Prog. Aerospace Sci. Vol. 23, pp. 105–150, 1986
Printed in Great Britain.
0376-0421/86 $0.00 + .50

BRAKING PERFORMANCE OF AIRCRAFT TIRES

SATISH K. AGRAWAL

41 Concord Rd., Marlton, New Jersey, 08053, U.S.A.

(*Received 5 December 1985*)

Abstract—This paper brings under one cover the subject of aircraft braking performance and a variety of related phenomena that lead to aircraft hydroplaning, overruns, and loss of directional control. Complex processes involving tire deformation, tire slipping, and fluid pressures in the tire–runway contact area develop the friction forces for retarding the aircraft; this paper describes the physics of these processes. The paper reviews the past and present research efforts and concludes that the most effective way to combat the hazards associated with aircraft landings and takeoffs on contaminated runways is by measuring and displaying in realtime the braking performance parameters in the aircraft cockpit.

CONTENTS

1. INTRODUCTION

Aircraft tires are placed under very high performance requirements in providing braking and directional control during airplane ground maneuvers such as landing and takeoff: the tires must support the aircraft weight, transmit braking and accelerating forces to the runway surface, and also supply forces necessary for directional control of the aircraft. A proper combination of the characteristics of tire, runway, and aircraft, and the pilot technique has made it possible to meet these diverse requirements over a large range of operational and environmental conditions. However, the control (on the ground) of aircraft has become increasingly difficult with the advent of high-performance jets, because of higher landing and takeoff speeds, particularly during operations on runways covered with environmental contaminants, such as water, snow, and ice; in addition, heavy crosswinds prevailing during such operations could adversely affect aircraft control. Aircraft operations under these environmental constraints is the primary subject matter of this report.

The degree of aircraft control is influenced by the forces developed in a small area formed when the tire contacts the runway. The magnitude of the forces depends upon a large number of factors associated with the components of the contact area—tire, braking system, runway surface, and contaminants.

Under extreme operational and environmental conditions these forces may approach zero, resulting in severe and hazardous loss of aircraft control. The loss of control is reflected in the inability to stop the aircraft within the extent of the runway, sliding of the aircraft to the side of the runway, or a combination thereof.

Traditionally, the braking and directional ability of an aircraft is measured by a single parameter, known as the coefficient of friction. This is a measure of the contact-area forces as a fraction of the aircraft weight; the higher the coefficient, the better the aircraft control. Extensive research and development efforts during the past 30 years have been expended in attempts to clarify the interaction of various phenomena of the contact area and their influence on the coefficient of friction. Equally important has been the question of predicting an aircraft's controllability on contaminated runways. These efforts have resulted in many improvements in the design of aircraft tires and braking systems, development of new and improved runway surfaces, and preventive and corrective procedures for runway maintenance to continue aircraft operations during adverse weather conditions. The efforts are continuing; however, accidents and incidents involving aircraft overruns and loss of directional control remain a concern.

It is the purpose of this paper to review past efforts, discuss current research and developments, and outline ways to combat and assess the loss of aircraft ground control on environmentally contaminated runways. The article is written with a view to provide the reader with a physical description of the processes taking place in the tire–runway contact area. The lack of ample experimental data is intentional; the available data merely indicate trends and cannot be used like a handbook. The author has also avoided complex mathematical arguments which are readily available in the references quoted. The paper provides a basic understanding of the general subject matter of aircraft braking to allow interested readers to pursue the more advanced studies, both experimental and analytical.

2. FRICTION AT THE TIRE–RUNWAY CONTACT

2. 1. An Overview

When talking about the tire–runway friction, one is interested in both the maximum friction coefficient under the best of conditions and the available friction under adverse conditions. While the knowledge of the former is necessary for design of tires and aircraft landing gear systems, the latter is a quantitative measure of an aircraft's marginal ability for executing ground maneuvers. Whereas the coefficient of friction in a dry contact is adequate (without implying that further improvement is unnecessary) there is no argument that increased friction on contaminated runways is highly desirable for improving the operational safety of an aircraft. Considerable research has been devoted to identifying ways by which the available friction could be increased; the measurement of available friction has also been a continuing effort.

Basically, during rolling contact between a rubber block and a dry, uncontaminated runway surface, friction is generated by adhesion and hysteresis—two energy dissipation processes (more about these later). A tire can be thought of as an array of rubber blocks with the composite frictional behavior of the blocks representing the frictional behavior of the tires. However, since the tire tread elements undergo deformations and develop complex stress and load cycles on passing through the contact area, local slipping of elements occurs and affects the mechanism of friction generation.

The forces necessary for executing aircraft ground maneuvers—braking, and cornering—must be generated in the tire–runway contact area. The mechanics of force transfer from the wheel center to the ground involves a 'frictional coupling' provided by adhesion and hysteresis and the 'slipping' of tire tread elements in the contact area. Adhesion, hysteresis, slipping, tire deformation, and available friction are strongly influenced by the presence of water in the contact area; other factors that influence these phenomena include load, speed, temperature, and the type of runway surface.

Aircraft tires are among the most complex structures both geometrically and mechanically, with a double curvature and an anisotropic hollow structure made of flexible filaments of high modulus material such as textiles, metal, or glass embedded in and bonded to a matrix of low modulus material such as rubber or a rubber-like polymer. The tire body is subjected to finite deformations when transmitting braking, accelerating, and cornering torques; these deformations are rate and temperature dependent. These complexities coupled with the fact that a runway surface is mathematically difficult to define have made a purely theoretical analysis of the tire–runway interactions more difficult than that associated with the majority of engineering structures. The presence of water in the tire–runway contact area injects intricate fluid flow phenomena into the already complex problem. It is difficult to give a complete definitive description of all possible interacting factors, and for the most part it has been necessary to rely on rather disjointed experimental evidence which merely indicates trends and magnitudes, as well as on some relatively simplistic theoretical models which are, however, helpful in explaining the general characteristics of the observed phenomena. Many excellent references[1–14] have combined theoretical and experimental information to provide researchers with some insight into the phenomena taking place in the tire–runway contact area. Throughout this article, the author has taken the liberty of tapping these resources.

2.2. Mechanism of Rubber Friction—Adhesion and Hysteresis

Generally speaking, a specimen of any material in sliding contact with a clean or contaminated surface develops a resisting force, called the friction force, in the plane of contact. In the case of a uniformly loaded rubber block or a tire tread element sliding over a rough, rigid surface, this force is generated primarily by two mechanisms:[1,2] hysteresis and adhesion (Fig. 1). Hysteresis and adhesion are two energy dissipation processes. Hysteresis is caused by damping losses within the rubber as the rubber chains are periodically deformed or agitated by the microscopic and macroscopic roughness of the surface.

During this deformation an unsymmetrical pressure distribution develops around the aggregate as shown in Fig. 1. By integrating the pressure over the contact area between the rubber and aggregate, and resolving the resultant force along the direction of travel, hysteresis losses are computed. Adhesion is the interface phenomenon in which the close contact between the surfaces of rubber and aggregate form large molecular junctions. As the rubber block or tread element moves on, these bonds are broken and new junctions are formed. The breaking and forming of bonds produces periodic stretching and relaxing of rubber polymer chains and gives rise to adhesion losses.

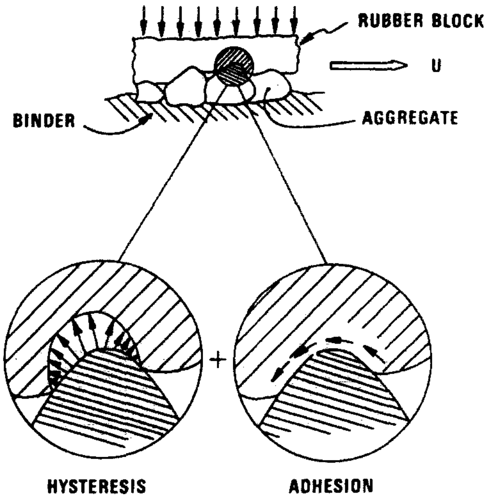


FIG. 1. Mechanics of friction generation (from Ref. (2)).

Since the mechanism of friction is different in both cases, influencing factors, such as load, speed, temperature, and contaminants, cannot be expected to affect adhesion and hysteresis in a like manner. Consequently, it is impossible to describe the behavior of adhesion or hysteresis from observation of friction as a function of any one factor. In addition, one must also consider how adhesion and hysteresis are affected by the presence of water on the runway surface. The presence of a thin water film affects the adhesion term by weakening of junctions or preventing them altogether from forming. The hysteresis term is affected in two ways: when the sliding velocity is modest, the water film provides cooling and thereby reduces the hysteresis losses and hence friction. When the waterfilm thickness is considerable, the fluid is not readily displaced (from the tire–runway contact) and acts as a cushion, decreasing or eliminating rubber deformation with the result that hysteresis friction approaches zero; the adhesion term is zero. Obtaining high friction on a runway covered with a thin film of water is largely a matter of removing or penetrating the water film. It will be shown later that removal of water from the tire–runway contact is also the solution to the problem of aircraft hydroplaning (or aquaplaning, as the British call it).

2.3. Mechanics of Tire–Runway Friction

The mechanism of force transmission is more complex for rolling tires than for a single rubber block or a single tread element; more variables are involved and tire elements undergo complex stress and load cycles[1,2,5,7,8] on passing through the contact area. Adhesion and hysteresis, and particularly adhesion, govern the ability of rotating pneumatic tires to resist longitudinal as well as lateral forces of the order of magnitude of the normal load without letting bodily sliding occur. The mechanics of tire deformation in the contact area also affects the resistance to sliding, because the tire by virtue of being a double curvature structure cannot be developed into a flat contact without simultaneous bending and compressing of its surface. Thus, when a loaded and inflated tire contacts the runway surface under free rolling conditions, the tread elements in contact with the runway will generally undergo a small deformation in the plane of the carcass in passing through the contact area. These deformations can be minimized by making the carcass structure of the tire as rigid as possible as in a radial tire.[5] Friction between the tread and the runway surface prevents the free contraction or expansion of the tread surface, so that local shear stresses are set up in the tread elements between the essentially rigid runway and the deforming or straining tire carcass. The tread elements are also subjected to an inhomogenous normal pressure distribution caused by the contact of the tire with the

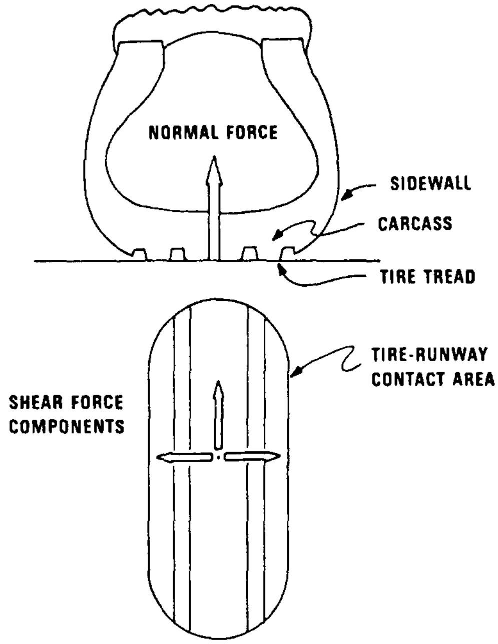


FIG. 2. Shear forces in tire runway contact area.

runway surface. The contact area forces are shown in Fig. 2. These forces are modified when braking or driving torque is applied to the wheel center.

When a braking torque is applied to a free rolling wheel, two sets of additional forces act: reaction of the wheel axis, and equal and opposite to it the reaction of the runway surface in contact with the tire. Also, because of tangential elasticity of the tire, the braking torque will stretch the tire tread elements in the zone immediately before contact and simultaneously compress the elements in the zone immediately after contact. Thus, an element of tread in braking is stretched, unstretched, and compressed as it passes through the contact area. The tread straining is prevented by the force with which each element grips the runway surface, and tangential stresses are developed in the contact plane. The magnitude and direction of the tangential stresses acting in the contact area are determined by the sum of the stresses generated in free rolling and additional stresses developed by the application of the braking torque. The precise way in which these stresses are distributed in the contact area depends upon many variable associated with the tire and the runway.

2.4. Concept of Slip

If the coefficient of friction between a tire and a surface were zero, the tire tread and carcass would deform freely without developing tangential stresses; if the tire were inelastic, there would be complete sliding of the tread elements as the deformation occurred in the contact area. In reality, however, both friction at the contact and elasticity of tire work together to develop tangential stresses which can cause local slipping of the tread elements on the runway.

Conditions in the contact area of a slipping wheel are shown in Fig. 3 taken from Ref. 7. It shows the contact area of a small, solid wheel through a transparent track. An element of the tire circumference is lengthened by application of braking torque, Fig. 3(b), or compressed during acceleration, Fig. 3(c). All the cases shown in Fig. 3 develop pure circumferential slip: the velocity, v, of the wheel center and the circumferential velocity of the wheel, V, point in the direction of travel. Pure circumferential slip is distinguished from sideways slip when the tire is negotiating a curve while free rolling, braking, or

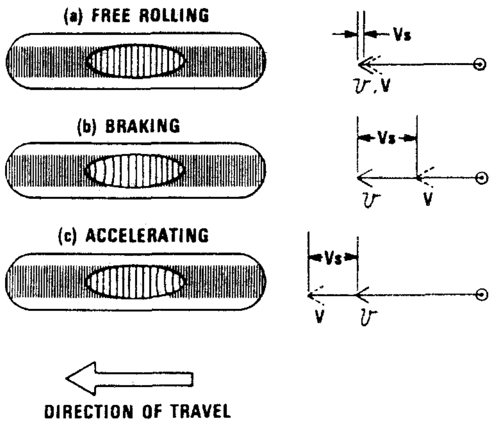


FIG. 3. Conditions in the contact area of a solid wheel undergoing slipping (from Ref. (7)).

accelerating. In general slip can be defined as a quantity, $\bar{S}$, as follows:

$$\bar{S} = \frac{\bar{v} - \bar{V}}{|\bar{v}|} \tag{1}$$

where:

$\bar{v}$ = velocity of the runway relative to wheel center
$\bar{V}$ = Circumferential velocity of the wheel (in the contact area) measureid relative to the wheel axle.

For the cases shown in Fig. 3, slip S can be defined as follows:

$$S = 1 - \frac{V}{v} \text{ and } V_s = v - V. \tag{2}$$

where V_s is defined as the circumferential slip velocity, so that

$$S = \frac{V_s}{v}. \tag{3}$$

An operating condition in which $v = V$ is defined as a state of zero circumferential slip. However, a small amount of slip is present even when the tire of an aircraft is in the state of free rolling, Fig. 3(a). The slip velocity can be positive, Fig. 3(b), or negative, Fig. 3(c), depending upon whether braking or accelerating torque, respectively, is applied.

Another operating condition of particular interest is when $V=0$, or $V_s = v$; it indicates that the wheel stops rotating but slides with a slip velocity equal to the wheel center velocity. Because sliding friction is much lower than that available when the braked wheel is rotating, modern brake control systems incorporate antiskid devices to avoid this. As the slip velocity becomes large, the tread elements and the carcass cannot distort sufficiently to maintain the tread in non-sliding contact with the runway.

Sliding starts when the ensuing stresses reach the local frictional stress limit. It may be recalled that the local frictional limit depends upon the adhesion and hysteresis components which in turn depend upon normal load, sliding velocity, temperature, and contamination. Thus the slip velocity is also a complex function of these variables.

3. SLIP IN BRAKING AND CORNERING

A tire runs under slip as it transmits braking, driving, or cornering forces to the ground. Braking and driving slips were discussed in Section 2.3. The cornering slip occurs when the wheel rolls in a direction at an angle, θ, with its plane, and the cornering slip velocity is then

$$V_s = v \sin \theta,$$

and the slip is

$$S = \sin \theta. \tag{4}$$

The maximum value of the coefficient of friction is obtained when a maximum number of tread elements produce maximum adhesion. The contribution by all the elements of the tread is not equal or uniform throughout the contact area; however, the magnitude of slip at which maximum friction coefficient occurs is termed critical slip.

Slip during braking and accelerating is traditionally expressed as a percentage. Thus, if a braked tire is rolling at a translational velocity of 100 knots and the circumferential velocity of the tire in the contact area is 90 knots, slip velocity will be 10 knots and slip $S = 10\%$. The suggested slip velocity of 10 knots does not by any means represent local tread velocities in the contact area; each tread element in the contact area distorts differently. It has been shown by experiments that the friction coefficient during braking increases as the slip increases; the friction coefficient reaches a maximum at the critical slip and then starts falling as the slip approaches 100%. The tire is in a state of 'skidding' at 100% slip. Figure 4 illustrates a typical variation of coefficient of friction as a function of wheel slip during braking.

Just as in braking, an element of tire tread in cornering also undergoes a deflection, this deflection is normal to the wheel. The accompanying surface stress increases until the local value of limiting friction is reached and the element begins to slide back toward its undeformed position. Here again, sliding starts when the ensuing stresses exceed local frictional stresses. The coefficient of cornering friction increases with the slip angle, θ, as shown in Fig. 5.

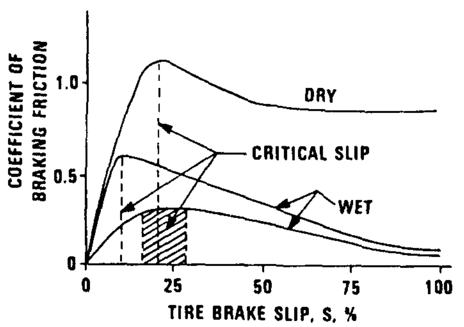


FIG. 4. Typical relationship between tire slip and coefficient of braking friction on wet and dry runways (from Ref. (9)).

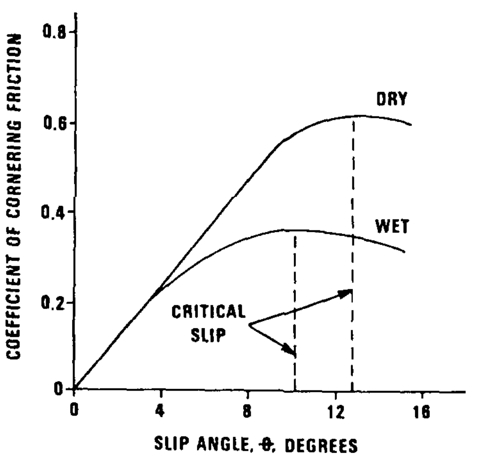


FIG. 5. Typical relationship between tire slip angle and cornering friction coefficient on wet and dry runways (from Ref. (9)).

3.1. Significance of Slip

The maximum friction in braked rolling occurs when the tire slip is between 5 to 30% (Fig. 4) depending upon the conditions in the contact area. Similarly, maximum cornering effectiveness occurs when the slip angle is within a particular range, Fig. 5. At a slip angle of 90° the coefficient of sliding governs entirely, as in the case of 100% braking slip. Superposition of braking (or driving) and cornering follows the same trend, but the resulting friction determines the magnitude of both slip angle and side force. As long as the friction does not exceed the critical values obtained under braking, driving, or cornering, braking (or driving) forces and side forces can exist together. When a higher frictional demand is placed on one of the components, however, the other breaks down and bodily sliding of the aircraft would occur in a direction tangent to the path of the tire at the instant of break-away.(10)

Exact relationships between side forces due to slip angles and friction forces due to braking, when both slips are present, are not available in abundance. However, it has been suggested(15) that during combined aircraft braking and cornering, the braking coefficient maximum decreases in magnitude and shifts to higher slip percentage values as the slip angle increases, Fig. 6(a). It can also be observed that maximum cornering friction coefficient at any slip angle occurs when the brake slip is small, Fig. 6(a). The fact that maximum coefficients for braking and cornering have conflicting requirements has an important implication(15) during aircraft operations on wet runways when heavy crosswinds are also present: to maximize aircraft stopping performance, the antiskid system must control the wheel motion at increasing brake slips as the aircraft yaws (or uses crab approach to offset crosswinds(16)); on the other hand, to maximize aircraft directional control, the same antiskid system must control the wheel motion at low slips.

Tire slip has also been used as a primary input quantity in the design of equipment for measuring friction between a tire and a runway covered with water, snow, and ice. By maintaining a constant brake slip or by introducing a constant slip angle, highly versatile friction equipment is used worldwide to indicate runway slipperiness for developing runway maintenance procedures or for predicting the braking performance of an aircraft (see Section 8).

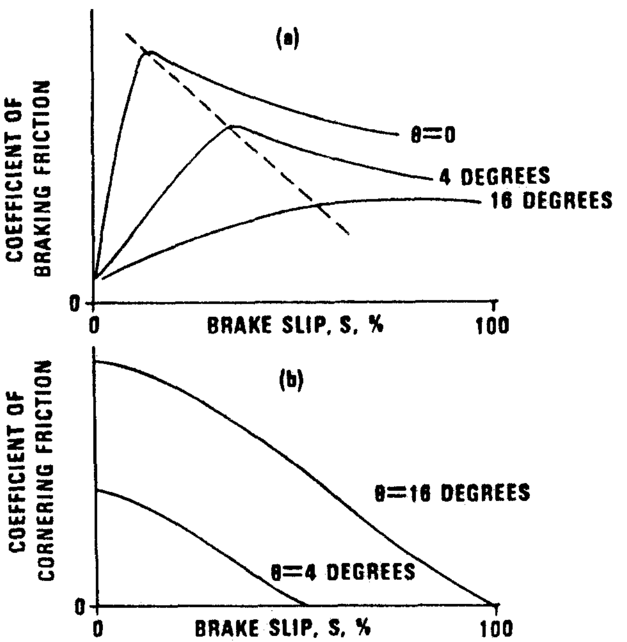


FIG. 6. Typical relationship between braking and cornering friction (from Ref. (15)).

4. FACTORS THAT AFFECT TIRE–RUNWAY FRICTION

The magnitude of the available friction coefficient in the tire–runway contact area is affected by a large number of factors associated with the aircraft, aircraft tire and braking system, the runway surface, and the environment. Some factors affect friction in one way only, others influence it in many ways. References 3, 10, and 17–19, provide a comprehensive list of factors that influence the tire–runway friction; not all of those factors are important.

4.1. Environmental Contaminant—Water

A contaminating film, generally of water, on the runway is, perhaps, the most important factor that adversely affects the braking performance and control of an aircraft. The characteristics of the water film that affect the braking performance includes its thickness, viscosity, temperature, and density. One can single out thickness of the water film as the primary variable that governs the friction level developed in the tire–runway contact area.

In general, as the water depth or thickness increases on a runway surface, the available coefficient of friction decreases with increasing speed. Section 2.2 described the mechanics of friction degradation due to presence of water film in the contact area. However, the variation of friction coefficient with water depth is not well defined because many other factors influence it in different ways. Figure 7 illustrates typical relationships between the available coefficient of friction and speed for a given runway surface as a function of water depth. It may be pointed out that 'water depth' as used here is a measurement convention and is dependent upon the type of equipment used to measure it. The vast variation in the available friction coefficient values in Fig. 7 reflects the difficulty one would encounter when trying to predict the braking performance of an aircraft about to land on a runway during rainfall. However, if one could relate the prevailing rainfall to the water depth on the runway, it would be possible to substantially narrow down the band representing the variation in the available coefficient of friction; this would also improve the prediction of the probable braking performance of aircraft. Several attempts have been made recently to relate the rainfall rate to accumulated water depth on a runway.[20,21,22] An empirical method,[20] an experimental technique,[21] and a mathematical model[22] provided general relationships between the rainfall intensity and water build up on a runway. The efforts

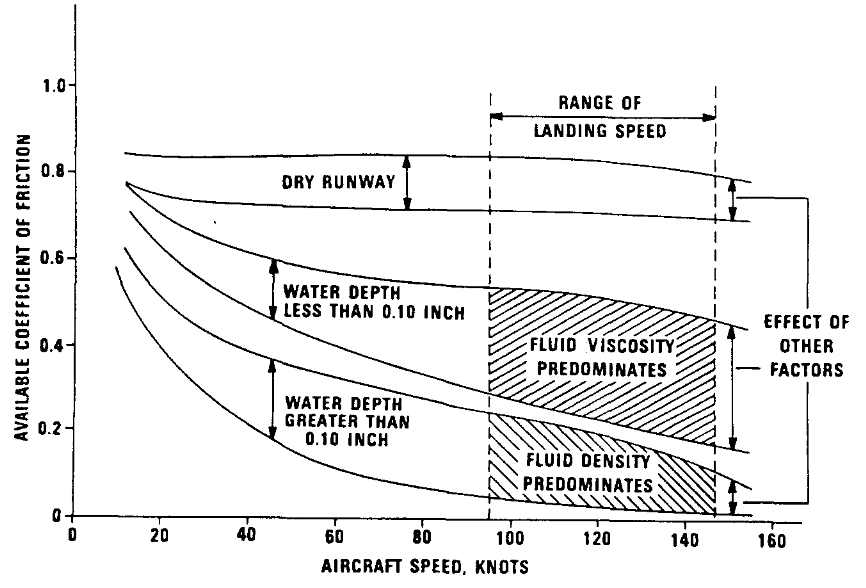


Fig. 7. Typical relationship between aircraft speed and available friction as a function of water depth.

are continuing, and if successful, methods could be developed to provide quantitative information to the pilot about the frictional potential of the aircraft–runway combination in real time.

In the meantime, significant progress has been made in understanding the runway surface factors that help reduce the build up of water. Among the important factors are runway crown, surface texture, and runway grooves.

4.2. Runway Surface Factors—Crown, Texture, and Grooves

Adequate runway crown allows water to drain off rapidly. Generally, runways are sloped between 1 and 1.5% in the transverse direction. Excessive slopes are not recommended because the aircraft load distribution would be significantly affected.

Runway surface texture has been a subject of intense investigation[22,23–26] in the recent years. Two ranges have been identified which conveniently describe total surface texture (Fig. 8): micro- and macrotexture. Microtexture consists of the fine, small-scale, surface irregularities as found on individual aggregates, whereas macrotexture defines the coarse,

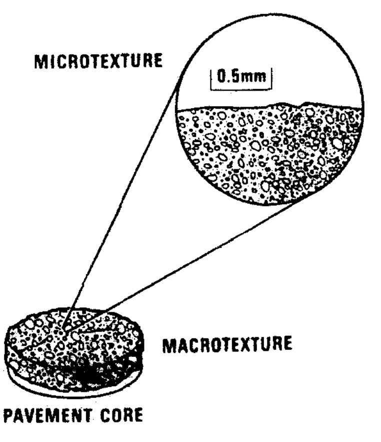


Fig. 8. Two components of the runway surface texture – microtexture and macrotexture (from Ref. (26)).

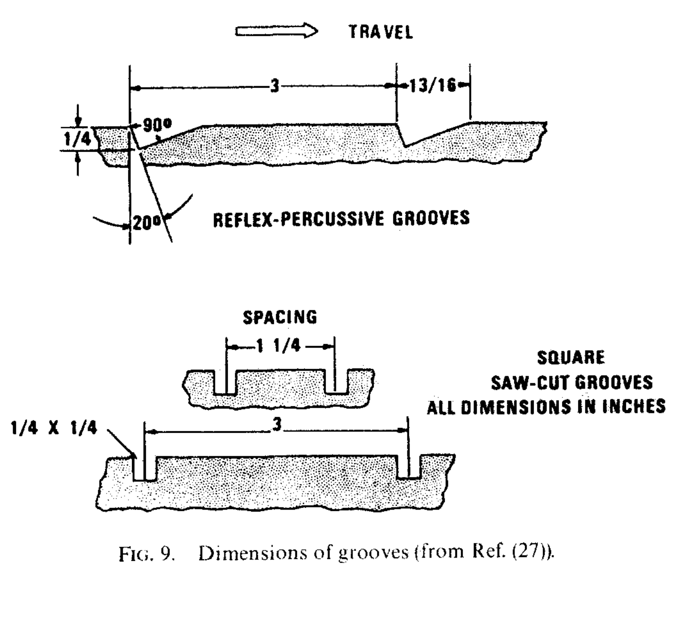


Fig. 9. Dimensions of grooves (from Ref. (27)).

large-scale, surface irregularities of the whole runway surface. A surface must have both macrotexture and microtexture to maintain adequate friction level at the tire–runway contact. The macrotexture provides relief channels for rapid expulsion of water from the tire–runway contact area; this process can be characterized by bulk-water drainage effectiveness.[17] The microtexture provides the harshness or grittiness needed to penetrate the thin water film formed between the tire and the surface aggregates to permit adhesion to develop.

Grooves are small channels cut into the surface of existing runways. A square cross-section is the most widely used shape for the grooves; however, other promising designs have been recently investigated.[27] Figure 9 shows the dimensions of square grooves and recently developed reflex-percussive grooves. It has been established[28,29,30] that available coefficients of friction on grooved runways, covered with water, are higher than on non-grooved runways under otherwise identical operational conditions.

4.3. Aircraft Factors—Tire and Braking System

Among the various tire factors, inflation pressure, tread design, rubber compound, and tread depth are important[3,31] in relation to the braking performance on water covered runways. Other tire properties are equally important for other reasons; for example, heat generation on dry runways[32] influences tire wear and other related damage. Chevron cutting also reduces tire tread life but is not perceived as a major factor for tire performance. Researchers are continuously working on developing new materials for tires to combat blow out and other damage during landing rollout. Recently, much emphasis is being placed on radial design tires as a cost-effective alternative to bias tires for use on civil aircraft; military aircraft frequently use radial tires.

In general, tires with circumferential ribs will develop significantly higher friction coefficients than smooth tires (as with completely worn-off ribs).[19] References 4 and 31 state that differences in rubber compound have little or no effect on braking or cornering capabilities of aircraft tires, but inflation pressure does so significantly, particularly when the runway surface is flooded. It will be shown in the next section that the hydroplaning behaviour of a tire is directly related to inflation pressure.

Aircraft antiskid brake control systems are designed to prevent tire blow out during operations on dry runways and to minimize the stopping distance of an aircraft on wet runways. Modern antiskid brake systems are very effective when available friction coefficients are high; however, on flooded runway surfaces, such systems may become ineffective. Section 6 will describe the current state of the art[33,34] in the design of brake control systems.

5. HYDROPLANING

What is hydroplaning? Someone may say it is an exciting water sport behind a speed motorboat. Others will say that it is a serious hazard to aircraft landing on a water covered runway. Still others may relate it to an episode of total loss of control while driving an automobile on a rain slicked highway. Each one is correct in their definition of the word.

Hydroplaning is a condition that exists when two contacting surfaces in relative motion are separated by a fluid layer. In the case of automobiles and aircraft, the fluid layer separates the tire from the pavement. When in a state of hydroplaning, driving, braking, or cornering maneuvers are impossible because the fluid-filled interface between the tire and the runway cannot support significant shear forces. For a given set of operational and environmental conditions as well as tire factors there exists a speed above which a given aircraft tire will hydroplane. This 'critical' hydroplaning speed will change if the conditions in the contact area are changed. On the other hand, hydroplaning will not occur below a certain minimum speed irrespective of other conditions in the contact area.

The surest way to prevent an automobile from hydroplaning is to drive more slowly. On the other hand, an aircraft must land at a certain minimum speed, and the only means for preventing hydroplaning is to alter those operational and environmental conditions so as to push the critical hydroplaning speed above the landing speed of the aircraft. This brings up two important questions: (1) what is the critical hydroplaning speed and how is it measured, and (2) what factors will raise the critical hydroplaning speed above the landing speed of the aircraft, and is it possible to control or modify those factors? Much research conducted to date[3,12–15,17–19,27–30,35–56] has provided at least partial answers to these questions.

5.1. The Onset of Hydroplaning

Tire hydroplaning was first noticed in 1957 during experiments[35] on a treadmill where a small pneumatic tire undergoing free rolling motion on a water-covered belt experienced slow-down of the angular motion. The slow-down (or spin-down) continued until the wheel stopped rotating. This reduction in wheel angular speed is different from that caused by braking; but whether braked or not, a wheel can be in a state of hydroplaning whenever it is moving forward. There are two major differences between a skidding and a hydroplaning wheel: (1) tire–runway contact is maintained in the former, but a water layer physically separates the tire and the runway in the latter, and (2) friction is generated by adhesion and hysteresis in the former, but these terms are zero in hydroplaning[1] because the continuous water film obliterates all pavement features.

Significant gains in the understanding of the phenomena of hydroplaning were made in the early 1960's followed by the development of analytical models and experimental measurements of the phenomena taking place in the contact area of a hydroplaning tire. Hydroplaning is affected by some of the same factors of the tire–runway contact area that affect the tire–runway friction (Section 4). The amount of water on the runway is again a principal factor and identifies two types of hydroplaning that can occur during aircraft landing or takeoff: viscous hydroplaning and dynamic hydroplaning.

5.2. Viscous and Dynamic Hydroplaning

Theoretically, the friction forces at the tire–runway contact during hydroplaning should be zero; however, small fluid drags and mechanical drags may be present which may keep the wheel rotating at reduced speed. The fluid film that keeps the tire from contacting the runways surface does so by two fluid properties—viscosity and density; in either case, the forces from the fluid pressures balance the vertical loading on the wheel. In both cases the fluid encountered by the moving aircraft tires must be expelled from the contact area in order to alleviate hydroplaning. A practical solution in the 1960's was found by providing air-jets ahead of each aircraft wheel to clear the excess water from the runway. However, under certain conditions a very thin film of water would still remain on the runway which prevented intimate contact between the tread rubber and the microtexture of the asperities of the runway surface. Since viscosity predominates in developing fluid pressures between two contacting surfaces separated by a thin film, this phenomenon is commonly referred to as viscous hydroplaning.

Dynamic hydroplaning denotes those instances on flooded runways where inertial forces in the water film are sufficiently large to completely separate the tires from the runway. Generally, dynamic hydroplaning occurs when the amount of fluid encountered by the aircraft tires exceed the combined drainage capacity of tire tread pattern and the runway surface. Although viscosity or inertia of fluid may predominate, both effects are present to some degree in all cases of hydroplaning. In the last two decades, though, more attention has been focussed in the understanding and analysis of dynamic hydroplaning, if only because heavy rainfall more often creates the conditions conductive to hydroplaning of the dynamic type.

5.3. Critical Hydroplaning Speed and its Measurement

The minimum speed above which an aircraft tire will hydroplane is conventionally called the critical hydroplaning speed. The critical hydroplaning speed is a characteristic of the tire–runway contact area and is affected by the factors related to the contact area. Early research[36,37,3] has developed mathematical expressions for the critical hydroplaning speed in terms of a single parameter of the tire–runway contact area—tire inflation pressure:

$$Vc \propto P^{1/2}$$

or,

$$Vc = K.P^{1/2} \tag{5}$$

where:

Vc = critical hydroplaning speed, in knots
P = tire inflation pressure, in pounds per square inch
K = constant.

Equation (5) has taken different forms over the years.

(1) By assuming ground bearing pressure equal to the tire inflation pressure; by assuming the hydrodynamic lift coefficient of tires to be equal to 0.70; and limited to smooth tires or on runways covered with large fluid depths[37] it was deduced that:

$$Vc = 9\,(P)^{1/2}. \tag{6}$$

(2) Under conditions mentioned in (1) above, but for a non-rotating tire to spin up and undergo hydroplaning:[17]

$$Vc = 7.7\,(P)^{1/2}. \tag{7}$$

(3) Under conditions mentioned in 1 above, but taking into account the ratio of tire footprint width to the footprint length (aspect ratio):[56]

$$Vc = 6.91\,(P)^{1/2}\,(l/w), \tag{8}$$

where:

w/l = tire footprint aspect ratio
w = footprint width
l = footprint length,

(footprint is the impression of a tire on ground).

Another expression that describes the minimum speed at which hydroplaning will start was developed in Ref. (41) as follows:

$$Vc = 508\left(\frac{Q}{B.t.C_H}\right)^{1/2}, \tag{9}$$

where:

Vc = Hydroplaning speed (km/hr)
Q = Wheel load (kp)
B = Contact area width (mm)
t = Waterfilm thickness (mm)
C_H = Lift factor.

Much of the experimental data collected over the years generally support Eq. (5), even though test conditions and measurement techniques may have been significantly different in each investigation. This brings up the question of the measurement of hydroplaning speed, since there is no universally accepted definition of hydroplaning. Experimental verification of Eq. (6) was presented in Ref. (37); the results are reproduced in Fig. 10.

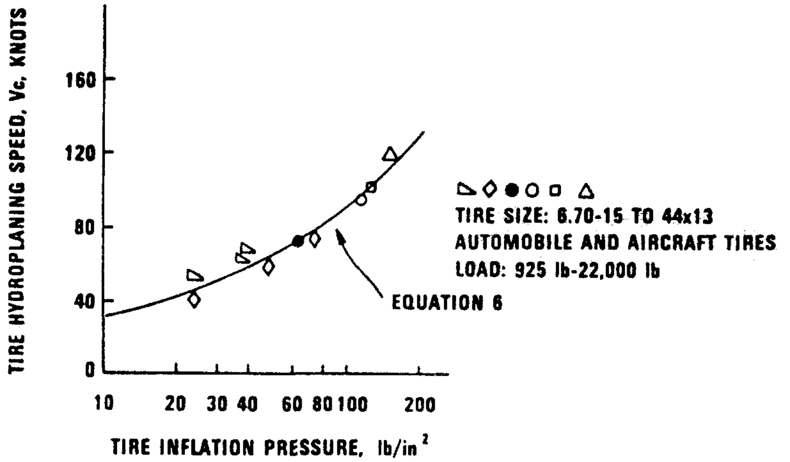


FIG. 10. Experimental and calculated tire hydroplaning speed (from Ref. (37)).

Figure 10 shows an excellent correlation between Eq. (6) and experimental data, but the technique used for measuring hydroplaning speed is not made explicitly clear in Ref. (37). However, several manifestations of hydroplaning were discussed, and any one could have been used in the measurement of hydroplaning speed. These manifestations are: detachment of tire footprint, suppression of tire bow wave, wheel spin-down, peaking of fluid drag, loss in directional stability, and loss in tire braking friction.

When spin-down is used as an indication of the critical hydroplaning speed,[(46,51)] a question is raised as to what value of spin-down should be used to indicate hydroplaning. Reference (3) suggests that total spin-down (wheel stops rotating) occurs between 80 and 120 % of the hydroplaning speed computed from Eq. (6). The loss in braking friction could be used to indicate hydroplaning if the minimum value of available friction can be found. However, this may require a large number of tests with good repeatability and accuracy.

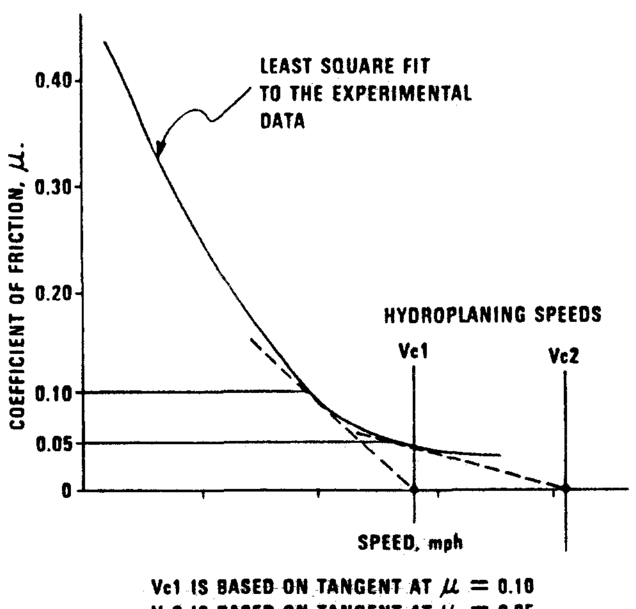


FIG. 11. A method for computing hydroplaning speed from experimental data (from Ref. (52)).

The method creates a problem, however, when no minimum value of friction coefficient can be identified because of a flat friction coefficient–speed curve. Still another method can be to linearly extrapolate the friction coefficient–speed curve to intersect the speed axis. Reference (52) used this last approach. Figure 11 shows the method schematically: intersection of a tangent drawn from a predetermined value of friction coefficient on the curve to the speed axis is used to compute hydroplaning speed.

Direct measurement of hydroplaning is difficult, if only because complex instrumentation is required to identify total tire–runway separation. For most practical purposes, a state of hydroplaning is indicated if the coefficient of friction available in the tire–runway contact area falls below 0.05.

5.4. Mathematical Analysis of Hydroplaning

A purely mathematical analysis of tire–runway interaction is difficult, and much of the analytical work which has been conducted on hydroplaning has been of an empirical nature as already noted in Section 5.3. However, several impressive analyses,[12–14,36–56] carried out between 1963 and 1984, have significantly enhanced the understanding of hydroplaning and related phenomena.

The physical process taking place when a tire moves from a quasi-dry section of a runway to a flooded section where dynamic hydroplaning could occur is as follows:[54]

(a) In the quasi-dry state, a steady-state pressure distribution exists under the tire. This pressure distribution may be the bearing pressure associated with dry contact or the hydrodynamic pressure associated with a thin water film on the runway. In either case, the net upward force in the contact area is not large enough to force tire–runway separation.

(b) When the tire approaches the flooded section of the runway, the thick water wedge ahead imposes forces on the forward section of the tire in contact with the runway. In this process, the relative momentum of the fluid is converted partially into dynamic fluid pressures. The forces on the tire from this pressure can be sufficiently high to cause local distortion of the tire surface.

(c) During the distortion of the tire, however, a static imbalance exists between the downward loading on the tire and the upward hydrodynamic forces developed in the fluid film under the tire. This imbalance exists until the tire distortion is stabilized and, consistent with the stabilized film thickness distribution in the tire–runway contact area, a hydrodynamic pressure distribution is developed.

In developing a mathematical model to represent the above physical problem, difficulty is encountered when modelling the tire deformation. One could start with an arbitrarily selected water film distribution under the tire and then add to it incremental tire deformation as a result of hydrodynamic pressures. The procedure is repeated until the film thickness distribution and pressure distribution are stabilized. Many investigations[12,38,44,45,47,50,54,58] have used this approach; however, the results are limited due to constraints imposed by simplifying assumptions. Still, it is worthwhile to describe some of the past efforts to gain insight into the phenomenon of hydroplaning.

5.4.1. *Model for Viscous Hydroplaning*

Viscous hydroplaning was investigated in Ref. 42. Tire–runway separation is caused primarily by viscous forces during viscous hydroplaning. The frictional coupling of the tire–runway contact is simulated by a rubber block undergoing slipping on a two-dimensional sinusoidal asperity in the presence of a thin film (Fig. 12). The contact area is divided into an inlet region, an outlet region, and a central region. The water depth profile in the inlet and the outlet region is assumed to be exponentially varying, and the central

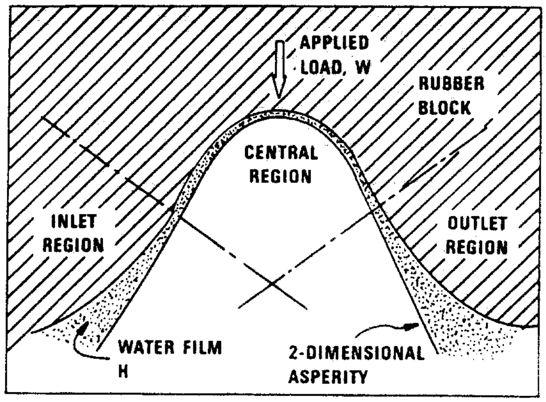


FIG. 12. Viscous hydroplaning model (from Ref. (42)).

region has a constant water depth profile. Using Reynold's equation for lubrication, pressure distribution between the rubber block and the asperity is computed. The pressure build up on individual asperities of the surface provides a net uplift which forces the tire tread apart from the surface. The results show that the important factor in minimizing viscous hydroplaning is the provision of an adequate microtexture in the surface aggregates which contribute toward adhesion; hysteresis and viscous shear were shown to be insignificant. The model is limited by the assumptions of idealized surface geometry and water depth profiles; the model results were also not verified by experiments.

5.4.2. *Models for Dynamic Hydroplaning*

Whereas viscosity is the primary fluid property responsible for developing viscous hydroplaning, fluid density effects are predominant during dynamic hydroplaning (Section 5.2.). Equation (6) (Section 5.3) quantified, for the first time, the phenomenon of hydroplaning in terms of minimum speed above which hydroplaning would occur. The equation is based on the assumption that dynamic pressure of water will be sufficient to support the tire and associated loading on it. The equation has proven useful, and much of experimental data and results from mathematical models are compared against it, but the validity of Eq. (6) is limited to smooth tires on runways covered with a large quantity of water. Another model (Ref. (45)) established that the dynamic pressure of water alone would not be sufficient to cause hydroplaning at the known hydroplaning speed computed from Eq. (6), but that the tire surface must distort locally in the contact area; the analysis modelled the tire as a semi-infinite solid in a condition of plain strain. The analysis developed an equation for calculating the thickness of the fluid film under the tire moving over a water-covered surface. This equation related water film thickness to the length of tire–runway contact, tire curvature, velocity, effective elastic modulus, fluid density, and water depth on the surface. The results from this equation were shown to agree with some experimental data.[39]

Yet another analysis (Ref. (14)) describes a theoretical approach for treating the onset of hydroplaning. The analytical model divides the flow field into three regions (Fig 13): an exterior flow region characterized by free surfaces at ambient atmospheric pressure, an inlet region wphere the flow is nearly inviscid, and a footprint region where the flow is primarily governed by viscous forces. The footprint region is further divided into a thick film region where only hydrodynamic forces act on the tire and a semidry region where the pressure distrubution on the tire surface is largely independent of whether or not hydrodynamic forces are present. Each region was considered separately, and a complete

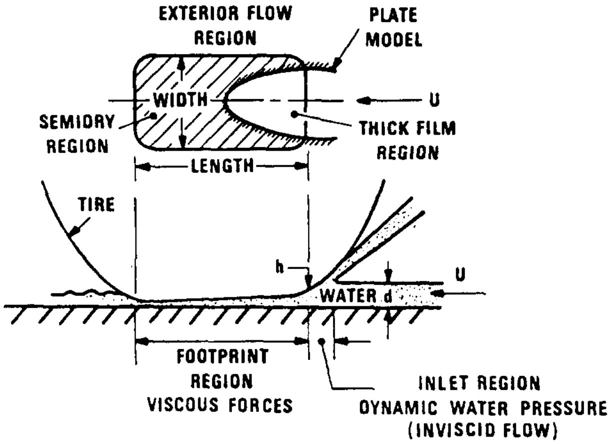


FIG. 13. Viscous–dynamic hydroplaning model (from Ref. (14)).

solution was obtained by matching the individual solutions at the flow boundaries. Two major assumptions in the development of the model were a planar tire surface in the footprint region and the neglect of inertial forces in the analysis. Initial solutions of the simplified model failed to represent hydroplaning phenomena realistically and it was concluded that the model should be refined by introducing the deformed shape of the tire surface in the footprint region. A tire deformation model was developed by considering a plate representing the thick film region of the tire–runway contact; the plate being clamped at the boundary with the semidry region and extending into the inlet region as a semi-infinite solid (Fig. 13). The tire deformations were computed by coupling the equations of fluid flow and plate deflection. The solution of the model was carried out by finding the increase in the size of the thick-film region and the corresponding decrease in the size of the semidry region as the speed increased. Since friction is almost entirely developed in the semidry region, a reduction in friction with speed is associated with the reduction in the size of the semidry region. Results showed that the growth of the thick film region (or the reduction of the semidry region) with increasing speed is strongly dependent upon the drainage properties of the pavement.

Many of the results of this analysis were incorporated in Refs (59) and (55) in developing an empirical method for evaluating and rating the fluid drainage characteristics of a runway surface. Because of the significance and usage of this method, it is described in greater detail in Section 8.3.2.

Fluid inertial forces and the presence of turbulence in the fluid flow were included in the mathematical models described in Refs (47), (13) and (12). The flow analysis in these models is basically the same as presented in Ref. (60) for turbulent flow in bearing films. The analysis starts with the general momentum equations for fluid flow applied to a control volume. The control volume is bounded by the stationary tire surface at top and a moving pavement surface at the bottom (Fig. 14). In addition, four surfaces perpendicular to the pavement completely enclose the control volume. As the fluid passes through the leading edge, the depth of water is reduced to the gap between the tire surface and pavement surface. Requirements of continuity of flow indicate that fluid must escape around the side edges, and through the leading edge as forward spray. It is assumed that no side flow exists at the leading edge, and the fluid flow through the trailing edge and the side edges exists with zero acceleration and thus at ambient pressure. In the analysis, turbulence is treated by means of turbulent viscosity correction factors, and convective inertia is accounted for by convective derivatives of mean fluid velocities averaged over the water film. With these assumptions and simplications, the resulting equations are solved by numerical techniques.

In the solution of the above models, the tire–pavement gap is a prerequisite. In Ref. (47), this gap was estimated from experimental data from Ref. (61). In Ref. (13), the

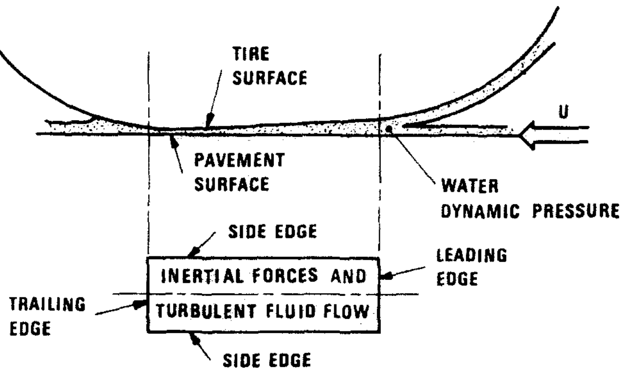


FIG. 14. Dynamic hydroplaning model (from Refs (12, 13, 47)).

tire–pavement gap was measured at selected points of the footprint and supplied to the flow model; a tire deformation model was also developed and verified. Thus, Ref. (13) coupled the fluid flow analysis with a tire deformation model for dynamic hydroplaning allowing for interaction between fluid inertial forces and tire surface deformation. Further progress was reported in Ref. (12) where an interactive tire–fluid model is developed; the fluid flow model is essentially the same as in Ref. (47); the tire deformation model was adapted from Ref. (62).

5.5. Visualization of Hydroplaning Phenomena

Many of the manifestation of hydroplaning phenomena described and observed in Ref. (37) have been verified by unique instrumentation designs and experimental techniques. Photographs of the contact area through a transparent glass plate(37,48) have clearly established that central and forward portions of the tire are detached from the surface leaving the tire–runway contact area shaped like a horseshoe. A moiré fringe method(12) has been used in measuring tire deformations in the contact area. A moiré pattern is an optical illusion, the kind produced when two sets of closely spaced parallel lines are

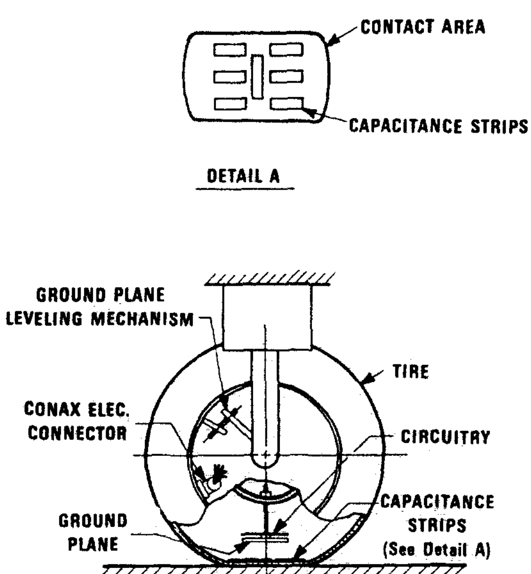


FIG. 15. Tire deformation measurement system (from Ref. (53)).

superimposed at a slight angle to each other. By shining a spot light through a glass plate (containing a grid of parallel lines) on a tire surface, a shadow of parallel line grid pattern appears on the tire. An observer viewing this shadow pattern through the original grid 'sees' a moiré fringe pattern superimposed on the tire surface. The pattern exposes the contours of the tire providing a topographical map of the tire. When the tire is deformed, the fringe pattern is changed.

Another unique method for measuring tire deformation was reported in Ref. (49). In this method a molten metal is poured inside the tire which is in the state of hydroplaning. The metal solidifies quickly, and when the tire is cut away, the metal cast reveals the deformed shape of tire.

In yet other investigations[(53,54)] the tire deformation was measured by providing complex instrumentation inside the tire body. The instrumentation was limited to a non-rotating tire; however, modification can be made to adapt it to a rotating tire. The measurement is based on the equation for capacitance change between two parallel plates as a result of a change in plate separation. The parallel plates are mounted within the toroidal space in the tire (Fig. 15). One plate is mounted on the wheel rim and the other one on the inside of tire surface. By placing the plates inside the tire, the fluid flow under the tire is not disturbed, and experimental conditions can be adequately controlled. When tire distorts by dynamic and hydrodynamic pressures, the plate separation changes.

5.6. Minimizing the Potential of Hydroplaning

In general, actions which minimize hydroplaning can be classified as passive measures and active measures. The passive measures to minimize hydroplaning include provision of adequate texture in the runway surface, runway grooving, adequate runway crown, and grooves in the tire. Moulding the grooves in the tire circumference is a designer's equivalent to pavement macrotexture.[(59)] The tread grooves in the tire footprint are vented to atmosphere and provide escape channels for water. Runway surfaces with porous aggregates (porous friction overlays) also resist hydroplaning;[(64,65)] however, large deposits of rubber (as a result of repeated landings) are difficult to remove from the porous friction surfaces.[(59)]

Runway crown and grooves help reduce water build up on the runway surface; the role of runway grooving in alleviating hydroplaning will be discussed in Section 6.

Active measures include changes to aircraft parameters, such as, tire inflation pressure and landing speeds, and the use of devices such as, antiskid brake control system. A direct consequence of Eq. (6) (Section 5.3.) is that the speed at which hydroplaning will occur will increase if the tire inflation pressure is increased. Similarly, landing at a speed below the computed hydroplaning speed could decrease the potential of hydroplaning. However, operational requirements of the aircraft may not permit either of these actions to be used. At the present time, no aircraft is equipped with remote tire–pressure control devices, although remote tire-pressure monitoring devices are in use.[(63)] While the manipulation of inflation pressure and landing speed can delay the onset of hydroplaning, the use of an antiskid brake control system can prevent the wheel from locking when the conditions are such that wheel-lock is imminent with minimum braking. It may be recalled that available friction levels are higher when a wheel is rolling than when it is locked.

6. MAXIMIZING THE AVAILABLE FRICTION AT WET TIRE–RUNWAY CONTACT

Available friction at the tire–runway contact under adverse weather conditions can be maximized if the aircraft wheel operates at critical slip (see Fig. 4). However, slip is not a control variable and its magnitude varies with the changes in operational factors associated with the contact area and the environmental conditions prevailing during aircraft operations. Still, with the use of modern brake control systems,[(33,34)] it is possible to operate an aircraft wheel (on lightly wetted runways) under optimum wheel-slip conditions. On the other hand, when runways are flooded with water, the antiskid braking system may not be efficient; under these conditions, braking performance is enhanced by grooving the runways, thereby, keeping the surface from becoming flooded. Operations of antiskid braking systems and advances in runway grooving will be described in the following sections.

6.1. Antiskid Brake Control System

The operation of a braking system is shown in Fig. 16.[66] A braking torque, T, is applied to the aircraft wheels by pressing the brake pedal; this torque attempts to decelerate the aircraft. The braking force, F, developed at the tire–runway contact attempts to restore the wheel velocity to that resulting from free rolling. At a certain brake pressure, the wheel operates at critical slip and a corresponding maximum friction coefficient is developed at the tire–runway contact. Further increase in brake pressure may lead to wheel lock accompanied by a significant drop in the coefficient of friction. An antiskid system controls the brake pressure to force the wheel/tire to operate at or near the critical slip during ground maneuvers.

References (15, 34, 66–68) describe in some details the operation of airplane antiskid braking systems. Early antiskid or antilock systems consisted of an on–off operation that simply protected the tire from locking; these systems did little to optimize aircraft braking performance. But significant advances in solid-state electronics have led to the development of antilock systems to seek out and operate around the peak of the friction–speed curve (see Fig. 4) regardless of the runway surface wetness. The newest commercial aircraft, such as, Boeing-767/757, utilize digital control technology[34] which provides more accurate brake pressure control.

Basically, an antiskid braking system is a feedback control circuit (Fig. 17[66]). The braking system relies upon either the slip velocity or the slip ratio, and requires an instantaneous wheel speed and a reference speed to determine the onset of a wheel skid. Clearly, the onset of the wheel skid is determined by the magnitude of slip as defined in Eq. (2):

$$S = 1 - \frac{V}{\upsilon}$$

where:

S = slip ratio
V = instantaneous wheel speed
υ = reference speed.

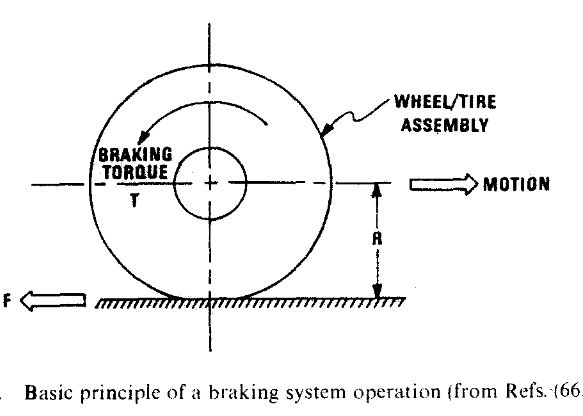


Fig. 16. Basic principle of a braking system operation (from Refs. (66, 67)).

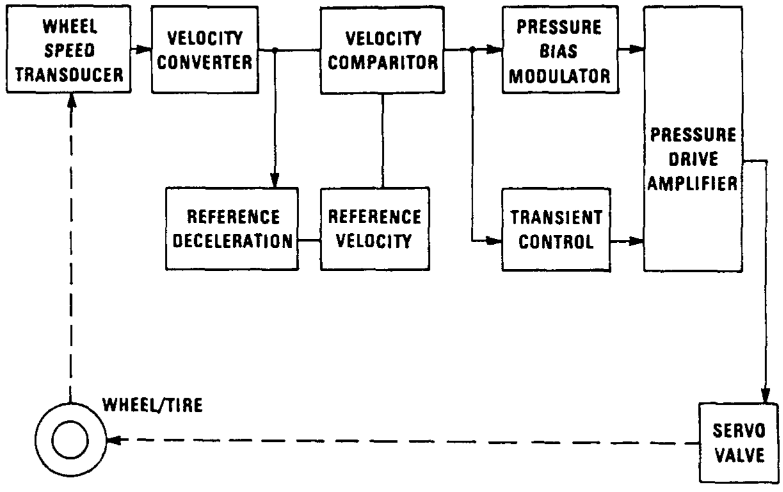


FIG. 17. Block diagram showing modern antilock control logic (from Ref. (66)).

During braking, the velocity comparitor (Fig. 17) continuously compares the reference speed with the instantaneous wheel speed. When the braked wheel slip-ratio exceeds a threshold, a signal is generated and sent to the pressure-bias modulator to reduce the brake pressure and to allow the wheel to spin up. When the instantaneous wheel speed approaches the reference speed, another signal is transmitted to the modulator to increase the brake pressure. Generally, the reference speed is established from the actual wheel speed at touchdown. At touchdown, the velocity comparitor develops an error signal which forces the reference speed to increase until the error signal ceases.

An important aspect of the efficient operation of an antiskid brake system is the availability of adequate friction levels at the tire–runway contact. When available friction levels are high, the maximum braking torque applied to the wheel is successfully transmitted to the ground and the antiskid braking system can modulate the braking pressures near the maximum.[(68)] However, when the available friction coefficients at the tire–runway contact are low, the braking performance of an aircraft is adversely affected in two ways. First, the low friction levels force the brake modulation at very low pressure. Since response characteristics of most braking systems are sluggish at low pressure levels, the braking performance is degraded. Second, low friction levels generate low wheel spin-up accelerations which slow down the recovery from a skid and further degrade the braking performance. In addition, the use of wheel speed signal to generate the reference speed is not always desired. When brakes are applied during severe hydroplaning or before touchdown, there is no reference speed available because the wheels are not spun-up; the antiskid is 'lost' and wheels remain in a locked condition until the pilot releases the brake pedals.[(34)]

Many of the brake control problems associated with low available friction or early brake application are avoided by providing hydroplaning protection feature and touchdown protection features.[(34,67)] The hydroplaning protection feature on the Boeing Airplane Company's new 757/767 airplanes is shown in Fig. 18.[(34)] A ground speed signal from the airplane's inertial reference system (IRS) is sent to the aft wheels. When the wheels are in the state of hydroplaning and stop rotating, this 'direct' reference speed is available to guide the wheels to spin-up as the wheels come out of hydroplaning. When the aft wheels spin-up, their wheel speed provides 'normal' reference speed to the forward wheels which then spin-up as well. In providing IRS signals to the aft wheels, advantage is taken of the fact that the forward wheels help remove water from the path of the aft wheels; this path-clearing action may bring aft wheels out of hydroplaning before the forward wheels do. Reference (67) suggests an additional reason that aft inboard wheels

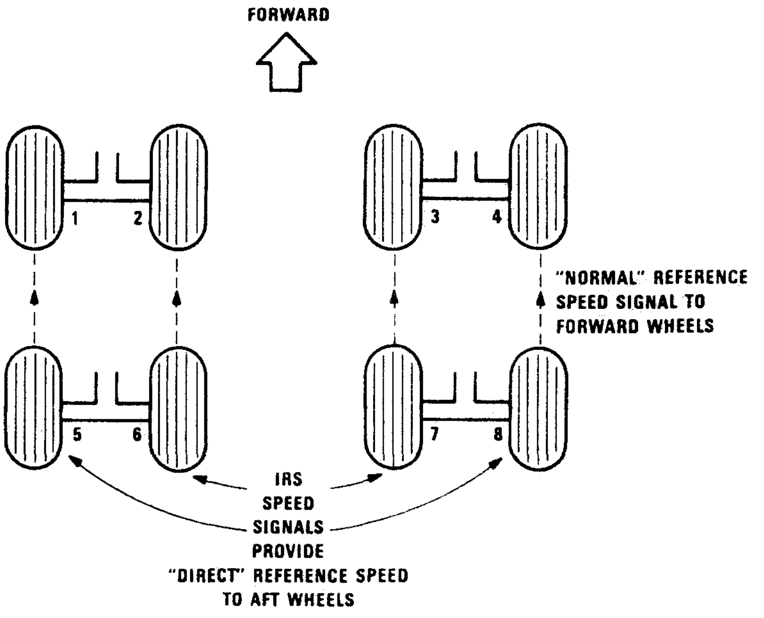


FIG. 18. Hydroplaning protection feature of Boeing 757/767 Airplan (from Ref. (34)).

are ideal for IRS signal: due to the presence of the runway crown, more of the vertical load supported by each gear is carried by the inboard wheels than by the outboard wheels. This results in higher friction forces at the contact areas of the inboard wheels and the runway. Higher friction forces develop higher spin-up accelerations, and consequently require less time to spin-up fully and to provide the 'normal' reference speed for the forward wheels.

In summary, the performance of antiskid braking systems operating under adverse weather condition is highly dependent upon wheel spin-up accelerations. Efficient operation of the antiskid braking systems requires an accurate ground reference speed. Modern antiskid braking systems use a redundant ground speed signal derived from the airplane's inertial navigation or reference system to provide protection against prolonged locked-wheel operation.

6.2. Runway Grooving

High-speed aircraft operations on wet runways by the British Royal Air Force and the United States Air Force, during the middle 1950's had clearly indicated the need for lengthening the runway or to provide rapid surface drainage characteristics on the runway to prevent aircraft skidding and what was undoubtedly 'aquaplaning' althought it was not recognized as such at that time. Between 1955 and 1963, the British researchers experimented with mechanical roughening of the runway surface to produce sharp texture or to produce grooves. In 1960, saws were developed to install transverse grooves in runway surface, and in 1961, the main asphalt runway at Farnborough was grooved with saws.

As mentioned in Section 5.6, runway grooving is a passive measure which is very significant in minimizing the occurrence of hydroplaning. In the United States, the effectiveness of runway grooving was demonstrated by extensive research and testing by the National Aeronautics and Space Administration (NASA)[28] in the middle 1960's and by the Federal Aviation Administration (FAA)[27,29,30,64] in the late 70's and early 1980's. Together, the FAA and NASA have shown that runway grooves can delay hydroplaning beyond the landing speeds of many jet aircraft, and maximize available friction levels under conditions which would not necessarily be conducive to aircraft hydroplaning.

6.2.1. *Rectangular Grooves for Runways*

An important aspect of grooving the runway is to determine the most effective groove pattern for a given runway exposed to weather conditions unique to the region where the airport is located. In its search to determine an optimum groove pattern for runway applications, NASA, in middle 1960's, conducted a test program which included groove dimensions as the major variable. Since preliminary work in Great Britain[69] was conducted by placing the grooves 1 in apart, NASA researchers[28] selected rectangular grooves with spacings between 1 and 2 in, and groove width and depth varying between 1/8 in and 3/8 in. In total these dimensions produced 18 different groove patterns. Tests were conducted at the Aircraft Landing Dynamics Facility, Langley, to determine the braking and cornering capability of an aircraft tire on these grooves in the presence of water; the tests covered aircraft speeds up to 100 knots; additional tests were conducted to investigate the effect of alternating freezing and thawing on grooved runway surfaces. Some of the test results are shown in Fig. 19. On the basis of these tests and subsequent tests with a F-4D Jet Fighter plane and 990 4-engine jet transport airplane, NASA concluded that rectangular grooves 1/4 in wide × 1/4 in deep and spaced 1 in apart were

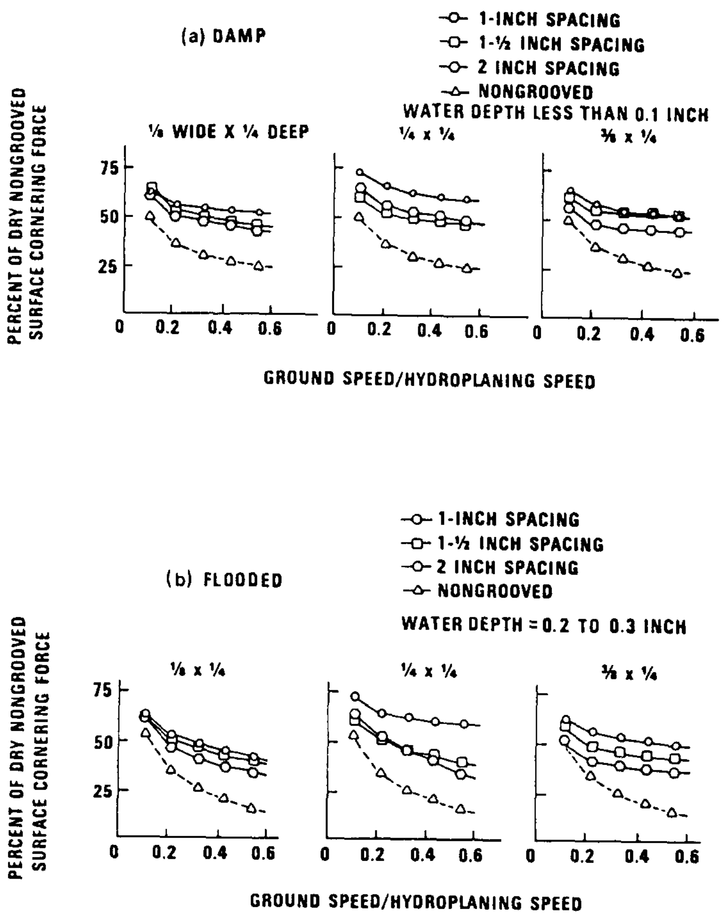


FIG. 19. Cornering capability of a smooth tire on various grooved surfaces. Smooth, type VIII, 27.5 × 7.5 tire, 4 yaw angle, inflation pressure 400 lb/in² (from Ref. (28)).

more effective than other groove patterns in enhancing braking and cornering capability of an aircraft on wet runways. In general, the research results[28] showed that transverse grooves (1) substantially increased braking capability and directional control, (2) improved runway surface water drainage, and (3) provided rapid wheel spin-up accelerations. The grooves were also shown to minimize the effect of tire tread design or tire wear[28] and the susceptibility to dynamic tire hydroplaning.[28,70] Further tests also showed[71] that aircraft strut vibrations during travel over grooved runways were no different from those over non-grooved runways.

In order to promote widespread use of runway grooves as an important safety improvement, the FAA continued the investigation to establish the effectiveness of grooves beyond aircraft speeds of 100 knots, and to find ways to reduce the overall cost of grooving a runway. A comprehensive test program was conducted at the high speed tracks of the Naval Air Engineering Center, Lakehurst. Groove spacing was a major variable

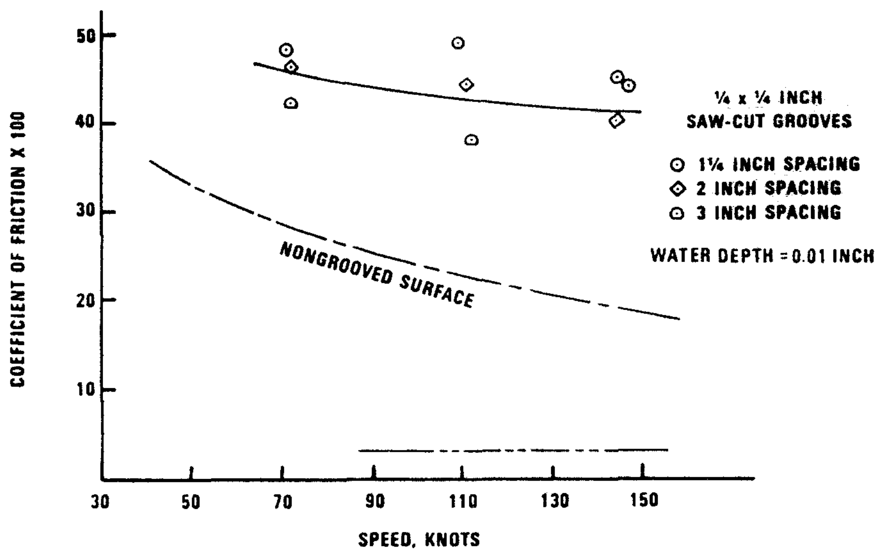


FIG. 20 Braking performance of an aircraft tire on *wet* surfaces. Smooth. Type VII, 49 × 17 tire, inflation pressure 140 lb/in² (from Ref. (64)).

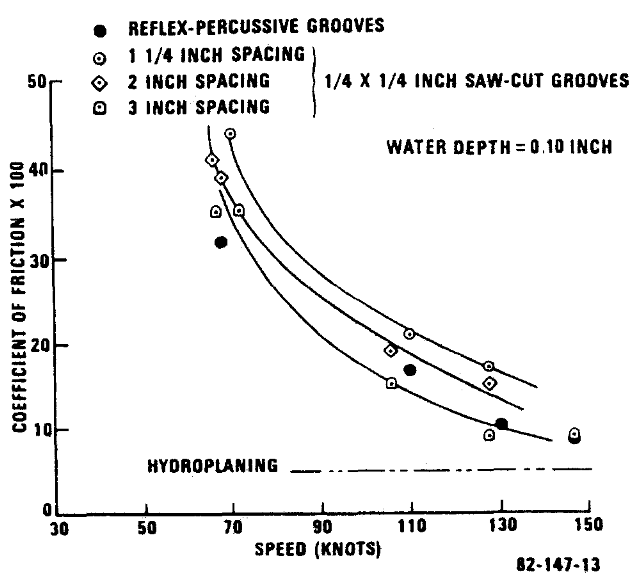


FIG. 21. Braking performance of an aircraft tire on *puddled* surfaces (from Ref. (64)).

affecting the cost of grooving.[29,64] Results of maximum braking tests to speed of 150 knots (Figs 20–22) revealed that the spacing of the square grooves (1/4 in deep × 1/4 in wide) could be increased to 3 in without encountering a state of hydroplaning; available coefficients of friction were insensitive to groove spacing when water depth on the surfaces was either less than 0.01 in (defined as 'wet' in Fig. 20) or in excess of 0.25 in (defined as 'flooded' in Fig. 22). However, when water depth on the runway was of the order of 0.10 in (defined as 'puddled' in Fig. 21) the available coefficients of friction were higher for closer spacings. Clearly, there is a performance trade off when selecting a groove pattern with 3 in spacing over a pattern with 1 in spacing. But, it was also found that the cost of grooving at 3 in spacing was significantly lower than grooving at 1 1/4 in spacing (Fig. 23).[29] It could be argued, then, that if performance were the only criterion for the selection of a groove pattern, it is only at those airports where seasonal and topographical conditions produce 'puddled' runway conditions that the choice of close groove spacing will be beneficial. But, if performance were not the only criterion, any groove spacing could be selected based on cost; all groove patterns develop sufficient braking to allow gradual reduction in speed of the aircraft.

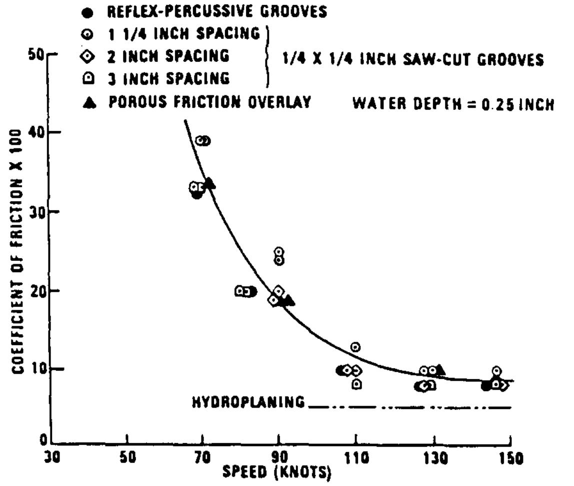


FIG. 22. Braking performance of an aircraft tire on *flooded* surfaces (from Ref. (64)).

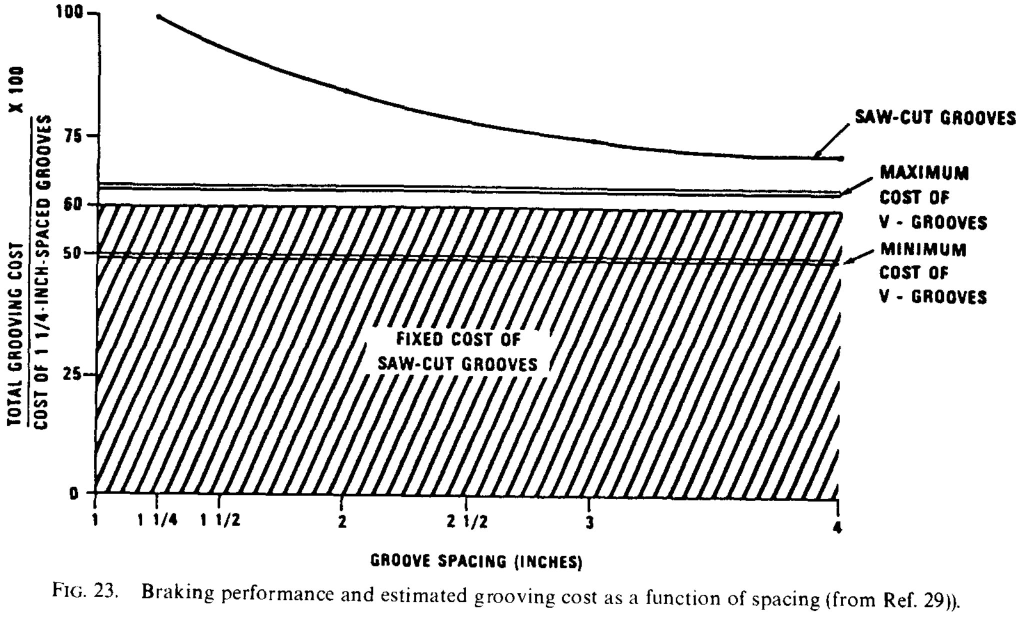


FIG. 23. Braking performance and estimated grooving cost as a function of spacing (from Ref. 29)).

6.2.2. *Grooving, Drainage, and Hydroplaning*

The improved braking performance of an aircraft tire and a near elimination of hydroplaning on a grooved runway is believed to be a dual process of water removal from the tire–runway contact area. First, the grooves influence the surface water drainage (runoff) by providing channels through which water can flow freely. Second, the grooves provide forced water escape from the tire–runway contact when the aircraft travels on a water-covered runway. Since the maximum amount of water that can be removed from the contact area is limited, both the free flow and the forced water escape are important.

Groove roughness plays an important role in determining the flow of water out of the contact area. Being laminar in nature, the free flow is enhanced if the groove channels are smooth, while the forced water escape is essentially turbulent and would require a rough groove channel to provide a shallow velocity profile for increased flow. The free flow, however, may also be turbulent during rain because of the mixing of the pelting rain. Thus, neither a smooth nor a rough groove alone will provide optimum out-flow of water from the contact area.

The effectiveness of grooving in providing a forced water escape is influenced by the amount of water on the runway and the speed of aircraft. When runways are flooded, grooves will be very effective in providing relief to the predominantly hydrodynamic pressures developed on flooded runways. However, when only a thin film of water is present on the runways, pressure relief is accomplished by sharp textured aggregates in the runway surface: the sharp aggregates break through the thin film of water and bring about the adhesion between the tire and the runway surface. In the intermediate wetness between thin film and flooding, defined as 'puddled', both the grooves and the sharp-textured aggregates are desirable for removal of water and developing adhesion in the contact area.

Although the use of grooves in the runway surface will shift the onset of hydroplaning to a higher speed, they cannot, in all cases, completely eliminate the probability of the occurrence of hydroplaning. As the operating speeds of the aircraft increase, the time available for fluid particles to escape from the tire–runway contact decreases; any acceptable increase in the number of escape paths, either by providing patterns in the tire tread or by increasing the number of grooves per unit length of the runway would not totally compensate for the reduction in this available time. Closer groove spacings increase the number of discharge channels, but will also increase the total flow resistance encountered by water during escape. The question, therefore, arises as to whether the mass of water entrapped in the contact area will respond rapidly enough to show significant changes in the available friction as a function of groove spacings. Figure 22 seems to indicate that under flooded conditions it matters little whether the runway grooves are spaced 3 inches apart or 1 1/4 inches apart. However, under puddled conditions, Fig. 21 indicates that groove spacing, drainage characteristics, and amount of water affect the available friction.

6.2.3. *Reflex-percussive Grooves*

A new groove pattern has been recently developed that uses a reflex-percussive cutting process. In 1972, the reflex-percussive method of concrete removal was recognized by the Concrete Society of Great Britain. This method was first developed to obtain very rough finish on the pavement. When the cutting head strikes the surface of the concrete, it causes the material directly under the area of impact to deflect downward, thus creating a momentary and localized compression. The compressive strain is mainly elastic, and a rebound occurs causing the concrete to attempt to pass through its relaxed state into one of tension nearly equal to the initial compression. However, being very weak in tension, the concrete fractures and elastic energy is given up as kinetic energy of the flying fragments. The great advantage of this method of cutting is its ability of not loosening the aggregate particles within the matrix or creating micro fractures in the undamaged surrounding concrete. The use of the percussive method for removal of rubber deposits was successfully demonstrated in Canada in 1976,[72] and for repairs or for recesses for insertion of shallow equipment, e.g. airfield lighting was accepted by the British Airport Authority in 1973. In the United States, the method was used to provide coarse texture on the highway surfaces.[73]

The reflex-percussive cutting process was adapted to produce the non-symmetrical V-shaped grooves shown in Fig. 9. These grooves are still in an experimental state;[27,30,74] however full scale installation on sections of a runway in the United States is underway. In sharp contrast to the square grooves which are usually cut by means of diamond-tipped rotary saws, the reflex-percussive grooves are installed in the surface by cylindrical heads as shown in Fig. 24. The cylindrical head rotates about its axis in a random manner as it strikes the surface and moves forward. High speed braking tests showed (Fig. 25) the

FIG. 24. Cutting heads for installing reflex-percussive grooves (from Ref. (27)).

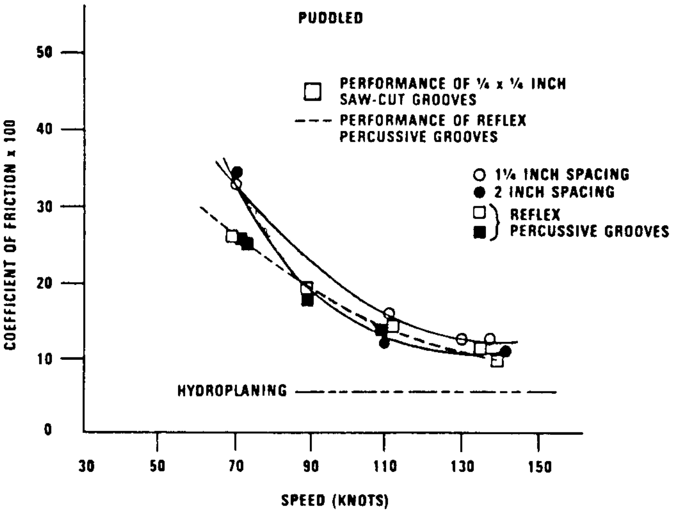


FIG. 25. Braking performance of a worn tire on puddled surfaces. Smooth, type VII, 49 × 17 tyre, inflation pressure 140 lb/in² (from Ref. (27)).

coefficient of friction developed at tire–runway contact were similar in magnitudes for square saw-cut grooves and reflex-percussive grooves. However, since the overall cost of the reflex-percussive grooves could be as low as half the cost of saw-cut grooves spaced 1 1/4 in apart, the former is a viable cost-effective alternative to saw-cut grooves.

7. EQUIPMENT AND FACILITIES FOR TIRE–RUNWAY RESEARCH

An accurate measurement of friction coefficient developed at the tire–runway contact is essential for assessing the braking, accelerating, and cornering capability of an aircraft. In addition, measurement of other pertinent parameters associated with the contact area would be helpful for a rational explanation of the various phenomena taking place in the overall system consisting of the aircraft landing gear, the tire and brake assembly, the runway surface, and the environmental contaminants. Clearly, an array of aircraft operating over a range of wetnesses on the runway surfaces and instrumented to accurately measure and isolate the effects of individual parameters of the contact area would be the ideal as research equipment; none exists, however, at the present time.

Basically, there are four classes of research equipment in use: aircraft,[65] tire–wheel assemblies rolling on concrete tracks,[28,29] tire–wheel assemblies spinning on rotating drums,[75–79] and automobiles equipped with tire–runway friction measuring devices.[80,81] In addition, the use of aircraft simulators[81–83] has been proven valuable in conducting parametric studies of the tire–runway contact area phenomena. Each of these facilities has certain merits.

Use of an instrumented aircraft to measure contact area parameters is most realistic, particularly, if controlled water depth on the runway can be provided; water depth is the primary variable significantly affecting the ground maneuvers when runways are wet. Aircraft can be operated on runways in normal use to collect data in an operational environment. However, high speed tests may not be feasible, particularly when aircraft must operate on flooded runways; high speed testing on runways covered with snow and ice is also difficult.

Ground test tracks can provide extreme environmental conditions for high speed tests with a tire–wheel assembly. Water depth control is accomplished by installing a water delivery system (on the tire–wheel assembly) that wets the track ahead of the tire. The tire–wheel assembly can provide variable cornering capability in addition to accommodating different tire sizes and braking systems including antiskid devices. Test surface interchangeability is an inherent advantage, but, obtaining an even test surface is expensive.

Another class of research equipment consists of a tire spinning on a drum: test surfaces could be provided on the outside of a large steel drum or by installing concrete strips on the inside of a drum. Most operating conditions which the tire encounters in service can be duplicated; however, the contact area is curved instead of flat. This effect can be minimized by making the drum diameter large.[78] When the outside of the drum is used it is difficult to provide a realistic runway surface; although thin layers of metallic spray on the drum surface can produce low microtexture. This limitation is overcome with the use of an internal drum[1,78] where a concrete pavement can be installed on the inside surface of the drum. The internal drum permits precise control of the surface evenness and water depth; snow, ice, and slush conditions can also be created on internal drum equipment.[84]

A steel belt looped around two metal drums provides a flat surface for testing with a tire–wheel assembly.[85,86] Many operational conditions can be created on a steel-belt surface; however, like an external drum equipment, real pavement surfaces cannot be accommodated.

Tire–runway friction measuring devices installed on or attached to automobiles present yet another class of ground equipment used worldwide for different purposes. In these devices, basically, a small tire is forced to roll under circumferential slip or slip angle; the path of the tire is wetted either by an auxiliary source or from a water-delivery system installed on the automobile. In either case, the automobile moves at speed between 20 m.p.h. and 100 m.p.h. on the runway sections. Runway slipperiness is measured in terms of the coefficient of friction developed at the contact area. The devices do not reproduce the dynamic phenomena of the aircraft tire–runway interaction; however, efforts have been underway for the past 20 years[65,81,87] to correlate runway slipperiness measured by the ground devices to the braking performance of an aircraft; to date, universally acceptable correlation criteria have not been developed.[18,80]

In summary, the equipment and facilities in use around the world for the measurement of braking performance of an aircraft are compared in Table 1. It will be necessary for some of the facilities to undergo major modifications if they are to provide a reasonable reproduction of the phenomena taking place in the aircraft tire–runway contact area. A brief description of the specific capabilities of major facilities will be given in the next few paragraphs.

TABLE 1. QUALITATIVE COMPARISON OF THE CAPABILITIES OF THE VARIOUS TEST EQUIPMENT

	TEST EQUIPMENT/FACILITY						
		Ground tracks		Drums			
Requirement	Aircraft	Water-jet	Jet-engine	Internal	External	Belts	Ground devices
Flat test surface	Yes	Yes	Yes	No	No	Yes	Yes
Real pavement	Yes	Yes	Yes	Yes	No	No	Yes
Control of water depth	Mod.*	Mod.	Mod.	Yes	Only damp	Yes	Yes
Control of surface evenness	No	Yes	Yes	Yes	No	Yes	No
Repeatability of test conditions	With mod.	With mod.	With mod.	Yes	Yes	Yes	Yes
Interchangeability of test surfaces	Yes†	With mod.	With mod.	Yes	No	No	Yes
Snow and ice testing	Yes‡	No	Yes	Yes	No	No	Yes
Range of aircraft speed/loading	Yes	Yes	Yes	Yes§	Yes	Yes§	No
Reasonable reproduction of aircraft tire/runway contact dynamics	Yes	Yes	Yes	Yes	No	No	No

*Modification: installation of on-board water delivery system.
†Different runways.
‡Limited to low test speeds.
§Redesign.

7.1. EQUIPMENT/FACILITIES AT NASA

7.1.1. *Landing Dynamics Facility at Langley, Virginia*

The Landing Dynamics Facility (Fig. 26) at the Langley Research Center, Langley, Virginia, is capable of testing full-size aircraft landing gear systems under many conditions which simulate landing and takeoff operations of an airplane. A tire-wheel assembly, loaded vertically to 50,000 lb and attached to a massive carriage, is accelerated to test speeds of up to 220 knots by a hydraulic jet catapult. The catapult develops a maximum thrust of 1,530,000 lb and accelerates the carriage to a maximum of 18 g's. Following acceleration, the carriage coasts freely into the 1800 ft of test surface before engaging the arresting gears; the carriage is stopped thereafter by arresting cables. Surface wetness is achieved by a water sprinkler system installed on the track.

FIG. 26. Ground Track Facility at NASA – Langley.

Exceptionally suitable for a vast range of conditions that could be encountered during aircraft and space shuttle operations on dry runways, the Langley facility does not provide accurate control of water depth on the entire test surface, particularly below 0.10 in of water depth. In addition, high acceleration forces encountered by the carriage preclude installation of an on-board water delivery system; testing in natural snow and ice conditions is also not feasible.

7.1.2. *Boeing-737 Aircraft*

For testing in natural snow and ice, NASA employs a Boeing-737 aircraft. The aircraft is instrumented to measure longitudinal, lateral, and normal accelerations at the aircraft center-of-gravity; other aerodynamic parameters are measured by suitable sensors installed on the aircraft. The aircraft is also used for testing on a wet runway; wetness is provided by water-carrying trucks equipped with sprinkler bars which deposit known amounts of water as the trucks move on the runway. The acceleration data obtained on-board the aircraft during tests is reduced by the use of a high-speed digital computer to provide time histories of braking distance, friction coefficient, and ground speed. The coefficient of friction is computed by incorporating aerodynamic constants, either measured or known from aircraft characteristics provided by the manufacturer.

NASA's Wallops Flight Center has available various test surfaces (Fig. 27) on runway 4/22 for testing with an aircraft or with ground friction measuring devices. Other equipment available for evaluation of aircraft braking/cornering performance include a Motion Base Simulator,[81] a Diagonal Braked Vehicle,[15] and an instrumented tire test vehicle in which the test tire can be subjected to circumferential slip of any magnitude and side slip to a desired angle.

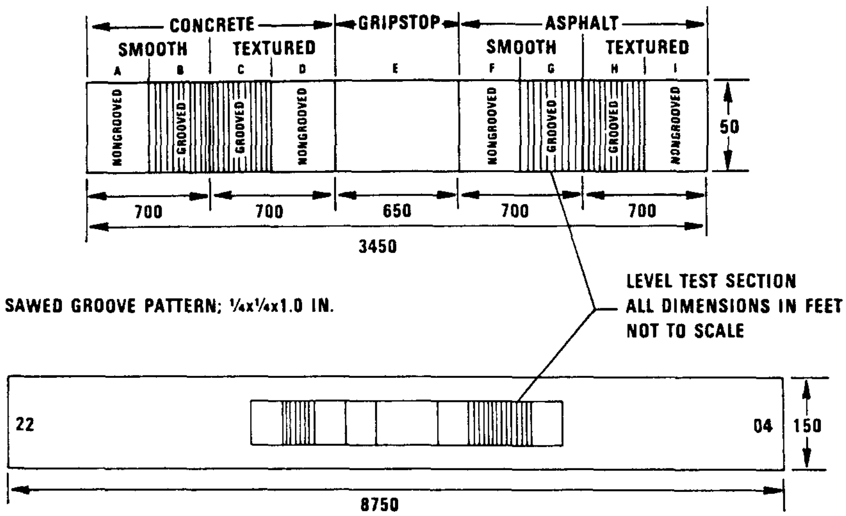


FIG. 27. Test Surface of Runway 4/22 at NASA Wallops.

7.2. Test Track at Naval Air Engineering Center, Lakehurst, New Jersey

Jet engines push and accelerate a carriage (Fig. 28) on guided steel rails, extending over a mile in length, to achieve speeds in excess of 150 knots. The tire–wheel assembly, loaded vertically to 35,000 lb, can simulate virtually any operational condition expected during landing and takeoff of an airplane. Four jet engines of the pusher vehicle develop a total thrust of 24,000 lb and speeds of up to 160 knots in approximately 1/2 mile length down

FIG. 28. Ground Track Facility at Naval Air Engineering Center—Lakehurst.

the track before the vehicle is disconnected from the carriage; the carriage then coasts freely into the test surfaces laid down between the guide rails. The carriage is stopped beyond the test surfaces by means of a series of arresting cables. Surface wetness is achieved by a water sprinkler system installed on the test track.

Suitable for providing natural snow and ice environment, the facility can also provide close control of water depth on the test surfaces by installing an on-board water delivery system.

7.3. Boeing-727 Test Aircraft at FAA

The FAA Boeing-727 aircraft is instrumented very much like the Boeing-737 aircraft at NASA. These two aircraft together provide a variety of operational conditions experienced by airplanes with tail-mounted engines and wing-mounted engines.

The FAA Technical Center located near Atlantic City, New Jersey, also offers two runways with unique grooving configurations. Runway 13/31 (Fig. 29) has an asphaltic

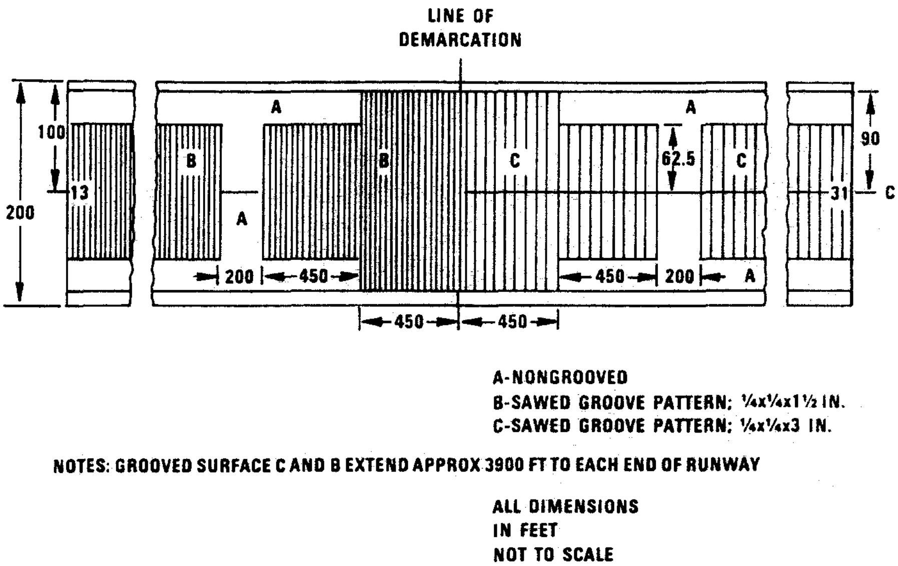


Fig. 29. Test surfaces of runway 13/31 at FAA technical center.

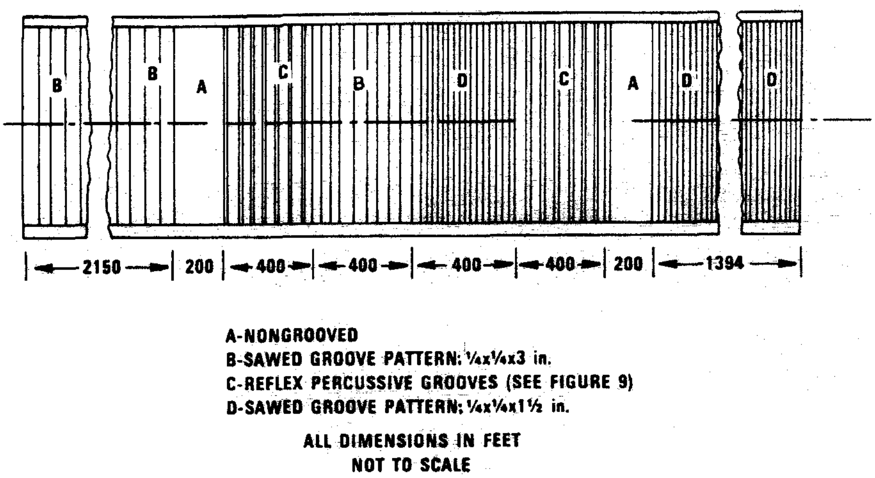


Fig. 30. Test surfaces of runway 4/22 at FAA technical center.

concrete surface with two groove patterns and two non-grooved sections. Runway 4/22 (Fig. 30) has a Portland cement concrete surface with sections of reflex-percussive grooves (Fig. 9) and saw-cut grooves, and two non-grooved sections. In addition, runway 4/22 is also equipped with an underground cable network connected to 68 metallic cans flush with the runway surface and 15 feet on either side of the runway centerline. Sensors capable of measuring runway surface contaminants (ice, snow, water, and slush) can be readily installed.

7.4. Internal Drum Machine at Bundesantalt für Strassenwesen (BAST), Cologne, Germany

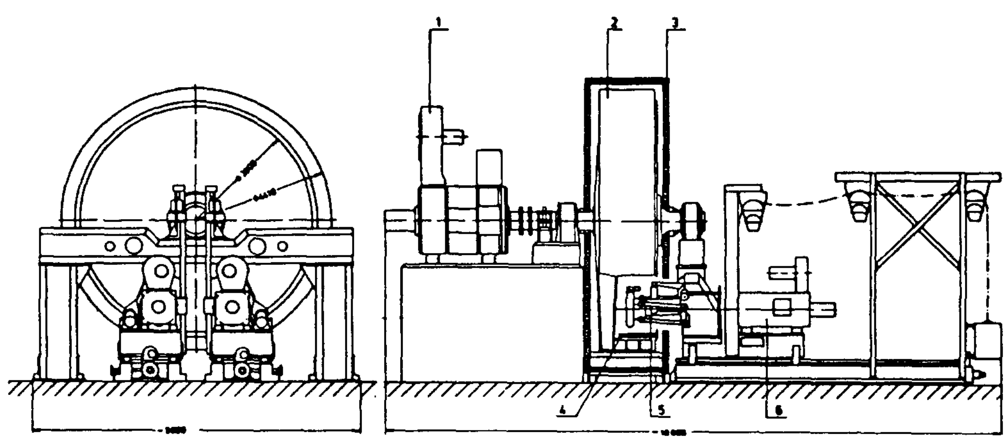
The internal drum machine of BAST in Cologne, Germany, was designed and built for testing automobile tires; however, it is also suitable for testing a nose-gear tire of a large jet aircraft or a main-landing gear of a small high-performance aircraft. The BAST machine (Fig. 31) consists of a 15 ft diameter steel drum with the inner surface capable of accommodating concrete runway surfaces of many textures and groove patterns. The test facility provides accurate control of surface evenness and water depth; the environmentally controlled chamber can create extreme conditions ranging from damp surfaces to ice covered surfaces. Repeatability of test conditions and ease of testing, and capability of real-time display of test results make the drum facility very attractive; however, the BAST machine is not capable, in its present form, to provide a vertical load in excess of 3,000 lb. An 18 ft diameter steel drum facility is under construction at BAST, and when completed in 1988, will have higher operational capabilities.

7.5. Other Facilities

There are many other equipment/facilities available around the world which are suitable for tests to determine the braking performance of an aircraft. The author did not have available detailed description or photographs to be included in this section; however, a few are listed below:

External drum equipment at Goodyear Aerospace, Akron, Ohio, U.S.A.

L-1011 test Tristar at Lockheed-California Company, Burbank, California, U.S.A.



1 DRUM DRIVE D-C MOTOR
2 DRUM
3 ENVIRONMENTAL HOOD
4 EXCHANGEABLE PAVEMENT SURFACE
5 WHEEL MOUNTING SUPPORT
6 WHEEL DRIVE D-C MOTOR

Fig. 31. Internal drum machine at Bundesantalt für Strassenwesen.

Landing Gear test facility at Wright-Patterson Airforce Base, Ohio, U.S.A.
Aircraft brake simulation capabilities at Boeing Airplane Company, Seattle, Washington, U.S.A.
High-speed external drum facility at Dunlop Limited, Fort Dunlop, U.K.

8. PREDICTION OF AIRCRAFT BRAKING PERFORMANCE

The subject of predicting the braking performance of an aircraft on runways covered with water or other contaminants has received much attention. The need for a prediction method is clear bearing in mind the reduced braking action and ground directional control available during landing on a water covered runway. The subject is complex considering the many parameters of the contact area that must be accounted for in the development of the prediction method, with ample allowances for varying pilot techniques.

Much of the research in the past 25 years has been directed in designing a 'ground vehicle' which could measure the friction at the vehicle tire–runway contact, in the hope that this would lead to a prediction of the corresponding friction coefficient available at the aircraft tire–runway contact; the governing equations could then be solved for the stopping distances. A recurring question has been 'how closely' does the performance of a ground vehicle 'correlate' with that of an aircraft. Research to date[18,55,59,65,81,87–95] has been impressive; however, these efforts have not succeeded in presenting an accepted approach to predicting the stopping capability of an aircraft with any certainty.

8.1. Ground Vehicles

Working independently and jointly, research organizations around the world have developed various ground vehicles for measuring the coefficient of friction developed between a tire and the runway. These vehicles are equipped with devices in which a tire is forced to operate with a longitudinal slip or at a slip angle; some of the devices have two tires operating identically. Table 2 compares the commonly used ground vehicles. A brief description of these vehicles follows:

(a) The Saab friction testor incorporates a fifth wheel mounted behind the rear axle of the vehicle. This wheel is driven by a chain transmission connected to the rear axle: the drive ratio provides a constant slip of between 10 and 12 %. Equipped with an on-board water delivery system, the tester can be operated at speed of up to 100 m.p.h. The torque required to drive the wheel is a measure of the coefficient of friction.

(b) The Skiddometer (BV-11) consists of a three-wheel trailer towed behind a vehicle: the wheels are connected by means of roller chains and sprockets with differing number of teeth. The gear ratio provides a slip of about 17 % to the central wheel. Equipped with an onboard water delivery system, the tester can be operated at speed of up to 100 m.p.h. The torque required to drive the wheels is a measure of the coefficient of friction.

(c) The Mu-Meter consists of a three-wheel trailer towed behind a vehicle; the two outer wheels are held at a fixed toe-out angle of 7 1/2 degrees from the direction of travel. The side force generated between the wheels, as the vehicle moves, is a measure of the coefficient of friction. Equipped with an on-board water delivery system, the tester can be operated at speed of up to 100 m.p.h.

(d) The Tapley Meter and the James Brake decelerometer are basically air-damped accelerometers which can be mounted on a vehicle floor. Vehicles equipped with these devices are decelerated fron 20 or 30 m.p.h. on a runway wetted by an auxiliary water delivery system.

(e) The Diagonal Braked Vehicle (DBV) is an automobile modified to permit braking of one front wheel and the diagonally opposite rear wheel, allowing the other diagonally

TABLE 2. VARIOUS GROUND VEHICLES

Ground vehicle	Tire pressure/ load	Operational mode/speed	Worldwide use	Measurement capability	Wetness control
SAAB friction tester, Sweden	30 psi*/310 lb	10% slip/up to 100 m.p.h.†	70	Measures coefficient of friction	On-board water delivery system
Skiddometer BV11, Sweden	17 psi/225 lb	17% slip/up to 100 m.p.h.	300	Measures coefficient of friction	On-board water delivery system
Mu-meter, Great Britain	10 psi/250 lb	7½-degree slip angle/ up to 100 m.p.h.	300	Measures coefficient of friction	On-board water delivery system
Tapley meter, Great Britain	Mounted inside a vehicle	Senses deceleration/ 30 m.p.h. to stop	N/A	Measures braking efficiency	Auxiliary source
James brake decelerometer, N/A	Mounted inside a vehicle	Senses deceleration/ 30 m.p.h. to stop	N/A	Measures braking efficiency	Auxiliary source
Diagonal braked vehicle, NASA‡, USA	24 psi/1300 lb	100% slip on diagonally opposed wheels/80 m.p.h. to full stop	N/A	Measures stopping distance	Auxiliary source

N/A: not available.
* psi: pounds per square inch.
† m.p.h.: miles per hour.
‡ NASA developed the vehicle, but does not manufacture it.

opposite pair of wheels to roll freely. The tests are conducted with the braked wheels at 100% slip (locked wheels). The DBV measures stopping distance by decelerating the vehicle from 60 or 80 m.p.h. to a complete stop on a runway wetted by an auxiliary water delivery system.

8.2. Experimental Efforts to Correlate Aircraft and Ground Vehicle Performance

1968 (Refs (87) and (92)) Joint Program between NASA and British Ministry of Technology

Test Vehicles:	21 ground vehicles, 2 aircraft.
Test Site:	NASA Wallops Flight Center.
Wetness:	on-board water delivery system and auxiliary water supply.
Purpose:	correlation between aircraft braking performance and measurements by ground vehicles.
Conclusion:	'Good' to 'Fair' correlation. Ground vehicles in general cannot be used for estimating aircraft stopping capability. However, limited testing with DBV indicates the possibility of estimating aircraft stopping distances; further research recommended.

1970 (Ref. (65)) Joint Program between NASA and United States Air Force

Test Vehicles:	4 ground vehicles, 1 aircraft—C-141A.
Test Sites:	50 runways in U.S.A. and Europe.
Purpose:	correlation between aircraft stopping performance and ground vehicle performance.
Wetness:	wet, flooded, slush, snow, ice, and also dry surfaces. Natural rain, on-board water delivery system, and auxiliary water supply.
Conclusion:	a DBV can be used to predict aircraft stopping distance on contaminated runways.

1971–72 (Ref. (94)) Joint Program Between FAA, United States Air Force, and NASA

Test Vehicles:	2 ground vehicles, 2 aircraft—Boeing 727-100, McDonnell Douglas DC-9.
Test Sites:	smooth and grooved runways.

Wetness:	wet and dry runways.
Purpose:	correlation between aircraft stopping performance and ground vehicle performance.
Conclusion:	no consensus.

1973 (*Ref.* (*88*))

Test Vehicles:	5 ground vehicles, 2 aircraft—Lockheed L-1011, Boeing 737 Advanced.
Test Sites:	one runway.
Wetness:	auxiliary water supply and on-board water delivery system.
Purpose:	evaluation of special landing requirements of Concorde SST aircraft.
Conclusion:	no consistent or precise correlation between various ground vehicles. The DBV provides a reasonable relationship for the two aircraft tested.

1978 (*Ref.* (*81*)) *Joint Program between FAA and NASA*

Test Vehicles:	various ground vehicles; one aircraft—Sabreliner-80.
Test Sites:	NASA Wallops Flight Center.
Wetness:	auxiliary water supply and on-board water delivery system.
Purpose:	to establish an aircraft test technique for evaluating runway friction; to determine degree of correlation between measurements from various ground vehicles and aircraft.
Conclusion:	'Good' agreement between actual aircraft braking performance and performance from ground vehicles; additional research recommended.

1983–Present (*Final Report Forthcoming*) *Joint Program between FAA and NASA*

Test Vehicles:	5 ground vehicles, two aircraft—Boeing-737, Boeing-727.
Test Sites:	NASA Wallops Flight Center Runway 4/22. FAA Technical Center Runway 13/31, Brunswick Naval Air Station.
Wetness:	wet, freezing rain, snow, and slush. Natural rain, auxiliary water supply, and on-board water delivery system.
Purpose:	degree of correlation between aircraft braking data and ground vehicle friction data. Evaluation of the validity of a correlation prediction theory (see Sections 5.4.2 and 8.3).
Conclusion:	Final Report forthcoming.

In many of these efforts, the degree of 'correlation' was qualified as good; however, a quantification criterion was not generally established. Therefore, the answer to the question as to 'how closely' does a ground vehicle correlate with the aircraft remains unanswered. The reason for a less-than-perfect correlation between the performance of a ground vehicle and an aircraft is not clear. Information available to date seem to indicate that when ground vehicles are operated on a runway in accordance with the procedures established by the developers, they all show a generally accepted relationship between speed and available friction coefficient, with a drop in friction coefficient as the speed is increased. Tests with an aircraft on a runway, and with a tire–wheel assembly on ground tracks or drum surfaces, also show these trends between the available friction coefficient and speed. However, there is no acceptable method that could employ a ground vehicle to predict the performance of an aircraft with reasonable accuracy. One explanation could be that, perhaps, the ground vehicles do not reproduce the dynamics associated with an aircraft tire on the runway surface; vastly different loading and aerodynamic conditions are encountered during operation of aircraft and ground vehicles. Lack of accurate control of the operational parameters could also affect a close correlation between the performaces of various equipment. It is important to note that the magnitude of the available friction coefficient is small on contaminated runways, and in many cases the cumulative effect of experimental error and fluctuations in operational variables could lead to wide variations in the measured quantity. It should be recalled (Section 4.1) that since water depth is the primary variable that governs the friction level at the contact area, any fluctuation in water depth during a test could have a significant effect on the measurement. Many test facilities have on-board water delivery systems (see Tables 1 and 2) which deliver uniform water flow in front of the tire and minimize variations in water depth; however, runway surface irregularities could still affect the water depth distribution.

8.3. Prediction of Aircraft Braking Performance Through Empirical Methods

8.3.1. *Prediction Equation Through Dynamic Similitude*

A study was conducted in 1974 jointly by the United State Department of Defense, the FAA, NASA, and the Boeing Airplane Company[18] to develop an equation to compute the stopping performance of an aircraft on wet runways, and to further investigate if a ground vehicle could be developed that would provide information about the stopping capability of an aircraft. An aircraft simulator[82] was used to identify major parameters that influence the stopping distance of an aircraft. Aircraft dynamics was simulated by analog computer, and wherever possible, actual aircraft components were used; simulation of tire–runway contact area was accomplished by providing friction-speed curves based on experimental data. The study included five airplanes—Boeing-727, Boeing-737, Boeing-747, Lockheed C-141A, and McDonnell Douglas F-4. Using the principles of dynamic similitude, an equation was developed (Fig. 32) relating the stopping distance of an aircraft to three non-dimensional groups: the available friction coefficient, the ratio of airplan lift and drag, and a term containing airplane speed, air density, gravity, and engine thrust.

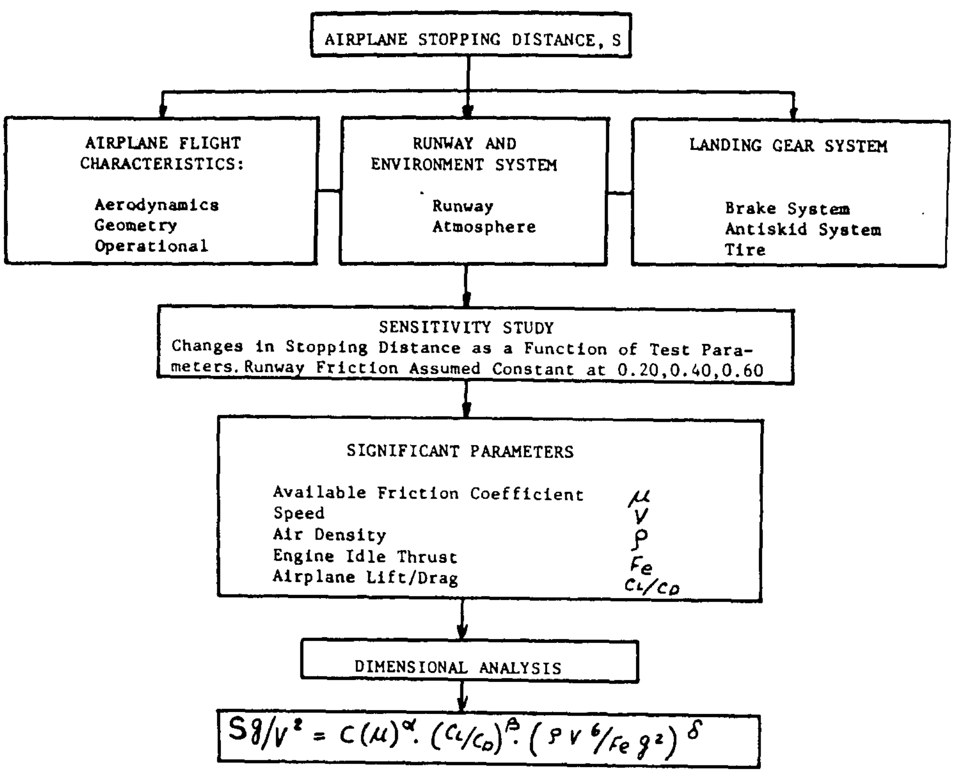


FIG. 32. Prediction equation through dynamic similitude.

$$\frac{S\,g}{V^2} = C(\mu)^{\alpha}.\,(C_L/C_D)^{\beta}.\,(\rho V^6/F_e\,g^2)^{\delta} \tag{10}$$

The exponents α, β, and δ, and the coefficient C result from the sensitivity study and the dynamic similitude; these exponents and coefficient have unique values for each aircraft included in the study. Equation (10) permits calculation of stopping distance of an aircraft if an 'accurate' measurement of friction coefficient, μ, is available. The study concluded that the most desirable approach to design a ground vehicle that could predict the stopping distance of an airplane would be to involve a vehicle that demonstrates dynamic similarity in the braking process. Still, the ground vehicle tire characteristics would have to be transformed to or correlated with aircraft tire characteristics. In addition, scaling factors must be applied to accommodate various aircraft tires in use, and correction factors must be developed to account for changes in weather conditions. The study further concluded that DBV and Mu-Meter did not meet the required criteria for assessing aircraft stopping performance.

8.3.2. *Prediction Method Using Runway Surface Texture and Drainage Characteristics*

Based on the fact that runway surface texture plays an important role in developing friction at the tire–runway contact area, an empirical method was developed (Refs (55) and (59)) that characterizes the runway surface by two coefficients: the microtexture drainage coefficient, C_{MIC}, and macrotexture drainage coefficient, C_{MAC}. For the method it is assumed that these two coefficients quantify the capacity to develop viscous and dynamic pressures, respectively, (see Section 5.4.2.) in the tire–runway contact area; for example, $C_{MIC}=0$ means viscous forces are absent and $C_{MAC}=1$ means maximum dynamic pressures are present. The method is based on the premise that once these coefficients are established for a wet runway surface, the prediction of available friction coefficients for any tire is a matter of simple computations involving empirical relationships between the fluid pressures, both viscous and dynamic, and the speed.

The method is based on realistic parameters associated with the tire–runway contact area, and comparison with experimental data shows that the method gives reasonable estimates[55] of friction coefficients for both aircraft and automobile tires used in the study. However, the use of simplifying assumptions, and lack of experimental data to compute essential elements of the method raises questions as to its universal applicability. The division of the contact area into three zones (Fig. 33), and the assumption that

$$\mu_{wet} = \mu_{dry}\cdot\left(\frac{A_3}{A}\right) \tag{11}$$

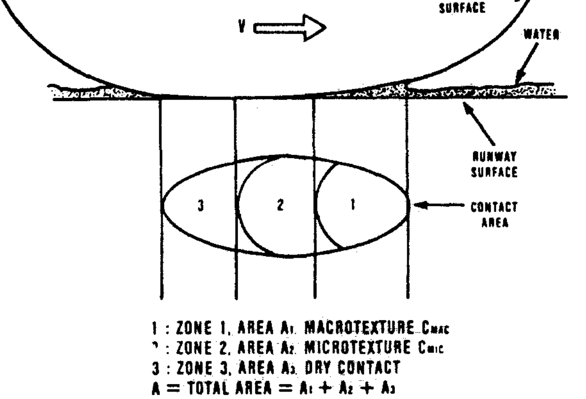


FIG. 33. Division of the contact area to predict braking performance through runway drainage characteristics (from Ref. (55)).

gives a linear relationship between wet and dry friction coefficients. It is implied in this assumption that should the dry area, A_3, be half the total contact area, A, wet friction will be equal to half the friction under dry conditions. This assumption is not justified because it can only be rationally satisfied when $A_3 = A$; this argument also suggests that division of the contact area is irrelevant.

Another assumption in the methodology characterizes the fluid pressures as single-valued functions of the speed throughout the contact area, which when multiplied by drainage coefficients equal areas of zones 1 and 2. Experimental and analytical studies[3,12–14,42,47] have clearly shown that fluid pressures in the contact area depend upon the distribution of fluid film thickness and vary throughout the contact. Many other factors,[95] such as, tire loading, size, tread compound, tread depth, tread construction, temperature, water depth, and braking techniques are also not explicitly accounted for in the methodology. The method is, in general, based on assumptions which are neither justified nor verified.

8.4. Aircraft Operations on Runways Covered with Slush, Ice, and Snow

When an aircraft is operating on a flooded runway or on a runway covered with slush, ice, or snow, the friction forces developed at the tire–runway contact can be very small. Hydroplaning can occur on a flooded or a slush-covered runway, and in addition, the presence of slush has a very severe effect on aircraft takeoff performance[65,96] as it leads to deterioration in the accelerating capability of an aircraft by developing slush drag. This arises directly from the slush density and also from the rearward momentum imparted in the aircraft by the slush impinging on it. Since slush drag increases much faster than the aircraft speed (approximately parabolically[97]), it prolongs the takeoff distance and can therefore be a major hazard.

The airplane ground performance on ice-covered runways is also poor. The presence of dry ice alone is not responsible for this degradation, rather, a very thin film of water (of the order of 0.004 in[98]) is formed between the tire and ice by frictional melting when the tire slides over icy surfaces. While friction on dry ice is generated by adhesion and hysteresis (see Section 2.2), the mechanics of friction generation is by fluid friction or viscosity when a thin film of water is present. If it is assumed that heat is generated at the tire–ice contact, the relative amounts of heat conducted into the two bodies will be proportional to the ratio of their thermal conductivities. As ice has a thermal conductivity two orders of magnitude higher than rubber,[99] most of the heat will flow into ice, and the surface temperature rise will depend on heat dissipation per unit area for ice. Experimental evidence[100] indicates that the temperature rise at the surface occurs quickly enough for water to be formed before the tire elements pass through the contact area. Since tire surface temperature is continuously rising due to heat conduction, there is a greater likelihood of large local melting of ice in the contact area as the airplane is decelerated. This would mean that the additional lubricating effect may produce lower friction coefficients at lower speeds—a trend opposite to what is generally seen on water covered surfaces.

The presence of snow on a runway is a common sight in North America and Europe; it degrades aircraft maneuverability by developing low friction coefficients and by significantly reducing visibility. Accumulation of snow and ice on aircraft surfaces may cause deterioration of their lifting ability and create aerodynamic problems; uneven cleaning of one wing can be sufficient to cause roll-disturbance at lift off.[101]

While winter driving aids, such as snow tires and chains, can be utilized to combat snow and ice conditions on highways, a solution for aircraft is to keep the runways clean. Use of mechanical means, chemical solvents, and thermal devices[102] have generally been satisfactory in alleviating the snow and ice buildup problem on runways. In severe ice and snow conditions, however, the only alternative is to close the runway. In the mean time, another major effort is underway jointly by the FAA and NASA for developing relationships between the performance of ground vehicles (Section 8.1) and aircraft (Sections 7.1.2. and 7.3) on runways covered with snow and ice;[103] the results of this effort were not available at the time this paper was being written. The results may provide rational guidance for snow and ice removal from runways. In addition, the development and use of reliable sensors which can be installed on runways to predict the onset and accretion of snow and ice conditions can help the airport management in improving procedures necessary for snow control.

8.5. Runway Maintenance

If a runway could be kept clean of snow, ice, slush, water, rubber deposits, and any other contaminant, aircraft would safely execute most ground maneuvers. This is not always possible, if only because of economic constraint. In addition to keeping the runways clean, it is also important to maintain the runway surface friction characteristics at a desirable level. In the U.S.A. the FAA provides guidance through an advisory circular[104] for the design, construction, and maintenance of skid resistant runway surfaces; in many countries around the world the use of ground vehicles is widespread[80] (Table 2) to evaluate the braking action under diverse weather conditions. As described in Section 8.1, the ground vehicles are equipped with devices whereby a tire is tested under a longitudinal slip or at a slip angle. The output of each device is a measure of the coefficient of friction developed at the tire–runway contact. Effectiveness of the friction devices and possible correlation in the outputs from various devices has been the subject of many studies.[59,88,93,104–105] In general these devices are reliable and when specific operational conditions are identified, a reasonable correlation exists on the outputs from many of the devices.[105] One advantage of an acceptable correlation between various ground vehicle performance data is the uniform reporting of the surface conditions in terms of the developed coefficient of friction at the tire–runway contact; the information can be utilized to develop runway maintenance criteria. At the present time, the FAA advisory circular[104] recommends a frequency of runway surface friction measurements based on annual aircraft operations. When the average of measured friction values drops below a minimum, the circular recommends corrective measures to restore the surface characteristics to a desirable level. These measures could range from the removal of rubber deposits to resurfacing of the entire runway depending upon the degradation of the surface characteristics. Efforts are continuing to refine the operational parameters of the various ground vehicles to achieve better 'correlation' among them and to promote their use for establishing adequate runway surface maintenance procedures.

9. SUMMARY AND RECOMMENDATIONS

9.1. Summary

When an aircraft is braked on a wet runway, a complex process involving tire deformation, tire slipping, and fluid pressures in the tire–runway contact area enables the development of friction forces necessary for stopping the aircraft. For most effective braking, the tire slip must be optimum and the force due to fluid pressures must be a minimum; the latter implies that water must be drained off the runway. Modern brake systems incorporate highly effective antiskid and antilock devices to control the brake pressure to force the tire to operate at or near the critical slip. Runway grooves help reduce the water build up during heavy rain storms and provide forced water escape from the tire–runway contact area when the tire is braked on wet runways; circumferential grooves on the tire surface also help water escape through the channels. Continued efforts to visualize the interactions in the tire–runway contact will provide information to help improve safety during aircraft maneuvers on contaminated runways. In addition, proper monitoring and documentation of the runway surface characteristics will provide information for adequate maintenance of the runway.

Efforts to date have succeeded in providing good runway surfaces that combine the ability of the sharp-textured aggregates to combat viscous hydroplaning and the force water escape capability of grooves to alleviate dynamic hydroplaning. Advances in electronics have led to new braking systems that can utilize the maximum available friction coefficients developed at the contact area as a result of improvement in both the surface characteristics and the tire designs. However, only limited success has been achieved in predicting the aircraft braking performance (on water covered runways) by auxiliary means: ground vehicle methods attempt to model an aircraft tire by an automobile tire through testing; empirical methods state the need for scaling factors or runway drainage factors for transforming the characteristics of an automobile tire to that of an aircraft tire; purely analytical efforts have failed to model the phenomena of hydroplaning; and classical mechanics cannot analyze a tire structure without major simplifying assumptions. Efforts are continuing, however, to refine existing relationships and to develop measurement techniques which could provide more meaningful information about the runway surface characteristics. Despite all this, landings and takeoffs of the aircraft on runways covered with water, ice and snow could still result in loss of directional control and overrun.

9.2. Recommendations for Further Work

Significant progress has been made in the past few years in understanding the braking process of an aircraft tire on water covered runways. However, there is room for further progress in two specific areas: (1) prediction of the braking potential of an aircraft, and (2) procedures for runway surface maintenance.

9.2.1. *Prediction of the Braking Potential of an Aircraft*

One way to determine the braking potential of an aircraft on water or ice/snow covered runways is to measure the friction at the aircraft tire–runway contact and display it and derived data in the cockpit; the information so generated would be based on the realistic parameters of the contact area. A cockpit display unit has several advantages: it can provide the pilot with the instantaneous deceleration, available runway length to stop the aircraft, takeoff performance—speed and drag data, and actual coefficient of friction developed at the contact area.

The first step in the development of a reliable cockpit display unit is to establish definitive relationships between the aircraft deceleration and contact area friction coefficient. This would necessitate instrumenting the landing gear or the tire–wheel assembly of a test aircraft to measure accurately the friction coefficient. It is essential that the aircraft be self contained in terms of providing uniform water depths on the runway: an on-board water delivery system could fulfill this need. The friction coefficients or corresponding deceleration values can be coupled to Eq. (10) (Section 8.3.1.) or other similar equation to compute the stopping distance of the aircraft; a small computer can be used to generate all the pertinent performance parameters. Should there be definitive relationships between deceleration and friction coefficient, an aircraft can be equipped with bi-axial or tri-axial accelerometers at an appropriate location in the aircraft, and tire–wheel instrumentation will no longer be necessary.

It should be pointed out that the cockpit display unit cannot avoid future overruns or hydroplaning accidents; however, it will provide realtime information regarding the aircraft performance on contaminated runways; it may guide the pilot in taking corrective measures to control the aircraft or to warn following aircraft; it would remove to some extent the subjectivity involved in current procedures for reporting runway slipperiness.

9.2.2. *Runway Maintenance Procedure*

Runway surfaces are constantly deteriorated by repeated landings and takeoffs by aircraft. This deterioration can be measured in terms of the gradual reduction of the friction coefficients developed at the tire–runway contact. The primary action at the contact area leading to this deterioration is the continuous polishing of the surface aggregates as a result of aircraft operations; large rubber deposits on the runway surface can also lead to performance deterioration. In order to properly assess this deterioration, it is necessary to monitor and document the runway friction characteristics as a function of speed and time.

The proposed method to accomplish proper runway surface maintenance is shown in Fig. 34, and is summarized below.

(1) Using a suitable ground vehicle, measure the runway surface friction at three speeds.
(2) Compute the friction–speed gradient at 40 m.p.h. speed.
(3) Repeat steps 1 and 2 at a fixed interval, for example, after every six months.
(4) Plot the friction–speed gradient and the friction coefficient at 40 m.p.h. as a function of time.
(5) Monitor the changes in friction–speed gradient: if the gradient-changes are abnormal, decrease the time interval between measurements.
(6) Continued abnormal gradients will indicate a need for corrective measures to raise the friction levels available at the tire–runway contact.

The corrective measures could include the removal of rubber deposits, resurfacing part of the runway, resurfacing the whole runway, reconstruction of the runway, or any combination thereof depending upon the severity of the deterioration. In each case, the new surface aggregates reflect higher overall texture than before the corrective measures were taken. It should be remembered, however, that any of these measures are of little consequence in combating hydroplaning or providing the aircraft with any significant improvement in braking action on snow and ice covered runways; grooving is still the most effective means to help alleviate hydroplaning, and runways must be cleaned of ice and snow deposits. Still, the runway surface characteristics must be maintained at desirable levels to reduce aircraft overruns or skidding in moderate rainfall conditions.

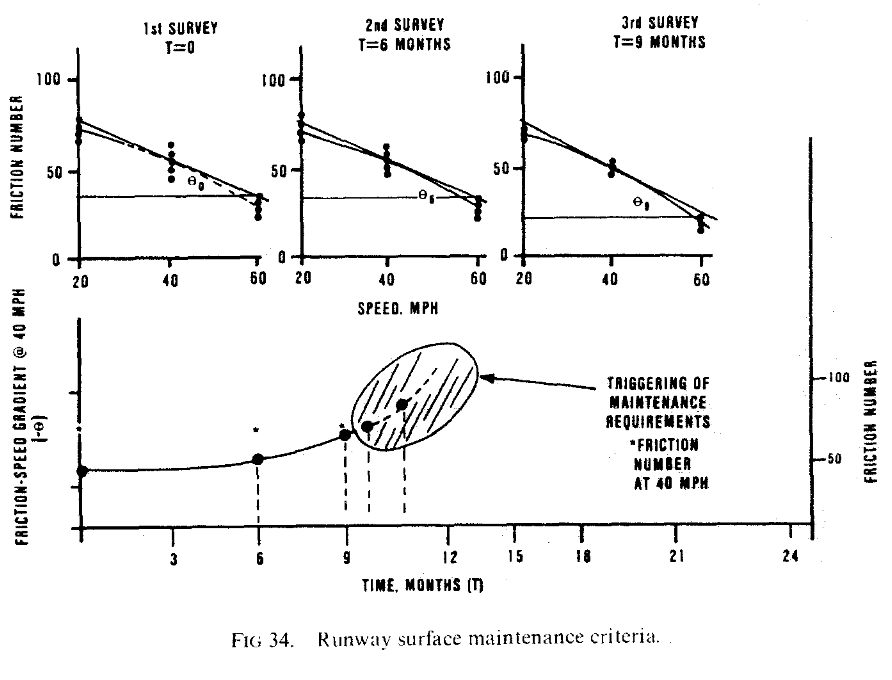


FIG. 34. Runway surface maintenance criteria.

ACKNOWLEDGEMENTS

The author deeply appreciates and gratefully acknowledges the assistance provided by the following in preparing this paper:

Professor Wolfgang E. Meyer, Mr. Hector Daiutolo, Mr. Thomas J. O'Brien, Mr. Herman D'Aulerio, Mr. Walter B. Horne, Mr. Thomas J. Yager, Mr. Ronald A. Clarke, Mr. Daniel Spaluto, Mr. Richard A. Johnson, Mr. Thomas H. Morrow, Ms. Barbara J. Ledwell.

REFERENCES

1. MEYER, W. E. (1968) Friction of tires. American Society for Testing and Materials, *Symposium on Automobile Tire Performance Testing*. Atlantic City, New Jersey.
2. KUMMER, H. W. (1965) Rubber and tire friction. Ph.D. Dissertation, The Pennsylvania State University, University Park Pennsylvania.
3. HORNE, W. B. and DREHER, R. C. (1963) Phenomena of pneumatic hydroplaning. Report NASA TN D-2056. National Aeronautics and Space Administration, Washington, D.C.
4. ALBERT, B. J. and WALKER, J. C. (1965) Tyre to wet road friction at high speeds. *Proceedings of the Institute of Mechnical Engineers*. Vol. 180, Part 2A, No. 4.
5. CLARK, S. K. (1971) *Mechanics of Pneumatic Tires. Monograph Number 122*. National Bureau of Standards, Washinngton, D.C.
6. SMILEY, R. F. and HORNE, W. B. (1958) Mechanical properties of pneumatic tires with special reference to modern aircraft tires. Report No. TR R-64. National Aeronautics and Space Administration. Washington, D.C.
7. SCHALLAMACH, A. (1971) Skid resistance and directional control. *Mechanics of Pneumatic Tires, Monograph Number 122*. National Bureau of Standards, Washington, D.C.
8. SEGAL, L. (1974) Tire traction on dry, uncontaminated surfaces. *Physics of Tire Traction—Theory and Experiment*. Plenum Press, New York.
9. KUMMER, H. W. and MEYER, W. E. (1966) Skid or slip resistance? *J. Mater.* **1** (3).
10. KUMMER, H. W. and MEYER, W. E. (1960) Rubber and tire friction. Engineering Research Bulletin B-80. The Pennsylvania State University, University Park, Pennsylvania.
11. DODGE, R. N. and CLARK, S. K. (1981) A Comparison of some static and dynamic mechanical properties of 18 × 5.5 and 49 × 17 Type VII aircraft tires as measured by three test facilities. NASA Contractor Report No. 165720. The University of Michigan, Ann Arbor, Michigan.
12. BROWNE, A. L. and WHICKER, D. (1983) An interactive tire–fluid model for dynamic hydroplaning. Frictional interaction of tire and pavement. ASTM, STP-793, American Society for Testing and Materials, Philadelphia, Pennsylvania.
13. AGRAWAL, S. K. (1979) Transient aspect of hydroplaning: hydroplaning phenomenon during sudden changes in the fluid layer on a pavement. Ph.D. Dissertation, The Pennsylvania State University, University Park, Pennsylvania.
14. DAUGHADAY, H. and TUNG, C. (1969) A mathematical analysis of hydroplaning phenomena. Report No. AG-2495-S-1 Cornell Aeronautical Laboratory, Buffalo, New York.
15. HORNE, W. B. (1974) Wet runways. Presented to the Federal Aviation Administration Airworthiness Review Committee, Washington, D.C.
16. NEWELL, B. (1981) Landing on frictionless surfaces. *Professional Pilot*, Safety Corner, October Issue.
17. YAGER, T. J. (1983) Review of factors affecting aircraft wet runway performance. American Institute of Aeronautics and Astronautics. Paper No. AIAA-83-0274, New York.
18. WARREN, S. M., WAHI, M. K., AMBERG, R.L., STRAUB, H. H. and ATTRI, N. S. (1974) Combat traction II, phase II. Technical Report No. FAA-RD-74-211, Vol. 1, Federal Aviation Administration, Washington, D.C.
19. HORNE, W. B., YAGER, T. J. and GLENN, T. R. (1968) Review of causes and alleviation of low tire traction on wet runways. NASA TN D-4406. National Aeronautics and Space Administration, Washington, D.C.
20. GALLOWAY, R. M., SCHILLER, R. E. JR., and ROSE, J. G. (1971) The effect of rainfall intensity, pavement cross slope, surface texture, and drainage path length on pavement water depths. Research Report No. 138-5, Vehicle Pavement Interaction Research Study No. 2-8-69-138, Texas Transportation Institute, Texas A and M University, College Station Texas.
21. REED, J. R., KIBLER, D. F. and AGRAWAL, S. K. (1984) Mathematical model of runoff from grooved runways. Transportation Research Circular No. 274, Transportation Research Board, Washington, D.C.
22. KING, D. J. and CERWIN, S. A. (1982) System for inventorying road surface topography. Report No. FHWA/RD-82/062. The Federal Highway Administration, Washington, D.C.
23. YAGER, T. J. and BUHLMAN, F. (1982) Macrotexture and drainage measurements on a variety of concrete and asphalt surfaces. ASTM STP 763. American Society for Testing and Materials, Philadelphia, Pennsylvania.
24. HENRY, J. J. and HEGMON, R. R. (1975) Surface texture versus skidding: measurements, frictional aspects, and safety features of tire–pavement interactions. ASTM STP 583, American Society for Testing and Materials, Philadelphia, Pennsylvania.
25. BOND, R., LEES, G. and WILLAMS, A. R. (1974) An approach towards the understanding and design of the pavement's textural characteristics required for optimum performance of the tyre. *Physics of Tire Traction—Theory and Experiment*. Plenum Press, New York.

26. FORSTER, S. W. (1978) Automated aggregate microtexture measurement: description and procedures. *Public Roads*, **42** (3).
27. AGRAWAL, S. K. (1984) Modified reflex percussive grooves for runways. Report No. DOT/FAA/PM-84-08. The Federal Aviation Administration, Washington, D.C.
28. YAGER, T. J. (1968) Comparative braking performance of various aircraft on grooved and ungrooved pavements at the landing research runway, NASA Wallops Station. Paper No. 3, NASA SP-5073. The National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia.
29. AGRAWAL, S. K. and DAIUTOLO, H. (1981) Effects of groove spacing on braking performance of an aircraft tires. Transportation Research Record 836. Transportation Research Board, Washington D.C.
30. AGRAWAL, S. K. (1984) High speed braking of an aircraft tire on grooved wet surfaces. ICAS Paper No. 84-5 3.2. *Proceedings of the 14th Congress of the International Council of Aeronautical Sciences*. Toulouse, France.
31. YAGER, T. J. and MCCARTY, J. L. (1977) Friction characteristics of three 30 × 11.5, Type VIII, Aircraft tires with various tread groove patterns and rubber compounds. NASA Technical Paper 1080. The National Aeronautics and Space Administration, Washington, D.C.
32. CLARK, S. K. and DODGE, R. N. (1984) Heat generation in aircraft tires under braked rolling conditions. NASA Contractor Report 3768, The National Aeronautics and Space Administration, Washington, D.C.
33. LONGYEAR, D. M. and HIRZEL, E. A. (1979) Advanced braking controls for business aircraft. SAE Paper No. 790599. Society of Automotive Engineers Inc., Warrendale, Pennsylvania.
34. DEVLIEG, G. H. (1984) 757/767 brake and antiskid system. ICAS Paper No. 84-5.3.1. *Proceedings of the 14th Congress of the International Council of Aeronautical Sciences*. Toulouse, France.
35. HARRIN, E. N. (1958) Low tire friction and cornering forces on a wet surface. NACA TN 4406, National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia.
36. GRAY, W. E. (1962) Measurement of "acquaplaning height" on a meteor aircraft, and photos of flow pattern under a model tyre. Technical Note No. Aero. 2855, British Royal Aircraft Establishment.
37. HORNE, W. B. and LELAND, T. J. W. (1963) Runway slipperiness and slush. *J. R. Aeronaut. Soc.* **67** (633).
38. GADD, G. E. (1963) A Note on the undercarriage aquaplaning of aircraft landing on water-covered runways. *J. R. Aeronaut. Soc.* **67** (189).
39. GRAY, W. E. (1963) Aquaplaning on runways. *J. R. Aeronaut. Soc.* **67**(302).
40. WALLACE, K. B. (1964) Airfield pavement skidding characteristics. Report DR6, Department of Civil Engineering, University of Melbourne, Australia.
41. GENGENBACH, W. (1967) The effect of wet pavement on the performance of automobiles. Ph.D. Dissertation, University of Karlsruhe, Translated by Calspan Inc., Buffalo, New York.
42. MOORE, D. F. (1967) A theory of viscous hydroplaning. *Int. J. Mech. Sci.* **9**
43. BARRETT, R. V. (1967) Measurement of drag and spray produced by model pneumatic wheels moving through water layers. Ph.D. Dissertation, University of Bristol, U.K.
44. MARTIN, C. W. (1967) Hydrodynamics of tire hydroplaning. *J. Aircraft* **4** (2).
45. BONESS, R. J. (1968) A theoretical treatment of aquaplaning tire. *Automobile Engineer*.
46. EHRLICH, I. R., SCHAEFER, A. R. and WRAY, G. A. (1970) Parameters affecting model-tire hydroplaning and rolling restoration. Report SIT-DL-70-1405, Davidson Laboratory, Stevens Institute of Technology, Hoboken, New Jersey.
47. BROWNE, A. L. (1971) Dynamic hydroplaning. Ph.D. Dissertation, Northwestern University, Chicago, Illinois.
48. YEAGER, R. W. and TUTTLE, J. L. (1972) Testing and analysis of hydroplaning. SAE Paper No. 720471. Society of Automotive Engineers Inc., Warrendale, Pennsylvania.
49. I'ANSON, R. (1973) An investigation of dynamic aquaplaning using small pneumatic tires. Ph.D. Dissertation, University Bristol, Bristol, U.K.
50. BATHELT, H. (1973) Calculation of the aquaplaning behavior of smooth and profiled tires. *ATZ Int.* **75** (10).
51. STOCKER, A. J., DOTSON, J. T. and IVEY, D. L. (1974) Automobile tire hydroplaning: a study of wheel spin-down and other variables. Research Report TT1-2-10-70-147-3F. Texas Transportation Institute, Texas A and M University, College Station, Texas.
52. AGRAWAL, S. K., MEYER, W. E. and HENRY, J. J. (1977) Measurement of hydroplaning potential. Report No. PTI-7701, The Pennsylvania State University, University Park, Pennsylvania.
53. BENSON, W. (1979) A capacitive method for measuring waterfilm thickness during transient phase of hydroplaning, Ph.D. Dissertation, The Pennsylvania State University, University Park, Pennsylvania.
54. AGRAWAL, S. K. and HENRY, J. J. (1980) A simple tire deformation model for transient aspect of hydroplaning. *Tire Sci. Technol.* **8** (3-4).
55. HORNE, W. B. and BUHLMANN, F. (1983) A method for rating the skid resistance and micro/macrotexture characteristics of wet pavements. ASTM STP 793. American Society for Testing and Materials, Philadelphia, Pennsylvania.
56. HORNE, W. B. (1984) Predicting the minimum dynamic hydroplaning speed for aircraft, bus, truck, and automobile tires rolling on flooded pavements. Paper Presented to American Society for Testing and Materials, ASTM, Committee E-17. Texas Transportation Institute, College Station, Texas.
57. HORNE, W. B., YAGER, T. J. and TAYLOR, G. R. (1965) Recent research on ways to improve tire traction on water, slush, or ice. *Proceedings of the AIAA Aircraft Design and Technology Meeting*. Los Angeles, California.
58. ESHEL, A. (1967) A study of tires on wet runway. Ambex Corporation Report No. RR 67-24. The National Aeronautics and Space Administration, Washington, D.C.
59. HORNE, W. B. (1976) Status of runway slipperiness research. NASA SP-416. The National Aeronautics and Space Administration, Washington, D.C.
60. SMALLY, A. J., VOHR, J. H., CASTELLI, N. and WATCHMAN, C. (1968) An analytical and experimental investigation of turbulent flow in bearing films, including convective fluid inertia forces. Report No. NYO-3930-2, MTI-68TR80. Mechanical Technology Incorporated, Latham, New York.

61. HORNE, W. B. and JAYNER, V. T. (1965) Pneumatic tire hydroplaning and some effects on vehicle performance. SAE Paper 970C. International Automotive Engineering Congress. Detroit, Michigan.
62. WHICKER, D. and ROHDE, S. M. (1981) Modeling tire deformation for power loss calculations. SAE Paper No. 810161. Society of Automotive Engineers, Warrendale, Pennsylvania.
63. KWONG, W. W. (1982) Service evaluation of airborne tire pressure indicating systems. DOT/FAA/RD-82/89. The Federal Aviation Administration Technical Center. Atlantic City, New Jersey.
64. AGRAWAL, S. K. (1983) Braking of an aircraft tire on grooved and porous asphaltic concrete. Report No. DOT/FAA/RD-82/77. The Federal Aviation Administration Technical Center, Atlantic City, New Jersey.
65. YAGER, T. J., PHILLIPS, W. P., HORNE, W. B. and SPARKS, H. C. (1970) A comparison of aircraft and ground vehicle stopping performance on dry, wet, flooded, slush-, snow-, and ice-covered runways. NASA TN D-6098. The National Aeronautics and Space Administration, Washington, D.C.
66. BREWER, H. K. (1983) Design and performance aspects of antilock brake control systems. ASTM STP 793. The American Society for Testing and Materials. Philadelphia, Pennsylvania.
67. HORNE, W. B., MCCARTY, J. L. and TANNER, J. A. (1976) Some effects of adverse weather conditions on performance of airplane antiskid braking systems. NASA TN D-8202. The National Aeronautics and Space Administration, Washington, D.C.
68. TANNER, J. A. (1982) Review of NASA antiskid braking research. Paper No. 821393, Society of Automotive Engineering, Warrendale, Pennsylvania.
69. MARTIN, F. R. (1968) Pavement surface treatments at airports in Great Britain. Paper No. 17. Pavement Grooving and Traction Studies. NASA SP-5073. National Aeronautics and Space Administration, Washington, D.C.
70. WILLAMS, J. R. (1968) Aquaplaning—The British Ministry of Technology Programme. Paper No. 5, Pavement Grooving and Traction Studies. NASA SP-5073. National Aeronautics and Space Administration, Washington, D.C.
71. YAGER, T. J. (1968) NASA studies on effect of grooved runway operations on aircraft vibrations and treadwear. Paper No. 14, Pavement Grooving and Traction Studies. NASA SP-5073. National Aeronautics and Space Administration, Washington, D.C.
72. ANON. (1976) Report on the rubber removal using "Klarcrete" impact hammering technique on Runway 14/32 Toronto International Airport. Report AK-71-09-045. Transport Canada, Airport and Construction Services, Ontario, Canada.
73. CREECH, M. F. (1973) Mechanical alteration of the texture of old concrete pavements with the Klarcrete machine. Report No. VHRC 73-RP4. Virginia Highway Research Council. Charlottsville, Virginia.
74 AGRAWAL, S. K. and DAIUTOLO, H. (1981) Reflex-percussive grooves for runways: an alternative to saw-cutting. Transportation Research Record No. 836. Transportation Research Board, Washington, D.C.
75. ANON. (1977) Air Force Flight Dynamics Laboratory. Landing Gear Test Facility. Wright-Paterson Air Force Base, Ohio.
76. ROBERTS, J. B. (1974) An advanced high-speed dynamometer for testing aircraft tires, wheel and brakes. Paper Presented at Applied Mechanics Group Meeting in London on April 10, 1974. Vickers Design and Project Division. Hampshire, England.
77. ANON. (1984) Measuring the stresses and strains of aircraft wheels. *Aircraft Eng.* April Issue.
78. KREMPL, G. (1967) Investigation of motor vehicle tires (in German). *ATZ* **69** (1).
79. KELLER, H. (1976) Untersuchungen von Straβenbelagen und Reifen im Innentrommelprufstand der Bundesnastalt fur Straβenwesen. Automobile-Industrie. No. 2.
80. JASPERSE, S. (1982) Friction measuring holds promise as pavement testing tool. *Airport Services Management*, December Issue.
81. YAGER, T. J. and WHITE, E. J. (1981) Recent progress towards predicting aircraft ground handling performance. NASA Technical Memorandum No. 81952. National Aeronautics and Space Administration, Washington, D.C.
82. AMBERG, R. L. (1969) Baseline simulation for evaluation of brake antiskid systems. Boeing Document D6-58384-3TN. Boing Commercial Airplane Company, Seattle, Washington.
83. STARR, C. (1984) Progress towards better simulation of transport aircraft. *Int. J. Aviation Safety* **1** (4).
84. ZOEPPRITZ, H. P. (1977) An overview of european measuring methods and techniques. Transportation Research Record 621, Transportation Research Board, Washington, D.C.
85. BIRD, K. D. and MARTIN, J. F. (1978) The calspan tire research facility: design, development, and initial test results. SAE Paper 780635, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.
86. LANGER, W. J. and POTTS, G. R. (1980) Development of a flat surface tire testing machine. SAE Paper 800245, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.
87. SUGG, R. W. (1967) Joint NASA-British Ministry of Technology skid correlation study—results from British vehicles. Paper No. 24, NASA SP-5073. National Aeronautics and Space Administration, Washington, D.C.
88. MERRITT, L. R. (1974) Concorde landing requirement evaluation tests. Report No. FAA-FS-160-74-2. Federal Aviation Administration, Washington, D.C.
89. PRESTON, O. W., KIBBEE, G. W., MUROYAMA, R. H. and STROLEY, R. A. (1971) Development of a basic methodology for predicting aircraft stopping distance on a wet runway. Report No. FAA-RD-70-62. Federal Aviation Administration, Washington, D.C.
90 SHRAGER, J. J. (1962) Vehicular measurements of effective runway friction. Final Report-Project No. 308-3X. Federal Aviation Agency, Washington, D.C.
91. MEYER, W. E., KUMMER, H. W. and LYNCH, F. J. (1966) Design and development of an airport runway surface traction measuring device. Final Report-Project No. 510-003-01E. Federal Aviation Agency, Washington, D.C.
92. HORNE, W. B. and TANNER, J. A. (1968) Joint NASA-British Ministry of Technology skid correlation study. Paper No. 23, NASA SP-5073. National Aeronautics and Space Administration, Washington, D.C.
93. WILLIAMS, J. H. (1975) Analysis of the standard USAF runway skid resistance tests. Report No. AFCEC-TR-75-3. Air Force Civil Engineering Center, Tyndall Air Force Base, Florida.

94. Horne, W. B., Yager, T. J., Sleeper, R. N. and Merritt, L. R. (1977) Joint FAA–USAF–NASA Runway Research Program, Part I and II. NASA TMX-73909, NASA TMX-73910. National Aeronautics and Space Administration, Washington, D.C.
95. Hainline, B. C., Amberg, R. L. and Srinath, S. K. (1983) Prediction of aircraft braking friction on wet runways—a look at past and current research activities. SAE Paper No. 831562. Society of Automotive Engineers, Inc., Warrindale, Pennsylvania.
96. Joyner, U. T., Horne, W. B. and Leland, T. J. W. (1963) Investigation on the ground performance of aircraft relating to wet runway braking and slush drag. Report No. 429. NATO Advisory Group for Aeronautical Research and Development, Paris, France.
97. Barrett, R. V. (1970) Research into slush drag, wheel spray and aquaplaning at Bristol University using small pneumatic tyres, Report and Memoranda No. 3682. Department of Aeronautical Engineering, University of Bristol, U.K.
98. Bowden, F. P. and Tabor, D. (1964) *The Friction and Lubrication of Solids.* Oxford University Press, London, England.
99. Karlekar, B. V. and Desmond, R. M. (1977) *Engineering Heat Transfer.* West Publishing Company, New York.
100. Hayhoe, G. F. and Kopac, P. A. (1981) Evaluation of winter driving traction aids. Report No. PTI 8105. The Pennsylvania State University, University Park, Pennsylvania.
101. Roed, A. (1985) Winter aerodynamics. *Int. J. Aviation Safety*, March Issue.
102. Pravda, M. F., Trimmer, D. S. and Wolf, D. A. (1975) Heating systems for airport pavement snow, slush, and ice control. Report No. FAA-RD-75-139. Federal Aviation Administration, Washington, D.C.
103. Schwartz, A. C. (1985) Highway research will help airports. *Airport Forum* **16**, March Issue.
104. Anon. (1985) Method for design, construction, and maintenance of skid resistant airport pavement surfaces. Advisory Circular No.150/5320-12A Federal Aviation Administration, Washington, D.C.
105. Morrow, T. H. (1982) Report on the performance, reliability, and correlation of the Mu Meter and Saab Friction Tester. Report No. FAA-AAS-82-VI. The Federal Aviation Administration, Washington, D.C.