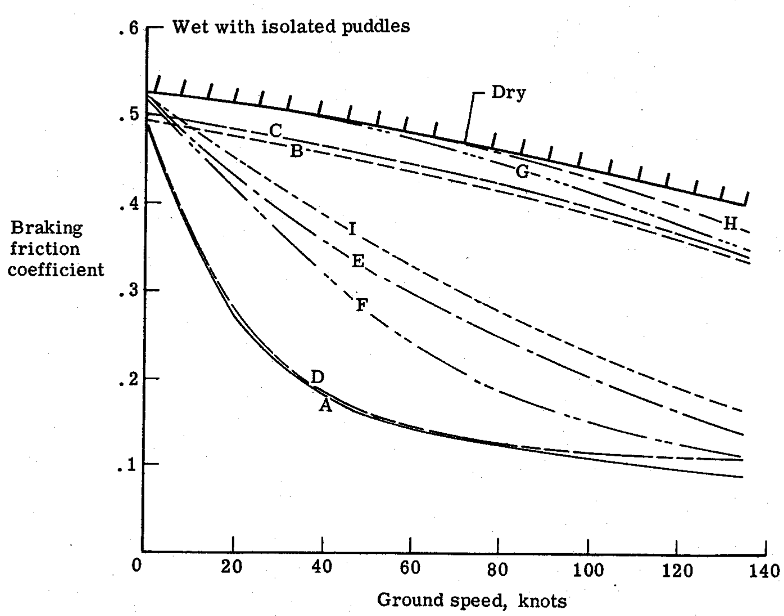
Figure 1.3: Overview: Trends Observed for Highways (after Gauss, 1976; cited by Hegmon, 1987)



(a) C-141A.

Figure 1.4: Overview: Trends Observed for Aircraft Tires (after Yager, Phillips and Horne, 1970)

Surface	Material	Treatment	Grooves
A	Concrete	Canvas belt	Ungrooved
B	Concrete	Canvas belt	1 in. by 1/4 in. by 1/4 in.
C	Concrete	Burlap drag	1 in. by 1/4 in. by 1/4 in.
D	Concrete	Burlap drag	Ungrooved
E	Asphalt	Gripstop	Ungrooved
F	Asphalt	Small aggregate	Ungrooved
G	Asphalt	Small aggregate	1 in. by 1/4 in. by 1/4 in.
H	Asphalt	Large aggregate	1 in. by 1/4 in. by 1/4 in.
I	Asphalt	Large aggregate	Ungrooved



(b) 990A.

Figure 1.4 (cont'd): Overview: Trends Observed for Aircraft Tires (after Yager, Phillips and Horne, 1970)

Surface	Material	Treatment	Grooves
A	Concrete	Canvas belt	Ungrooved
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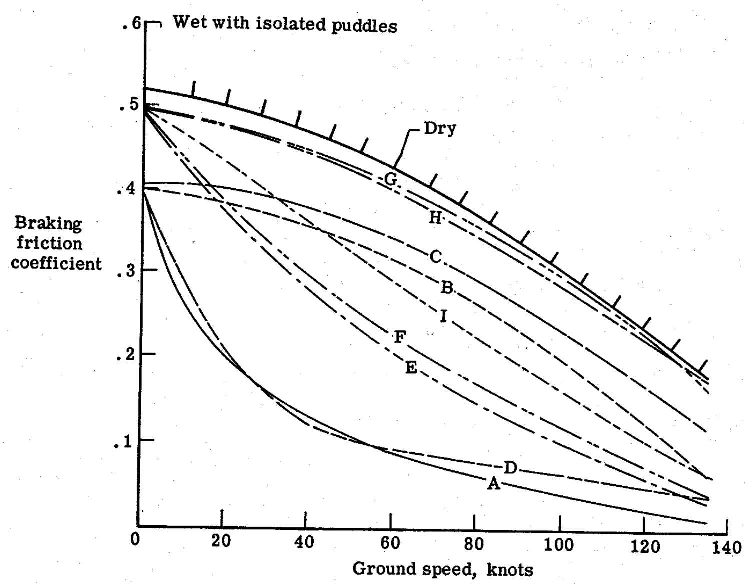
I	Asphalt	Large aggregate	Ungrooved



(c) F-4D.

Figure 1.4 (cont'd): Overview: Trends Observed for Aircraft Tires (after Yager, Phillips and Horne, 1970)

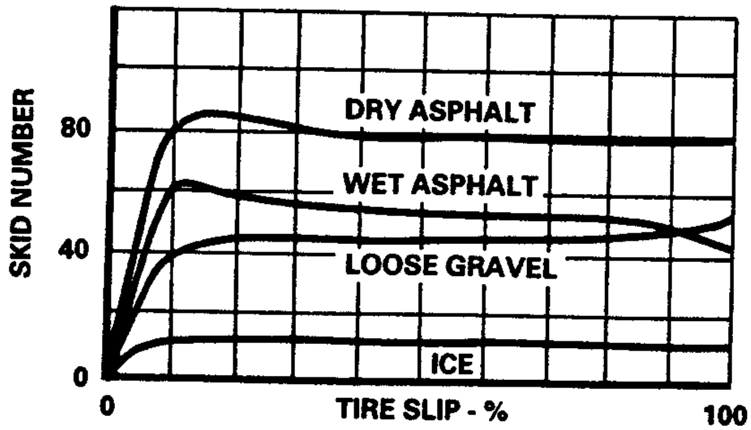


Figure 1.5: General Overall Trend: Friction Versus Slip Ratio for Various Surfaces (after Grimm and Bremer, 1976; cited by Hegmon, 1987)

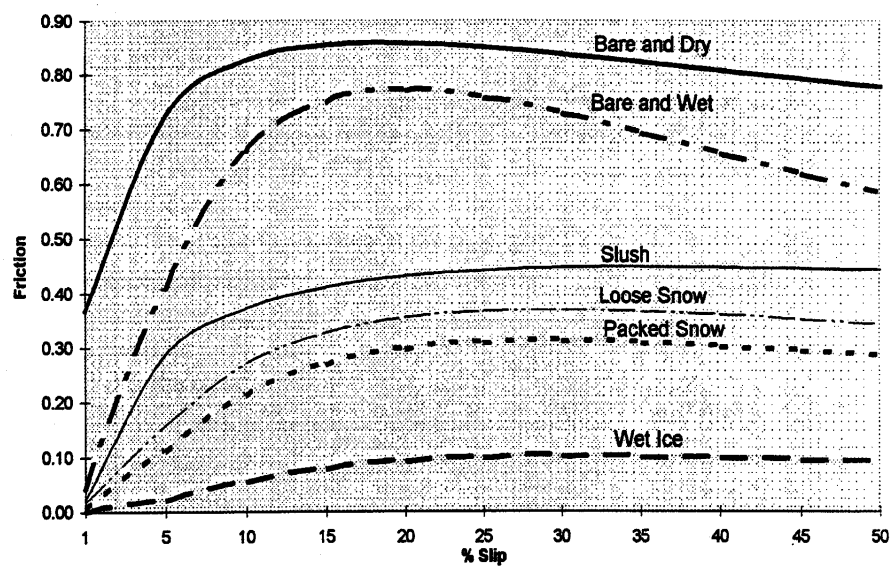


Figure 1.6: Trend Observed for the Runar Operated at Variable Slip - Source: Tests at the 1996 North Bay Trials (after Wambold, 1996)

1.3 Key Wet Runway Friction Issues

Many factors affect the friction level of a damp or wet runway, and operations on them, including the following

(a) Water Buildup on the Runway

a. the environmental conditions causing water or moisture to accumulate on the runway.
b. the water film depth that is likely to accumulate, and the factors that control this.
c. transient effects, such as:
    - the time required for the runway to "dry off" after water or moisture has been produced on the runway, and the factors that control this
    - variations in rainfall intensity during a storm
    - the action of rains to wash contaminants off the runway

(b) The Friction Level of a Wet or Damp Runway

a. the magnitude of the friction factor, and the factors that control it, which include:
    - pavement parameters – texture, slope, whether or not the runway is grooved
    - tire parameters – tire treaded or smooth, pressure, tread depth
    - friction-measurement parameters – speed, slip ratio, tire used

b. the relationship between friction factors measured by ground vehicles, and the effective braking coefficient experienced by an aircraft. This is important because the friction measurements available to assess aircraft operations are most likely to be produced by ground vehicles. Hence, one must be able to assess this relationship in order to apply them to aircraft operations.

1.4 Report Structure

This report is divided into the following sections:

(a) Section 1 – Introduction and Purpose
(b) Section 2 – Water or Moisture Buildup on a Runway Surface
(c) Section 3 – The Friction Level of a Wet Runway
(d) Section 4 – Evaluation Methods
(e) Section 5 – Assessment of the State-of-the-Art
(f) Section 6 – References

2.0 WATER OR MOISTURE BUILDUP ON A RUNWAY SURFACE

2.1 Environmental Conditions Causing Water or Moisture Buildup

The mechanisms include:

(a) a rainstorm
(b) dew formed in early morning or late evening
(c) frost which is melted by solar radiation during the day
(d) mist or fog

The important issues affecting wet runway friction include the following:

(a) the depth of the water film that can build up on the runway under steady-state conditions – this is addressed in section 2.2
(b) the influence of transient effects during a storm, such as rainfall duration, and variations in rainfall rate during a storm, and the time required for water to run off the surface – these are addressed in section 2.3.
(c) the time required for the pavement to become dry after a storm – this is addressed in section 2.4.

2.2 Water Depths Produced on the Runway

All of the available information is focussed on the first mechanism listed above (i.e., a rainstorm). No information was found pertaining to the amount of moisture expected from the other mechanisms in section 2.1. The available predictors are discussed below.

2.2.1 Texas Transportation Institute and the Galloway Equation

Equation 2.1 was developed based on tests at the Texas Transportation Institute (TTI) by Galloway, 1971 – cited by Horne, 1974 – to predict the water depth, d, on ungrooved pavements under calm wind conditions. It should be further noted that the water depth predicted by equation 2.1 is the film depth lying above the mean pavement texture depth.

$$d = 3.38*10^{-3} \{(1/T)^{-0.11} * L^{0.43} * I^{0.59} * (1/S)^{0.42}\} - T \qquad [2.1]$$

where: d = water depth (in)
T = average pavement texture depth (in)
L = drainage path length (ft)
I = rainfall intensity (in/hr)
S = pavement cross slope (ft/ft)

Figures 2.1 and 2.2 show the water depths predicted by the Galloway Equation for pavement texture depths of .04 in (1 mm), and 0.01 in (0.25 mm), respectively. The following trends are evident:

(a) rainfall intensity – the water depth increases with this parameter in a near-linear manner for all cases considered.
(b) pavement texture – the water depth decreased as the pavement texture is increased. The water depth increased by about 50% when the pavement texture was decreased from 1 to 0.25 mm.
(c) cross slope – the water depth was increased by about 50% when the pavement cross slope was decreased from 2% to 0.5%.
(d) drainage path length – the water depth increases with the drainage path length.

The Galloway Equation has been used by a number of researchers. In a study of safety on roads and highways, Horne, 1994 used it to investigate the rainfall rates necessary to cause the surface water depth to equal the tire tread depth (which he considered to be a minimum condition for hydroplaning). See Table 2.1.

Table 2.1: Minimum Rainfall Rate Required for Hydroplaning (after Horne, 1994)

Rainfall Rate Req'd for Surface Water Depth to Equal Tire Tread Depth (Min. Hydroplaning Speed Condition)				
Pavement Texture Depth, in	Tire Tread Depth, in	Drainage Path Length, ft	Pavement Cross Slope, %	Rainfall rate, in/hour
#6 ; 0.004	0.04	24	0.5	0.5
#6 ; 0.004	0.26	24	0.5	10.5
#6 ; 0.004	0.04	24	2.5	1.5
#6 ; 0.004	0.26	24	2.5	33.3
#3; 0.047	0.04	12	0.5	1.7
#3; 0.047	0.26	12	0.5	14.2
#3; 0.047	0.04	12	2.5	5.1
#3; 0.047	0.26	12	2.5	44.8

Yager, 1991, developed equation 2.2 based on the Galloway Equation (i.e., equation 2.1) to evaluate the rainfall rate required to flood the runway surface ($I_{\text{to cause flooded runway surface}}$).

$$I_{\text{to cause flooded runway surface}} = K \{(\text{Macrotexture depth}^{0.89}) / [\text{Runoff length}^{0.43} * (1/\text{Cross Slope})^{0.42}]\}^{1.695} \qquad [2.2]$$

where: K= 1253 for metric units & 15430 for US customary units

The values predicted by Yager, 1991 using equation 2.2 are shown in Figure 2.3. Yager , 1991 then used equation 2.2 to determine the rainfall rates required to flood the runway for the Shuttle Landing Facility (Figure 2.4). Yager, 1991 found that equation 2.2 errs conservatively as it underestimates the rainfall rates necessary to actually cause flooding. Compare Figures 2.4 and 2.5. Yager, 1991, concluded that equation 2.2 needs to be modified.

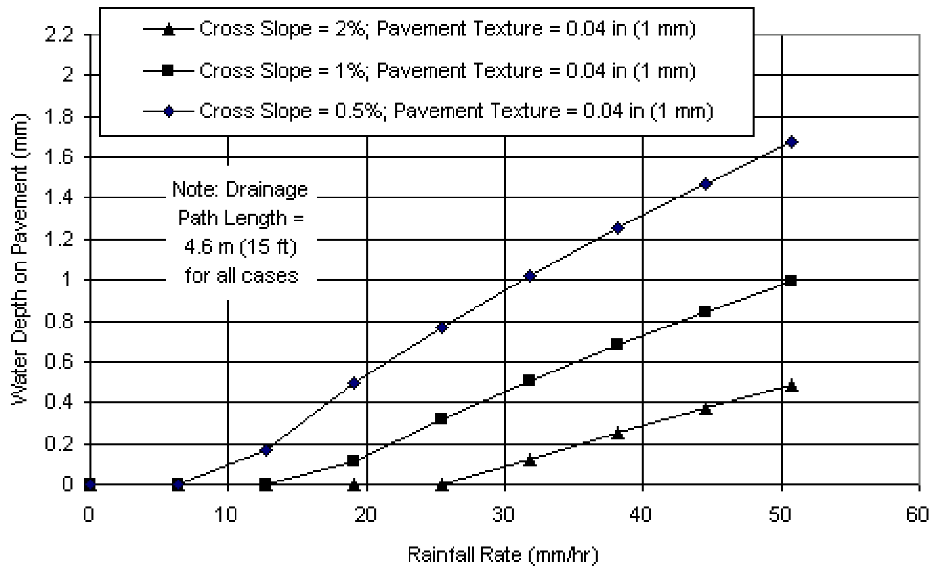


Figure 2.1: Water Depths Predicted by the Galloway Equation for a Pavement Texture Depth of 1 mm

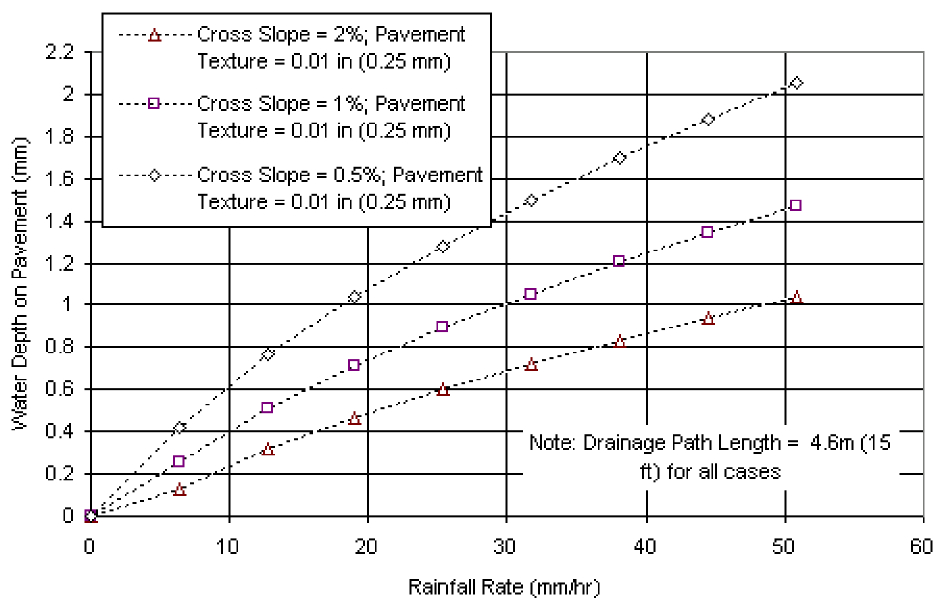


Figure 2.2: Water Depths Predicted by the Galloway Equation for a Pavement Texture Depth of 0.25 mm

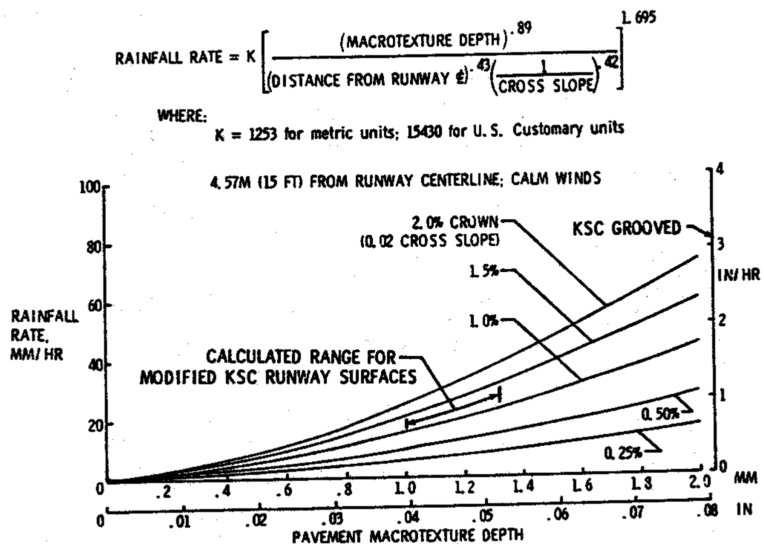


Figure 2.3: Rainfall Rate Required to Flood the Runway Surface (after Yager, 1991)

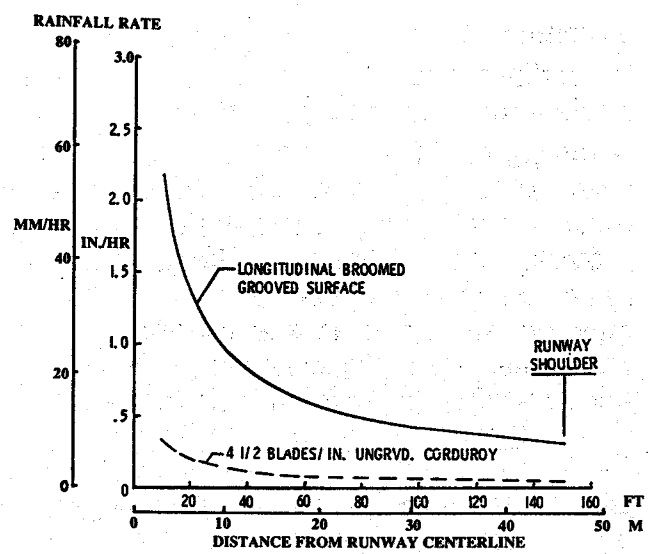


Figure 2.4: Calculated Rainfall Rate Required to Flood the Shuttle Runway Surfaces (after Yager, 1991)

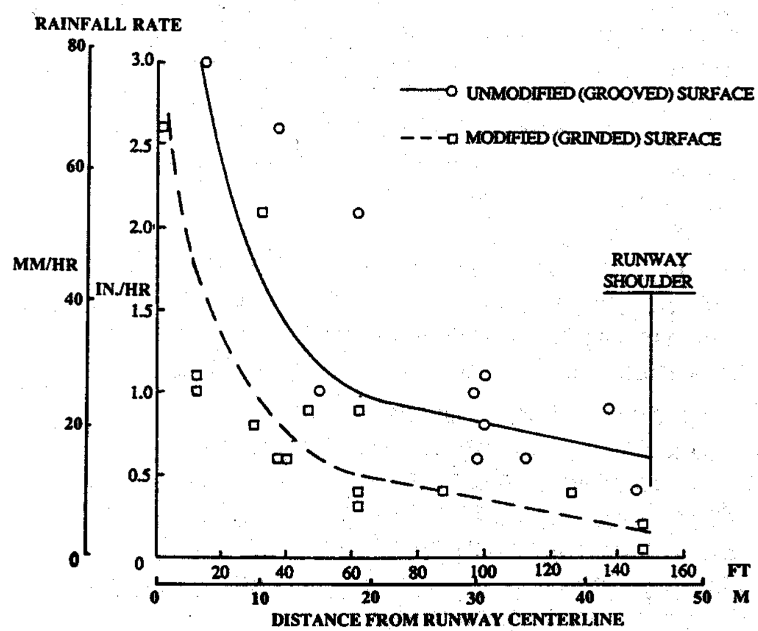


Figure 2.5: Measured Rainfall Rate Required to Flood the Shuttle Runway Surfaces (after Yager, 1991)

2.2.2 Pennsylvania Transportation Institute

Wambold et al, 1984 incorporated an adaptation of the Galloway Equation (Galloway, 1975) into the PTI's (Pennsylvania Transportation Institute) MAPCON (Methodology for Analyzing Pavement COndition Data) pavement model, as follows:

$$WT = j1 * (MTD^{j2} * RAIN^{j3} * CSLP^{j4}) - MTD \quad [2.3]$$

where: WT = estimated water film thickness (mm)
MTD = mean texture depth (mm)
RAIN = rainfall intensity (mm/hr)
CSLP = cross slope (m/m)
j1, j2, j3, & j4 = empirical coefficients – Wambold et al, 1984 suggested 0.005979, 0.11, 0.59, and –0.42 as typical values for these coefficients, respectively, for a runoff length of 11 m.

The trends predicted by the Pennsylvania Transportation Institute equation and the Galloway Equation (Figure 2.6) are similar as:

(a) the water depth is decreased as the pavement cross slope is increased
(b) the water depth is decreased as the pavement texture is increased

However, it predicts significantly lower water depths than does the Galloway Equation (Figure 2.6). The reasons for this variation could not be established.

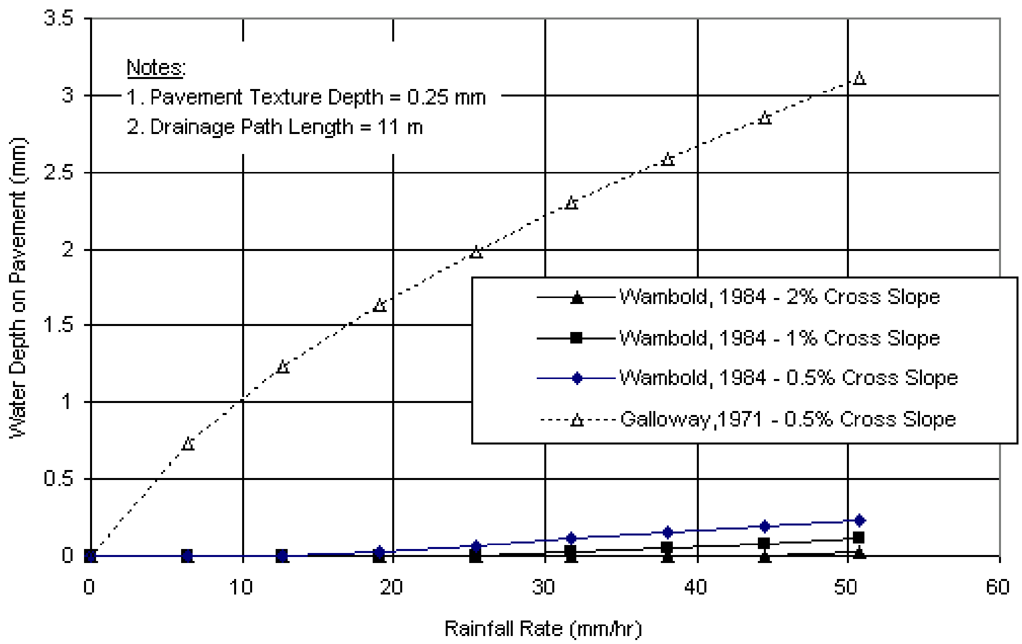


Figure 2.6: Water Depths Given by the Pennsylvania Transportation Institute Equation

2.2.3 Road Research Laboratory (Ministry of Transport, England)

Based on field measurements on roads in England, Ross and Russam, 1968 proposed the following equation for the water depth, d, in cm:

$$d = 0.017 * (L*I)^{0.47} * S^{-0.2} \quad [2.4]$$

where: L = the drainage length (m)
I = rainfall intensity (cm/hr)
S = slope (m/m)

Although this equation is less detailed than equations 2.1 to 2.4 (e.g., because it does not include the pavement texture depth as a parameter), it predicts water depths that are in general agreement with those obtained from the Galloway Equation (Equation 2.1). Compare Figure 2.7 with Figures 2.1 to 2.2.

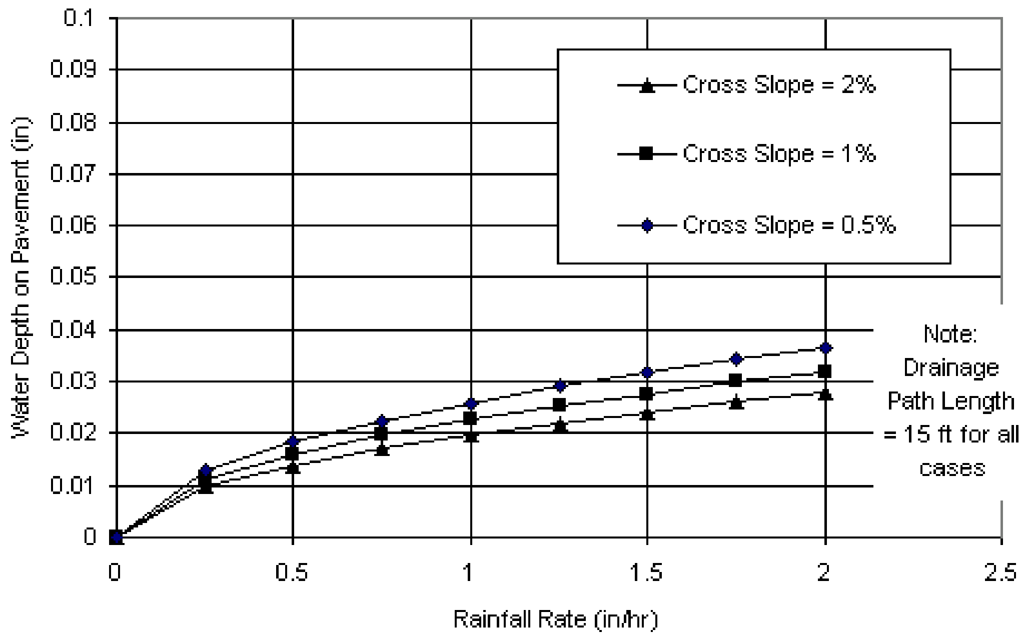


Figure 2.7: Water Depths Predicted Using Ross and Russam, 1968

2.2.4 Factors Controlling Water Buildup on the Runway Surface

The available equations (sections 2.2.1 to section 2.2.3) provide information regarding the important factors controlling the water depth. They fall into the following general categories:

(a) environmental – the rainfall rate is the only environmental parameter in each of the above predictors. This reflects the fact that the predictors are applicable to the steady-state case where the rainfall rate does not change with time. It is well known that in practice, the rainfall rate usually changes during a storm. This is discussed further in a subsequent section.

It should be also noted that neither the wind speed nor direction is a parameter in the above equations. Again, this reflects the fact that equations 2.1 to 2.4 have been developed for relatively basic conditions. It is known that the wind speed and direction can affect the water distribution on the runway. Based on dye tests on runways, Horne, 1974 observed that winds don't appreciably affect drainage patterns as long the water flows beneath the top of the pavement texture.

However, he found that water distribution patterns on flooded runways were affected by winds.

(b) pavement parameters – the factors considered to be important (based on the fact that they are included in the above equations) are as follows:
   a. the pavement cross slope
   b. the pavement texture depth – the above equations do not explicitly consider the effects of grooving
   c. the drainage length

2.3 Transient Effects

The analyses presented in section 2.2 are applicable to the steady-state case where the rainfall rate does not change with time. In practice, this is known to be a simplification for several reasons, including:

(a) rainfall rates usually vary during a storm
(b) there is a time lag at the beginning of a rain fall, or following a change in rainfall rate, until the flow off the pavement reaches a stable value.

2.3.1 Runoff Time for Water on the Pavement Surface

Very little information was found in the literature regarding this.

The only information was provided in Harwood et al, 1989, who referred to the kinematic wave method developed by Reed et al, 1984. Estimates using this analysis method by Harwood et al, 1989 indicated that the runoff time would be usually less than 10 minutes, and often would be 5 minutes or less. As a result, Harwood et al, 1989 used a constant runoff time of 5 minutes for all conditions (e.g., rainfall intensities, pavement surface texture, pavement slope, etc) in their WETTIME model. (The WETTIME model was developed as a tool for highway authorities for assessing wet pavement exposure for different geographic regions).

2.3.2 Relationship Between Rainfall Intensity and Duration

In developing the WETTIME model, Harwood et al, 1989 criticized existing wet pavement exposure models because they "make no distinction between hours of precipitation based on rainfall intensity or duration". Harwood et al, 1989 argued that one would expect that on average, a rainfall would last longer when more rain falls within an hour. Based on analyses of precipitation data for 99 stations located throughout the United States, they found that the duration of rainfall increased with the hourly rainfall amount up to 0.05 in of rainfall in 1 hour (Table 2.2). Above that level, the pavement wetness typically lasted for the whole hour. Harwood et al, 1989 incorporated this relationship into their WETTIME pavement model.

Table 2.2: Variation of Duration of Rainfall During an Hour Hourly Rainfall Amount (after Harwood et al, 1988)

Hourly Rainfall Amount (in)	No. of Hours Available	Mean Duration of Rainfall (min)	Most Common Duration of Rainfall (min)	Duration of Rainfall in WETTIME model (min)
0.01	262	13.0	5	15
0.02	72	33.0	40	30
0.03	60	42.0	55	45
0.04	59	43.0	55	45
0.05	47	45.9	60	60
0.06-0.07	26	49.6	60	60
0.08-0.09	65	53.5	60	60
0.10 and over	146	54.5	60	60

2.3.3 Effect of Rainfall Rate Variations During a Storm

It is well known that the rainfall rate usually varies during a storm. The effect of rainfall rate variations was investigated using the following approach for the following cases:

(a) the Galloway Equation (i.e., equation 2.1) was used to predict the water depth.

(b) two hypothetical rainstorms were considered:
   a. a "heavy & fast" rainstorm in which a peak rainfall rate of 40 mm/hr was reached (Figure 2.8)
   b. a "light & slow" rainstorm in which a peak rainfall rate of 10 mm/hr was reached (Figure 2.9)

(c) two runoff time cases were considered as follows:
   a. Instantaneous – in this case, the runoff time was presumed to be zero, and the Galloway equation (i.e., equation 2.1) was used directly to predict the water depth on the surface (Figure 2.8 and 2.9).
   b. 5 minute runoff time – this was the value used by Harwood et al, 1989 in their WETTIME model (section 2.3.1). The water depth on the surface for this case ($d_{5\text{ minute runoff time}}$) was predicted as follows:

$$d_{5\text{ minute runoff time}} = d_{previous} + d_{incremental} \qquad [2.5]$$

where: $d_{previous}$ = the water depth predicted by the Galloway Equation for the rainfall rate occurring 5 minutes prior to the present time
$d_{incremental}$ = the water added in the 5 minutes that elapsed between the present time and 5 minutes ago

(d) pavement parameters – these were standardized for all analyses as follows:
   a. texture depth: 0.25 mm
   b. cross slope: 0.5%
   c. drainage path length: 4.6 m (15 ft)

The results for the "heavy & fast" and the "light and slow" rain storms are shown in Figures 2.8 and 2.9 respectively. It can be seen that:

(a) for the "steady-state" portion of the rainstorm, the run-off time has no effect on the water depth on the runway. This follows the expected trend.

(b) the inclusion of a run-off time in the analyses causes a temporary increase in water depth at the start of the storm (as the rainfall rate is increasing), compared to the case where the water is assumed to run off immediately (i.e., a runoff time of zero). This is to be expected because during this period, more water is being added to the runway surface than is being removed.

(c) the significance of the run-off time, with respect to the water depth, depends on:
   a. the magnitude of the rainfall intensity reached during the storm;
   b. the rate at which the rainfall intensity varies during the storm, and;
   c. the pattern of the variation. More frequent variations will cause greater transient effects.

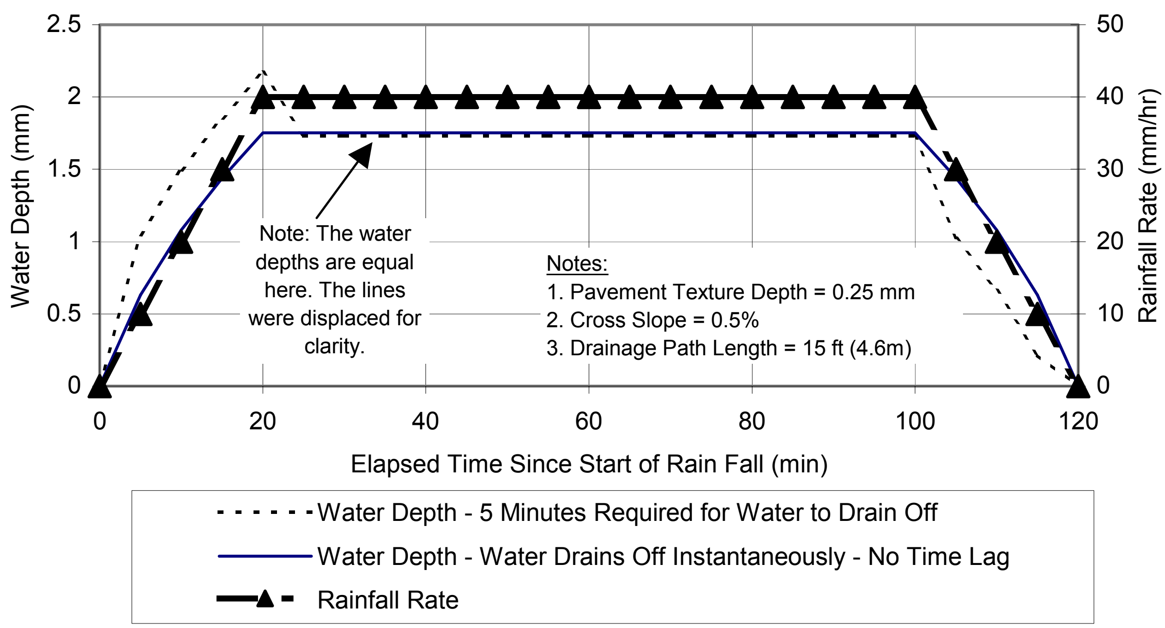


Figure 2.8: Effect of Rainfall Rate Variations During a Storm: Heavy Rainstorm with Fast Buildup to Peak

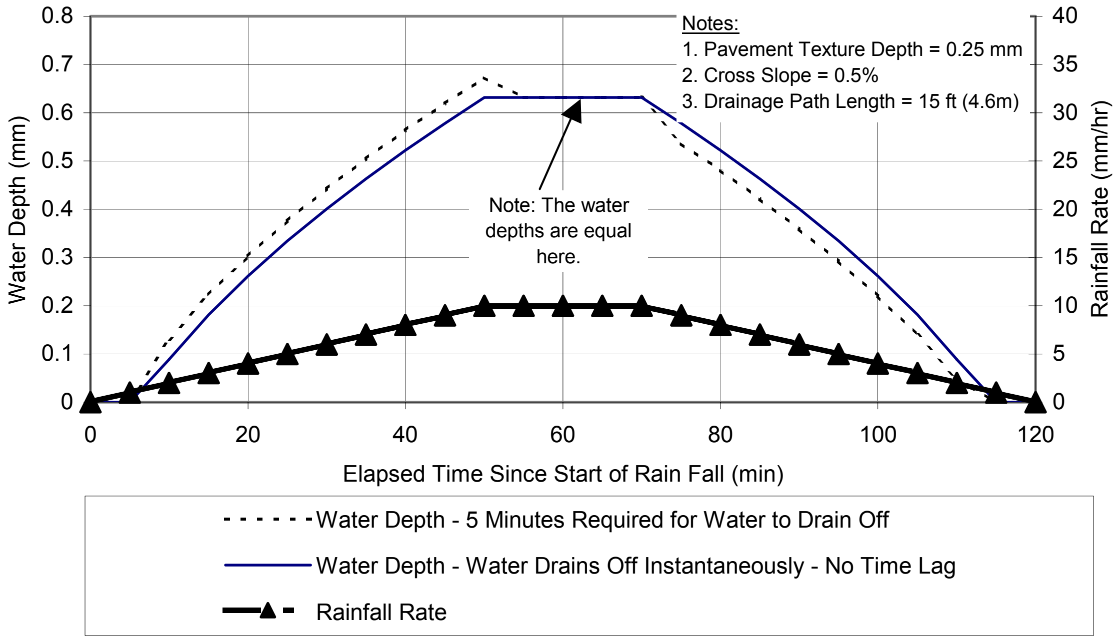


Figure 2.9: Effect of Rainfall Rate Variations During a Storm: Light Rainstorm with Slow Buildup to Peak

2.4 Pavement Recovery Time from a Wet to a Dry Condition

2.4.1 Importance

Each of the environmental mechanisms listed in section 2.1 will cause the runway surface condition to change over time. In each case, the runway wetness will decrease with the time elapsed at the end of a storm (for a rainfall) or as the day "warms up" (for frost or dew). It is obvious that the runway friction level will increase as the runway "dries up".

It is important to be able to evaluate the point at which the runway friction has increased to the point where the runway surface can again be considered to be "dry".

Only a small amount of information was found in the literature regarding this.

2.4.2 The WETTIME Exposure Estimation Model

The PTI (Pennsylvania Transportation Institute) developed the WETTIME Exposure Estimation Model (Harwood, 1987; Harwood et al, 1988; Harwood et al, 1989) for roads. They considered that the pavement's "recovery time" (i.e., the time required for the surface to become dry again) to be comprised of two parts:

(a) the time required for the remaining water (at the end of a storm) to run off the pavement, and;
(b) the time required for the pavement surface to dry up.

(i) Runoff Time at the End of a Rainstorm

Harwood et al, 1988 developed the following equation to estimate the time required for the remaining water to run off the pavement:

$$TC = \{0.94*L^{0.6} * n^{0.6}\} / \{I^{0.4} * S^{0.3}\} \quad [2.6]$$

where: TC = time of concentration or runoff time, in min
L = length of drainage path, in ft
n = Manning Coefficient
I = rainfall intensity (in/hr)
S = average slope of drainage path (ft/ft)

Harwood et al, 1988 used equation 2.6 to estimate the runoff time for typical ranges of the input parameters (for highways) as follows:

(a) Manning Coefficient: 0.01 to 0.05
(b) slope: 0.01 to 0.02 ft/ft, except on superelevated sections
(c) drainage path length: from 12 to 24 ft (for nil longitudinal grade) to 100 ft (with slopes up to 0.05 ft/ft)

These calculations showed that the runoff time is usually less than 10 minutes, and often 5 minutes or less. To keep the WETTIME model simple, they used a uniform runoff time of 5 minutes in it for all cases.

(ii) Pavement Drying Time

Harwood et al, 1988 noted that previous studies (i.e., NTSB, 1980; Blackburn, et al, 1978) had estimated the typical pavement drying time following rainfall and runoff at 30 minutes. Harwood et al, 1988 undertook detailed studies using laboratory tests, and field tests. Summary results are shown in Table 2.3.

Table 2.3: Parameter Estimates for the Pavement Drying Time Model (after Harwood et al, 1988)

Factor	Level	Mean Drying Time[1] (min)	Deviation (min) from Overall Mean Drying Time of 31.6 min
Temperature	below 67.5°F	35.3	+3.7
	67.5°F to 82.5°F	30.9	-0.7
	above 82.5°F	28.6	-3.0
Relative Humidity	below 50%	27.1	-4.5
	50% to 82.5%	30.0	-1.6
	above 82.5%	37.7	+6.1
Solar Radiation[2]	night or overcast	43.2	+11.6
	partly cloudy day	37.2	+5.6
	clear day	14.4	-17.2
Wind Speed[4]	no wind	43.2	+11.6
	wind present	20.0	-11.6[3]
Pavement type	asphalt concrete	35.5	+3.9
	Portland cement concrete	27.7	-3.9

Notes:

1. Harwood et al, 1988 note that "the mean drying times represent the effects of each factor taken one at a time, independent of the values of the other factors".
2. Harwood et al, 1988 suggest values of 0, 0.75, and 1.15 Langleys/minute for night, partly cloudy, and clear conditions, respectively.
3. Harwood et al, 1988 state: "use this parameter estimate only if the parameter estimate for the solar radiation factor has a positive value".
4. Harwood et al, 1988 state the wind speed categories for the WETTIME Exposure Model are 0, 2, 8, and 15 mph.

2.4.3 Assessment

The PTI WETTIME model is described in Harwood, Kulakowski, Blackburn, and Kibler, 1988.

The model has the following input variables, and levels for each one:

(a) solar radiation:	nighttime (0 Langleys/minute) partly cloudy day (0.75 Langleys/minute) bright, cloudless day (1.15 Langleys/minute)
(b) wind speed:	no wind (0 mph); 2 mph; 8 mph; and 15 mph
(c) air temperature:	60°F; 75°F; and 90°F
(d) relative humidity:	45%; 60%; 75%; and 90%
(e) pavement type:	asphalt concrete; and Portland Cement Concrete

The following comments can be made:

(a) the inputs to the model appear to be all measurable, and thus, it appears that the model would be usable.

(b) the pavement "drying time" is expected to be affected significantly by local conditions. Consequently, some calibration would likely be required if it were to be used in an operational mode at airports.

For example, neither the pavement nor the ground temperature appear to be variables in the WETTIME model. These parameters may affect the drying time in colder conditions, and it is our opinion that the model would need to be tested at Canadian airports before it could be relied upon.

In general, it can be stated that the issue of the pavement "drying time" is not well understood.

It is our opinion that the WETTIME model may be useful for general analyses. However, we expect that regular, onsite monitoring (e.g., by making friction measurements with ground vehicles throughout the "drying period") would be required for more reliable assessments.

2.5 Summary Assessment

(a) Water or moisture may be produced on the runway surface by various environmental conditions, such as rain, frost, dew, and fog. Only rain has been studied to any extent, with respect to the amount of water produced on the runway surface. No information was found regarding this issue for the other environmental conditions.

(b) Based on tests and observations, at least three equations have been developed to predict the water buildup on the runway surface. The key factors controlling the water depth include:

   a. Environmental – the rainfall rate is the only environmental parameter
   b. Pavement – the important factors include:
      - the pavement texture depth;
      - the pavement cross slope, and;
      - the drainage path length

(c) Each of the predictor equations is applicable to the basic case where:
   a. the rainfall rate does not change with time
   b. the winds are calm

(d) Comparisons between the predicted and observed rainfall rates to cause flooding for the Shuttle Landing Facility indicate that the Galloway equation errs conservatively, in that it underestimates the rainfall rates required to flood the runway.

(e) Dye tests at airport runways have shown that water patterns are affected significantly by winds when the runway is flooded.

(f) Runoff time – Simple calculations suggest that this is in the range of 5-10 minutes. However, more definitive information would be required for operational purposes.

(g) Very little information was found to assess the time required for a runway to dry (i.e., to go from “wet” to “dry”, or for frost on it to “burn off” during the day).

(h) Transient effects can be caused by variations in rainfall rates during a storm, and by the time lag required for the water to run off. Two hypothetical cases were analyzed. These calculations show that temporarily, the water depth on the runway could be up to roughly 20% higher than the steady-state value obtained from the predictor equations. In FTL’s opinion, this discrepancy is within the accuracy of the overall state-of-the-art for predicting water depths on a runway or pavement surface.

3.0 THE FRICTION LEVEL OF A WET RUNWAY

3.1 Available Information Sources

Information is available from the following general sources:

(a) tests with instrumented aircraft. Results from the following test programs were reviewed in this study:
   a. tests with a Boeing 727 on dry and wet runways (Horne, Yager, and Sleeper, and Merritt, 1977)
   b. tests with a C-141A on dry, wet, flooded, slush, snow, and ice conditions (Yager, Phillips, and Horne, 1970)
   c. tests with NASA's Boeing 737 aircraft and FAA's Boeing 727 aircraft on dry, wet, snow-, and ice-covered runways (Yager, Vogler, and Baldasare, 1990)

(b) tests done at NASA's (National Aeronautics and Space Administration) Landing Loads Test Track (LLTT) in Langley, Va. This facility is described in Joyner, and Horne, 1954, among other publications. This facility has a 100,000 pound carriage, and is capable of conducting tests at speeds up to 125 knots.

(c) tests with friction-measuring ground vehicles on airport runways, and at NASA's Wallops Island Flight Facility. A wide range of devices have been used. Summary descriptions are provided for most of the available devices in Henry, 2000.

(d) tests with friction-measuring ground vehicles on roads and highways. Most of these tests have been done in accordance with ASTM E274 (ASTM, 1990) which specifies tests to be done with a self-wetted, sliding locked wheel (i.e., 100% slip).

3.2 Friction Variations with Time

It is well known that the friction level of a given runway or pavement varies over both the long term and the short term. Data from the following general sources are presented and discussed in section 3.2:

(a) friction measurements made on highways in accordance with ASTM E274, and;
(b) friction measurements made using the Saab Surface Friction Tester (SFT) and the Griptester on airport runways in Canada.

Both of these data sources are considered to be relevant for assessing wet runway friction because each test method included self-wetting. The ASTM E274 method specifies a water film depth of 0.5 mm. Most of the SFT data were collected with a water film depth of 0.5 mm, although some were obtained at 1.0 mm film depth, while the Griptester data were collected for a range of water film depths.

3.2.1 Long-Term Variations in Friction Level

(i) Observations on Highways

Observations on highways have shown that the friction factor (obtained in accordance with ASTM E274) varies over the long term on an annual basis (Figures 3.1 to 3.3).

The data show that the Skid Numbers (SN) increased by about 5 to 10 over the winter (Figures 3.1 to 3.3). Saito and Henry, 1983 speculated that this increase is due to winter maintenance operations, such as de-icing chemicals, and maybe chemical reactions. Over the summer, a long-term trend was observed in the highway data, with the friction being decreased over the duration of the summer (Figures 3.1 and 3.2). Saito and Henry, 1983, attributed this to polishing by traffic.

It should be noted, however, that there were many short term fluctuations superimposed on this trend (e.g., Figure 3.3), which are discussed in section 3.2.2.

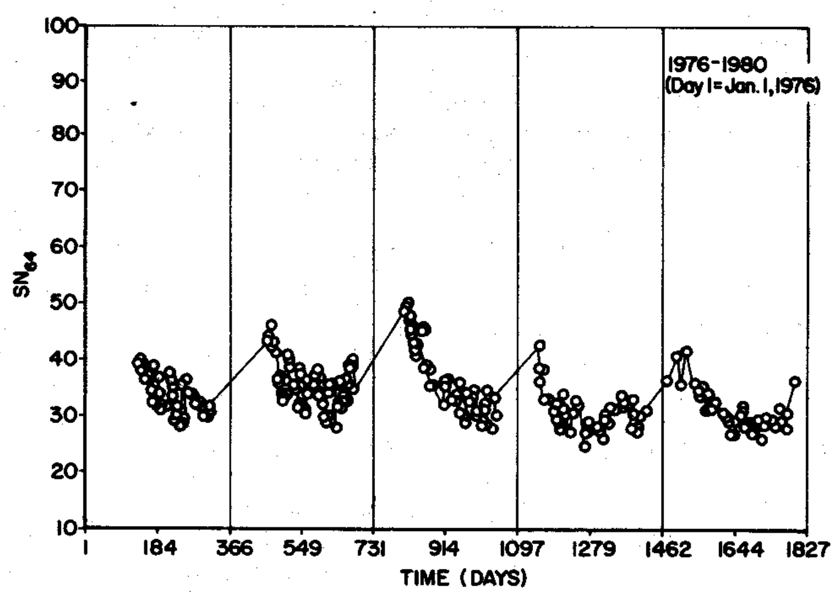


Figure 3.1: Seasonal Variations on Highways in Pennsylvania (after Saito and Henry, 1983)

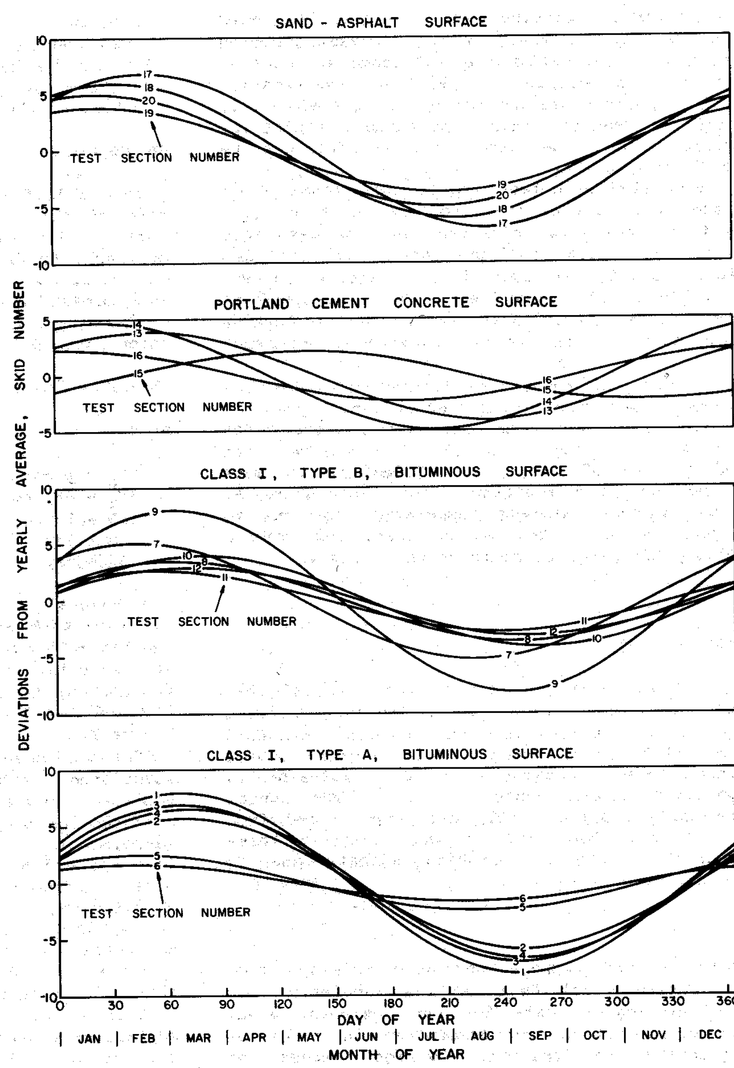


Figure 3.2: Seasonal Variations on Highways in Kentucky (after Burchett and Rizenbergs, 1980)

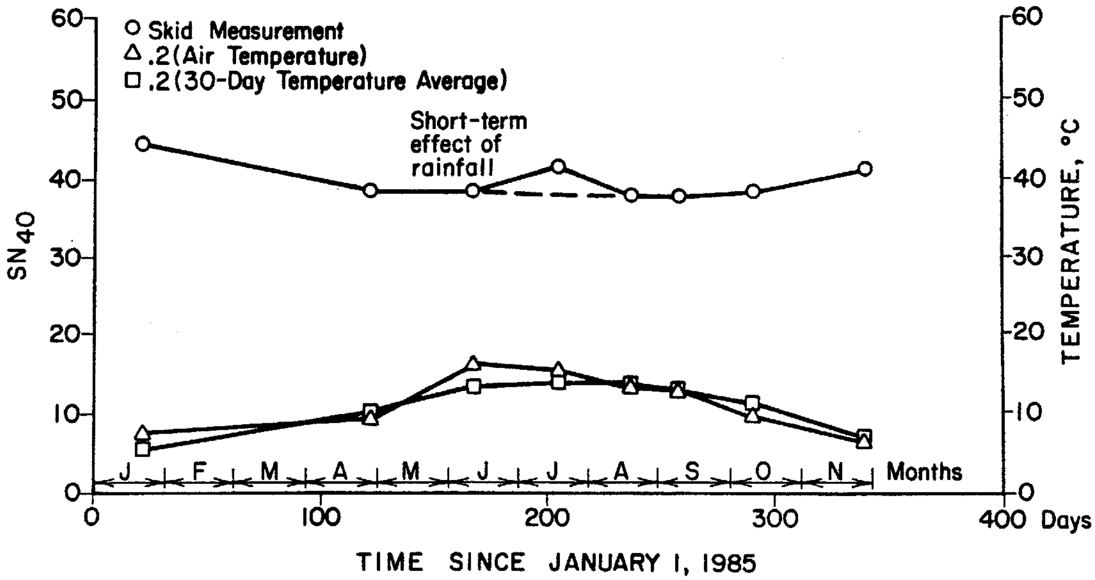


Figure 3.3: Long-Term Variations of Skid Resistance in Pennsylvania (after Kulakowski et al, 1990)

(ii) Observations on Airport Runways

Some information is available from Transport Canada's Summer Runway Monitoring Program, which has been operated since 1980 (Transport Canada, 1984; 1991; 1992; 1994a; 1994b; 1995; 1997a; 1997b). Friction coefficients were measured using a Saab Surface Friction Tester (SFT) for most years, excepting the 1995-97 period when the Griptester was used. Friction measurements were only measured once per year at several airports (about 100) which is much less frequent than the highway data shown in Figures 3.1 to 3.3. Thus, direct comparisons are not possible, although the Summer Runway Monitoring Program data are sufficient to indicate some long-term trends, on average.

For the smaller airports, the data show that the friction coefficient decreased by about 1 SFT friction coefficient per year over the 1991-1994 period (Figure 3.4). The 1995-1997 data show a greater friction drop per year, which is believed to be due to a change in the friction-measuring device used (i.e., the Griptester vs. the SFT), and the measurement method (i.e., different water film depths – see Figure 3.4).

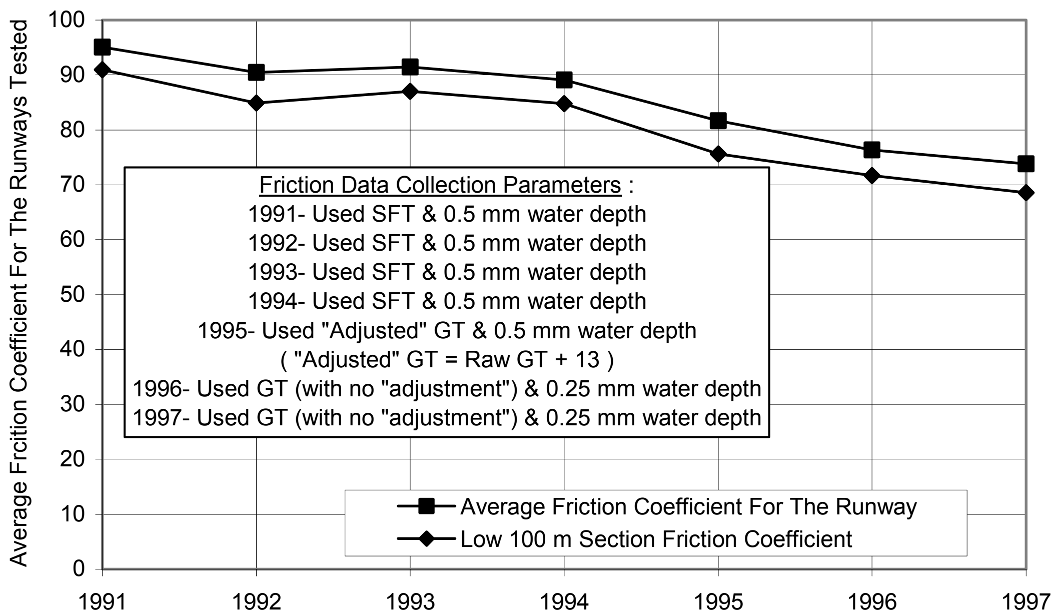


Figure 3.4: Long-Term Runway Friction Trends for the Smaller Canadian Airports (after Comfort, 1998)

The long term trends observed for the major Canadian international airports are shown in Figure 3.5. It can be seen that:

(a) the runway average and the low 100 m section friction coefficients are both lower than the corresponding values for the smaller airports. This is likely due to the lower traffic volumes on the smaller airports, which would cause less texture loss, and buildup of engine byproducts and rubber.

(b) for the 1991-94 period (when the same friction measurement techniques were used), the runway average and the low 100 m section friction coefficients are both relatively constant with time. In contrast, the corresponding values for the smaller airports steadily decreased with time (compare Figures 3.4 and 3.5). For the low 100 m section values, this result probably reflects more frequent rubber removal operations at the major international airports. For the runway average, the observed trends may reflect more frequent pavement maintenance operations at the major international airports.

(c) the runway average and the low 100 m section friction coefficients both decreased steadily over the 1995-97 period, probably in response to the change in friction measurement technique that occurred. This trend, as well as the amount of the friction decrease, is similar to that observed for the smaller airports (Figure 3.4).

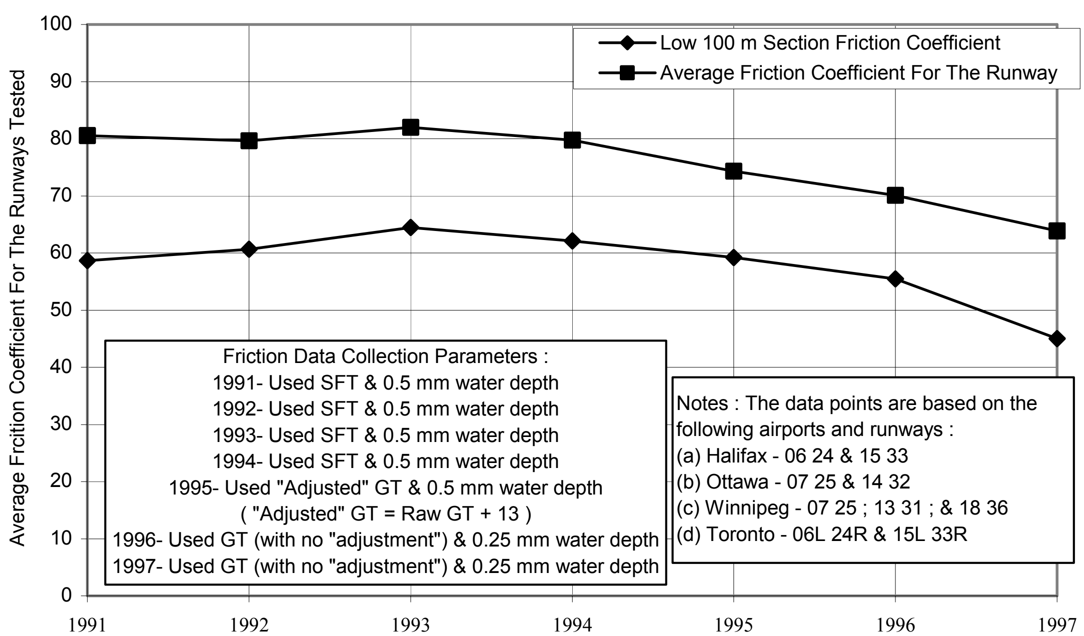


Figure 3.5: Long-Term Runway Friction Trends for the Major Canadian International Airports (after Comfort, 1998)

3.2.2 Short-Term Variations in Friction Level

(i) Observations on Roads and Highways

Short-term fluctuations in friction coefficient were found to be superimposed on the long term trends in the summer data (e.g., Saito and Henry, 1983; Burchett and Rizenbergs, 1980; Shakely, Henry, and Heinsohn 1983; Hill and Henry, 1981; Kulakowski et al, 1990). The friction coefficients were highly variable, by up to 20 SN's (Figures 3.6 and 3.7).

Saito and Henry, 1983 noted they were lowest at the end of a long dry period, and highest just after a rainstorm. This was believed to be due to the accumulation of dust, engine products (e.g., carbon), and other debris filling in the pavement microtexture, effectively causing "lower texture" pavement in the dry periods.

Kulakowski et al, 1990 present data showing that pavement rejuvenation efforts produce a significant increase in friction level, of up to about 15 SN's (Figure 3.7).

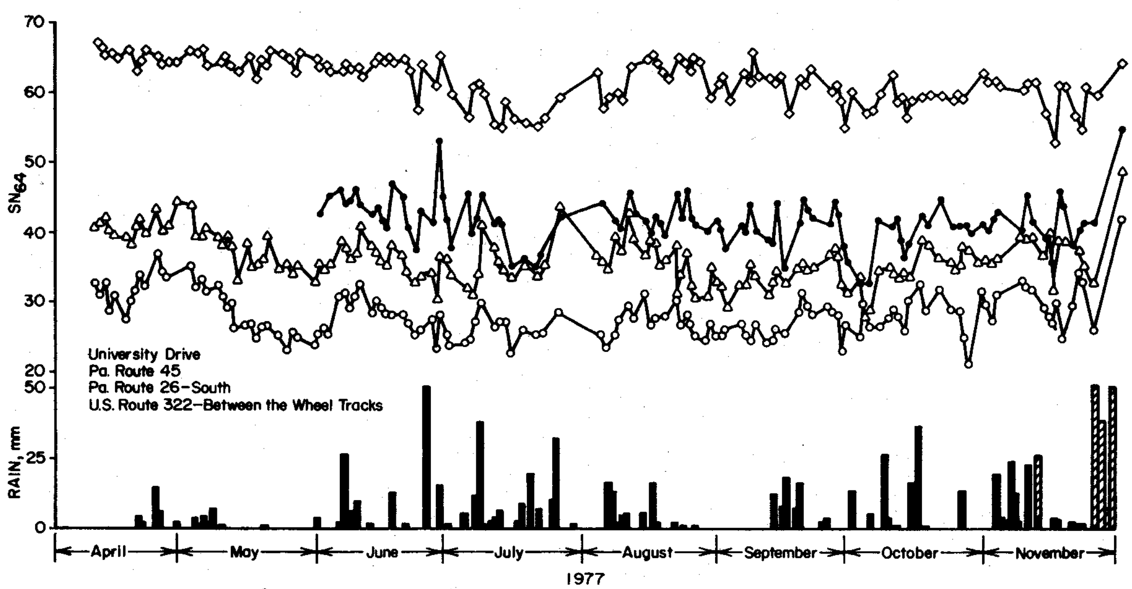


Figure 3.6: Short-Term Variations on Highways in Pennsylvania (after Saito and Henry, 1983)

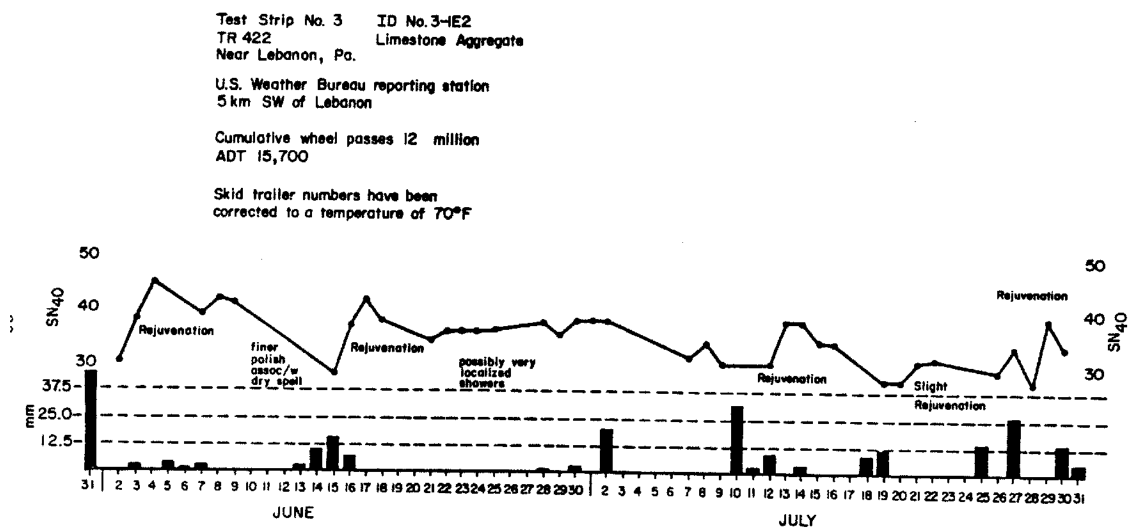


Figure 3.7: Short-Term Variations of Skid Resistance and Amount of Rainfall (after Furbush and Styers, 1972; cited by Kulakowski et al, 1990)

(ii) Observations on Airport Runways

Regular measurements made with an SFT have shown that the friction coefficient varies greatly over the short term (Transport Canada, 1989). See Figures 3.8 and 3.9 for sample results obtained at Dorval and Pearson International (Toronto) airports, respectively.

Transport Canada, 1989, found that the SFT friction factor could increase by up to about 0.25 after a rain storm, compared to the "before-rain" values. This was believed to be due to the buildup of contaminants on the runway in the dry periods, and the action of rains which wash them off. This observation needs to be interpreted with some care, as the beneficial effect of rainfalls will depend on their periodicity. This is discussed in section 3.2.3.

Runway rubber removal operations affected the friction coefficient significantly as well. These operations increased the SFT friction coefficient by about 10 SFT friction coefficients at both Dorval and Pearson International (Toronto). See Figures 3.8 and 3.9, respectively.

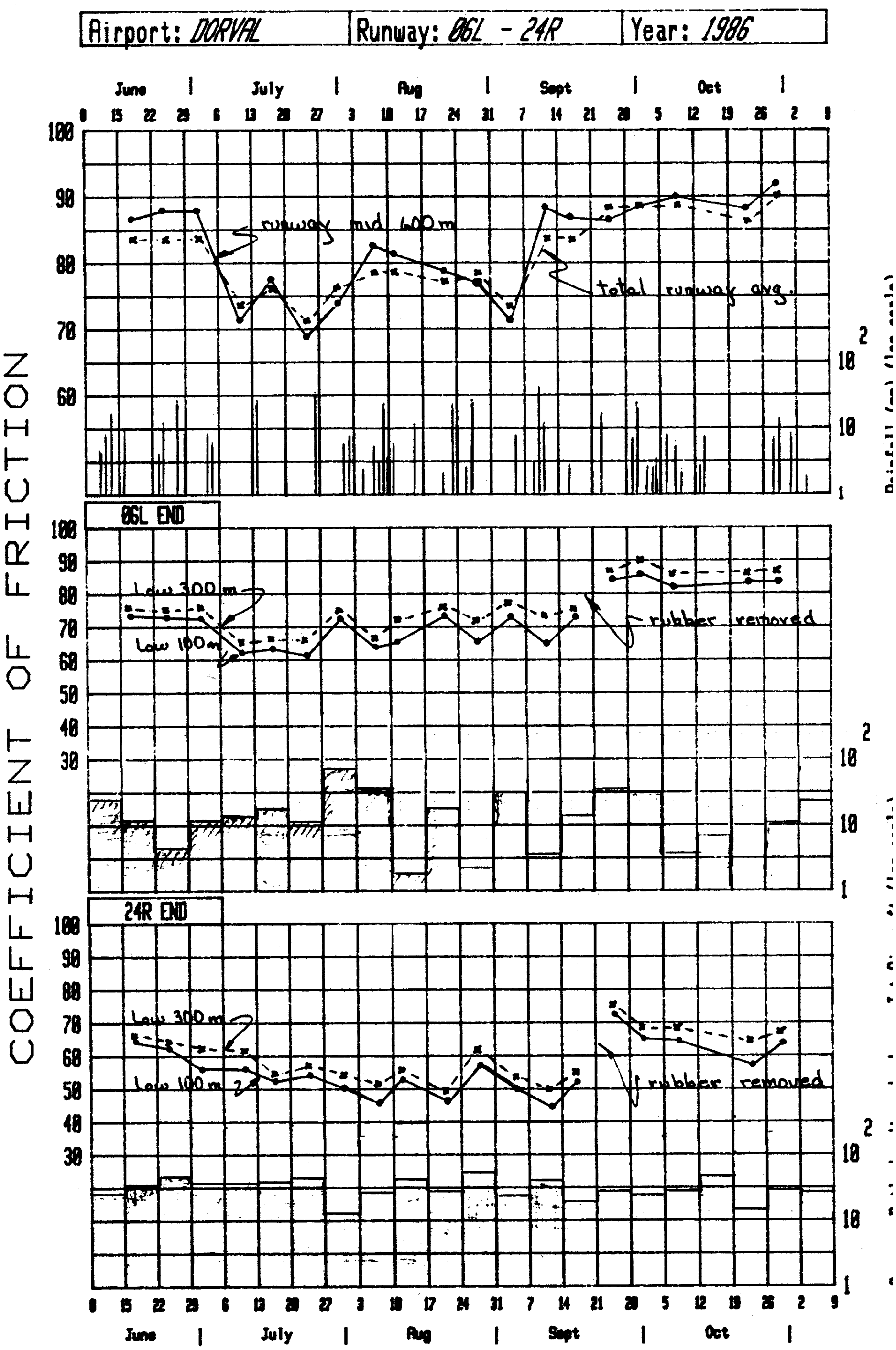


Figure 3.8: Friction Factor Variations at Dorval Airport (after Transport Canada, 1989)

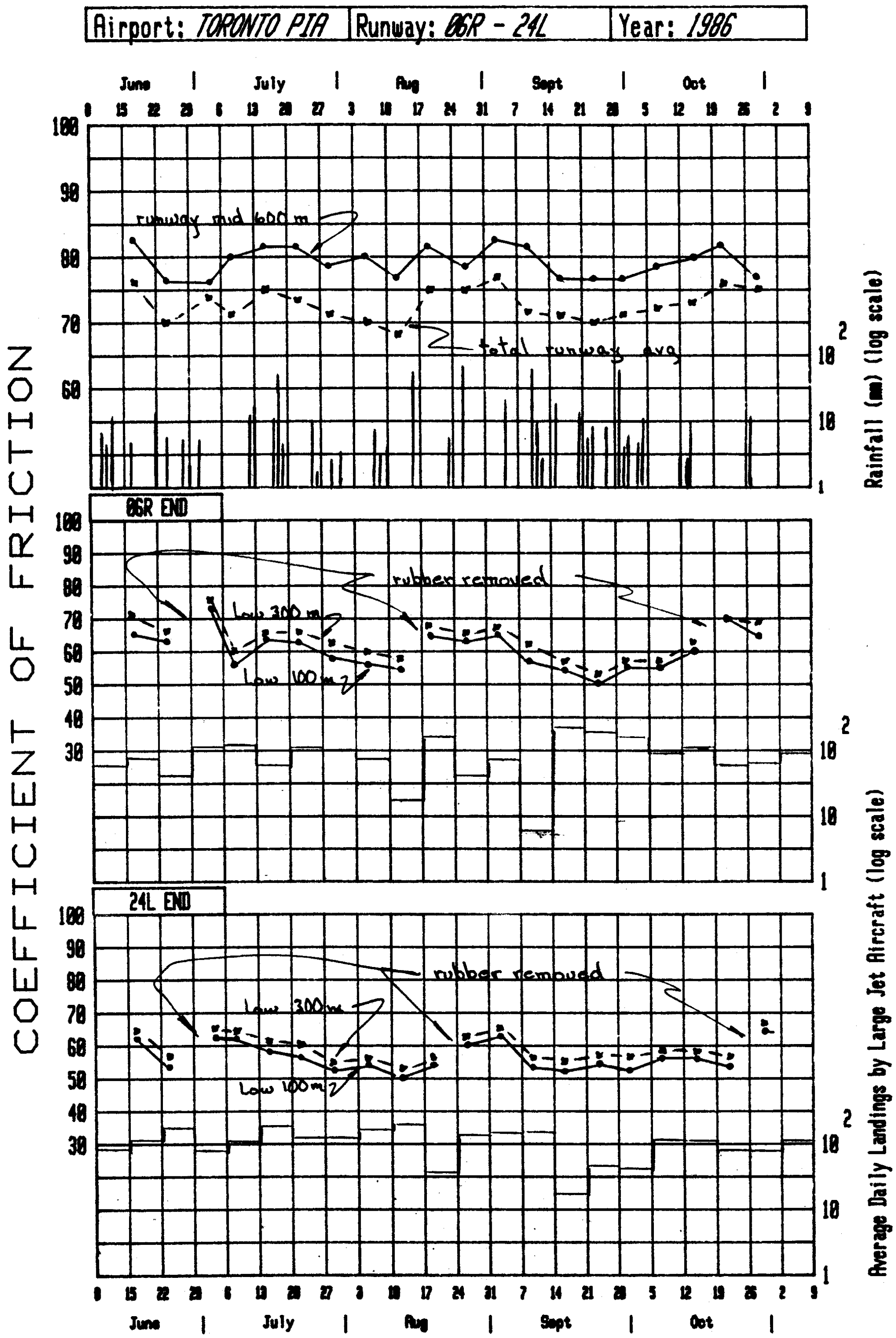


Figure 3.9: Friction Factor Variations at Toronto Airport (after Transport Canada, 1989)

3.2.3 Effect of Rainfall Periodicity

Field measurements on airport runways and on roads have both shown that the friction level tends to increase after a rainfall. This has a number of implications for assessing wet runway friction:

(a) the friction level of the runway changes continuously with time, and thus regular monitoring is required.

(b) over a rainstorm event, the friction level of a runway can be expected to vary with time over the period from dry to wet to dry again, generally as follows (also depicted in Figure 3.10):

   a. dry period before the rainstorm – the friction will drop as contaminants accumulate. The friction change will depend on factors such as:
      - the length of time between rain storms;
      - the intensity of the storms, and;
      - the amount and type of contaminants that are produced

   b. the rainstorm – the friction is expected to decrease. The greatest decrease will probably occur at the start of the rainstorm if contaminants are present, as they are likely to produce a greasy surface. The friction level will probably rise slightly during the rainstorm as the surface becomes wet as opposed to greasy.

   c. after the rainstorm – the friction will increase as the runway becomes dry. The "post rainstorm" friction levels may be higher than the "pre-rainstorm" ones if the rainstorm has removed contaminants from the runway.

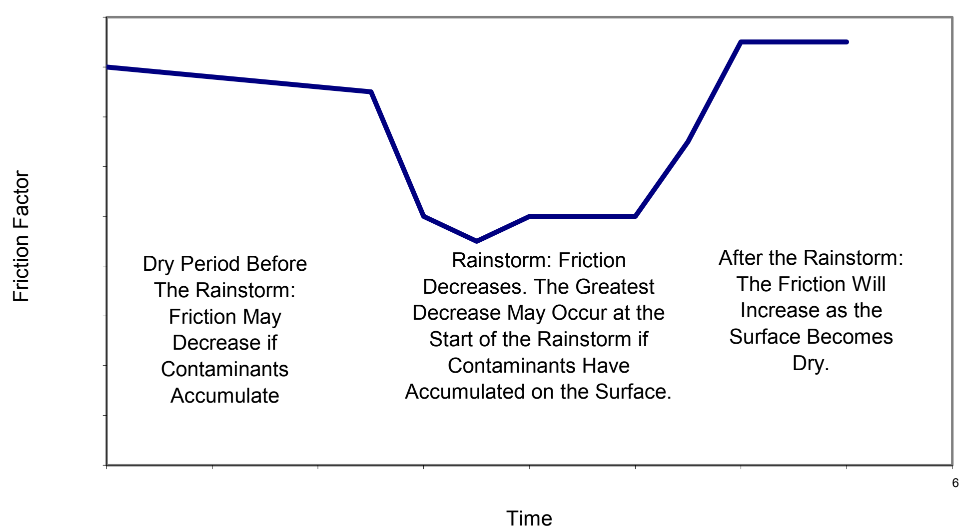


Figure 3.10: General Trends: Expected Friction Levels Before, During and After a Rainstorm

(c) beneficial and detrimental effects of a rainstorm (with respect to friction level) – from the above, it can be seen that these may be as follows:
    a. at the start of the rainstorm – the friction may be reduced if the surface becomes greasy.
    b. at the end of the rainstorm when the surface becomes dry again – the friction may be increased.

It should be noted that each of these effects are dependent on the periodicity of rainstorms. They are unlikely to be seen for a rainstorm that follows very soon after one that has just occurred, particularly if the first one was a severe rainstorm.

This is another reason why regular monitoring is required to evaluate friction levels.

3.2.4 Summary Assessment

(a) the road and runway data generally support each other with respect to the trends observed.

(b) friction coefficients on both roads and airport runways vary over the following general time scales:

    a. annually, or more, over several years - Cyclical variations have been observed as the friction coefficient was increased over the winter period, probably in response to winter maintenance operations. Over the summer period, the friction generally tended to decrease, owing to polishing.

    b. short term, on time scales of days or weeks - Friction coefficients varied in a highly irregular pattern, owing to the fact that they were caused by the combination of several irregular factors, such as:
        - the periodicity and intensity of rainfalls;
        - rubber buildup rates on the runway, and:
        - the periodicity and effectiveness of rubber removal or pavement maintenance operations

(c) the short term friction coefficient fluctuations were equal to, or often greater than, the long term fluctuations.

(d) because friction coefficients vary greatly in response to many factors that are not well understood or defined, it would be a very difficult, if not futile, exercise to try to predict friction coefficients from basic data.

(e) regular friction measurements are considered to be the most reliable, if not the only way, to establish the friction level of a runway at any given time.

3.3 Factors Controlling Wet Runway Friction: General Regimes

The friction vs. speed relationship has two general regimes as follows (also shown in Figure 1.2, in section 1):

(a) wet friction regime – tractive forces are developed between the tire and the pavement. The magnitude of these forces are dependent on a wide range of factors, which are discussed in sections 3.4 to 3.7.

(b) full hydroplaning regime – full hydroplaning occurs at speeds greater then those in the "wet friction" regime, although partial hydroplaning affects the tractive forces developed in the "wet friction" regime.

Full hydroplaning develops when sufficient pressure is built up under the tire to lift if off the pavement so that the tire is supported on a film of water. Because this film is incapable of transmitting significant shear forces, the tire has very low braking or cornering friction in this condition. Full hydroplaning is discussed in section 3.8.

3.4 Effect of Water Film Depth

3.4.1 Definitions

Yager, Phillips, and Horne, 1970 provided definitions for the runway wetness categories in common use, as follows:

(a) damp – this is defined as "having a moist (discoloured) surface where the average water depth is 0.01 inch or less on the pavement, as measured by the NASA water depth gauge";

(b) wet – this is defined as "having a moist surface where the average water depth lies between 0.01 and 0.1 inch as measured by the NASA water depth gauge", and;

(c) flooded – the water depth on the pavement exceeds 0.1 inch, as measured by the NASA water depth gauge.

3.4.2 Effect of Water Film Depth for High Tire Pressures

It should be noted that, for the purposes of this discussion, "high pressure" tires are those that would normally be found on the larger commercial and military aircraft. It is recognized that the tire pressures on these aircraft span a wide range, depending on the aircraft being considered. Thus a firm distinction between high and low pressure tires (which are discussed in section 3.4.3), is not possible. However, for the purposes of this discussion, they can be generally categorized as exceeding about 100 psi.

The relationship between water film depth and friction factor is complex for high pressure tires because it depends on many other factors, such as pavement texture and speed.

Figures 3.11, 3.12 and 3.13 show representative results obtained from aircraft tires tested at NASA's Landing Loads Test Track. The following trends are evident:

(a) on smooth concrete (i.e., a low-texture surface), the friction-speed relationship was practically identical for both damp and flooded conditions (Figures 3.11 and 3.12).

    In this case, damp conditions produced a similar loss in friction (compared to the dry value) as did flooded conditions. This is also evident in the results presented from Horne and Leland, 1962 (Figure 3.13).

(b) different trends were observed on a rough surface, as follows:

    a. friction factor magnitudes over the whole speed range – the friction factor was much higher on a rough surface than on a smooth one (Figures 3.11 and 3.12).

    b. the friction-speed relationship – this varied depending on the water film depth, as follows:

        - a damp runway: the friction-speed relationship was "flatter" (compared to the trend observed for a flooded runway – described subsequently) over the whole speed range, which indicates that higher friction was maintained as the speed was increased.

        - a flooded runway: the friction decreased rapidly as the speed was increased, compared to the results for a damp runway (Figures 3.11 and 3.12). This reflects the effects of partial dynamic hydroplaning which becomes more significant as the speed is increased.

          This differs from the damp runway results, in that higher friction was not maintained as the speed was increased.

Figure 3.14 shows results from tests with a C-141A aircraft (Yager, Phillips and Horne, 1970). These data indicate that the friction-speed relationship (inferred from the effective braking ratio plotted in Figure 3.14) was similar for surfaces with "wet with isolated puddles" and "flooded" surfaces. Higher effective braking ratios were measured over the whole speed range on grooved concrete, compared to ungrooved concrete, which reflects the better drainage provided by the grooved concrete surface.

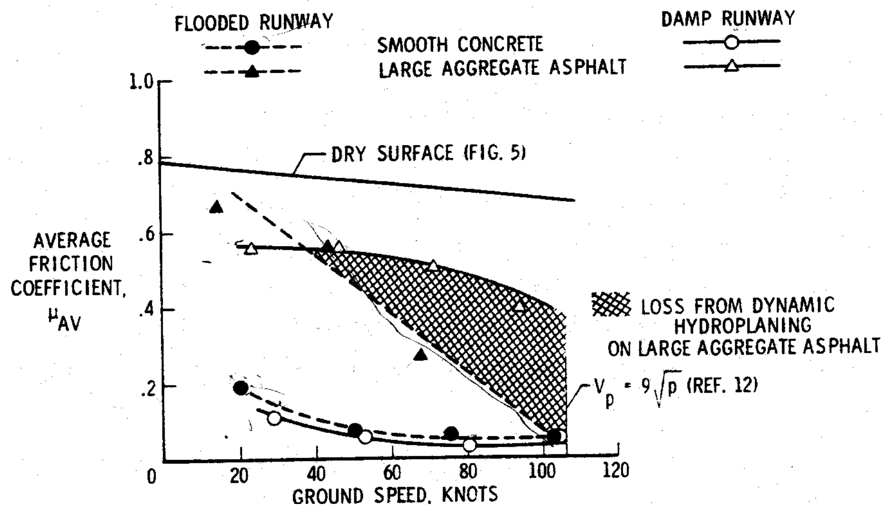


Figure 3.11: Effect of Water Film Depth Using an Aircraft Tire (after Horne et al, 1968)

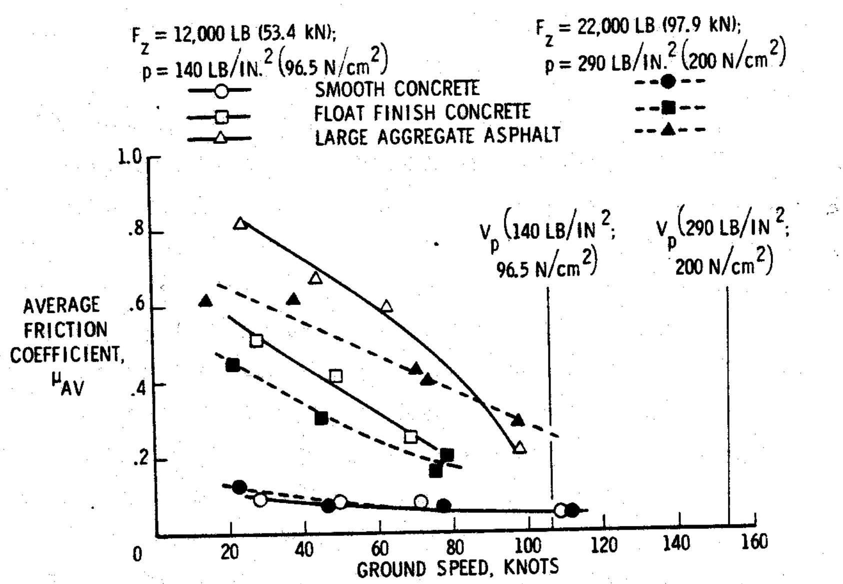
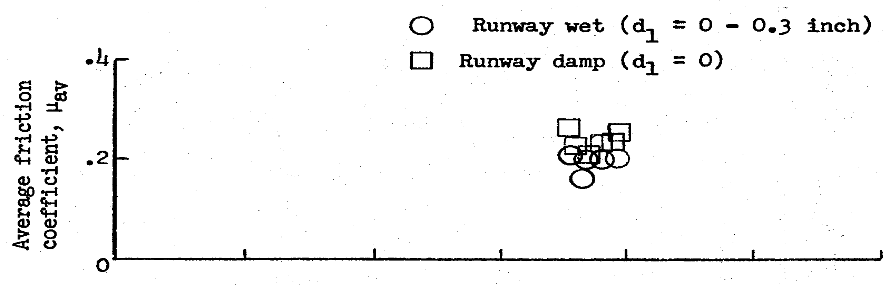
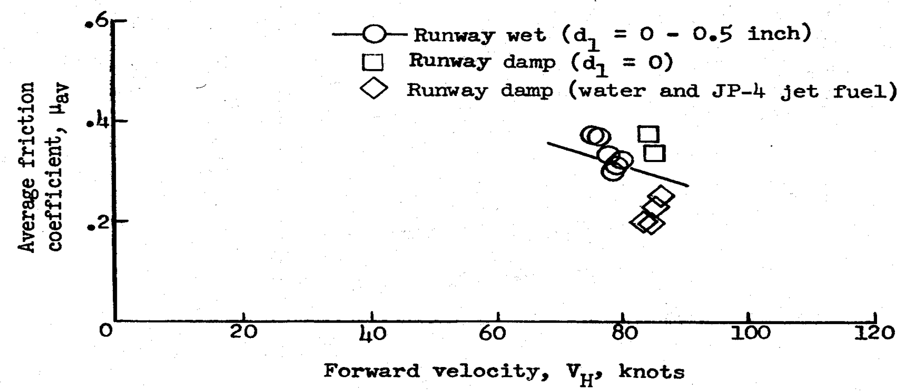


Figure 3.12: Effect of Water Film Depth for Two Aircraft Tires (after Horne et al, 1968)

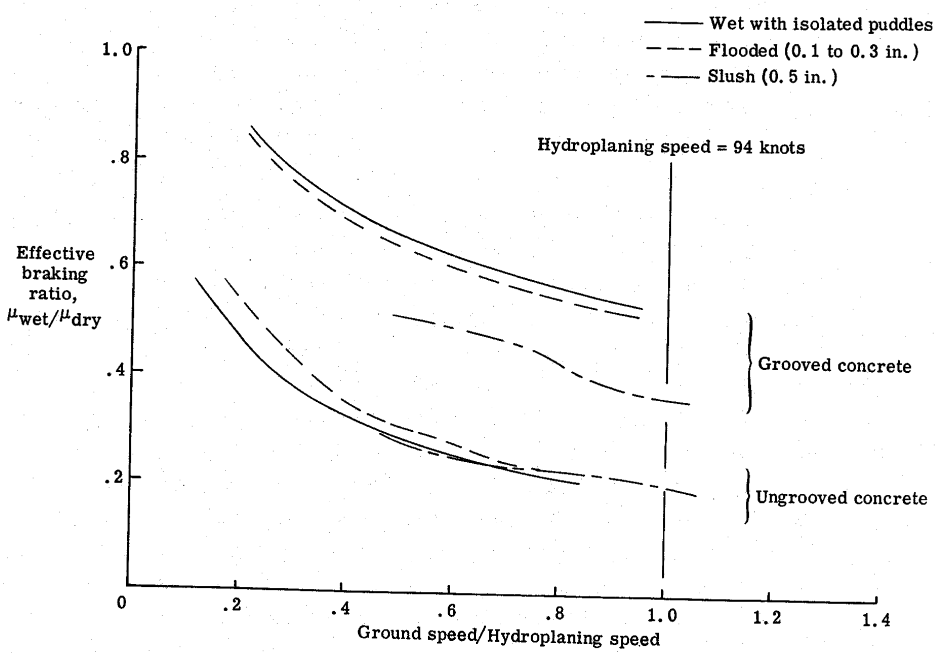


(a) Concrete runway; tire S1M3.



(b) Asphalt runway; tire S2M2.

Figure 3.13: Friction on Damp Versus Wet Conditions (after Horne and Leland, 1962)



(b) C-141A aircraft; five-groove tire; inflation pressure, 110 lb/in^2.

Figure 3.14: Effective Braking Ratios Measured for a C-141 Aircraft (after Yager, Phillips, and Horne, 1970)

3.4.3 Effect of Water Film Depth for Low Tire Pressures

"Low pressure" tires are commonly used on ground vehicles employed to measure runway friction, and on smaller aircraft. Inflation pressures for ground vehicles typically range from about 20 psi to 100 psi.

Information is available from a number of sources, including:

(a) tests conducted at 18 airport runways in 1994 and 1995 using the SFT by Transport Canada, 1995;
(b) tests done at NASA's Wallops Island Flight Facility in Nov/Dec 1994 using the Griptester and the SFT (Krol, 1995);
(c) tests done with the Griptester and the SFT at Muskoka airport in 1995 by Transport Canada, 1995
(d) tests done with the ASTM Skid Trailer (ASTM, 1990) which are summarized by Meyer et al, 1974, and;
(e) tests on highways, as well as a laboratory test program, done by the Pennsylvania Transportation Institute (Kulakowski, 1987; Kulakowski et al, 1990)

(i) Airport Runways Using the SFT (Transport Canada, 1995)

Tests were conducted at 18 airport runways in Canada during the 1994 summer period by Transport Canada, 1995 to compare the friction coefficients measured by the SFT at 0.5 mm and 1.0 mm water depth.

Based on analyses of these data, Comfort, 1998 found that, on average, the friction coefficients measured with a 1.0 mm water film depth were slightly lower than those at 0.5 mm for the runway average, the runway center third, and for the low 100 m section (Figure 3.15).

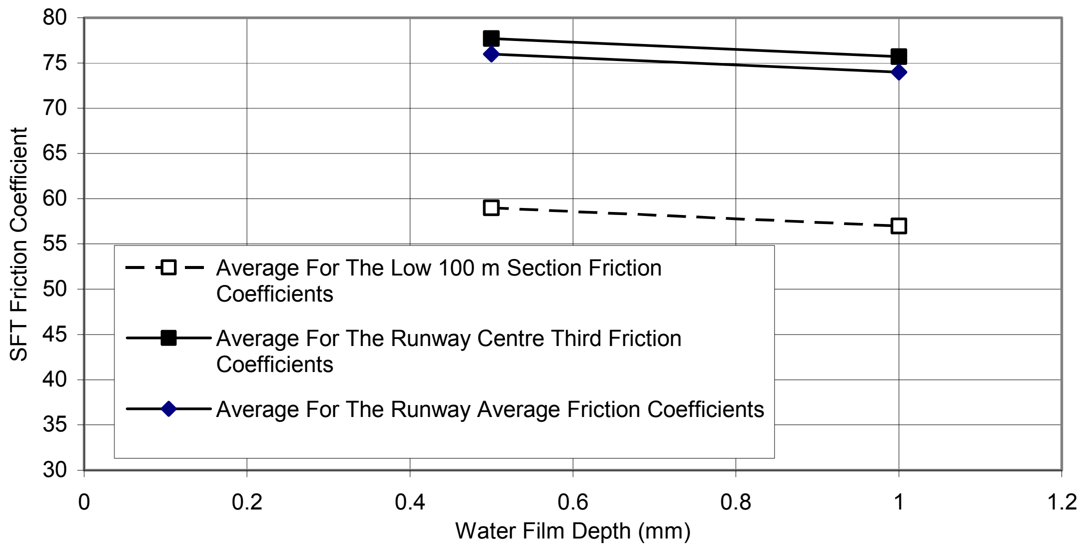


Figure 3.15: Comparative Tests with the SFT at 0.5 and 1.0 mm Water Film Depth (after Comfort, 1998)

However, the measured differences were small in relation to the respective friction coefficients, and the variability of the measured friction coefficients was similar for 0.5 mm and 1.0 mm water film depth. Comfort, 1998, concluded that, in many cases, the observed variations were not statistically significant at relatively high confidence levels.

(ii) Tests at NASA's Wallops Island Flight Facility

Test data collected with the Griptester and the SFT during the November to December, 1994 period (provided by Krol, 1995) were analyzed by Comfort, 1998. Tests were carried out on Surfaces A, B, D, E and F at the Wallops Island Flight Facility. Test surfaces "A" and "D" were smooth concrete while Test Surface "B" was textured concrete. Test surfaces "E" and F" were asphaltic concrete.

Results are shown in Figures 3.16 to 3.20 for:

(a) tests at 40 mph using Transport Canada's SFT (Figures 3.16 and 3.17);
(b) tests at 40 mph using the FAA's SFT (Figure 3.18);
(c) tests at 60 mph using the FAA's SFT (Figure 3.19), and;
(d) tests at 40 mph using the Griptester (Figure 3.20).

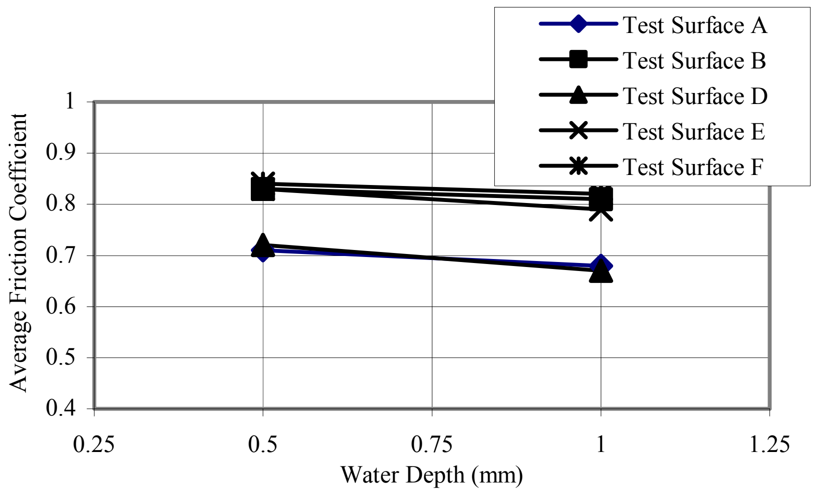


Figure 3.16: SFT Friction Coefficients at 40 mph for Canadian ASTM Tire 1 (after Comfort, 1998)

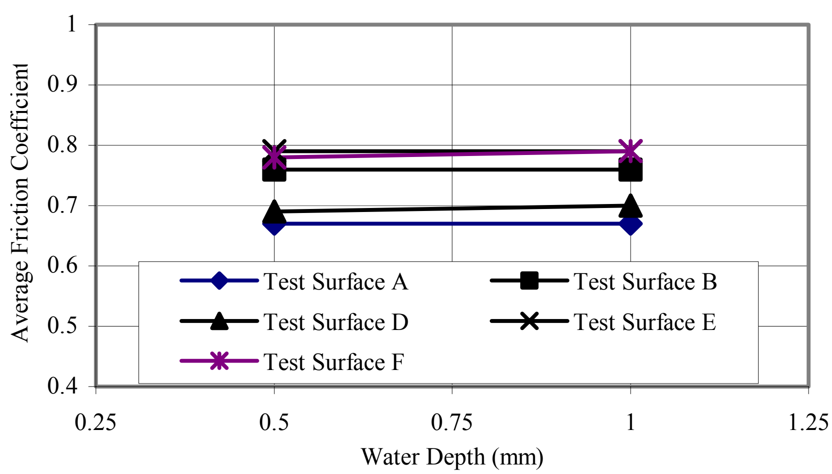


Figure 3.17: SFT Friction Coefficients at 40 mph for Canadian ASTM Tire 2 (after Comfort, 1998)

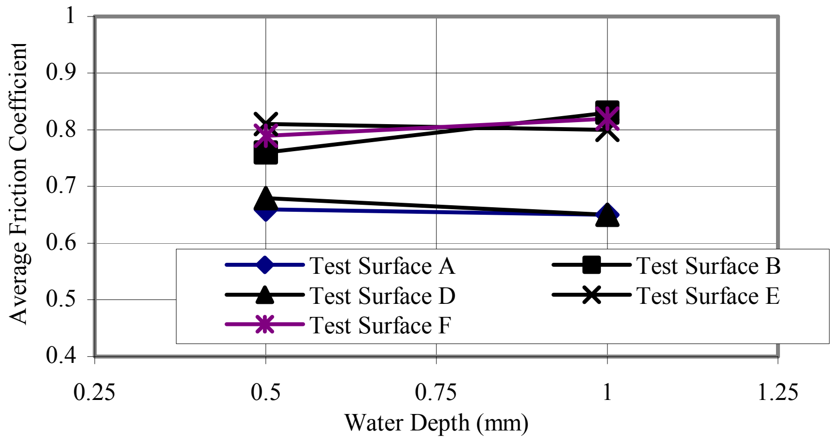


Figure 3.18: SFT Friction Coefficients at 40 mph for FAA ASTM Tire 1 (after Comfort, 1998)

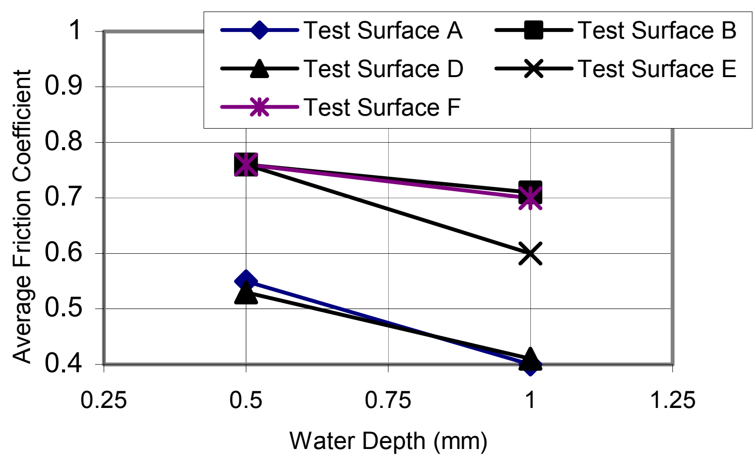


Figure 3.19: SFT Friction Coefficients at 60 mph for FAA ASTM Tire 2 (after Comfort, 1998)

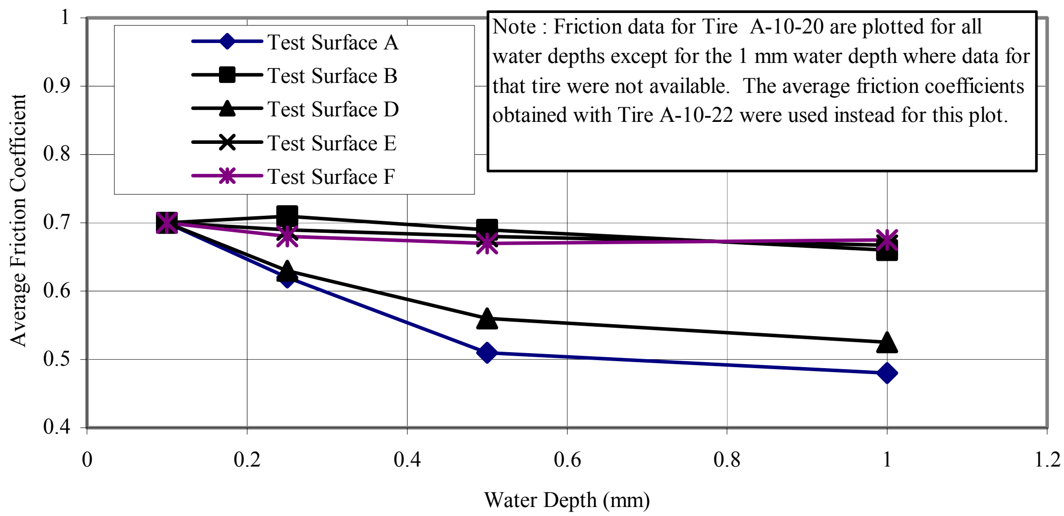


Figure 3.20: Griptester Friction Coefficients at 40 mph (after Comfort, 1998)

The friction coefficients measured at 40 mph with the SFTs were relatively independent of water film depth (Figures 3.16 to 3.18). At 60 mph, lower friction coefficients were measured on all surfaces with the SFT at 1.0 mm water film depth, compared to 0.5 mm (Figure 3.19).

The friction coefficients measured with the Griptester were insensitive to water film depth on the rougher surfaces (i.e., the textured concrete, and the asphaltic concrete). On the smooth concrete (i.e., surfaces “A” and “B”), the Griptester friction coefficients decreased with water film depth over the range from 0.1 to 1.0 mm (Figure 3.20).

(iii) Tests Done with the Griptester and the SFT at Muskoka Airport in 1995

The Griptester and the SFT were both tested with a range of water film depths on Runway 18 36 at Muskoka airport during the July-August, 1995 period (Krol, 1995).

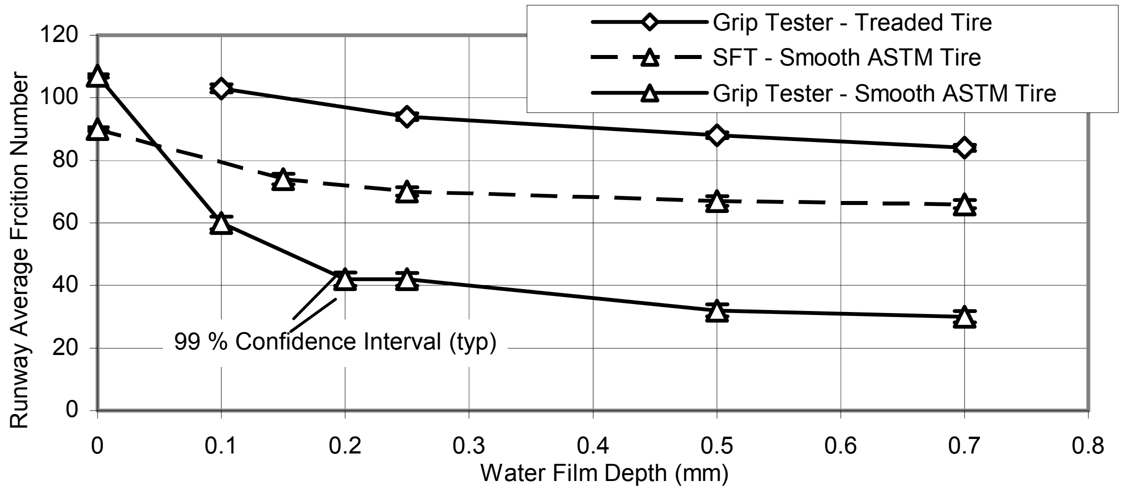


Figure 3.21: Effect of Water Film Depth on Friction: Tests on Runway 18 36 at Muskoka Airport (after Comfort, 1998)

These data show that the SFT friction coefficients and the Griptester friction coefficients obtained with the treaded tire were both relatively insensitive to water film depth (Figure 3.21). The friction coefficients obtained with a smooth tire on the Griptester show more sensitivity to water film depth, owing to the fact that less water drainage would have been possible with the smooth tire (Figure 3.21).

(iv) Tests Done with the ASTM Skid Trailer

The measured friction coefficients were independent of water film depth at depths greater than about 0.3 to 0.5 mm (Figures 3.22 to 3.23).

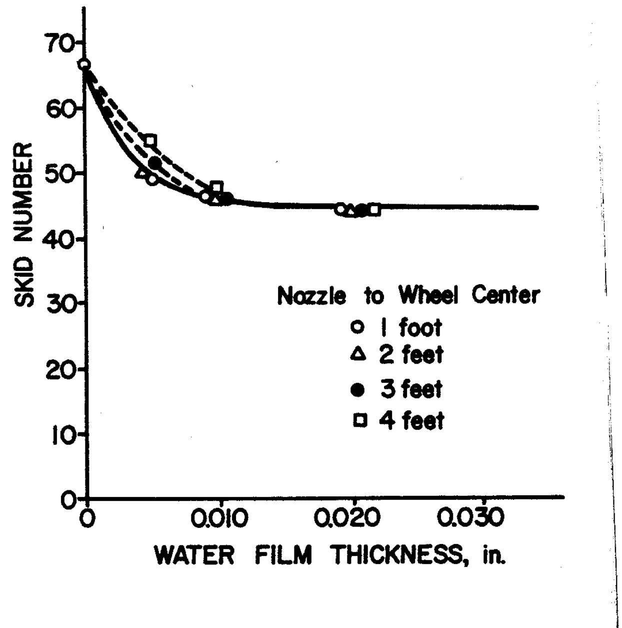


Figure 3.22: Effect of Water Film Depth (after Meyer et al, 1974)

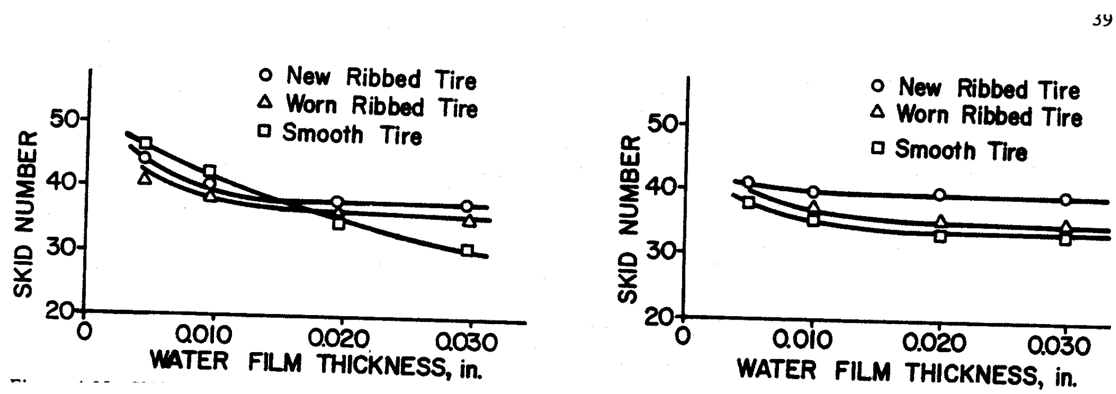


Figure 3.23: Effect of Water Film Depth (after Meyer et al, 1974)

(v) Field Tests with the ASTM Skid Trailer

Kulakowski, 1987; Kulakowski et al, 1990 conducted tests to investigate the effect of thin water films on tire-pavement friction. First, laboratory test were carried out.

Next, field test were conducted on four different pavement skid surfaces at the PTI Skid Resistance Research Facility which were described as: (a) “smooth asphalt”; (b) medium texture asphalt”; (c) high texture asphalt; and (d) “PCC (Portland Cement Concrete). Three test tires were used: (a) the smooth ASTM highway test tire (ASTM, 1988a); (b) the ribbed ASTM highway test tire (ASTM, 1988b); and (c) a worn passenger car tire. Friction measurements were carried out in accordance with ASTM E274 (ASTM, 1990). This test is carried out at 100% slip (i.e., locked wheel) with a tire inflated at 30 psi.

Based on analyses of the field data, Kulakowski and Harwood, 1990, recommended that the incremental wetness sensitivity, σ (equation 3.1) be used as a measure of the effect of water film depth on tire-pavement friction.

$$\sigma_{\text{for a film depth, d}} = \{[\Delta SN\ (1-e^{-d\beta})]\ /\ (SN_f + \Delta SN)\} * 100\ \% \qquad [3.1]$$

where: $\sigma_{\text{for a film depth, d}}$ = the percentage reduction in skid number, with respect to the skid number for a dry surface, caused by a water film of depth “d”

ΔSN = the estimated difference in skid number between a dry and a flooded surface (which was defined by “d” being greater than or equal to 0.015 inches)

SN_f = the estimated skid number for a flooded surface

β = a model parameter that was determined from the field test data. Values for “β” are listed in Kulakowski, 1987 for the surfaces tested.

The wetness sensitivities for the smooth ASTM tire and the ribbed ASTM tire are plotted in Figures 3.24 and 3.25, respectively. These results were selected for inclusion in this report as they span the range of possible cases.

For the smooth ASTM tire, the calculated reduction in friction with respect to a dry surface “levels off” at a film depth of about 0.3 mm for all surfaces tested (Figure 3.24). The results obtained with the ribbed ASTM tire also show that the friction decrease caused by a water film is independent of the film depth for layer thicknesses greater than about 0.3 mm (Figure 3.25).

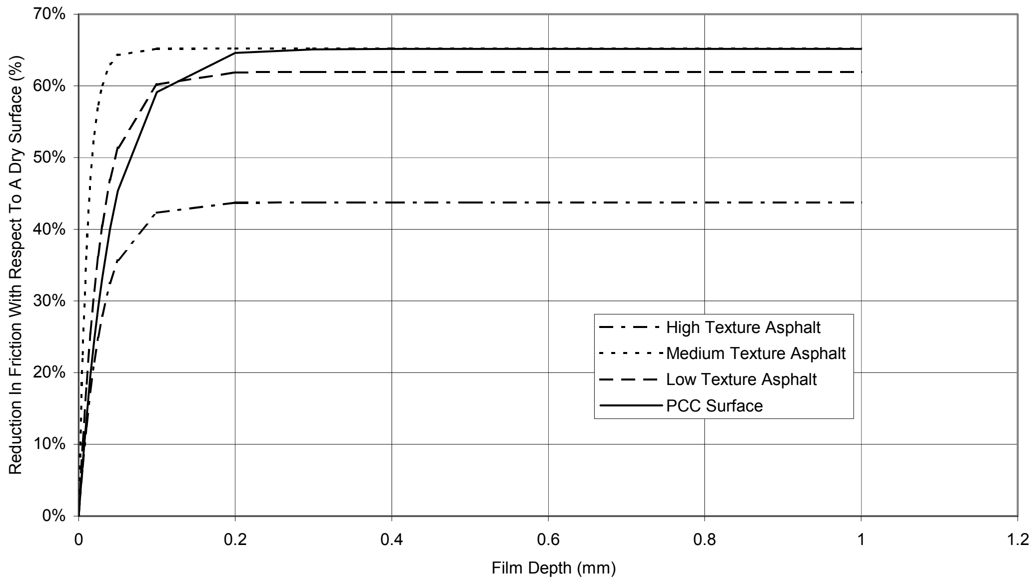


Figure 3.24: Effect of Film Depth: Results Calculated Using Equation 3.1 for the Smooth ASTM Tire

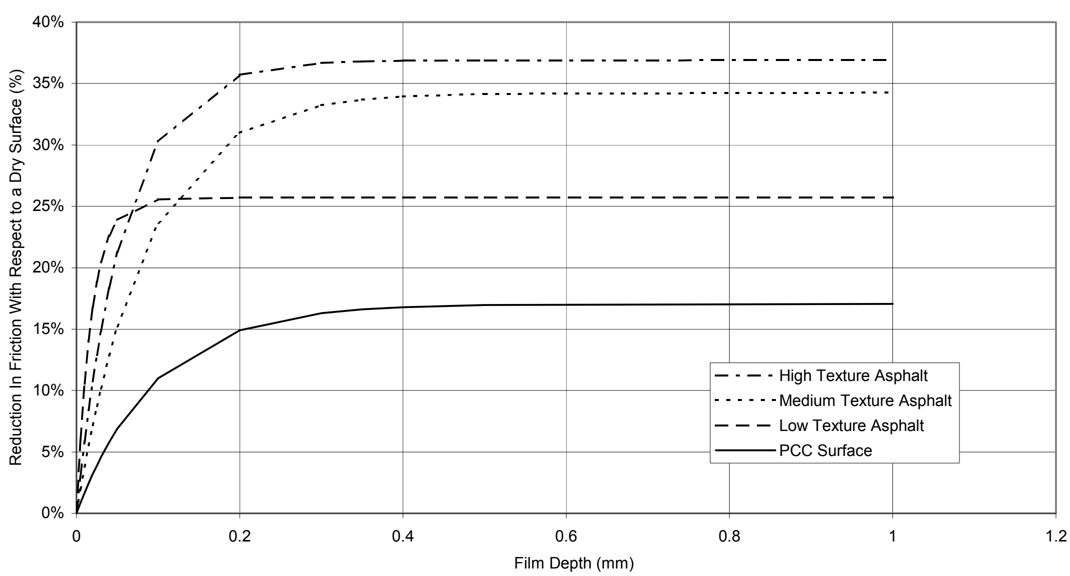


Figure 3.25: Effect of Film Depth: Results Calculated Using Equation 3.1 for the Ribbed ASTM Tire

3.4.4 Summary Assessment

(a) damp, wet, and flooded surfaces may be defined as having water film depths of less than 0.01 inch, between 0.01 and 0.1 inch, and more than 0.1 inch, respectively.
(b) the effect of water film depth varies with the tire pressure. Different trends have been observed for high-pressure aircraft tires, compared to low-pressure ground vehicle tires.
(c) for high pressure aircraft tires, the effect of water film depth varies with the surface texture.
(d) high pressure tires on low-texture surfaces – the friction-speed relationship was practically identical for both damp and flooded conditions. In this case, damp conditions produced a similar loss in friction (compared to the dry value) as did flooded conditions
(e) high pressure tires on high-texture surfaces –
    a. friction factor magnitudes over the whole speed range – the friction factor was much higher on a rough surface than on a smooth one.
    b. the friction-speed relationship – this varied with the water film depth:
        - a damp runway: the friction-speed relationship was "flatter" over the whole speed range, which indicates that higher friction was maintained as the speed was increased.
        - a flooded runway: the friction decreased rapidly as the speed was increased, compared to the results for a damp runway. This reflects the effects of partial dynamic hydroplaning which becomes more significant as the speed is increased. This differs from the damp runway results, in that higher friction was not maintained as the speed was increased.

(f) for low-pressure ground vehicle tires, the friction factor is essentially independent of the water film depth for thicknesses exceeding about 0.3 to 0.5 mm.

3.5 Effect of Pavement Texture

3.5.1 Ungrooved Pavement

Sample results from tests with aircraft tires are shown in Figures 3.26 to 3.28. On a damp runway, and one described as "wet with isolated puddles" (Figures 3.27 and 3.28, respectively), the friction factor reduced with the pavement texture over the whole speed range.

Figure 3.26 shows the observed relationship with texture depth for a flooded runway. The friction factor increased with the pavement texture although the relationship was speed-dependent. At high speeds, the friction factor increased over the whole pavement texture range, which probably reflects the improved drainage provided by the higher texture.

For the lower speeds, the friction factor tended to "level off" at the higher pavement texture, which probably indicates that viscous hydroplaning was predominant.

For ground vehicles, sample results are shown for the SFT and the Griptester in Figures 3.16 to 3.20 (in section 3.3.1). For all cases tested, the SFT friction coefficients at 40 mph were about 0.15 higher on the textured surfaces at Wallops (i.e., B, E, and F) compared to those on the smooth concrete (surfaces A and D).

The Griptester friction coefficients were about 0.2 higher on the same textured surfaces than on the smooth ones.

These results show that the ground vehicle results are also affected by surface texture, and they probably reflect the improved water drainage provided by higher texture surfaces.

3.5.2 Effect of Grooves

The effect of grooving the pavement is illustrated in Figures 3.28 and 3.29, which show friction data collected with aircraft tires.

On a flooded runway, the data indicate that grooving the pavement will increase the friction factor by about 0.2 to 0.4, depending on the speed at which the comparison is made. See Figure 3.29.

Similar increases were observed for the grooved surfaces on a runway with a "wet and puddled surface" (Figure 3.28).

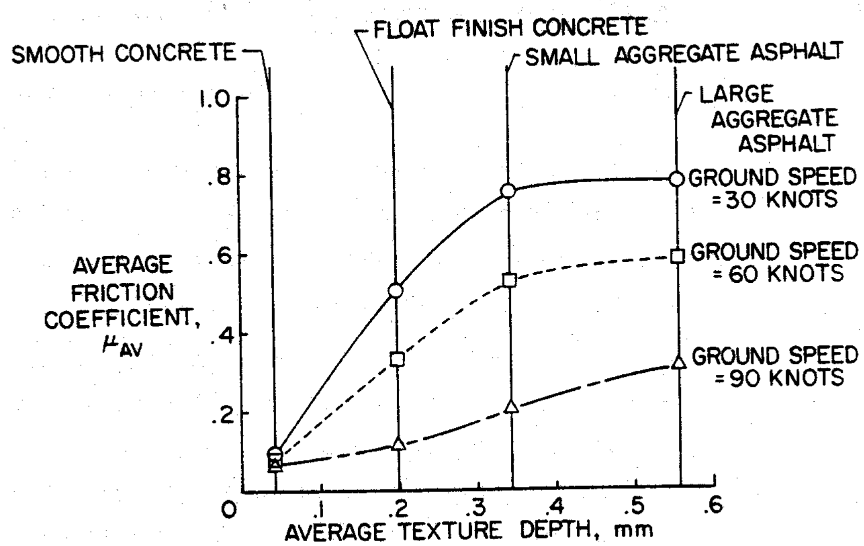


Figure 3.26: Effect of Pavement Texture (after Horne, Yager, and Taylor, 1968)

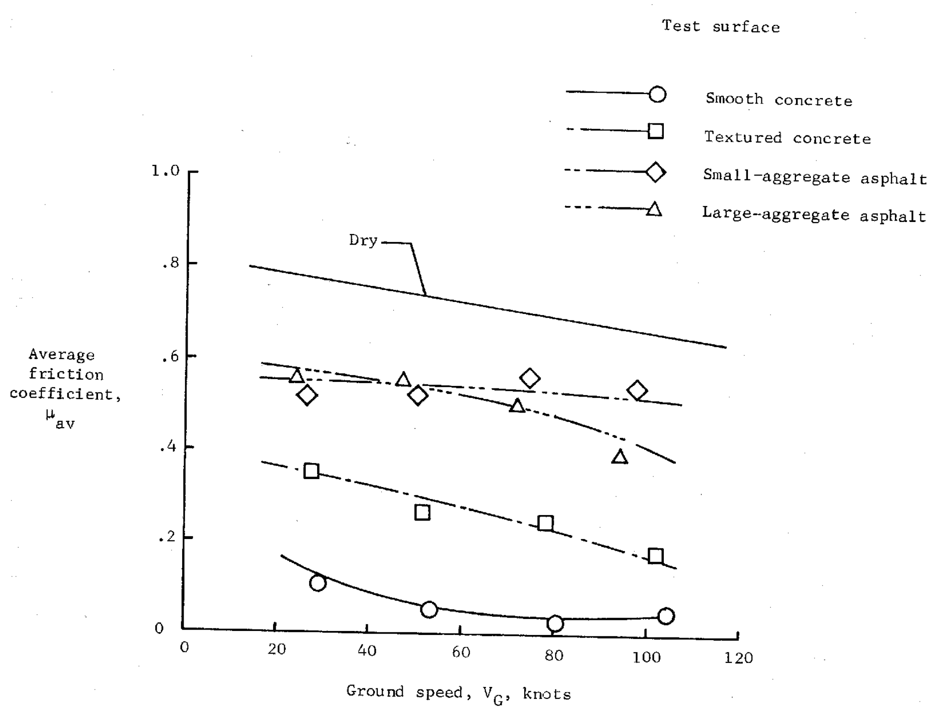
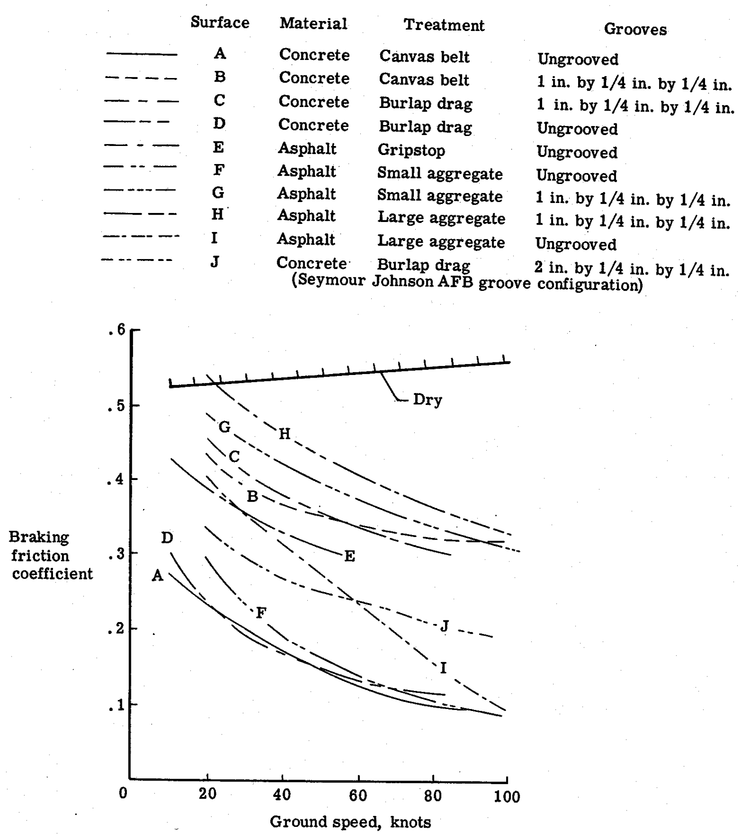


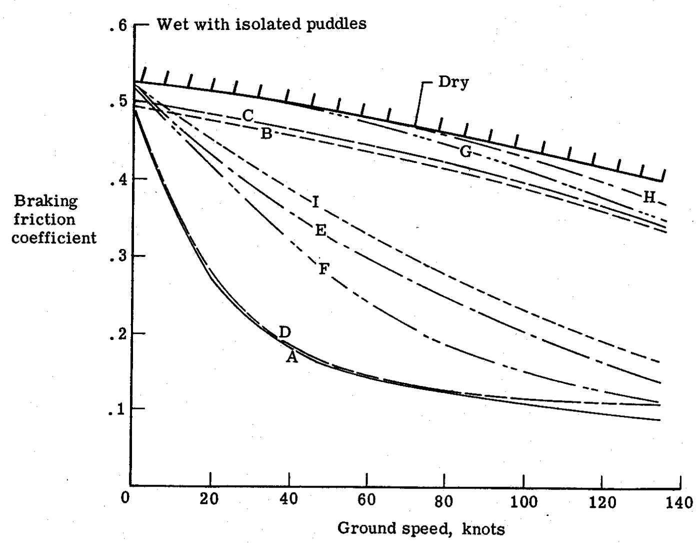
Figure 3.27: Effect of Surface Texture (after Leland, Yager, and Joyner, 1968)



(a) C-141A.

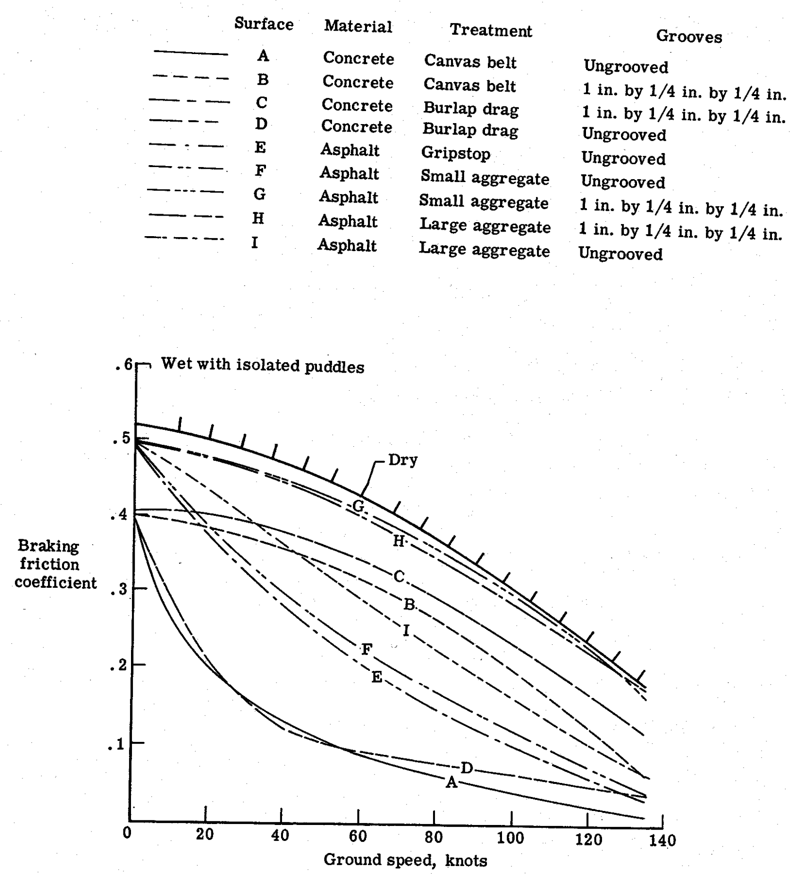
Figure 3.28: Trends Observed for Aircraft Tires (after Yager, Phillips and Horne, 1970)

Surface	Material	Treatment	Grooves
A	Concrete	Canvas belt	Ungrooved
B	Concrete	Canvas belt	1 in. by 1/4 in. by 1/4 in.
C	Concrete	Burlap drag	1 in. by 1/4 in. by 1/4 in.
D	Concrete	Burlap drag	Ungrooved
E	Asphalt	Gripstop	Ungrooved
F	Asphalt	Small aggregate	Ungrooved
G	Asphalt	Small aggregate	1 in. by 1/4 in. by 1/4 in.
H	Asphalt	Large aggregate	1 in. by 1/4 in. by 1/4 in.
I	Asphalt	Large aggregate	Ungrooved



(b) 990A.

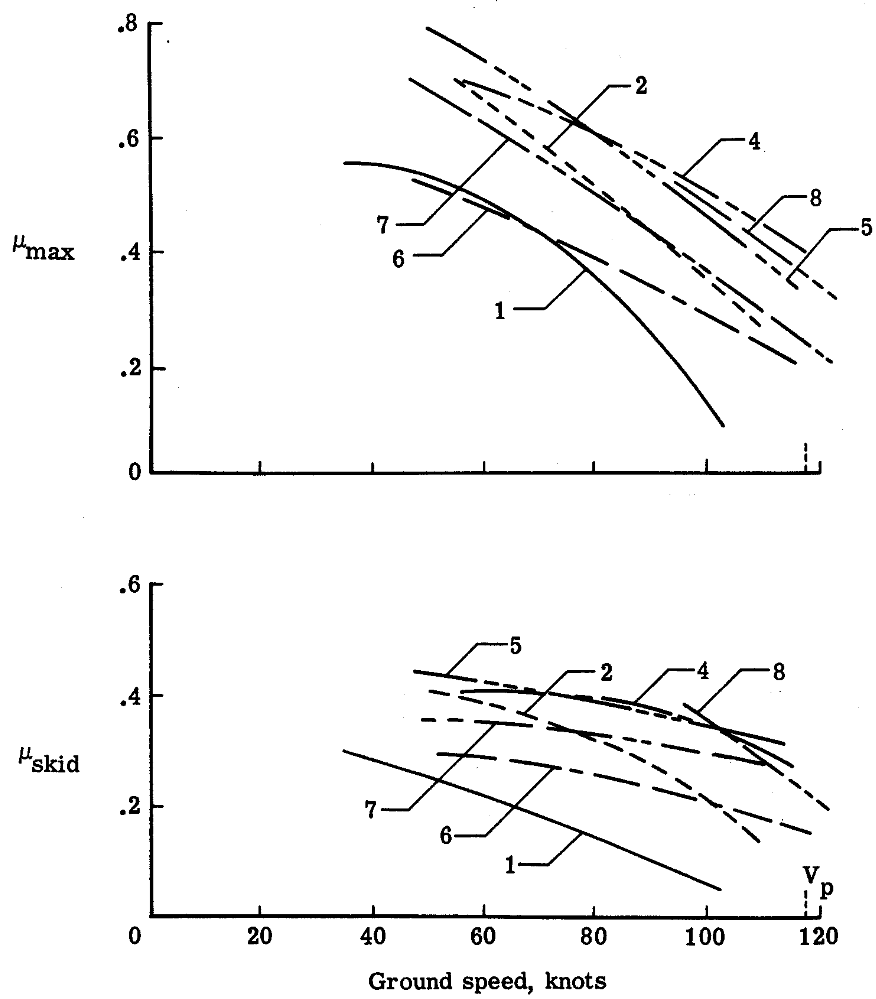
Figure 3.28 (cont'd): Trends Observed for Aircraft Tires (after Yager, Phillips and Horne, 1970)



(c) F-4D.

Figure 3.28 (cont'd): Trends Observed for Aircraft Tires (after Yager, Phillips and Horne, 1970)

Surface	Line code	Grooving technique	Grove pattern dimensions		Surface shape
			cm	in.	
1		None			
2		Combed	1.9 × 0.3 × 0.3	3/4 × 1/8 × 1/8	
3		Combed	3.2 × 0.6 × 0.6	1-1/4 × 1/4 × 1/4	
4		Sawed			
5					
6					
7			3.2 × 0.5 × 0.5	1-1/4 × 3/16 × 3/16	
8			2.5 × 0.6 × 0.6	1 × 1/4 × 1/4	



(a) Tire A.

Figure 3.29: Effect of Grooves (after Byrdsong and Yager, 1973)

3.5.3 Summary Assessment

(a) ungrooved pavement - the friction factors were increased in all cases (i.e., high-pressure aircraft tires vs. low-pressure ground vehicle tires; range of water film depths) for high-texture pavement, compared to smoother pavement.

(b) grooved pavement – data are only available for aircraft tires. However, these data show that higher friction factors were produced on grooved pavement in flooded conditions and on runways that were "wet and puddled".

3.6 Effect of Contaminants: Rubber and JP-4 Fuel

3.6.1 Available Information

None of the aircraft test programs reviewed in this project (listed in section 3.1) included tests on runways contaminated with rubber or JP-4 fuel. However, information was obtained from the following sources:

(a) tests at the NASA Landing Loads Test Track with JP-4 fuel on the surface (Horne and Leland, 1962)
(b) tests with NASA's Diagonal Braked Vehicle (DBV) on rubber-coated runways (Yager, 1983; Yager, Phillips, and Horne, 1970)
(c) tests with Transport Canada's Saab Surface Friction Tester (SFT) on rubber-contaminated airport runways in Canada (Transport Canada, 1989). These data were collected with a water film depth of 0.5 mm.

3.6.2 Effect of Rubber Deposits on the Runway

Sample results from the SFT friction measurements (Transport Canada, 1989) are shown in Figures 3.8 and 3.9 for runways at Dorval and Pearson (Toronto) airports, respectively. The SFT friction coefficient increased by about 10 after rubber removal operations had been carried out.

The NASA DBV data are presented in Figure 3.30. For ungrooved concrete, the presence of a rubber coating increased the wet/dry Stopping Distance Ratio (SDR) by about the same amount (i.e., about 0.3 to 0.5) over the full range of water depths tested (i.e., 0.25 mm to 4.3 mm). This suggests that the inferred friction decrease (from the observed increase in wet/dry SDR) was primarily caused by the presence of the rubber, and that the variation in water film depth had little effect.

For the artificial wetting tests (Figure 3.30), the SDR increase caused by rubber on the surface ranged from about 0.2 on grooved concrete, to about 1.5 on ungrooved asphalt. This probably reflects the fact that the ungrooved asphalt had the lowest texture of the three surfaces tested.

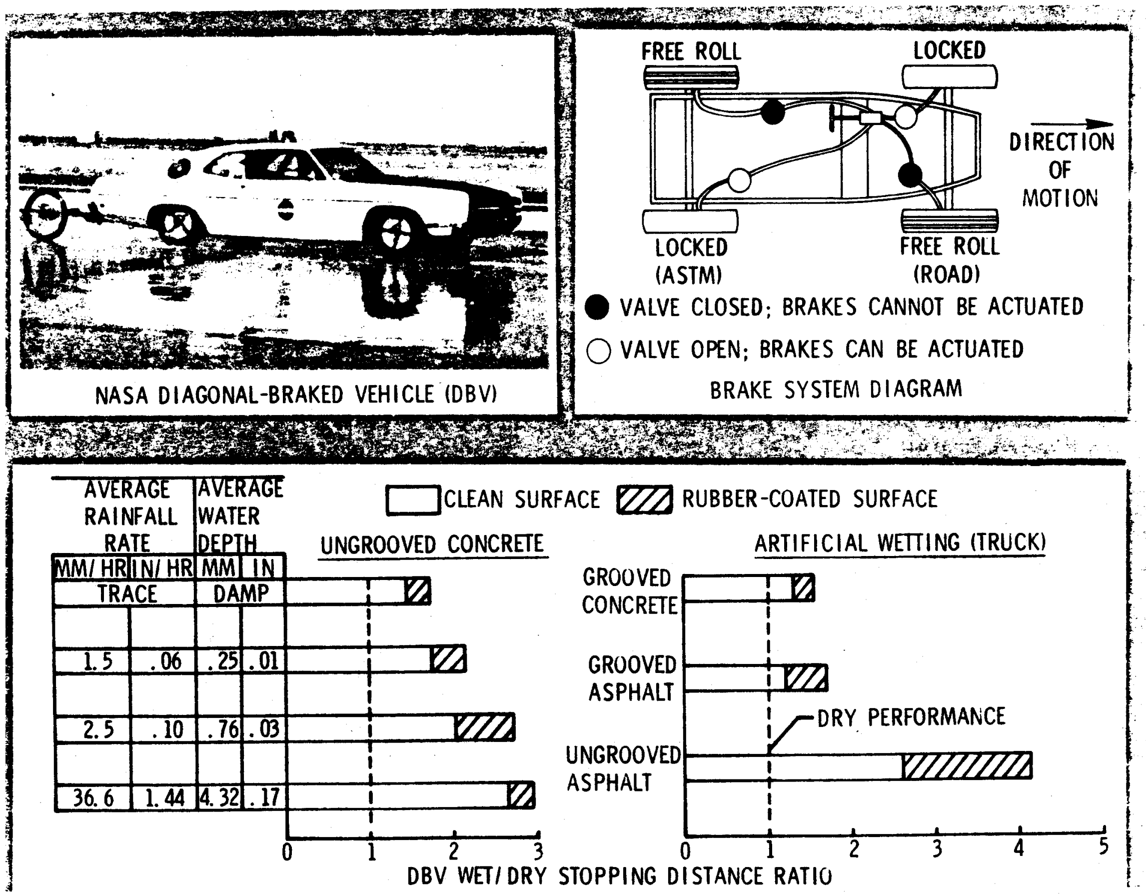


Figure 3.30: Effect of Rubber Coating on the Surface (after Yager, 1983)

3.6.3 Effect of JP-4 Fuel

Tests with an aircraft tire at the NASA Landing Loads Test Track (Horne and Leland, 1962) showed that the presence of JP-4 fuel reduced the friction factor to about 0.2 from a value of about 0.3 for wet and damp runway conditions on the same surface (Figure 3.13).

3.6.4 Assessment Summary – Effect of Rubber Deposits on Friction

(a) relatively little information is available. However, the little information that is available is derived from ground vehicles. No information was found from aircraft tests, or from tests using aircraft tires.
(b) it is generally known that the friction factor will be decreased by the presence of rubber deposits on the runway, and the available data support this.

(c) thus, one must rely on correlations between ground vehicle information and aircraft data to establish the expected effect of rubber on the runway.

3.6.5 Assessment Summary – Effect of JP-4 Fuel Deposits on Friction

(a) the friction factor experienced by an aircraft tire will be significantly reduced by the presence of JP-4 fuel on the runway, in comparison to the comparable value for a wet or damp runway.

3.7 Effect of Tire Pressure

Summary results are not included here as data showing the effect of this parameter have been presented in the previous sections. In brief, the effect of tire pressure can be summarized as follows:

(a) low vs. high water film depths (i.e., damp vs. flooded runway conditions) – the friction factors measured by low-pressure tires (in the range typical of those used for ground vehicles) are insensitive to water film depth at thicknesses exceeding about 0.3 to 0.5 mm (Figures 3.15 to 4.25).

The friction factors measured by higher-pressure tires exhibit a more complex relationship as it is also speed-dependent. At low speed, similar friction factors were measured on both damp and flooded conditions (Figure 3.11) which indicates that the friction factor is not dependent on film depth in this range. However, at higher speed, the friction factor measured on a flooded surface was significantly lower than the respective one for a damp surface (Figure 3.11). This variation reflects the influence of dynamic hydroplaning which becomes more significant at higher speed.

(b) low vs. high texture pavements – higher friction factors were measured with both low-pressure tires and with high-pressure tires on pavement with higher texture.

(c) effect of rubber deposits – the friction factors measured by low-pressure tires (in the range typical of those used for ground vehicles) decrease significantly by rubber deposits on the runway. Data for high-pressure tires are not available for comparison.

3.8 Hydroplaning

3.8.1 Definition of Hydroplaning

Hydroplaning is defined as the condition when a rolling or sliding tire on wet pavement is lifted away from the pavement surface as a result of water pressures built up under the tire. Horne et al, 1985, describe four manifestations of hydroplaning that are useful identifying the minimum speed at which hydroplaning commences, as follows:

(a) detachment of the tire footprint from the pavement;
(b) tire spindown;
(c) peaking of the fluid displacement drag, and;
(d) loss in tire braking/cornering traction.

3.8.2 Hydroplaning Phenomena and Contributing Factors

(i) Types of Hydroplaning

Three types of hydroplaning have been identified as listed below, and summarized in Table 3.1. See also Figure 3.31.

(a) viscous hydroplaning – this is the dominant mechanism contributing to friction loss on damp or wet runways, typically with low texture, at low speeds, for:

   a. thin water films less than 0.25 mm (0.01 in) thick (Leland, Yager, and Joyner, 1968; Yager, Phillips, and Horne, 1970; Yeager, 1974).
   b. smooth pavements – Horne, Yager, and Taylor, 1968 commented that:
      "fortunately, the texture existing on most runway surfaces is sufficient to break up and dissipate the thin viscous film which leads to this type of hydroplaning".
   c. low speed – as speed increases, inertial effects become more important than viscous effects with the result that the dynamic hydroplaning mechanism becomes predominant. See also Figure 3.32.

   Fluid pressures produced by viscous hydroplaning develop quickly as the ground speed is increased from a low value. They then tend to "level off" as the speed is increased towards the full hydroplaning speed (Figure 3.32). Thus, the majority of the friction loss associated with viscous hydroplaning occurs at low speeds.

   An opposite trend occurs with dynamic hydroplaning. For dynamic hydroplaning, the majority of the friction loss associated with viscous hydroplaning occurs at high speeds (Figure 3.32).

(b) dynamic hydroplaning – this occurs on flooded pavement. Typically, this occurs on thick water films when the water depth on the runway exceeds 2.5 mm [0.1 in] (Leland, Yager, and Joyner, 1968; Yager, Phillips, and Horne, 1970).

(c) reverted rubber hydroplaning – this occurs when the tire fails to spin up, which results in a non-rotating, tire being slid over the surface. High temperatures are produced which can generate steam in the tire footprint, causing revulcanization of the rubber. The factors contributing to the occurrence of reverted rubber hydroplaning are (Figure 3.31):
  a. poor pavement texture;
  b. high speed;
  c. a wet or flooded pavement, (although it can also occur on very smooth non-wetted surface, such as ice), and;
  d. a deficient brake system

Table 3.1: Effect of Water Depth on Hydroplaning Phenomena (after Horne, 1974)

TABLE I.- EFFECT OF WATER DEPTH ON TIRE HYDROPLANING PHENOMENA

RUNWAY WATER DEPTH RANGE, IN.	HYDROPLANING PHENOMENA EXPERIENCED
Greater than (0.05-0.10)	(a), (b), (c), and (d)
Between (0.02-0.03) and (0.05-0.10)	(b), (c), and (d)
Less than (0.02-0.03)	(c) and (d)

(a) DYNAMIC HYDROPLANING.- Unbraked wheel spindown, zero tire braking and cornering friction coefficients (aircraft ground speeds must be greater than tire dynamic hydroplaning speed, $V_p = 9\sqrt{p}$).*

(b) COMBINED DYNAMIC AND VISCOUS HYDROPLANING.- Reduced tire braking and cornering coefficients, slow recovery of wheel synchronous (ground speed) angular velocity from braking skid (from brake application).

(c) VISCOUS HYDROPLANING.- Reduced tire braking and cornering coefficients, slow recovery of wheel synchronous (ground speed) angular velocity from braking skid (from brake application).

(d) REVERTED RUBBER HYDROPLANING.- Very low tire braking friction coefficients at all ground speeds, tire cornering friction coefficient = 0 (only develops if prolonged locked wheel tire skid occurs due to pilot or antiskid failure to release wheel brake pressure after wheel skid from brake application).

* Where V_p tire dynamic hydroplaning speed, knots

p tire inflation, lb/in.^{2}

(ii)　　Factors Contributing to the Onset of Hydroplaning

These are summarized in Figure 3.31.

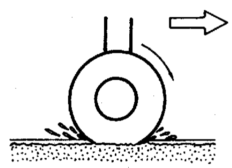
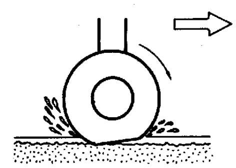
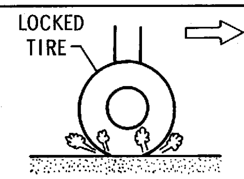
	HYDROPLANING		REVERTED RUBBER SKIDDING
	VISCOUS	DYNAMIC	
CAUSES			
CONTRIBUTING FACTORS	DAMP OR WET PAVEMENT MEDIUM TO HIGH SPEED POOR PAVEMENT TEXTURE WORN TIRE TREAD	FLOODED PAVEMENT HIGH SPEED LOW TIRE PRESSURE WORN TIRE TREAD	WET OR FLOODED PAVEMENT HIGH SPEED POOR PAVEMENT TEXTURE DEFICIENT BRAKE SYSTEM
ALLEVIATING FACTORS	PAVEMENT MICROTEXTURE PAVEMENT GROOVING GOOD TREAD DESIGN	PAVEMENT MACROTEXTURE PAVEMENT GROOVING INCREASED TIRE PRESSURE GOOD TREAD DESIGN	GOOD PAVEMENT TEXTURE PAVEMENT GROOVING IMPROVED ANTISKID

Figure 3.31: Principal Conditions for Hydroplaning to Develop on Wet Pavement (after Yager, 1983)

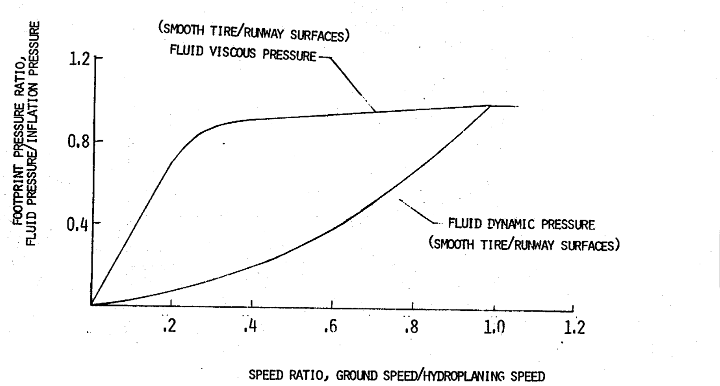


FIGURE 8.- FLUID PRESSURE DEVELOPMENT IN TIRE/RUNWAY CONTACT ZONE WITH GROUND SPEED (DATA OBTAINED FROM REFERENCE 5).

Figure 3.32: Fluid Pressure Development in the Tire Footprint Due to Hydroplaning (after Horne, 1974)

3.8.3 Predicting the Minimum Hydroplaning Speed

(i) NASA Equations for Dynamic Hydroplaning Speed for Aircraft and Truck Tires

The minimum speed for dynamic hydroplaning (for a flooded runway) is related to the tire pressure and aspect ratio (Horne, Yager, and Ivey, 1985; Horne, 1974; and Figures 3.33 to 3.34), as follows:

(a) Aircraft Tires: Horne et al, 1985; Horne, 1974 developed equations 3.2 and 3.3 to define the minimum hydroplaning speeds for aircraft tires during wheel spin-up and wheel spin-down. It is important to note that hydroplaning occurs at slower speed during wheel spin-up, and thus, for the same runway conditions, hydroplaning is more likely to occur for aircraft landings than takeoffs.

For aircraft tires, Horne et al, 1985; Horne, 1974 found that their hydroplaning speed data could be well defined based on only the tire inflation pressure (Figure 3.33), as follows:

Wheel Spin-down: $V\ (\text{kts}) = 9\ \sqrt{p(\text{psi})}$ [3.2]

Wheel Spin-up: $V\ (\text{kts}) = 7.7\ \sqrt{p(\text{psi})}$ [3.3]

where: p = tire inflation pressure, in psi

It should be noted that equations 3.2 and 3.3 apply only to the following cases (Horne and Joyner, 1965):

a. "smooth or closed pattern tread tires which do not allow escape paths for water", and;
b. "rib tread tires on fluid-covered runways where the depth of the fluid exceeds the groove depths in the tread of these tires".

Horne and Joyner, 1965, and also Horne and Dreber, 1963, cautioned that some cases have been observed where a complete loss in braking traction occurred at ground speeds "considerably less than the tire hydroplaning speed" predicted by equation 3.2. They noted that these special cases occurred on smooth surfaces, and inferred that "thin film lubrication" (i.e., viscous hydroplaning) was taking place.

(b) Ground vehicle or truck tires – investigations of truck accidents on highways (Horne, 1984; Horne et al, 1985) showed that truck tires may have a wide range of tire footprint aspect ratios, in contrast to aircraft tires for which the tire footprint aspect ratio remains relatively constant. These investigations showed that the footprint aspect ratio needed to be included as a parameter in the predictor equation for truck tires. Equation 3.4 was developed based on tests at TTI (Horne et al, 1985):

Spin-down: V (mph) = 23.3 * [p(psi)]$^{0.21}$ (1.4/Footprint Aspect Ratio)$^{0.5}$ [3.4]

where: Footprint Aspect Ratio is defined as: $\frac{\text{tire footprint width}}{\text{tire footprint length}}$

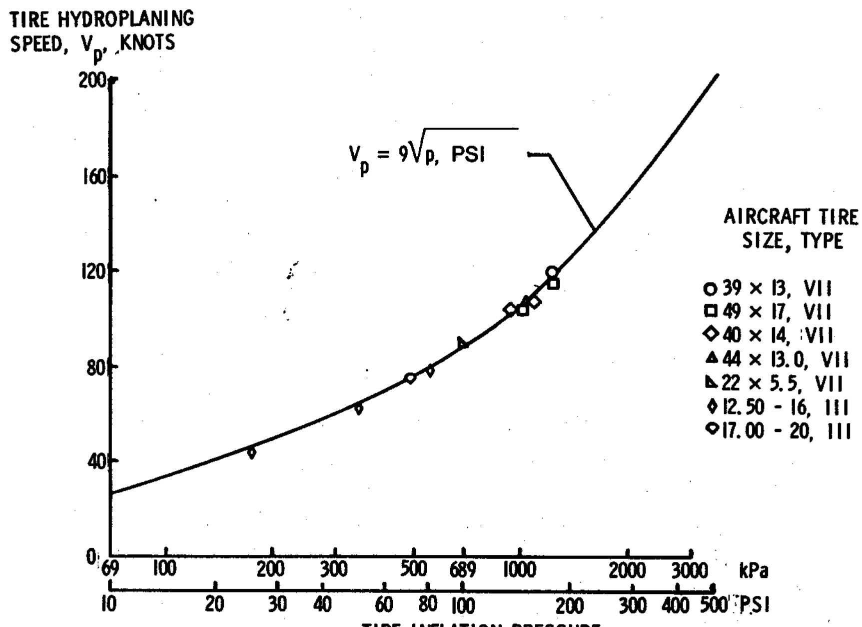


Figure 3.33: NASA Aircraft Tire Hydroplaning Speed Data (after Horne et al, 1985)

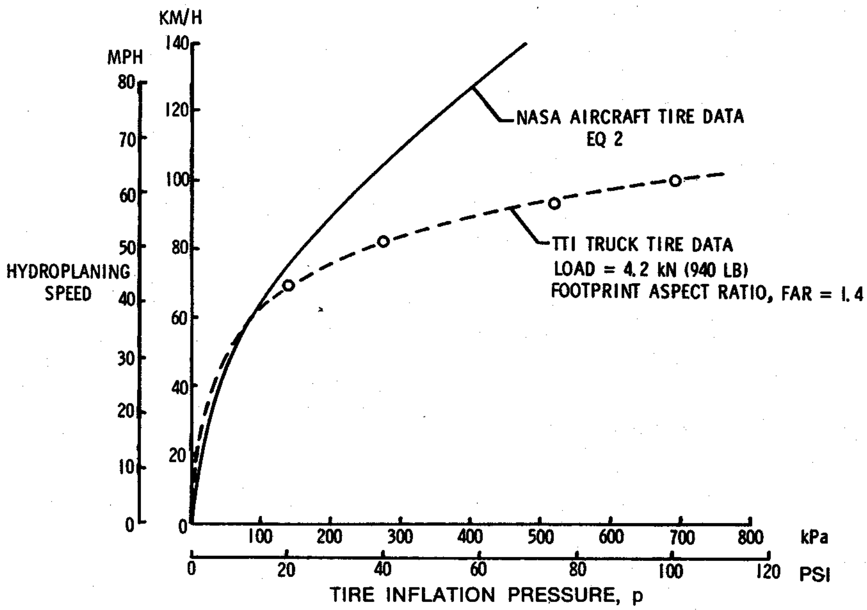


Figure 3.34: Comparison of NASA Aircraft Tire and TTI Truck Tire Hydroplaning Speed Data (after Horne et al, 1985)

Equation 3.4 predicts that hydroplaning will develop at lower speeds than equation 3.2 as the tire pressure is increased (Figure 3.34).

Further investigations were conducted at the 1997 NASA Wallops Flight Facility Friction Workshop. This was done in response to tire contact pressure measurements that were made during the 1997 North Bay winter test program which showed that the tire sidewall stiffness had a significant effect on the tire contact pressure for some tire pressure and load conditions, for the ground vehicles used to measure friction (Horne, 1998). This brought the relationship between the tire inflation pressure and the tire contact pressure into question. (One assumption made in developing equations 3.2 to 3.4 was that the tire inflation pressure is practically equal to the tire contact pressure, and for this reason, the tire contact pressure is not included as a parameter in equations 3.2 to 3.4).

The 1997 NASA Wallops tests showed that, for some cases, relations developed to predict the minimum hydroplaning speed based on the net contact pressure showed better agreement with the measured data than those based on the tire inflation pressure (Horne, 1998). Horne, 1998 developed a predictor for the minimum hydroplaning based on the measured friction factors on flooded and wet surfaces, and the test speed. This equation is not presented here because subsequent tests (at Wallops) showed that it significantly overestimated the measured hydroplaning speed. Horne, 1998, suggested that more tests were required, in which the water depth uniformity on the test track was better controlled.

Consequently, the range of applicability of equations 3.2 to 3.4 (beyond aircraft tires and high-pressure truck tires, which are the cases for which they were developed) is somewhat uncertain.

(ii) Low Pressure Tires

Wambold et al, 1984 incorporated the following equation into the Pennsylvania Transportation Institute's MAPCON (Methodology for Analyzing Pavement COndition Data) pavement model, as follows:

$$Vc = k1 * [(TD/25.4 + 1)^{k2} * MTD^{k3} * (k4 / WT^{k5} + 1)] \qquad [3.5]$$

(based on 10% spin-down; and 165 kPa tire pressure)

where: WT = estimated water film thickness (mm)
MTD = mean texture depth (mm)
TD = tire tread (mm)
Vc = critical hydroplaning speed (km/h)
k1, k2, k3, k4, & k5 = empirical coefficients – Wambold et al, 1984 suggest 8.4548, 0.05, 0.01, 1.8798, and 0.01 as typical values for these coefficients, respectively.

Equation 3.5 is not directly comparable to the NASA equations (i.e., equations 3.2 to 3.4) for a number of reasons:

(a) it is limited to a tire pressure of 165 kPa (24 psi) which is lower than most aircraft tires, as well as most of the ground vehicles used to measure friction at airports, and;

(b) it is applicable to the case where hydroplaning is defined as 10% wheel spindown

Nevertheless, equation 3.5 is instructive because it illustrates the effect of parameters such as film depth, tread depth, and pavement texture on hydroplaning (for low-pressure tires). It suggests that the hydroplaning speed will be essentially independent of film depth and tread depth (Figure 3.35). This supports the form of the NASA equations which do not include these factors as parameters in them.

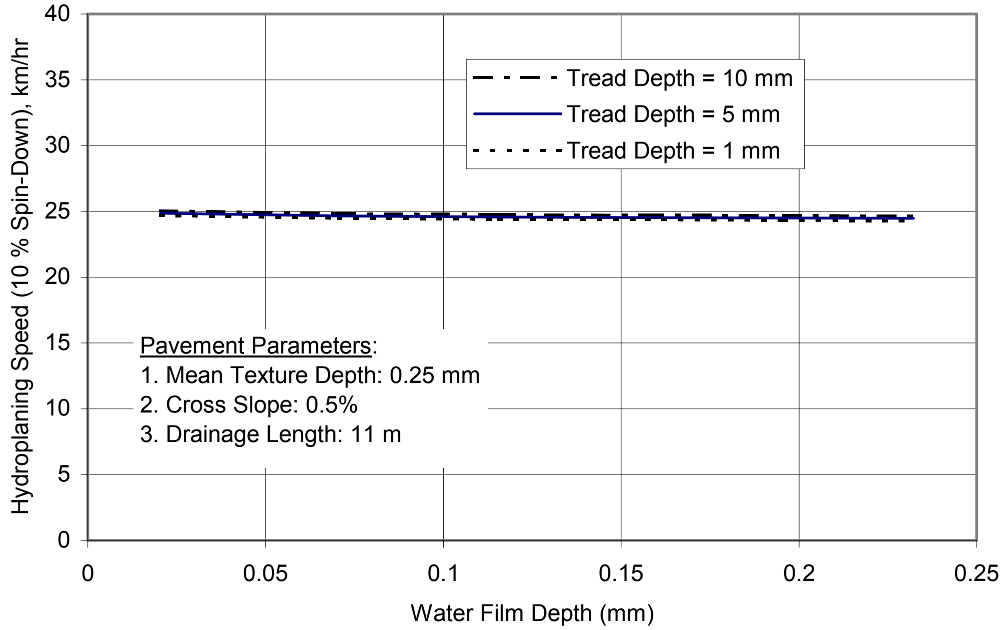


Figure 3.35: Hydroplaning Speed Predicted by Equation 3.5 for Low-Pressure Tires

3.8.4 Summary Assessment

(a) hydroplaning has been studied extensively. Three forms of hydroplaning have been identified (i.e., viscous hydroplaning, dynamic hydroplaning, and reverted rubber hydroplaning).

(b) the general conditions that cause hydroplaning have been identified. However, detailed technical information is not available to define the onset of hydroplaning quantitatively.

(c) equations have been developed to predict the minimum hydroplaning speed for dynamic hydroplaning. These have been generally corroborated with field observations.

4.0 EVALUATION METHODS

4.1 Overview

In principle, three types of information might be used for an evaluation of wet runway friction, and an aircraft's stopping distance on it, at a given time for a given surface and aircraft type, as follows:

(a) previous braking friction, or stopping distance, tests with that aircraft
(b) environmental and pavement condition measurements (e.g., water depth on the runway, wind conditions, pavement texture, presence or absence of rubber deposits, pavement cross slope, etc)
(c) friction measurements made with ground vehicles.

In fact, however, only a limited number of options are available, and they all have drawbacks for a number of reasons:

(a) aircraft data – only a small number of aircraft tests have been performed, with the result that the database is not very extensive. It is highly likely that test data would not be available for assessing the particular conditions of interest (e.g., aircraft type and configuration; environmental conditions; and pavement conditions).

(b) environmental and pavement condition parameters – there are several difficulties in using these data operationally:
   a. techniques for measuring the required environmental and pavement condition parameters quickly are not developed to allow measurements with a high degree of reliability and accuracy to be made in the time frame required to support aircraft operations at airports, and to account for the rapidly changing conditions that can occur at airport runways.
   b. the relationship between the environmental and pavement condition parameters and an aircraft's performance is only understood in a general manner. A universally accepted, proven method for predicting aircraft performance from these data is not available at present.

(c) ground vehicle friction measurements – these are capable of providing information quickly. However, they suffer from the drawback that up to now, they have been used with the primary purpose of providing data to guide runway maintenance operations (e.g., rubber removal, pavement rejuvenation) rather than as a tool to predict aircraft stopping distance performance.

As a result, the relationship between a given ground vehicle's friction measurements, and a given aircraft's stopping performance is not universally understood. Although correlations have been developed from tests in which ground vehicles have been tested at the same time as aircraft (e.g., Yager, Vogler, and Baldasare, 1990; Horne, 1998), a universal correlation approach is not available. Consequently, the correlations developed are unique to the conditions tested, such as:

a. the aircraft type and configuration;
b. the particular ground vehicle, and;
c. the particular pavement and environmental conditions.

In summary, the state-of-knowledge is primarily empirical.

However, a number of predictive methods have been developed, which are reviewed below.

4.2 The ESDU Approach

4.2.1 General Approach

This is described in ESDU, 1999a. The basic formulation of the model is given in equations 4.1 and 4.2.

$$\mu_{eff} = \mu_{datum} / [1+ (\beta q/p)] \qquad [4.1]$$

$$K = (\beta\, d_{tex})^{0.5} \qquad [4.2]$$

where: μ_{datum} = the friction factor of a reference surface, which was taken to be the dry value by ESDU, 1999a; 1999b; 1999c; 2000 in developing coefficients for the model.

μ_{eff} = the effective braking force coefficient developed by the aircraft

q = the dimensionless pressure, which is defined by the following ratio:

the dynamic pressure, which has been used as a parameter in previous hydroplaning studies (e.g., Horne and Joyner, 1965)
the tire inflation pressure

$= 0.5*\rho_w V_g^2/p$

where: p = tire inflation pressure

$0.5*\rho_w V_g^2$ = the dynamic pressure, , and:

ρ_w = the mass density of water

V_g= the ground speed

d_{tex} = the pavement texture depth
β = a dimensionless parameter established from analyses of field data

The ESDU Model has been developed for use in two general ways:

(a) Predict the aircraft μ_{eff} from field test database and from pavement texture data – this avoids the complication of analyzing ground vehicle data, and determining the relationship between the two types of data. Unfortunately, the available aircraft data are quite limited which limits the range over which the model might be applied in this manner.

    ESDU, 1999b; 1999c developed sample coefficients for a Boeing 727 aircraft and a combat aircraft from field test data for these aircraft to illustrate the model.

(b) Predict the aircraft μ_{eff} from ground vehicle data – This approach is more feasible because a wider range of ground-vehicle data are available. In general, this approach involves using ground vehicle data to establish the " β" value for a given runway condition, and then using this to predict an aircraft's μ_{eff} (ESDU, 1999a).

In principle, either method could provide reliable results. However, there are no results in the ESDU reports reviewed (i.e., ESDU, 1999a ; 1999b; 1999c; 2000) showing direct comparisons for either method (e.g., predicted μ_{eff} vs. measured μ_{eff}), or data allowing this type of comparison, which makes it difficult to evaluate the reliability of either approach.

4.2.2 Sample Results

The ESDU model is case-specific. Aircraft data are needed for the aircraft type(s) of interest for a wide range of pavement conditions. This limits its generality, and perhaps its reliability as well, depending on the extensiveness of the underlying database. Obviously, the model is dependent on the database being comprised of a representative sample of conditions (e.g., not biased towards one condition, such as damp on high-texture pavement versus another, such as flooded on low-texture pavement).

ESDU, 1999b developed coefficients for the Boeing 727 as this aircraft type has been tested most extensively (Table 4.1).

It is important to recognize that the model will have large variability if the underlying data have a large degree of variation. This is readily seen in the following example:

(a) selected input parameters (for illustration purposes only):
   a. dry friction factor (μ_{datum}): 0.8
   b. aircraft ground speed: 100 kts
   c. tire inflation pressure: 145 psi (1 mPa)

(b) predicted μ_{eff} values for the NASA Wallops results presented in Table 4.1 for concrete:
   a. rain damp – the predicted μ_{eff} varies from 0.74 to 0.34 for the two β values given in Table 4.1 (i.e., 0.06 and 1.06), which presumably both apply to the same case (i.e., rain damp on concrete)

   b. truck wet – the predicted μ_{eff} is 0.12 for the β value given in Table 4.1 (i.e., 4.4)

Thus, the ESDU model predicts that the aircraft's μ_{eff} will vary greatly over the range of wetness conditions from dry to damp to truck wet.

The ESDU model was further investigated by running it for the case given in ESDU, 2000. Figure 4.1 was used to establish β values.

The results are summarized in Table 4.2. The μ_{eff} values calculated in the example cover a wide range for 50%, 5% and 1% exceedence probabilities, which are all quite probable, and thus of practical interest.

This variation may be partly due to the fact that the water film depth or surface condition is not a parameter. The model may have been set up this way in recognition of the fact that this parameter is difficult to measure in the field, and that it was often only measured in a general way (e.g., damp, wet, flooded) in many of the field tests on which the model is based. This approach makes the model easier to apply.

However, this is probably part of the reason for the variability.

Table 4.1: Values of β and K for the Boeing 727-100QC (after ESDU, 2000)

Runway Surface			Wetness condition	β	κ, in$^{1/2}$
Location	Description	d_{tex}, in			
NASA Wallops	Concrete	0.006	Rain Damp	0.06	0.020
	Concrete	0.006	Rain Damp	1.06	0.080
	Concrete	0.006	Truck Wet	4.40	0.162
FAA Technical Center	Asphalt	0.008	Truck Wet	3.86	0.176
	Asphalt	0.008	Truck Wet	2.29	0.135
	Asphalt	0.008	Truck Wet	1.35	0.104
	Asphalt	0.008	Truck Wet	0.77	0.078
Brunswick Naval Air Station	Asphalt	0.017	Damp	2.60	0.221
	Asphalt	0.017	Damp	0.72	0.111
	Asphalt	0.017	Rain Wet	0.73	0.112
	Asphalt	0.017	Rain Wet	1.80	0.175
	Asphalt	0.017	Truck Wet	0.71	0.110
	Asphalt	0.017	Truck Wet	0.50	0.092
NASA Wallops	Slurry Seal Asphalt	0.019	Rain Damp	0.00	0.000
	Slurry Seal Asphalt	0.019	Truck Wet	0.28	0.073
	Slurry Seal Asphalt	0.019	Truck Wet	0.08	0.040
FAA Technical Center	Grooved Asphalt	0.028	Truck Wet	0.57	0.126
	Grooved Asphalt	0.028	Truck Wet	0.15	0.064
	Grooved Asphalt	0.049	Rain Wet	0.62	0.175
	Grooved Asphalt	0.049	Rain Wet	0.13	0.080
	Grooved Asphalt	0.049	Rain Wet	0.28	0.118
	Grooved Asphalt	0.049	Rain Wet	0.15	0.085
	Grooved Asphalt	0.049	Truck Wet	0.17	0.092
NASA Wallops	Grooved Concrete	0.072	Rain Wet	0.00	0.000
	Grooved Concrete	0.072	Rain Wet	0.41	0.173
	Grooved Concrete	0.072	Truck Wet	0.53	0.195
	Grooved Concrete	0.072	Truck Wet	0.50	0.190

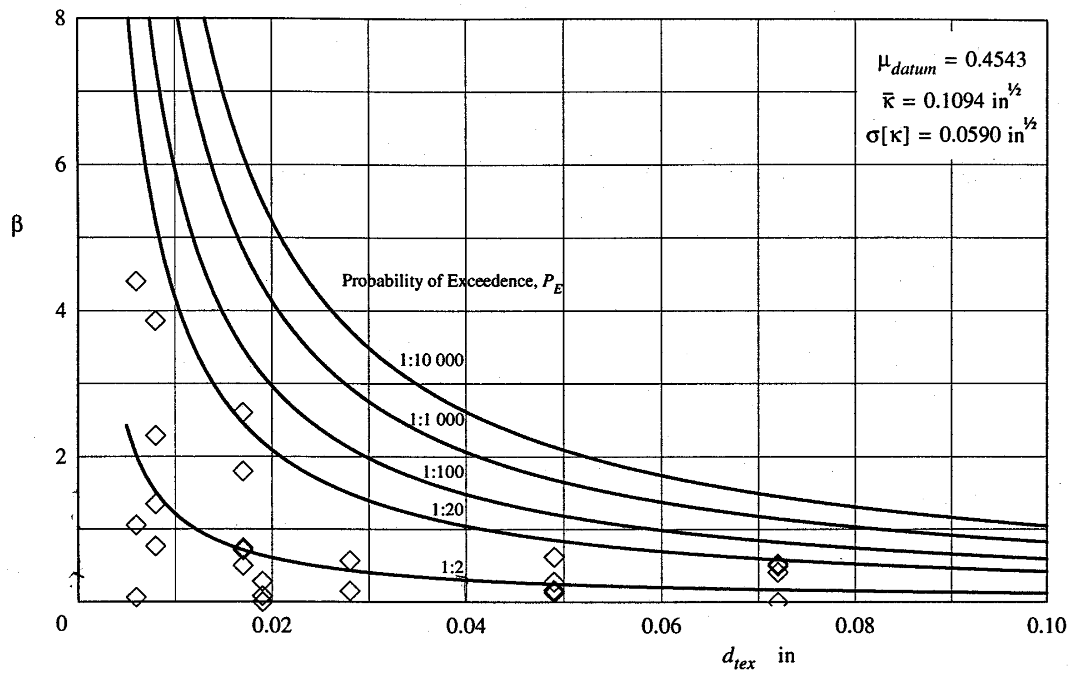


Figure 4.1: Effect of Texture on the β Parameter (after ESDU, 2000)

Table 4.2: Sample Results Obtained Using the ESDU Model for the Boeing 727

Exceedence Probability	Pavement Texture, mm	μ_{datum} (Figure 4.1)	Ground Speed (kts)	Tire Press. (psi)	Beta (scaled from Fig 4.1)	Calculated μ_{eff}
1:2 (50 %)	1	0.4543	100	145	0.3	0.33
1:20 (5 %)	1	0.4543	100	145	0.1	0.20
1:100 (1 %)	1	0.4543	100	145	1.4	0.16
1:2 (50 %)	0.25	0.4543	100	145	2.1	0.12
1:20 (5 %)	0.25	0.4543	100	145	7.1	0.04
1:100 (1 %)	0.25	0.4543	100	145	Off the scale on Fig. 4.1	Not possible to calculate this case

4.2.3 Assessment

The ESDU model is a useful step towards developing an overall analytical framework for quantifying and predicting wet runway friction. This overall framework is currently lacking in the state-of-the-art, which is primarily empirical.

However, the ESDU model has a number of drawbacks which make it less than ideal:

(a) it is highly statistical, and thus it relies on an extensive set of reliable field data being available. This limits its generality, and probably, its reliability as well. This may be the reason why the examples analyzed here show a large variation in the calculated μ_{eff}.

(b) it does not include all the parameters known to be significant, such as the water film depth.

4.3 Runway Hydroplaning Potential Curves

Horne, 1974; 1975 developed curves (Figures 4.2 and 4.3) to identify the cases where dynamic hydroplaning: (a) will occur; (b) may occur, and; (c) will not occur.

The inputs used for these curves were:

(a) the TTI water drainage equation (Galloway, 1971)
(b) dye tests used to visualize flow patterns in the presence of winds
(c) water film depth criteria in Horne, 1974, (which are copied in this report as Table 3.1) for:
   a. dynamic hydroplaning;
   b. combined dynamic and viscous hydroplaning;
   c. viscous hydroplaning, and;
   d. reverted rubber hydroplaning

These curves provide a simple means for assessing the hydroplaning potential for various conditions. Furthermore, they could be generalized for other cases with further dye tests and observations. Consequently, it is believed that they offer a useful approach by which an overall framework might be developed for dynamic hydroplaning, which is part of the wet runway friction problem.

The most important drawbacks of this method for general evaluations of wet runway friction are that:

(a) it is limited to dynamic hydroplaning

(b) it does not account for the degradation in μ_{eff} that may take place due to partial hydroplaning in wet runway conditions, without the onset of full hydroplaning.

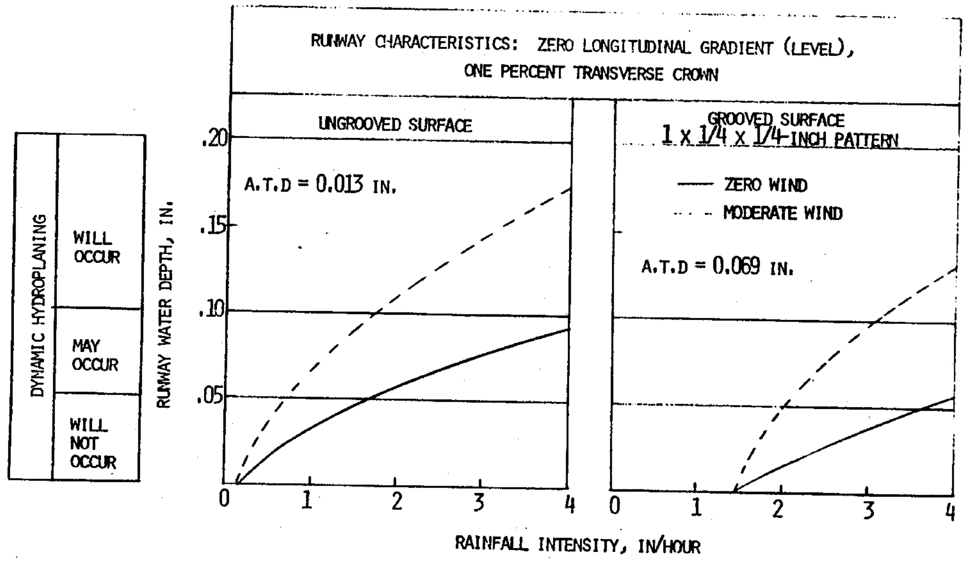


Figure 4.2: Runway Hydroplaning Potential Curves (after Horne, 1974)

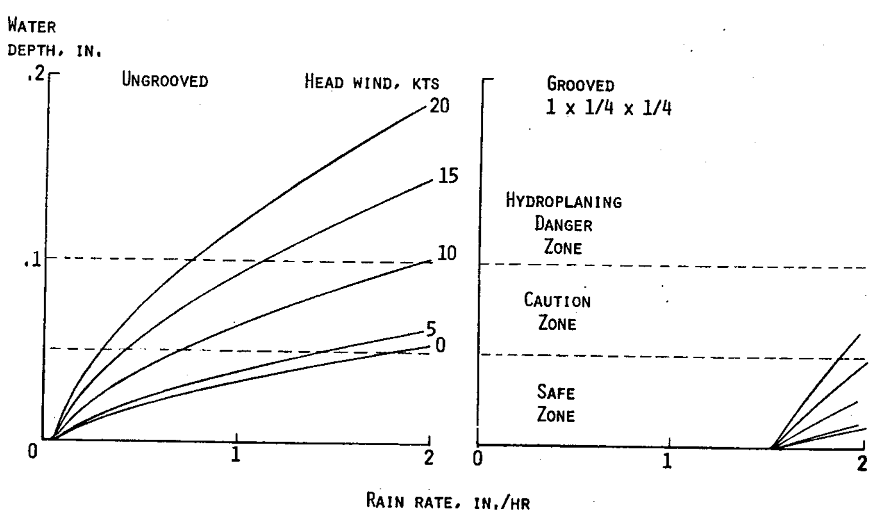


Figure 4.3: Runway Hydroplaning Potential Curves (after Horne, 1975)

4.4 Predicting Aircraft Braking Coefficients from Ground Vehicle Data

4.4.1 Approach

Horne, 1998 developed the following method to predict aircraft tire braking coefficients from ground vehicle data, based on previous research by NASA (Horne, 1983; Horne, 1991; Horne, 1996). It should be noted that equations 4.3 to 4.5 are applicable to damp, wet, and flooded pavements.

$\mu_{\text{max for an aircraft tire without including the effects of the aircraft's Antilock Braking System (ABS)}}$
$= \mu_{\text{ground vehicle test tire}} * \{\mu_{\text{ult for that aircraft tire}}\} / \{\mu_{\text{ult for that ground vehicle test tire}}\}$ [4.3]

$\mu_{\text{effective for an aircraft tire including the effects of the aircraft's ABS}}$
$= 0.2 * \mu_{\text{Max - ground vehicle test tire}} + 0.7143 * (\mu_{\text{Max - ground vehicle test tire}})^2$ [4.4]

$\mu_{\text{ult for that aircraft tire}} = 0.93 - 0.0011p$ [4.5]

where: p = tire pressure. Horne, 1998 does not specify the applicable units for “p” but based on other equations in Horne, 1998, it is presumed (by FTL) that “p” is in psi.

$\mu_{\text{ult for that aircraft tire}}$ = the maximum friction coefficient developed by that aircraft tire on dry pavement at very low speed (1-2 mph) for a given tire pressure

$\mu_{\text{ult for that ground vehicle test tire}}$ = the maximum friction coefficient developed by that ground vehicle test tire on dry pavement at very low speed (1-2 mph) for a given tire pressure

$\mu_{\text{ground vehicle test tire}}$ = the runway friction tester tire test friction coefficient

$\mu_{\text{Max - ground vehicle test tire}}$ – not defined in Horne, 1998

4.4.2 Results

Horne, 1998 presents results showing the correlation for the B-727, using ground vehicle data obtained from the BV-11, on truck wet asphalt and concrete (Figures 4.4 and 4.5, respectively). The predicted and measured $\mu_{\text{effective}}$'s show reasonable agreement.

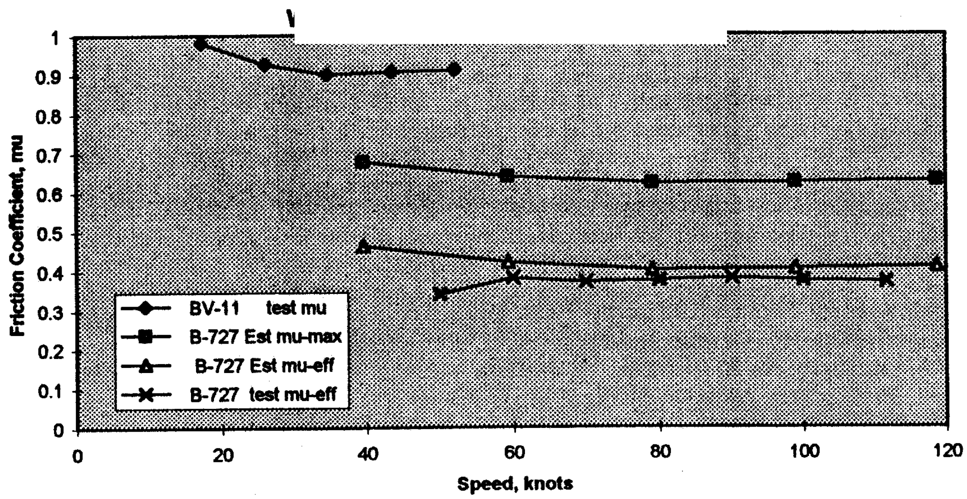


Figure 4.4: B-727/BV-11 Friction Correlation: NASA Wallops Grooved Asphalt, Truck Wet (after Horne, 1998)

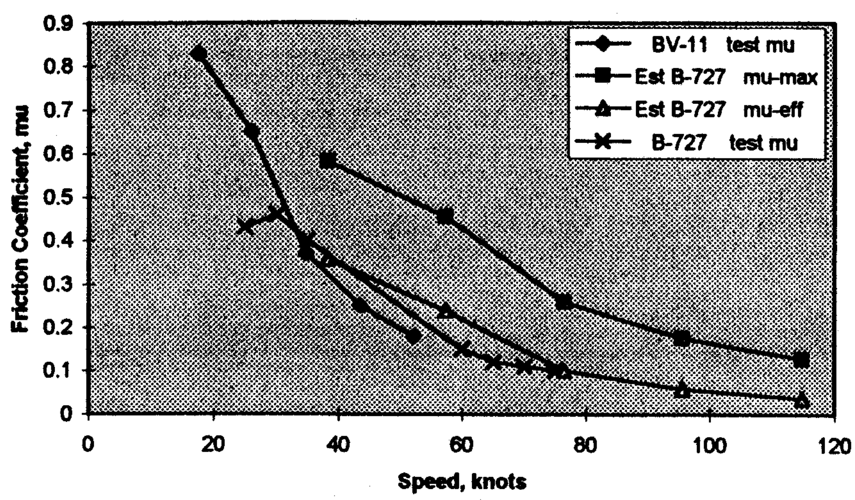


Figure 4.5: B-727/BV-11 Friction Correlation: NASA Wallops Smooth Concrete Surface, Water Truck Wet (after Horne, 1998)

4.4.3 Assessment

Definitive statements are not possible for a number of reasons:

(a) the model is not fully defined or specified in Horne, 1998, and;

(b) only limited comparisons (of the predicted vs. measured values) appear to have been done

Nevertheless, the limited information in Horne, 1998 suggests that this approach provides reasonable correlation between the measured and predicted values. This should be followed up with more investigations and more extensive comparisons.

5.0 ASSESSMENT OF THE CURRENT STATE-OF-THE-ART

In its simplest terms, the issue of wet runway friction, and its effect on aircraft operations, can be formulated by the following two basic questions:

(a) how much water is likely to build up on the runway?
(b) what is the resulting friction level experienced by an aircraft operating on the runway?

In practice, of course, the problem is more complex as it is affected by many factors as discussed in the following sections

5.1 Water Buildup on the Runway: Overview of Key Processes and State-of-Knowledge

5.1.1 Water Buildup on the Runway: Summary of Current State-of-Knowledge

The current state-of-knowledge is summarized below, in relation to the key issues. A more detailed summary of the current state-of-knowledge is provided in section 5.3.

(a) the environmental mechanisms causing water buildup – only rain has been studied to any significant extent. Other mechanisms such as fog, frost, or dew can also produce moisture on the runway. Information regarding the moisture buildup expected on the runway from these environmental mechanisms was not found in the literature. It is our opinion that these environmental conditions are most likely to cause damp runway conditions as opposed to wet or flooded ones.

(b) the amount of water built up during steady-state rainfall conditions - this has been studied extensively and several predictor equations have been developed. Although information gaps still exist, this subject area is relatively well understood.

(c) transient effects, such as winds, variations in rainfall rates during a rain storm, or time lags for water runoff – these are not well understood although the current state-of-knowledge is sufficient to allow preliminary assessments.

(d) pavement recovery from a wet or damp surface, to a dry condition – some information is available from studies done on highways in the United States. No information was found relating to airport runways in Canada.

5.1.2 Water Buildup on the Runway: Assessment

Of the two major questions referred to at the beginning of Section 5, the current state-of-knowledge regarding the issue of water buildup on the runway is considered to be further advanced.

Nevertheless, there are important gaps with respect to each of the sub-issues listed in section 5.1.1 above.

The net result of these gaps and uncertainties is that:

(a) the current state-of-knowledge is useful for general studies and evaluations;

(b) it is inadequate to predict or evaluate water buildup on the runway in a real-time operational mode, and;

(c) regular monitoring of friction levels is required for real-time assessments in an operational mode.

5.2 Wet Runway Friction and Its Effect on Aircraft: Overview

This topic encompasses several important issues as follows:

(a) the friction level of a damp, wet, or flooded runway, and the factors controlling it such as:
   a. measurement technique (e.g., slip ratio, speed, tire pressure and type)
   b. hydroplaning
   c. water film depth
   d. pavement texture, and the presence of contaminants
   e. long-term and short term variations in friction level.

(b) the relationships between the friction factors experienced by an aircraft; those recorded on aircraft tires tested under laboratory conditions (which did not include simulation of the aircraft's braking system), and; those recorded by ground vehicles used to measure friction at airports. This is an important issue for a number of reasons, including the following:
   a. ground vehicles are typically used at airports to monitor friction, and thus, this forms the majority of the information base that is available for evaluating an aircraft's performance in a real-time, operational setting;
   b. only a small number of aircraft tests have been done, and;
   c. most of the information regarding the friction factors "seen" by aircraft tires is derived from large-scale laboratory tests, at NASA's Landing Loads Test Track.

The current state-of-knowledge is summarized below, in relation to the key issues. A more detailed summary of the current state-of-knowledge is provided in section 5.4.

5.2.1 Wet Runway Friction: Summary of Current State-of-Knowledge

(i) Friction Level Variations with Time

Friction levels vary on long-term time scales (of months to years) in response to polishing and other actions that degrade the pavement texture. Friction levels also vary in the short-term in response to pavement rejuvenation actions, the buildup of contaminants, and rains which wash the contaminants off. The short-term variations are larger than the long-term ones.

(ii) Factors Controlling Wet Runway Friction Levels

The following factors affect the friction level of a wet runway:

(a) speed – the friction vs. speed relationship has two general regimes (for runways with enough water on the surface to cause hydroplaning to occur) :
   a. speeds lower than the minimum hydroplaning speed – the friction factor decreases with speed
   b. speeds above the minimum hydroplaning speed – the friction drops to nil, or to a very low value (depending on the definition used for hydroplaning)

(b) slip ratio – the friction factor tends to peak at slip ratios in the range of 10 to 20%, and to be lower at the locked wheel condition (i.e., 100% slip). This report has attempted to focus on friction factors in the 10 to 20% slip ratio range. This is the range where aircraft braking systems typically operate, and where ground vehicles generally collect data.

(c) water film depth – the effect of water film depth depends on the tire pressure.
   a. for low tire pressures (in the range used by ground vehicles), the friction factor is independent of film thickness for depths exceeding about 0.3 to 0.5 mm.
   b. for high tire pressures (in the range used by large commercial aircraft), the effect of film depth depends on the pavement texture. For smooth pavements, the film depth has little to no effect on the friction factor. For high-texture pavements, the effect of film depth depends on speed, being greatest at high speeds.

(d) pavement texture – the friction factor is increased on higher-texture, or on grooved pavement.

(e) rubber contaminants – they reduce the friction factors measured by ground vehicles at airports. However, no information is available to assess their effect on the friction levels experienced by aircraft, either from aircraft tests, or from large-scale tests with an aircraft tire.

(f) tire pressure – general statements are not possible because the effect of tire pressure depends on other factors as well, such as water film depth and pavement texture.

(iii) Hydroplaning

Hydroplaning has been studied extensively, and the general conditions causing hydroplaning have been identified. However, only general quantitative criteria are available to define the onset of hydroplaning.

Predictor equations have been developed by NASA which have been generally corroborated with field data for aircraft and large trucks. Recent observations have brought into question whether or not the NASA equations can be extended to friction-measuring ground vehicles.

(iv) Overall Evaluation Methods

Only a small number of approaches are available for undertaking an overall evaluation, such as relating the friction level experienced by an aircraft to either ground vehicle measurements or to basic pavement data, such as texture. They all suffer from a number of serious drawbacks

No universal, widely accepted, proven method is available for doing evaluations of this type.

5.2.2 Wet Runway Friction: Assessment

A relatively large database of information is available which provides an understanding of the basic processes and trends. However, the state-of-knowledge is primarily empirical.

The most significant limitation in the current information base is considered to be the relationships among:

(a) the friction factors experienced by an aircraft;
(b) the friction factors measured by ground vehicles, and;
(c) basic pavement parameters, such as texture, and water film depth

This gap makes it difficult to evaluate operations outside the range of current experience, and leaves detailed testing as the most reliable approach for evaluating them.

5.3 Detailed Summary of Current State-of-Knowledge: Water Buildup on the Runway

(a) water or moisture may be produced on the runway surface by various environmental conditions, such as rain, frost, dew, and fog. Only rain has been studied to any extent, with respect to the amount of water produced on the runway surface. No information was found regarding this issue for the other environmental conditions.

(b) based on tests and observations, at least three equations have been developed to predict the water buildup on the runway surface. The key factors controlling the water depth include:
   a. Environmental – the rainfall rate is the only environmental parameter
   b. Pavement – the important factors include:
      - the pavement texture depth;
      - the pavement cross slope, and;
      - the drainage path length

(c) each of the predictor equations is applicable to the basic case where:
   a. the rainfall rate does not change with time
   b. the winds are calm

(d) comparisons between the predicted and observed rainfall rates to cause flooding for the Shuttle Landing Facility indicate that the available equations err conservatively, in that they underestimate the rainfall rates required to flood the runway.

(e) dye tests at airport runways have shown that water patterns are affected significantly by winds when the runway is flooded.

(f) runoff time – simple calculations suggest that this will be in the range of 5-10 minutes for most practical cases. However, more definitive information would be required for operational purposes.

(g) very little information was found to assess the time required for a runway to dry (i.e., to go from "wet" to "dry", or for frost on it to "burn off" during the day).

(h) transient effects can be caused by variations in rainfall rates during a storm, and by the time lag required for the water to run off. Two hypothetical cases were analyzed. These calculations show that temporarily, the water depth on the runway could be up to roughly 20% higher than the steady-state value obtained from the predictor equations. In FTL's opinion, this discrepancy is within the accuracy of the overall state-of-the-art for predicting water depths on a runway or pavement surface.

5.4 Detailed Summary of Current State-of-Knowledge: Wet Runway Friction

5.4.1 Friction Level Variations with Time

(a) observations made on roads and runways generally support each other with respect to the trends observed.
(b) friction coefficients on both roads and airport runways vary over the following general time scales:
    a. annually, or more, over several years - Cyclical variations have been observed as the friction coefficient was increased over the winter period, probably in response to winter maintenance operations. Over the summer period, the friction generally tended to decrease, owing to polishing.
    b. short term, on time scales of days or weeks - Friction coefficients varied in a highly irregular pattern, owing to the fact that they were caused by the combination of several irregular factors, such as:
        - the periodicity and intensity of rainfalls;
        - rubber buildup rates on the runway, and:
        - the periodicity and effectiveness of rubber removal or pavement maintenance operations
(c) the short term friction coefficient fluctuations were equal to, or often greater than, the long term fluctuations.
(d) because friction coefficients vary greatly, it would be a very difficult, if not futile, exercise to try to predict friction coefficients.
(e) regular friction measurements are considered to be the most reliable, if not the only way, to establish the friction level of a runway at any given time.

5.4.2 Factors Affecting Wet Runway Friction

(i) Speed

The friction-speed relationship has two general regimes as follows:

(a) wet friction regime – tractive forces are developed between the tire and the pavement. The magnitude of these forces are dependent on a wide range of factors, which are summarized below.
(b) full hydroplaning regime – full hydroplaning occurs at speeds greater then those in the “wet friction” regime, although partial hydroplaning affects the tractive forces developed in the “wet friction” regime. The tire has very low braking/cornering friction in this condition.

(ii) Effect of Water Film Depth

(a) damp, wet, and flooded surfaces are defined as having water film depths of less than 0.01 inch, between 0.1 and 0.1 inch, and more than 0.1 inch, respectively.
(b) the effect of water film depth varies with tire pressure. Different trends have been observed for high-pressure aircraft tires, versus low-pressure ground vehicle tires.
(c) for high pressure aircraft tires, the effect of water film depth varies with the surface texture.
(d) high pressure tires on low-texture surfaces – the friction-speed relationship is very similar for both damp and flooded conditions. In this case, damp conditions produced a friction loss (compared to the dry value) that was similar to flooded conditions.
(e) high pressure tires on high-texture surfaces –
    a. friction factor magnitudes over the whole speed range – the friction factor was much higher on a rough surface than on a smooth one.
    b. the friction-speed relationship – this varied with the water film depth:
        - a damp runway: the friction-speed relationship was "flatter" over the whole speed range, which indicates that higher friction was maintained as the speed was increased.
        - a flooded runway: the friction decreased rapidly as the speed was increased, compared to the results for a damp runway. This differs from the damp runway results, in that higher friction was not maintained as the speed was increased.
(f) for low-pressure ground vehicle tires, the friction factor is essentially independent of the water film depth for thicknesses exceeding about 0.3 to 0.5 mm.

(iii) Effect of Pavement Texture

(a) ungrooved pavement - the friction factors were increased in all cases (i.e., high-pressure aircraft tires vs. low-pressure ground vehicle tires; range of water film depths) for high-texture pavement, compared to smoother pavement.
(b) grooved pavement – data are only available for aircraft tires. However, these data show that higher friction factors were produced on grooved pavement in flooded conditions and on runways that were "wet and puddled".

(iv) Effect of Rubber Deposits on Friction

(a) relatively little information is available
(b) it is generally known that the friction factor will be decreased by the presence of rubber deposits on the runway, and the available data from ground vehicles at airports support this.
(c) however, no information was found to quantify the friction decrease that will be seen by aircraft operating on contaminated surfaces, either from aircraft tests, or from tests using aircraft tires. Thus, one must rely on correlations between ground vehicle information and aircraft data to establish the expected effect of rubber on the runway.

(v) Assessment Summary – Effect of JP-4 Fuel Deposits on Friction

(a) the friction factor experienced by an aircraft tire will be significantly reduced by the presence of JP-4 fuel on the runway, in comparison to the comparable value for a wet or damp runway.

(vi) Effect of Tire Pressure

The effect of this parameter has been referred to in the previous sections. In brief, the effect of tire pressure can be summarized as follows:

(a) low vs. high water film depths (i.e., damp vs. flooded runway conditions) – the friction factors measured by low-pressure tires (in the range typical of those used for ground vehicles) are insensitive to water film depth at thicknesses exceeding about 0.3 to 0.5 mm. The friction factors measured by higher-pressure exhibit a speed-dependence.
(b) low vs. high texture pavements – higher friction factors were measured with both low-pressure tires and with high-pressure tires on pavement with higher texture.
(c) effect of rubber deposits – the friction factors measured by low-pressure tires (in the range typical of those used for ground vehicles) decrease significantly by rubber deposits on the runway. Data for high-pressure tires are not available for comparison.

5.4.3 Hydroplaning

(a) hydroplaning has been studied extensively. Three forms of hydroplaning have been identified (i.e., viscous hydroplaning, dynamic hydroplaning, and reverted rubber hydroplaning).

(b) the general conditions that cause hydroplaning have been identified. However, detailed technical information (e.g., reliable analytical models) are not available to define the onset of hydroplaning quantitatively. The knowledge is primarily empirical.

(c) equations have been developed to predict the minimum hydroplaning speed for dynamic hydroplaning. These have been generally corroborated with field observations.

5.4.4 Overall Evaluation Methods

The state-of-knowledge is primarily empirical, and a universally accepted, proven analytical method for quantifying wet runway friction is not available.

Some efforts have been made towards this goal such as:

(a) the wet runway friction model developed by ESDU, and;
(b) the dynamic runway hydroplaning potential curves developed by Horne, 1974; 1975.
(c) the correlation method developed by Horne, 1998

However, more work is needed before the goal of achieving an overall analytical framework can be reached.

5.5 Overall Recommendations

Efforts should be focussed on developing an overall understanding among: (a) the friction factors experienced by an aircraft; (b) the friction factors measured by ground vehicles, and; (c) basic pavement parameters such as water film depth and pavement texture.

Because the state-of-knowledge regarding wet runway friction is primarily empirical, it is FTL's opinion that the most reasonable method for evaluating it for operational conditions is to do on a case-by-case basis, with site-specific, and case-specific, measurements and monitoring.

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