

NASA TECHNICAL NOTE



NASA TN D-2056

NASA TN D-2056

NG64-10521

PHENOMENA OF PNEUMATIC TIRE HYDROPLANING

by Walter B. Horne and Robert C. Dreher

*Langley Research Center
Langley Station, Hampton, Va.*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1963

TECHNICAL NOTE D-2056

PHENOMENA OF PNEUMATIC TIRE HYDROPLANING

By Walter B. Horne and Robert C. Dreher

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PHENOMENA OF PNEUMATIC TIRE HYDROPLANING

By Walter B. Horne and Robert C. Dreher

SUMMARY

Recent research on pneumatic tire hydroplaning has been collected and summarized with the aim of describing what is presently known about the phenomena of tire hydroplaning. A physical description of tire hydroplaning is given along with formulae for estimating the ground speed at which it occurs. Eight manifestations of tire hydroplaning which have been experimentally observed are presented and discussed. These manifestations are: detachment of tire footprint, hydrodynamic ground pressure, spin-down of wheel, suppression of tire bow wave, scouring action of escaping fluid in tire-ground footprint region, peaking of fluid displacement drag, loss in braking traction, and loss of tire directional stability. The vehicle, pavement, tire, and fluid parameters of importance to tire hydroplaning are listed and described. Finally, the hazards of tire hydroplaning to ground and air-vehicle-ground performance are listed, and procedures are given to minimize these effects.

INTRODUCTION

When runway or road surfaces become flooded or puddled with either slush or water, both aircraft and ground vehicles such as automobiles can at some critical ground speed encounter the phenomenon of tire hydroplaning. The effects of hydroplaning can be serious to these vehicles since tires under hydroplaning conditions become detached from the pavement surface and the ability of tires to develop braking or cornering traction for stopping or guiding vehicle motion is almost completely lost. Tire hydroplaning was first noticed and demonstrated experimentally about 1957 during a tire treadmill study. (See ref. 1.) This investigation had been prompted by the low values of tire-to-surface friction found during wheel spin-up in landings of a large airplane on a wet runway (ref. 2) and by a rash of military aircraft overrun landing accidents on wet runways. In this tire treadmill study a small pneumatic tire riding under free rolling (unbraked) conditions on a water covered belt was observed to spin-down to a complete stop at a critical belt (ground) velocity. Later studies by the National Aeronautics and Space Administration on full-scale tires (refs. 3 to 9) along with actual operational experience gained from aircraft take-offs and landings performed on very wet runways have further substantiated the fact that hydroplaning can create a very serious slipperiness problem to most pneumatic-tired vehicles.

More recent hydroplaning research performed by the National Aeronautics and Space Administration and the Federal Aviation Agency (refs. 10 to 17) in this

country and by the Royal Aircraft Establishment (refs. 18 to 24) and others in England has enabled the phenomenon of tire hydroplaning to be more completely understood. The purpose of this paper is to synthesize this work and previous work with the aim of giving a physical description of tire hydroplaning along with definitions of the vehicle, pavement wetness, and tire conditions under which it can occur. Also included is a section that illustrates the various manifestations of hydroplaning in terms of vehicle or tire performance that have been uncovered to date. Finally, the hazards of tire hydroplaning to vehicle ground performance are listed and procedures are given to minimize these effects.

SYMBOLS

A,B	footprint regions
A_G	gross tire contact area, sq in.
$C_{L,S}$	hydrodynamic lift coefficient
D_B	drag force due to tire rolling at peripheral speed less than ground speed, $\mu F_{V,G}$
D_R	tire free rolling resistance, lb
D_S	drag due to fluid displacement, lb
d_S	fluid depth, in.
F_V	vertical load on tire due to airplane or vehicle mass, $F_{V,G} + F_{V,S}$, lb
$F_{V,G}$	portion of F_V supported by the runway (footprint region A in fig. 3), lb
$F_{V,S}$	vertical hydrodynamic pressure force (footprint region B in fig. 3), lb
g	acceleration due to gravity, 32 ft/sec ²
I	tire and wheel moment of inertia, slug-ft ²
M	vehicle mass, slugs
\bar{P}	average ground hydrodynamic pressure, lb/sq in.
p	tire inflation pressure, lb/sq in.

R	highway curve radius, ft
r	unloaded tire radius, ft
s_1	slip ratio
V_C	posted speed limit on highway curves, international statute miles per hour
V_G	ground speed, knots
V_P	tire hydroplaning velocity, knots (airplanes), international statute miles per hour (highway vehicles)
V_S	vehicle slide-out speed on highway curves, international statute miles per hour
x_c	vertical load center-of-pressure displacement, ft
α	wheel angular acceleration, radians/sec ²
δ	vertical tire deflection, ft
ρ	fluid mass density, slugs/cu ft
ω	wheel angular velocity, radians/sec
μ	instantaneous tire-to-surface friction coefficient
μ_{av}	average friction coefficient between slip ratios of 0.10 and 0.50
μ_{eff}	effective friction coefficient (average μ developed by aircraft as modified by pilot braking or anti-skid system)
μ_{max}	maximum friction coefficient
μ_{skid}	skidding friction coefficient (friction coefficient at slip ratio of 1)

PHYSICAL DESCRIPTION OF TIRE HYDROPLANING

Consider the case of an unbraked pneumatic tire rolling on a fluid covered runway as in an airplane take-off. As the moving tire contacts and displaces the stationary runway fluid, the resulting change in momentum of the fluid creates hydrodynamic pressures that react on the runway and tire surfaces. In line with hydrodynamic theory, the resulting hydrodynamic pressure force, acting on the tire as ground speed increases, tends to build up as the square of the ground speed,

as shown in figure 1, for the fluid drag component of this pressure force. This result allows construction of the model of tire behavior under partial and total hydroplaning conditions shown in figure 2.

As ground speed increases, fluid inertia effects would tend to retard fluid escape in the tire-ground contact region and the fluid wedge formed would tend to detach the tire from the ground. At some high ground speed the hydrodynamic lift developed under the tire equals the partial weight of the vehicle acting on the tire and any further increase in ground speed beyond this critical speed must force the tire to lift completely off the runway surface. The critical ground speed at which $F_{V,S} = F_V$ is termed the tire hydroplaning speed V_P . The tire is termed to be partially hydroplaning at ground speeds below V_P and totally hydroplaning at ground speeds in excess of the tire hydroplaning speed V_P .

DERIVATION OF TIRE HYDROPLANING SPEED

The following derivation of tire hydroplaning speed is based on earlier derivations given in references 10 and 11. The net torques or moments acting on an unbraked wheel must, at any time, equal the inertia torque $I\alpha$ acting on the wheel. (See fig. 3.) Including hydrodynamic effects, the angular acceleration can be expressed approximately as

$$\alpha = \frac{F_V(x_c) - [D_R + D_S + (F_V - F_{V,S})\mu](r - \delta)}{I} \quad (1)$$

When the vertical component of the hydrodynamic pressure force $F_{V,S}$ equals the vertical ground force F_V , the tire-ground frictional moment $(F_V - F_{V,S})\mu(r - \delta)$ reduces to zero, and since at this point the tire is entirely supported by the fluid on the runway, total tire hydroplaning must exist. To predict the ground velocity V_G at which this phenomenon will occur, it is assumed in line with hydrodynamic theory that the lift component of the hydrodynamic pressure force $F_{V,S}$ is proportional to the tire-ground contact area A_G , fluid density ρ , and to the square of the ground speed V_G . If other possible variables such as the effects of tire tread design, fluid viscosity, and runway surface texture are ignored, and the fluid depth on the runway is assumed to be greater than tire tread groove depth, the following approximate expression for tire hydroplaning speed V_P may be obtained:

$$F_V = F_{V,S} = \frac{1}{2} C_{L,S} \rho A_G V_P^2 \quad (2)$$

Rearranging terms leads to the following equation which may be used to find V_P in knots when A_G is expressed in square inches:

$$V_P = 0.592 \left(\frac{F_V}{A_G} \frac{288}{C_{L,S} \rho} \right)^{1/2} \quad (3)$$

Recent research in the Langley landing loads track involving bogie and nose-gear studies (refs. 12 and 13) indicates that equation (3) may be simplified to

$$V_P = 9\sqrt{p}, \text{ knots} \quad (4)$$

$$V_P = 10.35\sqrt{p}, \text{ statute mph} \quad (5)$$

where the tire inflation pressure p is expressed in pounds per square inch. This simplification is based on three main assumptions: (1) The term F_V/A_G (average tire-ground bearing pressure) in equation (3) may be approximated by the tire inflation pressure p , (2) Runway fluids which can collect in depths large enough to produce tire hydroplaning have densities approaching that of water, and (3) The hydrodynamic lift coefficient $C_{L,S}$ developed by tires on a fluid covered surface is approximately 0.7. (See ref. 11.)

It should be pointed out that the hydroplaning speeds obtained from equations (3) and (4) are valid for smooth and closed pattern tread tires which do not allow escape paths for water, and for rib tread tires on fluid covered runways where the fluid depth exceeds the groove depths in the tread of these tires. Little quantitative data are yet available on the hydroplaning speeds for rib tread tires on fluid covered runways where the fluid depth is less than the groove depth of the tread.

Correlation of hydroplaning speed, as determined by means of equation (4), with available experimental data is shown in figure 4. Note that the calculated hydroplaning speeds of equation (4) are in reasonable agreement with the experimental hydroplaning speeds obtained for a variety of tire sizes having a vertical load range from 925 to 22,000 pounds and an inflation pressure range from 24 to 150 pounds per square inch.

EXPERIMENTAL OBSERVATIONS OF TIRE HYDROPLANING

Since tire hydroplaning was first demonstrated experimentally during the NACA tire treadmill tests of 1957, the following eight manifestations of hydroplaning in terms of tire or vehicle performance have been observed and are described in this section of the paper: detachment of tire footprint, hydrodynamic ground pressure, spin-down of wheel, suppression of tire bow wave, scouring action of escaping fluid in tire-ground footprint region, peaking of fluid displacement drag, loss in braking traction, and loss of tire directional

stability. Most of these manifestations are clearly shown in a documentary film. (See ref. 17.)

Detachment of Tire Footprint

In the explanation of tire hydroplaning given earlier in this paper, it was assumed that as ground speed increased, a wedge of fluid progressively penetrates the tire-ground contact region and a hydrodynamic pressure is developed between the tire and the ground, the resulting hydrodynamic lift tending to detach the tire footprint from the runway surface. This effect is actually illustrated in photographs in figures 5 and 6 for aircraft and automobile tires, respectively. These photographs were obtained during a recent hydroplaning study made at the NASA Langley landing loads track. (See ref. 13.)

It is of interest to note that the portion of the footprint under the side walls of the automobile tire (photograph (c) of fig. 6) is the last portion of the footprint to become detached as ground speed increases. This result indicates that higher tire-ground bearing pressures exist under the tire side walls than in other locations of the automobile tire footprint. The aircraft tire which was more circular in cross section and stiffer than the automobile tire did not show this sidewall effect (fig. 5) but a similar effect (fig. 7) appears present in the photograph of the small tire footprint obtained from reference 18. It is apparent from the photographs of figures 5 and 6 that as ground speed increases, the "nearly dry" contact patch developed between the rolling tire and the ground is progressively reduced and then entirely eliminated when total hydroplaning is achieved.

Hydrodynamic Ground Pressure

Tire hydroplaning speed, in an earlier section of this paper, was defined as the ground speed required for the hydrodynamic lift acting on the tire to equal the weight of the vehicle being supported by the tire or $F_{V,S} = F_V$. Stated in another way, the tire hydroplaning speed is the ground speed required for the average hydrodynamic pressure acting in the tire footprint region to equal the average tire-ground bearing pressure or, in approximation, to equal the tire inflation pressure p . It has not been possible up to this time to measure the hydrodynamic pressure acting on the wetted surface of the tire, but successful measurements of hydrodynamic pressure acting on the ground surface under the tire have recently been made at the Langley landing loads track. These measurements of hydrodynamic ground pressure were accomplished with the aid of a recording flush-diaphragm-type pressure gage installed just below the surface of the runway at the center line of the tire path. Typical hydrodynamic pressure signatures obtained during tire passage over the fluid covered pressure gage are shown in figure 8. Several interesting points are suggested by the data shown in this figure: (1) The ground hydrodynamic pressure develops ahead of the initial tire-ground contact point due to action of the tire bow wave, (2) The peak ground hydrodynamic pressure is considerably in excess of the tire inflation pressure for the 85-knot ground speed pressure signature, and (3) Apparently negligible hydrodynamic ground pressures are developed at the rear of the tire-ground footprint

at the higher ground speeds. The first and third points mentioned combine to produce a larger forward shift of center of pressure and consequently a larger wheel spin-down moment for the 85-knot pressure signature than that shown for the 30-knot ground speed signature. The exact reason for the lack of hydrodynamic ground pressure observed at the rear of the tire footprint is not yet known but probably can be explained on the basis that tire inertia prevents the internal inflation pressure from restoring the tire to its undeflected radius in the rear of the footprint. The second point made, that the ground hydrodynamic pressure can exceed the tire inflation pressure, must indicate local inward buckling or deformation of the tire whenever this high hydrodynamic pressure condition occurs in the tire-ground contact region. Some evidence of these deformations is shown by the photographs of the automobile tire footprint at a ground speed of 32 knots in figure 6 and the model tire footprint of figure 7.

The hydrodynamic ground pressure signatures obtained on a tandem wheel landing gear at 30 and 85 knots ground speed on a runway covered with water 0.5 inch deep are shown in figure 9. It is of interest to note that tire spin-down (a manifestation of tire hydroplaning) did not occur on the front wheel of this landing gear until the average hydrodynamic ground pressure (51 pounds per square inch) slightly exceeded the tire inflation pressure (50 pounds per square inch). (See lower left pressure signature in this figure.)

Also to be noticed in this figure are the lower average hydrodynamic ground pressures that developed on the rear wheel as compared with the pressures developed on the front wheel of this tandem wheel landing gear. These lower pressures are believed to be the result of the path clearing action of the front tandem wheel which reduces the depth of fluid on the runway encountered by the rear tandem wheel.

Spin-Down of Unbraked Wheel

Perhaps the most striking manifestation of tire hydroplaning is the now well substantiated condition in which free rolling (unbraked) wheels slow down or stop completely on wet runways as shown in figure 10. Unbraked-wheel spin-down arises from two hydrodynamic lift effects which combine to produce a total wheel spin-down moment in excess of the wheel spin-up moment due to all tire drag sources. First, as ground speed increases, the hydrodynamic lift progressively detaches the tire footprint from the pavement surface (figs. 5 and 6) and makes the tire-ground frictional spin-up moment $(F_V - F_{V,S})\mu(r - \delta)$ in equation (1) tend toward zero values. Secondly, the center of pressure of the hydrodynamic pressure and resulting lift developed between the tire footprint and ground surface shifts increasingly forward of the axle as the ground speed increases (see fig. 8) and produces the wheel spin-down moment $F_V x_c$. At some high forward speed near the total hydroplaning speed of the tire, this wheel spin-down moment overcomes the wheel spin-up moment from all the drag sources and wheel spin-down commences.

Available wheel spin-down data such as are shown in figures 11 and 12 indicate that wheel spin-down can commence on tires at ground speeds considerably lower than the total hydroplaning speed V_p . For example, the data in

figure 12(b) indicate that on tandem wheels the front-wheel spin-down begins at 70 percent of the hydroplaning speed V_p . This figure shows that large reductions in tire-ground frictional moment can occur under partial hydroplaning conditions.

The fact that the rear wheels of the tandem landing gear did not spin down in figures 11 and 12 is further corroboration of the data shown in figure 9 and indicates that the path clearing action of front-mounted wheels on single and dual-tandem wheel landing gears tends to remove sufficient fluid from the paths of rear-mounted wheels of such landing gears to prevent hydroplaning or wheel spin-down to occur on the rear wheels.

Suppression of Tire Bow Wave

Photographs and motion pictures (see refs. 10, 13, and 15) taken of aircraft tires under partial and total hydroplaning conditions indicate that a large bow wave forms in front of the tire for all ground speeds below the hydroplaning speed V_p (partial hydroplaning region of fig. 2). As the ground speed increases, the angle of the bow wave with respect to the runway tends to reduce progressively until at some high ground speed in the total hydroplaning region of figure 2, the bow wave disappears completely. This effect is shown in figures 13, 14, and 15.

The similarity between tire bow spray patterns and bow spray patterns developed on hydroplane-type boat hulls at partial and total hydroplaning speeds is striking. It is also important to note that this is one manifestation of hydroplaning that can be witnessed in the field. If during high-speed operations in deep water or on slush covered runways such as in landing or take-off, no bow waves are observed to be forming ahead of the aircraft tires, there is a good probability that the aircraft and tires are undergoing total hydroplaning.

Scouring Action of Escaping Fluid in Tire-Ground Footprint Region

When wheels are locked during high-speed braking on dry pavement surfaces, large amounts of molten tread rubber are deposited by the tires on the pavement. This is not true under total hydroplaning conditions when the tire is completely detached from the pavement surface by the runway fluid. Instead of this effect, the escaping fluid under the action of high hydrodynamic pressures developed in the tire-ground contact region tends to clean the runway surface in the tire path with the result that white streaks instead of black streaks are formed by the tires on the pavement surface. This result was noted in the braking study of reference 11 and has also been observed during full-scale aircraft landings on flooded runways. It should be pointed out that this scouring action may also develop when smooth tires are braked on wet smooth pavement surfaces at ground speeds below the tire hydroplaning speed because of viscous effects which also produce high hydrodynamic pressures in the tire-ground contact region.

Peaking of Fluid Displacement Drag

It was shown experimentally in references 10 and 15 that fluid displacement drag reaches a maximum at a ground speed near the tire hydroplaning speed (fig. 16). Recent data obtained at the Langley landing loads track (fig. 17(a)) illustrate this effect more clearly. Shown in this figure is the effect of tire inflation pressure on both fluid drag magnitude and peak location with ground speed. It can be seen from these data that increasing the ground speed above the critical hydroplaning speed results in appreciable reductions in fluid drag. This result is attributed to the tires lifting off the runway surface at the higher ground speeds and consequently displacing less runway fluid from the tire paths. The drag at speeds above V_p may be slightly in error because of the normalizing processes used.

Loss in Braking Traction

When rib tread tires are braked on most wet but not flooded pavement surfaces, the wet-runway friction coefficients obtained are usually considerably reduced in magnitude from the dry-runway values experienced but an appreciable amount of braking traction is still retained for this wet condition even at the highest vehicle ground speeds as shown in figure 18. On the other hand, when deep puddles form on the wet pavement surface, an intermittent additional loss in braking traction occurs because of hydroplaning of the tires in the puddles whenever the vehicle ground speed exceeds the tire hydroplaning speed as shown in figure 19. Whenever the pavement surface is flooded with fluids such as slush or water to depths large enough to initiate tire hydroplaning, the braking traction loss becomes catastrophic (braking friction coefficients approach free rolling friction coefficient) at ground speeds near or in excess of the tire hydroplaning speed. (See fig. 20.) This result is obvious when the unbraked-tire spin-down data under hydroplaning conditions previously discussed are considered. (See figs. 10, 11, and 12.) It is apparent from these data that applying brakes to wheels that have either completely or nearly stopped rotating from hydroplaning effects cannot be expected to improve the existing tire retardation forces and friction coefficient at all.

Loss of Directional Stability

Another significant manifestation of tire hydroplaning is a loss of directional stability, as demonstrated during the slush study conducted by the Federal Aviation Agency with technical assistance of the National Aeronautics and Space Administration on a four-engine jet transport. (See refs. 10, 15, and 17.) Several test runs through the slush bed were made at speeds in excess of the predicted hydroplaning speed for the airplane (110 knots) in the presence of direct cross-wind components that did not exceed 9 knots. The test aircraft at a ground speed of 120 knots was observed to yaw and drift laterally on the runway while in the slush bed. (These instances are shown in the motion pictures of ref. 17.) These results appear to indicate that loss of tire directional stability at and above tire hydroplaning speeds could be extremely serious to some aircraft when take-offs and landings are conducted in the presence of high cross winds.

PARAMETERS OF SIGNIFICANCE TO HYDROPLANING

Fluid Parameters

Depth of fluid.- Results thus far indicate that tires will not hydroplane below certain minimum fluid depths on the pavement surface. Because of the large effects of other parameters such as tire tread design and runway surface texture, this minimum fluid depth is difficult to define. For the comparatively smooth belt surface and smooth tread tires used in references 1 and 9, hydroplaning occurred at fluid depths as low as 0.02 to 0.09 inch. In reference 11, where full-scale aircraft tires were used on a relatively smooth concrete test track, hydroplaning occurred on a smooth tread tire when the concrete runway was flooded with water to the extent that the fluid depth varied between 0.1 to 0.4 inch (average depth approximately 0.3 inch). Gray (refs. 18 and 22) used "plasticene" strips on the runway to measure minimum water thickness between tire and ground for a Meteor fighter under hydroplaning conditions. The results of this unique experiment, shown in figure 21, indicate that the minimum water depth required for hydroplaning to occur on this aircraft for a smooth runway was 0.17 inch and over double this value, 0.42 inch, for a grooved runway. The braking coefficients obtained for a rib tread automobile tire in reference 5 (see fig. 22) indicate that water depths of 0.2 to 0.3 inch are required for this tire to hydroplane on the concrete runway used for testing. (Friction coefficients approach zero at hydroplaning speed V_p .) The upper limit of fluid depth for hydroplaning has not been defined. Tire hydroplaning has occurred in tests at the Langley landing loads track and in the tests of reference 15 in or slightly greater than 2 inches of fluid.

Density of fluid.- Data at this time are insufficient to evaluate fluid density effects, but according to the reasoning of equation (3), the hydroplaning speed should be an inverse function of the fluid density. For example, runway slush having a specific gravity of 0.85 should require an 8 percent higher hydroplaning speed than water.

Tire Parameters

Inflation pressure.- The tire inflation pressure appears to be the most important single parameter in determining aircraft or tire hydroplaning speed. (See eq. (4) and figs. (4) and (17).) Increasing the tire pressure increases the tire hydroplaning speed and vice-versa.

Tire-tread design.- Tire tread design is believed to have two effects on hydroplaning speed. First, adequate tread designs, such as circumferential ribs, according to references 1, 5, and 11, tend to require higher ground speeds for hydroplaning than do smooth tread tires. Second, good tread design tends to increase the minimum fluid depth required for a tire to hydroplane. The loss in braking traction due to partial hydroplaning effects (partial hydroplaning region of fig. 2) is considerably less for rib-tread tires than for smooth-tread tires even when the fluid depth on the pavement surface is greater than the tread groove

depth. This effect is shown for an aircraft tire in figure 23 and for an automobile tire in figure 24.

Airplane Parameters

Landing-gear wheel arrangement.- In tandem-wheel landing-gear arrangements (see refs. 7, 9, 10, 11, 14, and 15 and figs. 11 and 12), the path clearing action of the front wheels tends to reduce the fluid depth encountered by rear tandem wheels to values that apparently lie below the minimum fluid depth required to support total tire hydroplaning. Consequently, the available experimental data indicate that total hydroplaning on the rear wheels of such gear arrangements is delayed to higher ground speeds or possibly eliminated.

Vertical load.- Increasing the weight on the aircraft or the vertical load on the tire has only a small effect on tire hydroplaning speed. This effect is small because the tire acts as an elastic body and changes in vertical load on the tire produce corresponding changes in the tire-ground footprint area such that the ratio of vertical load to footprint area F_V/A_G remains constant at a value approximating the tire inflation pressure p . Admittedly, the tire internal volume becomes smaller (raises inflation pressure) as the vertical load is increased on the tire, but for normal riding or landing conditions this rise in inflation pressure is very small. For example, increasing the vertical load on an aircraft tire from zero vertical load to maximum static load (32-percent maximum vertical tire deflection) only increases the tire inflation pressure by 3 or 4 percent and this increase will change the hydroplaning speed from equations (4) and (5) by 2 percent or less.

Pavement Surface Parameters

Pavement crown.- Although pavement crown has no direct effect on the hydroplaning phenomenon, it does inhibit hydroplaning by allowing water to drain off rapidly and prevent accumulations of water deep enough for hydroplaning to take place except under the most adverse conditions (heavy downpours). It is not expected that crowning the pavement would help much for a slush cover which does not drain off as readily as water.

Surface texture.- It is believed but not well substantiated at this time that a rough or open-textured pavement surface will require a greater fluid depth than a smooth surface for hydroplaning to take place. For example, "the hills and valleys" of an open-textured pavement surface provide paths in the tire-ground contact region for trapped water to escape and thus delay the buildup of the hydrodynamic pressure in the tire-ground region required to produce hydroplaning.

Pavement grooves.- It has been shown in references 18, 22, and 23 (see fig. 21) that transverse (to vehicle motion) pavement grooves can substantially increase the minimum water depth required for tire hydroplaning to occur. Through suitable pavement groove designs it may be possible to prevent hydroplaning from occurring except under the highest precipitation rates where vehicle operation

would be unlikely because of other factors such as reduced visibility and high winds. It is recognized, of course, that grooving pavement in "northern regions" might not be feasible because of an intolerable amount of pavement surface deterioration created by the surface water alternately freezing and thawing in the pavement grooves.

Pavement unevenness.- Pavement unevenness results in the formation of random puddles on the pavement surface during times of precipitation. The probability for puddle widths to be always greater than the vehicle wheel span is very small indeed. Thus, the probability for skid-producing yawing moments to occur on vehicles because of differential braking or cornering traction developed when some of the vehicle tires hydroplane and others do not is large. For this reason, pavements should be resurfaced when pavement unevenness due to unequal pavement settlement effects is seen to create a large number of puddles on the pavement during times of normal precipitation.

Additional Parameters

Surface winds.- The beneficial effect of pavement crown on water drainage can be completely canceled if the surface wind blows up the slope of the runway crown with sufficient speed. Thus, it can be expected that the critical pavement water depths required to support tire hydroplaning will be attained at lower precipitation rates under these high surface wind conditions than for the precipitation rates required under light wind conditions. It should be mentioned that under hydroplaning conditions, the resistive lateral or cornering force capability of pneumatic tires is very small and can be exceeded by the side forces produced on vehicles by cross winds of as little as 9 knots. (See refs. 13 and 17.) The loss in vehicle directional stability due to this effect can cause the vehicle to yaw and drift laterally off the pavement or runway surface with potentially grave consequences.

Hysteresis.- It was reported in reference 11 that the ground speed required for tires to spin up after encountering spin-down during hydroplaning was as much as 13 knots below the ground speed required to initiate the wheel spin-down. This result indicates a hysteresis effect which was noticed in the investigation of reference 1 but not reported. Because of this effect, the ground speed required for a tire to spin down and stop under accelerating ground speed conditions tends to be greater than the ground speed required to spin up the tire (after hydroplaning) under decelerating ground speed conditions. This result suggests that hydroplaning may be potentially more hazardous to aircraft during landing and rejected take-offs than during take-offs because of the greater total hydroplaning ground velocity range.

SUSCEPTIBILITY OF VEHICLES TO HYDROPLANING

Aircraft

For the purpose of determining how serious an operating problem might be created by tire hydroplaning, a survey was made in reference 13 of 40 different

civil and military aircraft currently being operated in the United States and the results are shown in figure 25. For this survey, a hydroplaning speed was calculated for each of these airplanes by means of equation (4) and this speed was compared with maximum take-off and landing speeds. The data shown in this figure indicate that essentially all aircraft considered are susceptible to total hydroplaning at some point in their take-off and landing velocity envelopes and that the nose wheels of the aircraft in the survey were somewhat more susceptible to hydroplaning than the main wheels.

Ground Vehicles

Most automobiles in use in the United States at this time require tire inflation pressures ranging from about 16 to 30 pounds per square inch. On the other hand, large trucks and buses in current use generally require tire inflation pressures considerably higher in magnitude, that is, from 50 to 90 pounds per square inch. These two inflation pressure bands for automobiles and buses are indicated in figure 26 along with the predicted tire hydroplaning speed of equation (5) in miles per hour. It can be seen from this figure that automobiles can encounter total hydroplaning at ground speeds considerably below the higher legal speed limits, say 60 to 70 miles per hour. Contrary to this, the higher inflation pressures used on trucks and buses yield hydroplaning speeds that are above legal speed limits and thus trucks and buses are not as susceptible to hydroplaning as are automobiles for normal operating speeds on highways.

HAZARDS OF TIRE HYDROPLANING TO VEHICLE OPERATION

Loss of Braking Traction

It is obvious when unbraked pneumatic tires stop completely under total hydroplaning conditions that the loss in braking traction derived from wheel brakes must be 100 percent for there is nothing to be gained by applying brakes to an already locked or nonrotating tire. Under total hydroplaning conditions, the main retardation forces developed by tires arise from: (1) drag forces created by the tire displacing fluid from its path, (2) small drag forces due to fluid viscosity effects. The available data indicate that the total of these retardation forces in terms of friction coefficient do not usually exceed 0.05 for hydroplaning tires at the minimum fluid depths required to support hydroplaning (0.1 to 0.3 in.). For greater fluid depths, such as shown for the jet transport aircraft braking test in slush, in figure 27, the effective friction coefficient from the fluid displacement drag term becomes large, especially at the higher ground speeds, and can partially restore the braking traction from wheel brakes that is lost under partial and total hydroplaning conditions.

The hazard to vehicle operation that results from loss in braking traction is increased vehicle stopping distance as shown in figures 28 and 29 for a four-engine jet transport and an automobile, respectively. It can be seen from figure 28 that the wet but not puddled runway condition (no hydroplaning) resulted in increasing the dry runway aircraft stopping distance by a factor of 1.6. For

the runway covered with 1/2-inch slush condition (hydroplaning occurred), the stopping distance was 2.6 times the dry runway stopping distance. The calculated stopping distance required for an automobile on dry and flooded (hydroplaning occurs) pavements shows a trend similar to that found for the aircraft, the dry-pavement automobile stopping distance being increased by a factor of approximately 2.0 to 2.6 when the automobile is braked on the flooded pavement surface. (See fig. 29(b).) These automobile-stopping-distance calculations were based on the following assumptions: vehicle weight, 3,700 pounds; aerodynamic drag coefficient, 1.0; frontal area of automobile, 25 square feet; and the automobile develops maximum braking coefficients shown in figure 29(a) (based on data obtained from ref. 4).

A rough estimate (based on the data shown in figs. 28 and 29) of the stopping distance required on flooded runways where hydroplaning is probable is indicated to be for both airplanes and ground vehicles as much as 3 times the dry-runway stopping distance. For example, pilots of aircraft having no thrust reversers or drag chutes should make sure at least 3 times the dry-runway stopping distance is available before a landing is attempted on flooded runways. The automobile driver should allow at least 3 times the normal spacing between his car and the vehicle ahead to allow for this reduced braking traction for there may be a truck or bus ahead that is not hydroplaning and therefore not experiencing low braking traction.

Loss of Directional Stability

Aircraft and automobile designers both depend upon the ability of a pneumatic tire to develop cornering or side forces as a means of steering or controlling their vehicles along pavement surfaces. When tires hydroplane and lift off the pavement surface, this ability to steer is practically lost since fluids cannot develop large shear forces and the tire-ground forces consequently drop to negligible values. For aircraft, this loss means ineffective nose wheel steering and differential wheel braking; for ground vehicles, the steering wheel tends to become a useless appendage.

The main hazard to vehicle operation that results from loss in tire directional stability is the inability of tires to develop resistive ground forces to overcome external forces produced on vehicles by cross winds and by centrifugal effects due to changes in vehicle direction such as occur for aircraft during high-speed turns onto taxiways and for automobiles on road curves.

The full-scale jet transport slush investigation (see refs. 10 and 15) demonstrated this loss very convincingly when it was found that cross winds as little as 9 knots in magnitude could yaw and displace the test aircraft laterally on the slush covered runway when the aircraft tires were hydroplaning. The ability of ground vehicles to negotiate road curves for different pavement conditions and speeds is shown in figure 30. In the United States, the posted maximum safe speed for negotiating road curves is based on an assumed low pavement friction coefficient level of $\mu = 0.12$ to 0.16 . For dry pavements and for all wet pavement conditions giving friction coefficients greater than 0.12 to 0.16 , the vehicle slide-out velocity V_S is greater than this posted speed limit V_C and

the vehicle can negotiate the curve safely. It can be seen from figure 30 that a ground vehicle (tire pressure of 25 pounds per square inch) entering a curve at ground speeds in excess of the corresponding tire hydroplaning speed (52 miles per hour) could not negotiate road curves at posted speed limits under pavement conditions conducive to hydroplaning since the friction coefficient for hydroplaning tires (μ does not exceed 0.05) produces vehicle slide-out speeds less than the posted speed limit speeds.

Low Friction Coefficients Not Associated With Tire Hydroplaning

The large mass of data just described suggests that tire hydroplaning can be reasonably explained in terms of fluid density effects alone and equation (4), derived on this basis, is seen to give good estimates of tire hydroplaning speed values. (See fig. 4.) Some data exist, however, that show a complete loss of tire braking traction (one manifestation of hydroplaning) occurring at ground speeds considerably less than the tire hydroplaning speed.

Such a loss at these lower speeds cannot be ascribed to hydroplaning from fluid density effects since the fluid dynamic pressures developed at these lower speeds is insufficient to lift the tire off the pavement surface. Since this type of braking traction loss occurs only when smooth tires are used on smooth wet pavement surfaces or when rib tread tires are used on very smooth wet pavement surfaces, it probably arises from thin-film lubrication effects on the tire-ground surfaces in which fluid viscous properties, previously ignored, tend to predominate. Two examples of thin-film lubrication are given.

The first example is shown in figure 31 which indicates the loss in braking traction experienced by a smooth tread aircraft tire when braked on a relatively smooth wet concrete runway at tire pressures of 120 and 260 pounds per square inch. It can be seen in part (a) of this figure that at ground speeds of 95 to 100 knots, both the $p = 260$ pounds per square inch curve and the $p = 120$ pounds per square inch curve drop to the residual free-roll friction coefficient. This result indicates complete loss of braking traction at this speed and is one of the manifestations of total tire hydroplaning. When these data are plotted against the velocity ratio V_G/V_P as in part (b) of this figure, it can be seen that the curve for $p = 260$ pounds per square inch reaches the free-rolling friction coefficient level (zero braking traction) at a ground speed 35 percent less than the total hydroplaning speed required by equation (4).

A similar result is shown in figure 32 for a rib tread aircraft tire when braked on a very smooth wet membrane that was placed on top of the track runway. It is of interest to note that the water depth for this test was insufficient to form puddles on the membrane. The ground speed for this particular test was 86 knots which gives a value of velocity ratio V_G/V_P of 0.68 and an estimated hydroplaning speed of 127.5 knots. Since the average friction coefficient developed for this speed is about 0.05 (approximately equal to tire free-rolling resistance), the loss in braking traction must be nearly complete at a ground velocity at least 32 percent less than the hydroplaning speed predicted by equation (4).

It is apparent from these data that the extreme pavement slipperiness demonstrated for thin-film lubrication conditions is the direct result of the inability of tires to penetrate a very thin but tenacious fluid film that coats smooth pavement surfaces when wet.

As might be expected from the preceding discussion, the loss in tire-braking traction due to thin-film lubrication can be greatly reduced by the addition of a thin nonskid coating to the existing smooth pavement surface. This effect is shown in figure 33 which presents friction-coefficient data obtained on a wet, but not puddled with water, enameled steel aircraft landing mat before and after being coated with a nonskid compound that the U.S. Navy uses on flight decks of its current aircraft carriers. The fine sand-like grit particles embedded in this compound provide thousands of sharp asperities in the surface which break through the pavement fluid film and sharply reduce the braking traction loss due to thin-film lubrication effects.

Fortunately, most runway and road pavements in use today are provided with textured surfaces so that thin-film lubrication is probably seldom encountered when vehicles are equipped with tires having adequate tread pattern designs.

CONCLUDING REMARKS

This report has given a physical description of pneumatic tire hydroplaning, has demonstrated many manifestations of the phenomena of tire hydroplaning, and has discussed the fluid, tire, and airplane parameters of importance. In concluding the report various suggestions or recommendations for avoiding and minimizing its hazards are made.

Avoidance of Hydroplaning Effects

As mentioned, there are two separate effects for which there is separation or loss in adhesion between tire and wet pavement surfaces with resulting large increases in pavement slipperiness, namely, hydroplaning (where inertia and density properties of the fluid predominate) and thin-film lubrication (where viscous properties of the fluid predominate).

Hydroplaning requires a critical minimum fluid depth to be present on pavement surfaces. This critical depth can range from approximately 0.1 to 0.4 inch depending upon the character of tire-pavement surfaces. Smooth tread tires operating on the smoother pavement surfaces require the least fluid depth, whereas rib tread tires operating on open-textured and transverse-grooved pavement surfaces require the greatest fluid depths. When this critical fluid depth is exceeded for any tire-pavement surface combination, the critical ground speed (hydroplaning speed) required for total hydroplaning to occur was found to be almost entirely dependent upon tire inflation pressure. This result led to the derivation of a simple relation for estimating tire hydroplaning speed which shows good correlation with available experimental values of hydroplaning speed.

Two methods appear to be appropriate for avoiding this phenomenon. The first method consists of increasing tire inflation pressure such that the vehicle's hydroplaning speed is greater than the highest vehicle ground speed. This method has large limitations because of probable vehicle and pavement structural design changes such a procedure will incur. The second method, which is considered the best practical solution, is to raise the critical minimum fluid depth for hydroplaning to occur to a value that will not be reached during rainfall precipitation rates under which vehicles operate. This can be done through use of a proper pavement crown and textured surface, adequate tire tread design, and possibly by pavement grooving. It is realized that such a method will not work as well for slush covered pavement surfaces since slush does not drain as readily as water, and aircraft operations should be limited for this condition if necessary.

Thin-film lubrication is not important at normal vehicle operating speeds when rib tread tires are used on wet rough-textured pavement surfaces. It becomes important and increases slipperiness when smooth tread tires are used on smooth pavement surfaces or when rib tread tires are used on very smooth pavement surfaces. Thin-film lubrication does not require the presence of large fluid depths on pavements. (The film thickness required is estimated to be less than 0.01 in.) The limited data available suggest that complete separation of tire and pavement surface from this fluid property can occur at ground speeds at least 35 percent less than the speeds required for hydroplaning to occur from fluid density effects. Fortunately, thin-film-lubrication effects are easily avoided or minimized by roughening or texturizing the pavement surfaces and by not using smooth tread or excessively worn patterned tread tires on air and ground vehicles.

Minimizing Hazards of Hydroplaning by Operational Means

The hazards of tire hydroplaning to vehicle operation are greatly increased stopping distances, and potential loss of ground directional stability. In order to minimize these hazards, it is most important for the vehicle operator to be aware of the existence of tire hydroplaning and to understand how and when it may occur. Such knowledge being assumed, certain procedures then suggest themselves to minimize hazards of tire hydroplaning where conditions are such that it may be encountered.

In the operation of aircraft when landings must be made on very wet runways, operational techniques such as minimum "safe" touchdown speed, early runway contact, and early use of spoilers, wheel brakes and reverse thrust should be employed to decrease the aircraft landing roll. Application of reverse thrust and wheel brakes should be made with caution, however, since asymmetrical thrust or drag on the aircraft for these slippery runway conditions will be difficult to control. Curtailment of operations in the presence of cross winds during take-off and landing on flooded runways which may greatly increase the possibility of aircraft skidding under these slippery runway conditions should be considered.

The ground vehicle operator should reduce his speed appropriately below the vehicle's hydroplaning speed on a flooded road, especially when rounding a curve

or driving in traffic. The use of excessively worn patterned tread tires or smooth tread tires on air or ground vehicles on wet pavements should be avoided.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 25, 1963.

REFERENCES

1. Harrin, Eziaslav N.: Low Tire Friction and Cornering Forces on a Wet Surface. NACA TN 4406, 1958.
2. Hall, Albert W., Sawyer, Richard H., and McKay, James M.: Study of Ground-Reaction Forces Measured During Landing Impacts of a Large Airplane. NACA TN 4247, 1958. (Supersedes NACA RM L55E12c.)
3. Sawyer, Richard H., Batterson, Sidney A., and Harrin, Eziaslav N.: Tire-to-Surface Friction Especially Under Wet Conditions. NASA MEMO 2-23-59L, 1959.
4. Sawyer, Richard H., and Kolnick, Joseph J.: Tire-to-Surface Friction-Coefficient Measurements With a C-123B Airplane on Various Runway Surfaces. NASA TR R-20, 1959.
5. Trant, James P., Jr.: NACA Research on Friction Measurements. Proc. First Int. Skid Prevention Conf., Pt. I, Virginia Council of Highway Invest. and Res. (Charlottesville), Aug. 1959, pp. 297-308.
6. Batterson, Sidney A.: Braking and Landing Tests on Some New Types of Airplane Landing Mats and Membranes. NASA TN D-154, 1959.
7. Horne, Walter B., Joyner, Upshur T., and Leland, Trafford J. W.: Studies of the Retardation Force Developed on an Aircraft Tire Rolling in Slush or Water. NASA TN D-552, 1960.
8. Horne, Walter B., and Joyner, Upshur T.: Some Effects of Runway Slush and Water on the Operation of Airplanes, With Particular Reference to Jet Transports. SAE Trans., vol. 70, 1962, pp. 99-108.
9. Harrin, Eziaslav N.: Investigation of Tandem-Wheel and Air-Jet Arrangements for Improving Braking Friction on Wet Surfaces. NASA TN D-405, 1960.
10. Anon.: Joint Technical Conference on Slush Drag and Braking Problems. FAA and NASA, Dec. 1961.
11. Horne, Walter B., and Leland, Trafford J. W.: Influence of Tire Tread Pattern and Runway Surface Condition on Braking Friction and Rolling Resistance of a Modern Aircraft Tire. NASA TN D-1376, 1962.
12. Horne, Walter B.: Slush and Water Drag Effects on a Bogie Landing Gear. 15th Annual Inter. Flight Safety Foundation Seminar "Notes," Otto E. Kirchner, Sr., reporter, Airplane Div., The Boeing Co., 1962, pp. 99-101.
13. Horne, Walter B., and Leland, Trafford J. W.: Runway Slipperiness and Slush. Jour. R.A.S., vol. 67, no. 633, Sept. 1963, pp. 559-571.

14. Shrager, Jack J.: Vehicular Measurements of Effective Runway Friction. Final Report, Project No. 308-3X (Amendment No. 1), FAA, May 1962.
15. Sommers, Daniel E., Marcy, John F., Klueg, Eugene P., and Conley, Don W.: Runway Slush Effects on the Takeoff of a Jet Transport. Final Report, Project No. 308-3X, FAA, May 1962.
16. Joyner, Upshur T., Horne, Walter B., and Leland, Trafford J. W.: Investigations on the Ground Performance of Aircraft Relating to Wet Runway Braking and Slush Drag. Presented to AGARD Flight Mechanics Panel (Paris, France), Jan. 14-18, 1963.
17. Anon.: Hazards of Tire Hydroplaning to Aircraft Operation. NASA Langley Research Center Film Serial No. L-775, 1963.
18. Gray, W. E.: Measurements of "Aquaplaning Height" on a Meteor Aircraft, and Photos of Flow Pattern Under a Model Tyre. Tech Note No. Aero. 2855, British R.A.E., Nov. 1962.
19. Maltby, R. L., and Chinn, H. W.: Investigation of Slush Effects on Take-Off - Progress and Plans. TOLS/4, British R.A.E., Dec. 1962.
20. Gadd, G. E.: A Note on the Undercarriage Aquaplaning of Aircraft Landing on Water-Covered Runways. British A.R.C.22,793, Apr. 26, 1961.
21. Anon.: Flight Tests To Determine the Coefficient of Friction Between an Aircraft Tyre and Various Wet Runway Surfaces - Part 6: Trials on an Old Asphalt Runway at A. & A.E.E., Boscombe Down. S & T MEMO 20/61, Ministry of Aviation (British), Mar. 1962.
22. Gray, W. E.: Aquaplaning on Runways. Jour. R.A.S. (Tech. Notes), vol. 67, no. 629, May 1963, pp. 302-304.
23. Willis, J. M. N.: Effects of Water and Ice on Landing. Shell Aviation News, no. 296, 1963, pp. 16-20.
24. Anon.: Flight Tests To Determine the Coefficient of Friction Between an Aircraft Tyre and Various Wet Runway Surfaces - Part 5: Trials on an Asphalt Surface at Upper Heyford. S & T MEMO 2/62, Ministry of Aviation (British), Apr. 1962.

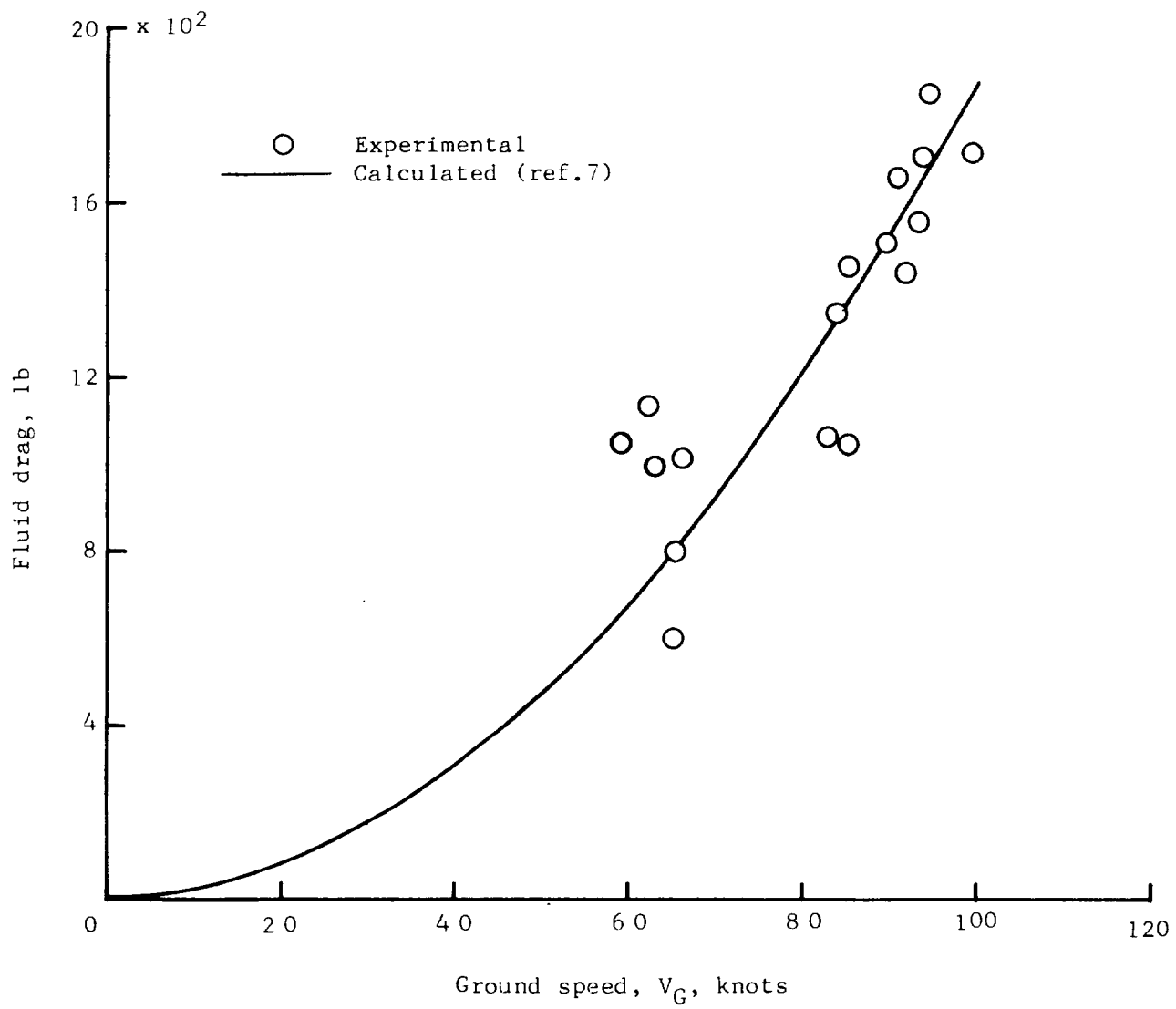


Figure 1.- Variation of fluid (slush) drag with ground speed on single wheel.
Tire pressure, 350 lb/sq in.

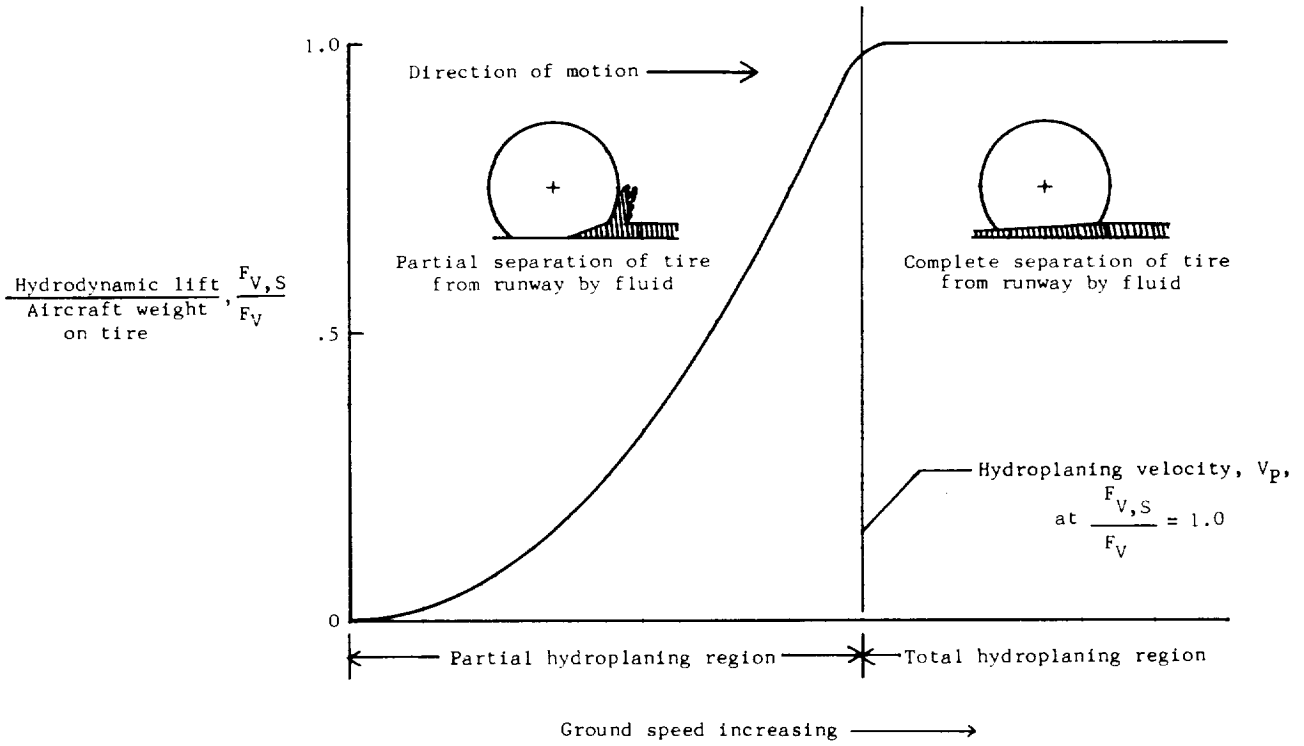


Figure 2.- Development of tire hydroplaning.

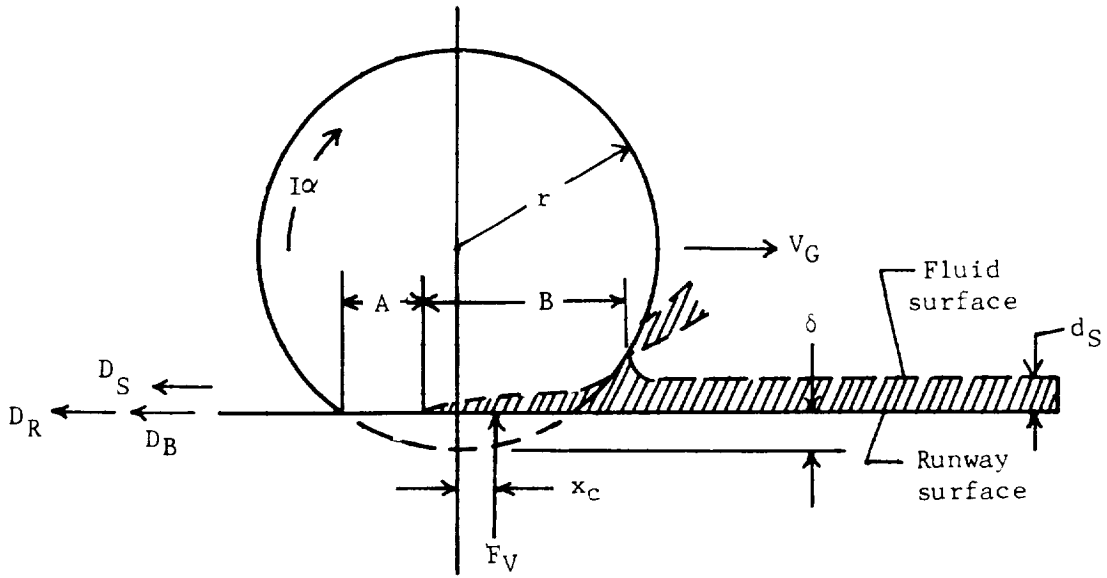


Figure 3.- Unbraked rolling tire undergoing spin-down on fluid covered runway.

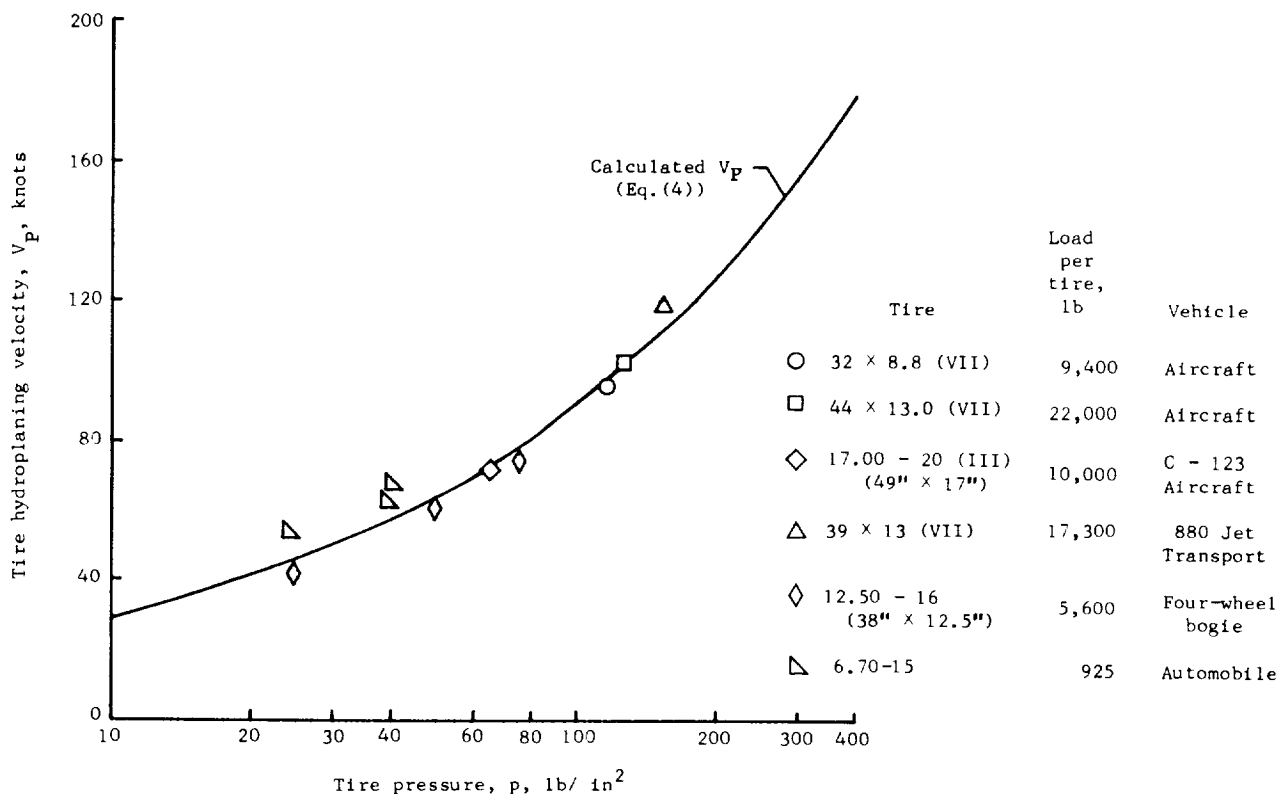


Figure 4.- Experimental and calculated tire-hydroplaning velocities. (Data obtained from ref. 13.)

Direction of motion →



(a) $V_G = 28$ knots.



(b) $V_G = 56$ knots.



(c) $V_G = 71$ knots.



(d) $V_G = 88$ knots.

Figure 5.- Photographs of 20 x 4.4 aircraft tire on glass runway at Langley landing loads track under partial and total hydroplaning conditions. Vertical load, 500 lb; tire pressure, 30 lb/sq in.; water depth, 0.5 inch. 63-9235

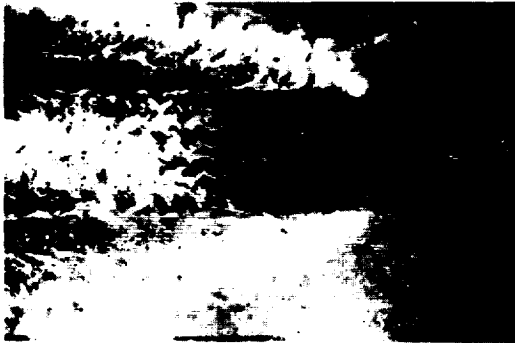
Direction of motion →



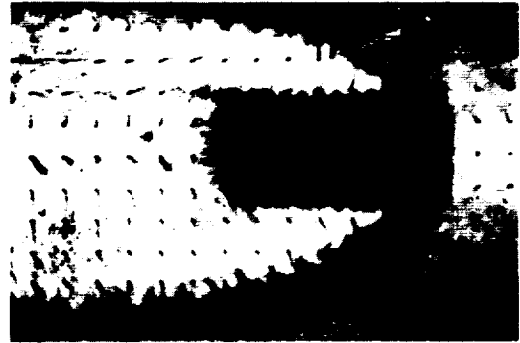
(a) Static footprint; $V_G = 0$.



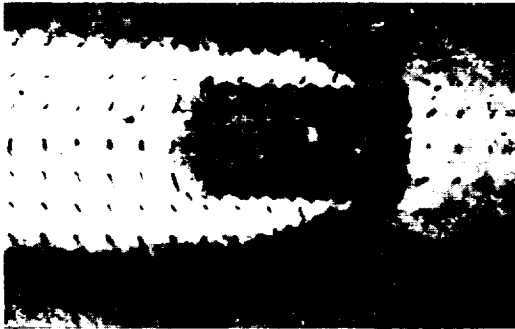
(b) $V_G = 24$ knots; $\frac{V_G}{V_P} = 0.597$.



(c) $V_G = 32$ knots; $\frac{V_G}{V_P} = 0.796$.



(d) $V_G = 41$ knots; $\frac{V_G}{V_P} = 1.020$.

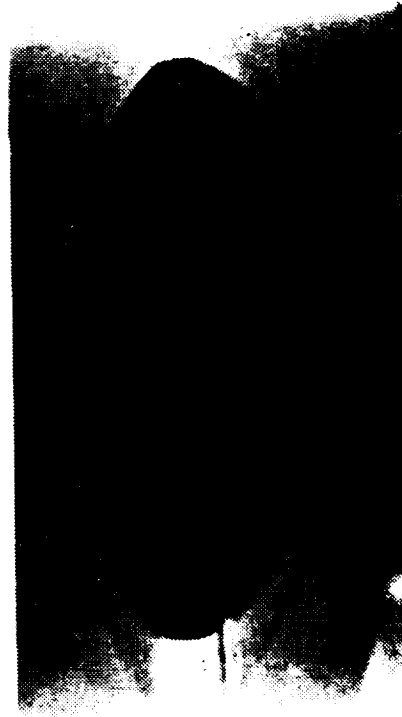


(e) $V_G = 53$ knots; $\frac{V_G}{V_P} = 1.318$.

Figure 6.- Photographs of 5.60-13 automobile tire on glass runway under partial and total hydro- 63-9236
planing conditions. Vertical load, 500 lb; tire pressure, 20 lb/sq in.; water depth, 0.5 inch.



$V_G = 50$ fps



$V_G = 0$

Figure 7.- Photographs of model tire (4.5" x 1.5") footprints obtained during perspex drum tests of 63-9237 reference 18. Water depth, 1/16 inch; wheel slip, 75 percent.

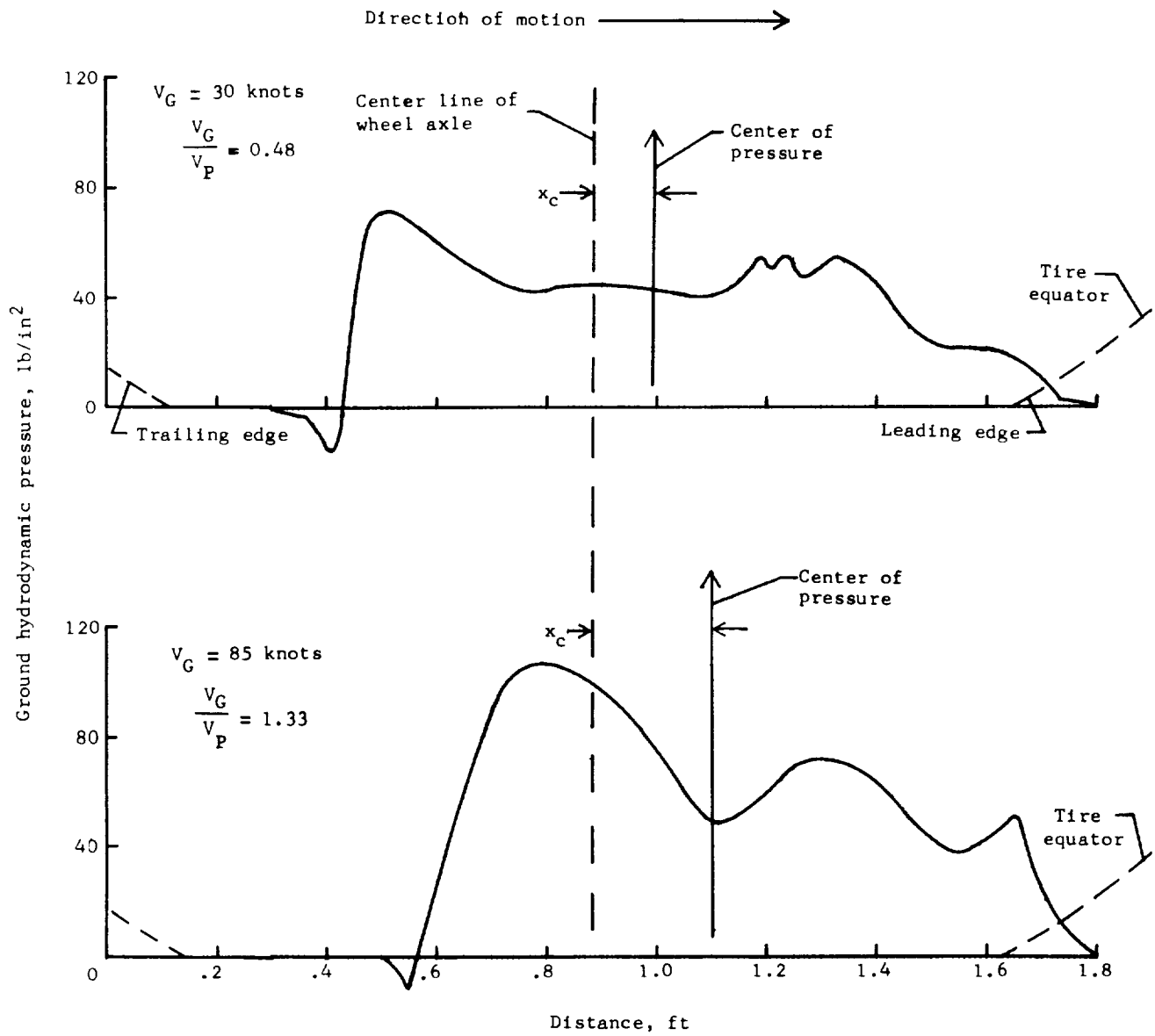


Figure 8.- Tire ground pressure signatures on water covered runway. Vertical load per tire, approximately 5,600 lb; tire pressure, 50 lb/sq in.; water depth, 0.5 inch.

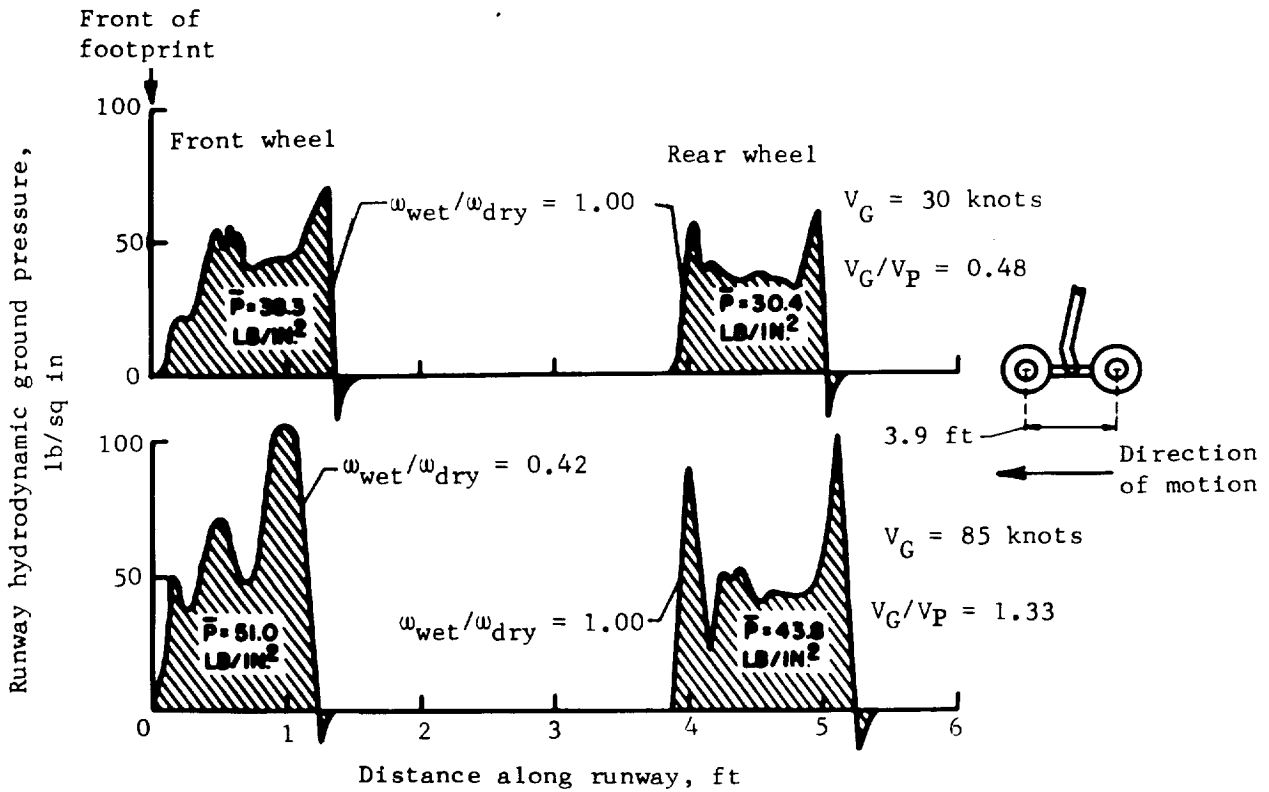


Figure 9.- Tandem wheel hydrodynamic ground pressures. Vertical load per tire, approximately 5,600 lb; water depth, 0.5 inch; tire pressure, 50 lb/sq in.

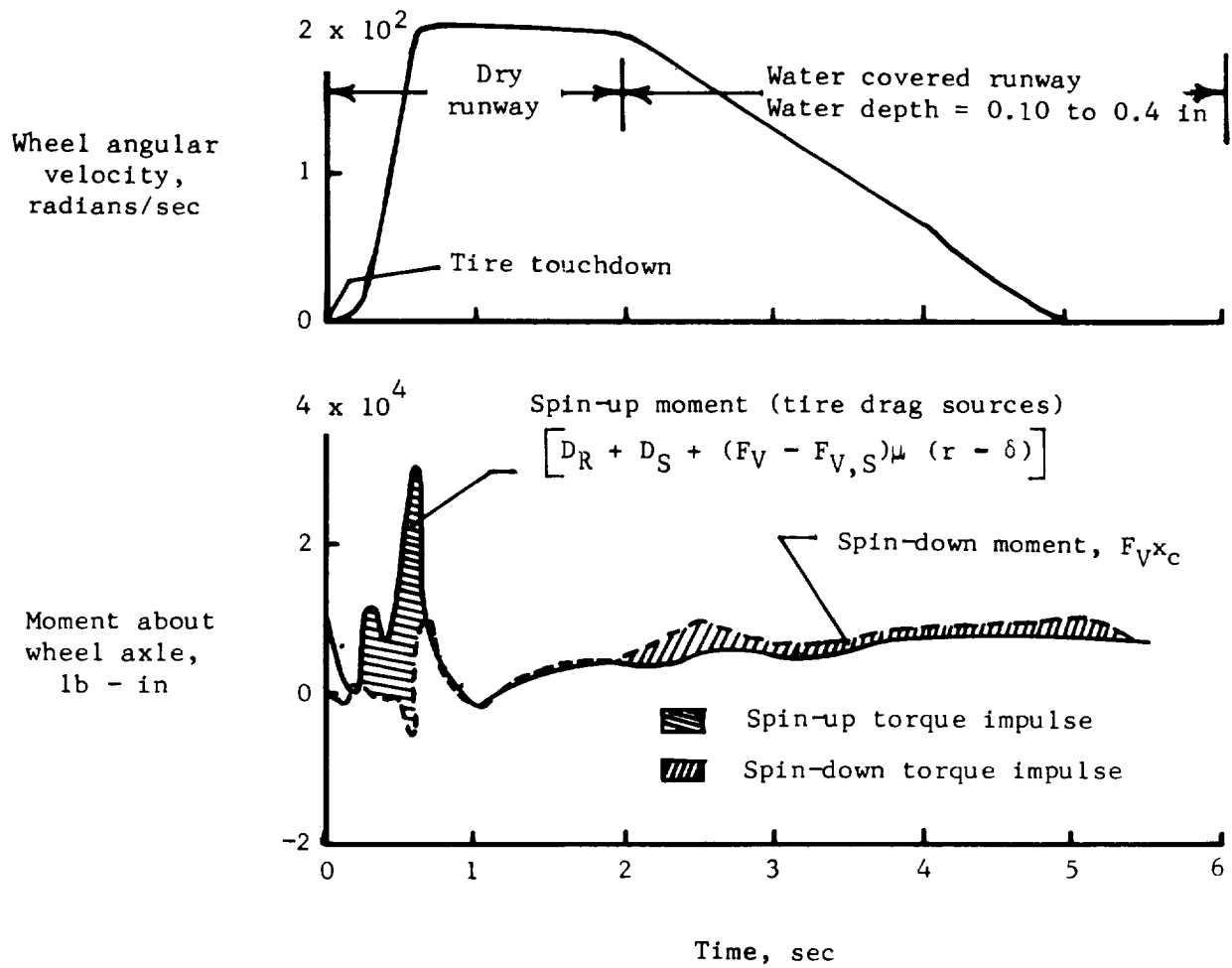


Figure 10.- Unbraked wheel spin-down due to hydroplaning. 32 x 8.8 aircraft tire; $F_V = 10,000$ lb; $p = 90$ lb/sq in. (Data obtained from ref. 11.)

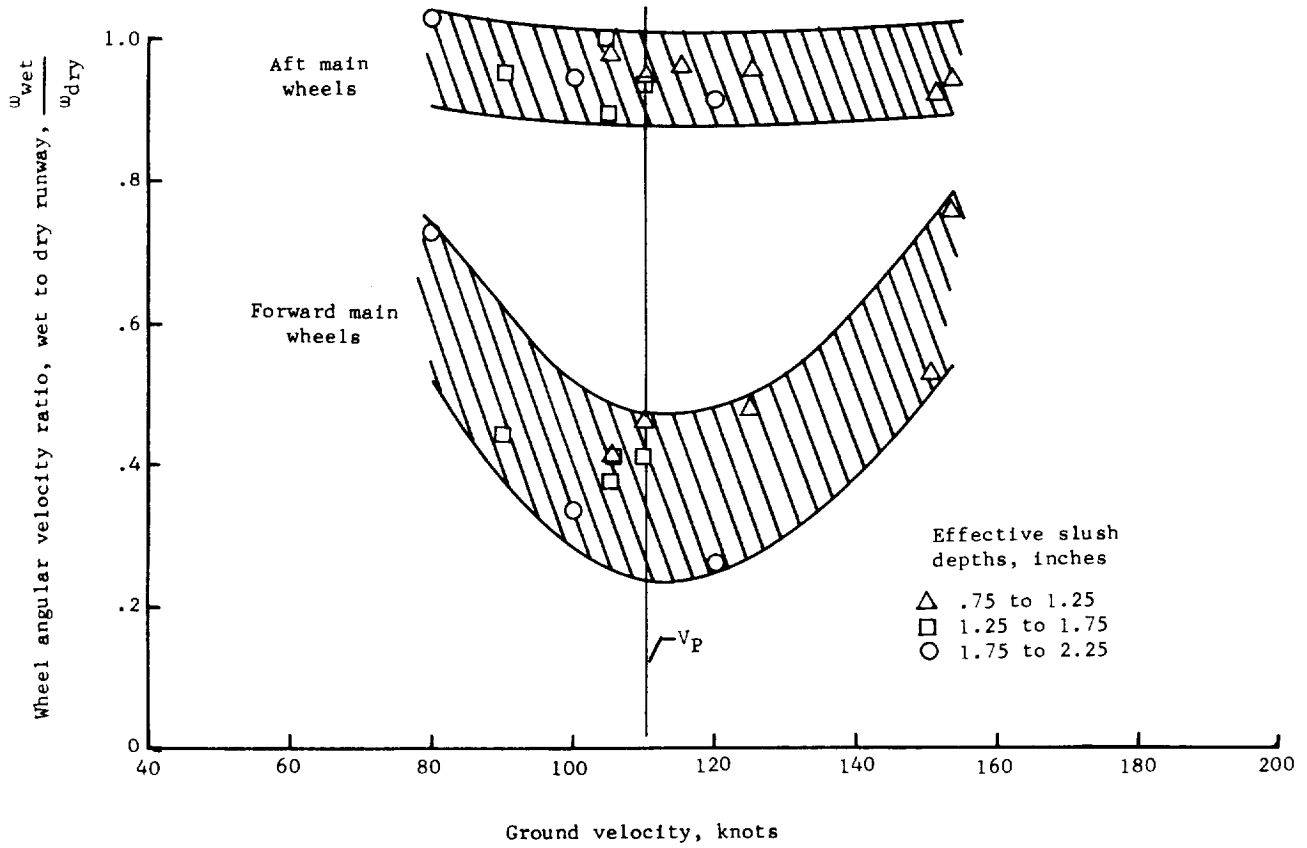
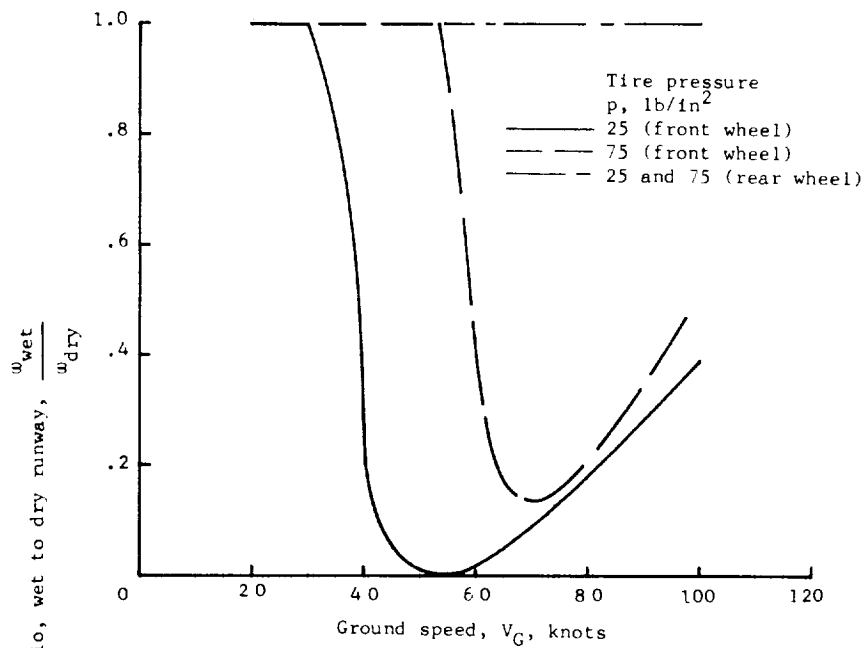
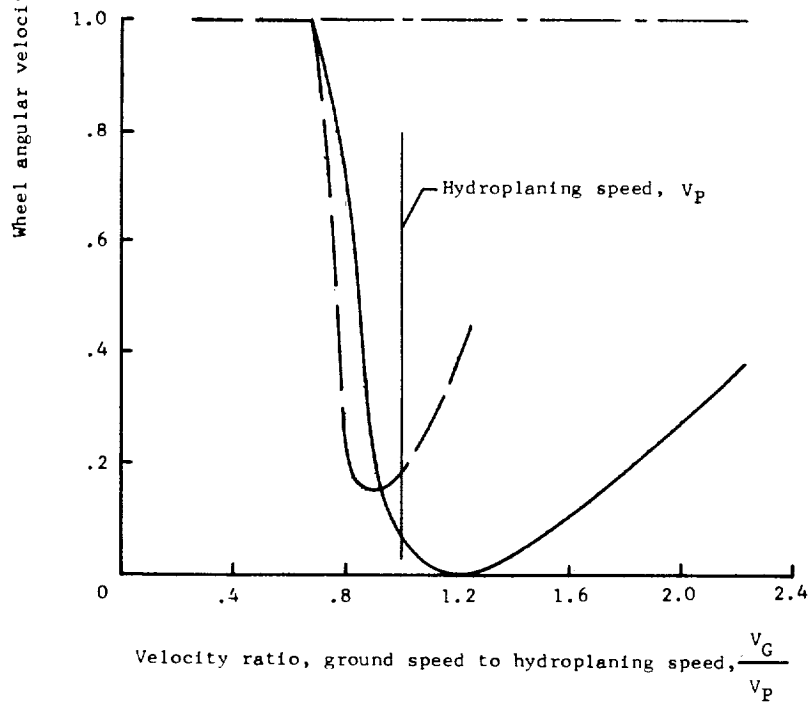


Figure 11.- Effect of slush on main wheel rotation. (Data obtained from ref. 15.)



(a) Variation of wheel spin-down with ground speed.



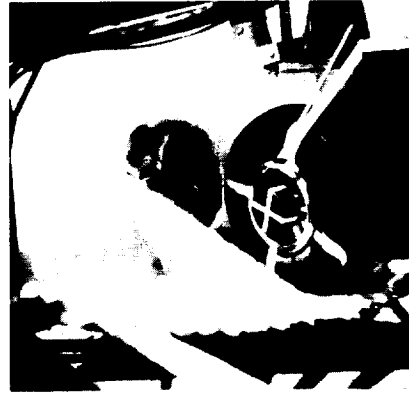
(b) Variation of wheel spin-down with velocity ratio.

Figure 12.- Effect of tire hydroplaning speed on wheel spin-down encountered on single tandem landing gear on water covered runway. $F_V \approx 12,000$ lb; water depth ≈ 1 inch.



Partial hydroplaning speed

(a) $V_G = 25$ knots; $\frac{V_G}{V_P} \approx 0.32$.



Total hydroplaning speed

(b) $V_G = 87$ knots; $\frac{V_G}{V_P} \approx 1.11$.

Figure 13.- Side view of spray patterns at partial and total hydroplaning speeds obtained during tests at Langley landing loads track. (See ref. 13.) Four-wheel bogie configuration; tire pressure, 75 lb/sq in.; $F_V \approx 22,300$ lb; water depth, 2 inches.



Partial hydroplaning speed

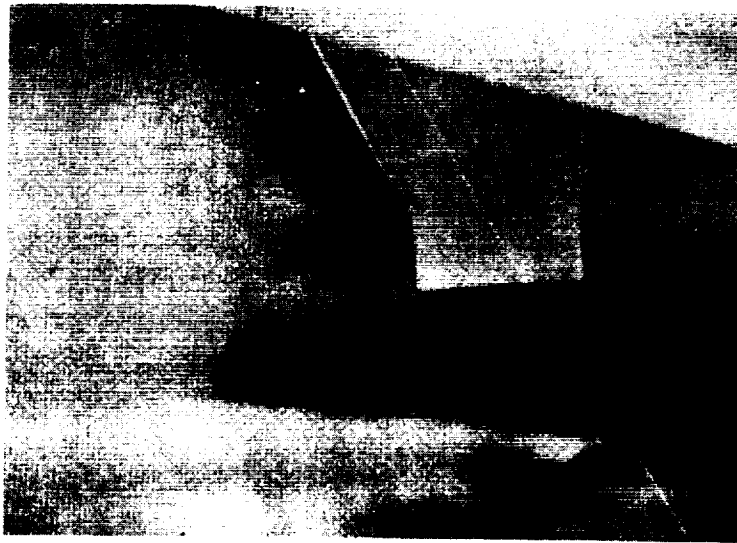
(a) $V_G = 27$ knots; $\frac{V_G}{V_P} \approx 0.60$.



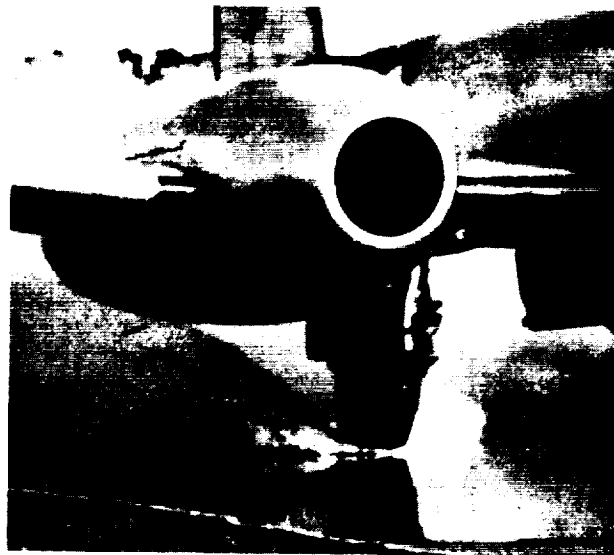
Total hydroplaning speed

(b) $V_G = 73$ knots; $\frac{V_G}{V_P} \approx 1.62$.

Figure 14.- Front view of spray patterns at partial and total hydroplaning speeds obtained during 63-238 tests at Langley landing loads track. (See ref. 13.) Four-wheel bogie configuration; tire pressure, 25 lb/sq in.; $F_V \approx 22,300$ lb; slush depth, 1 inch.



(a) Four-engine jet transport. $V_G = 155$ knots; $p = 150$ lb/sq in.; $\frac{V_G}{V_P} = 1.41$.
(Photograph from ref. 15.)



(b) British Meteor fighter. $V_G = 87$ knots; $p = 60$ lb/sq in.; $\frac{V_G}{V_P} = 1.25$.
(Photograph from ref. 22.)

Figure 15.- Disappearance of tire bow wave at total hydroplaning speeds during full-scale aircraft 63-9239 tests on slush and water covered runways.

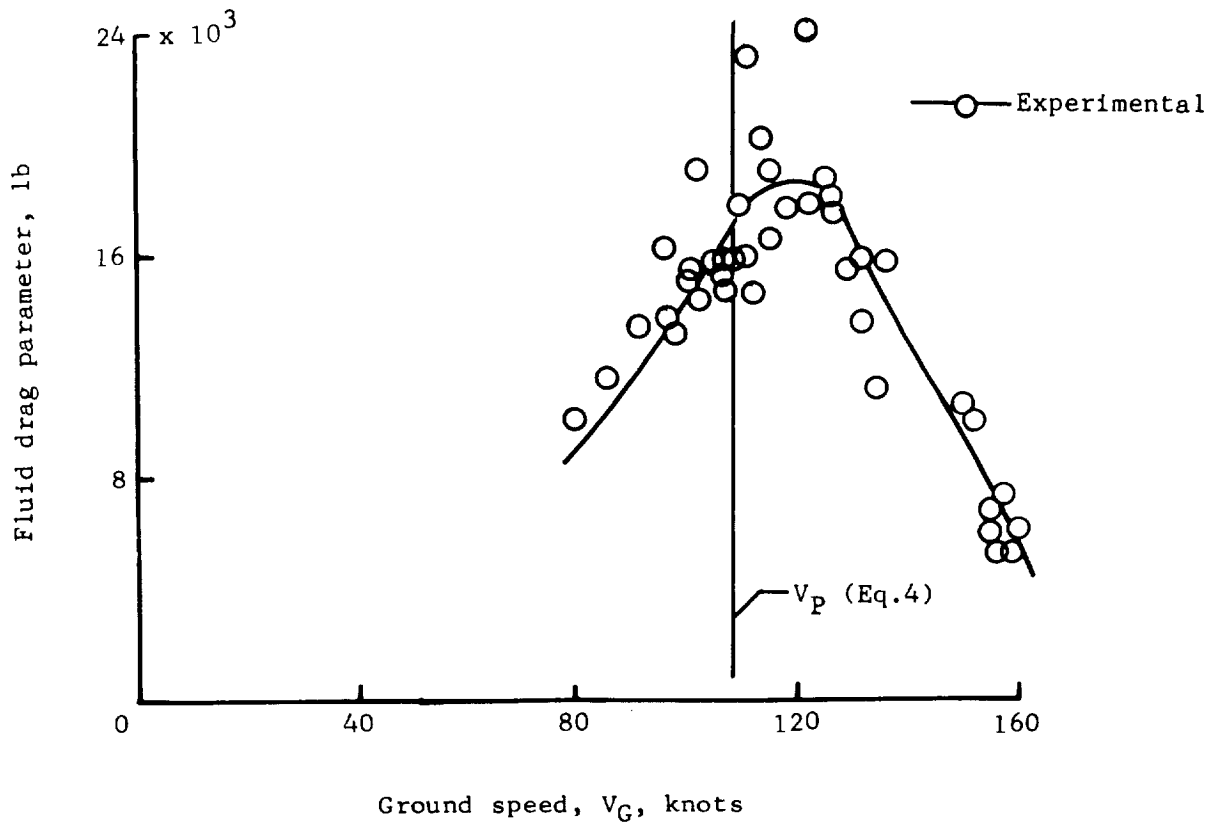
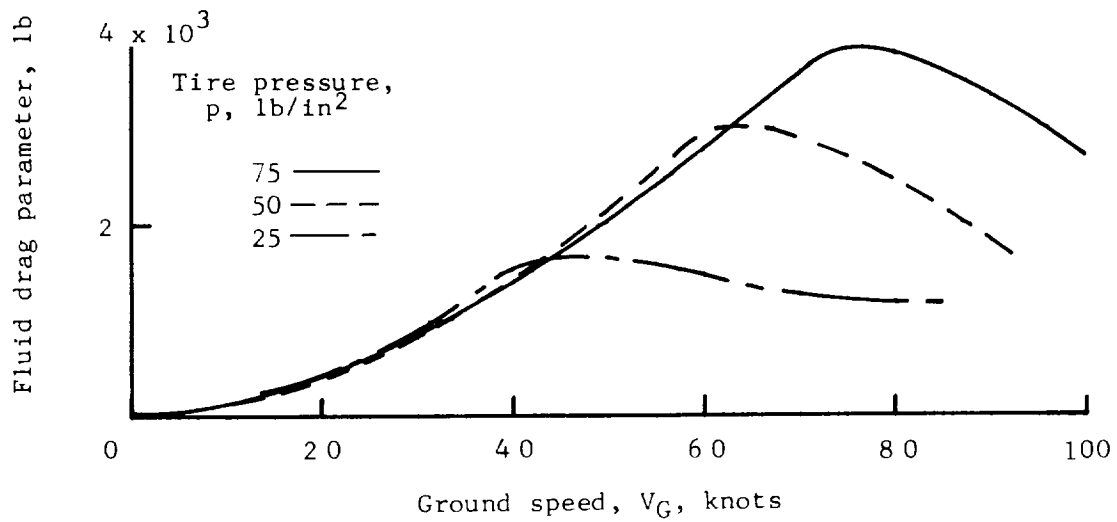
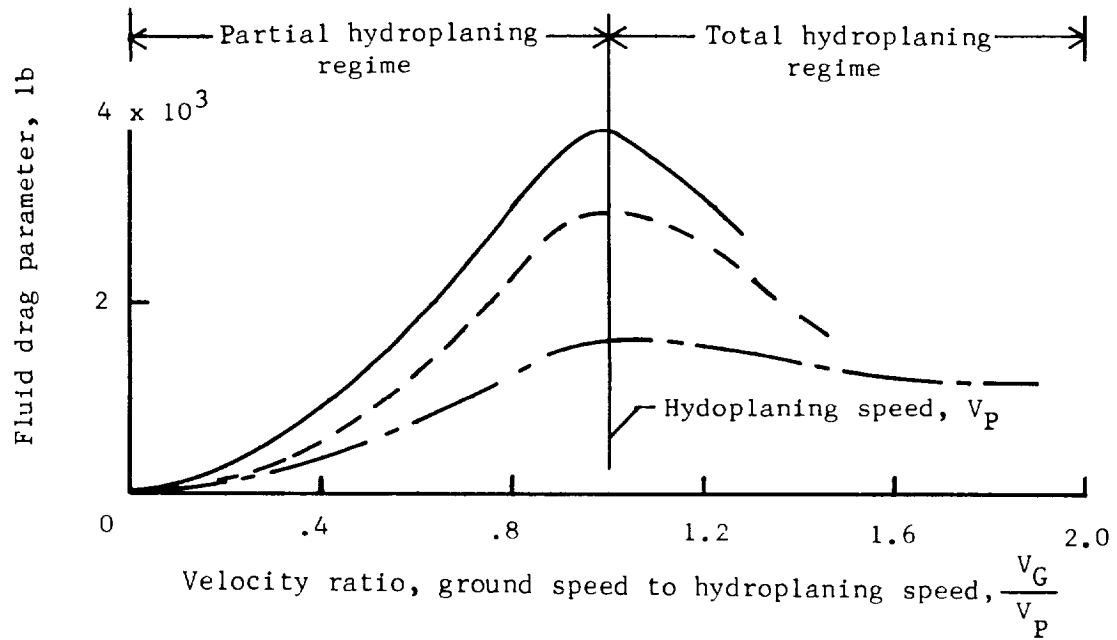


Figure 16.- Slush drag on jet transport. Main wheel tire pressure, 150 lb/sq in. (Data obtained from ref. 10.)

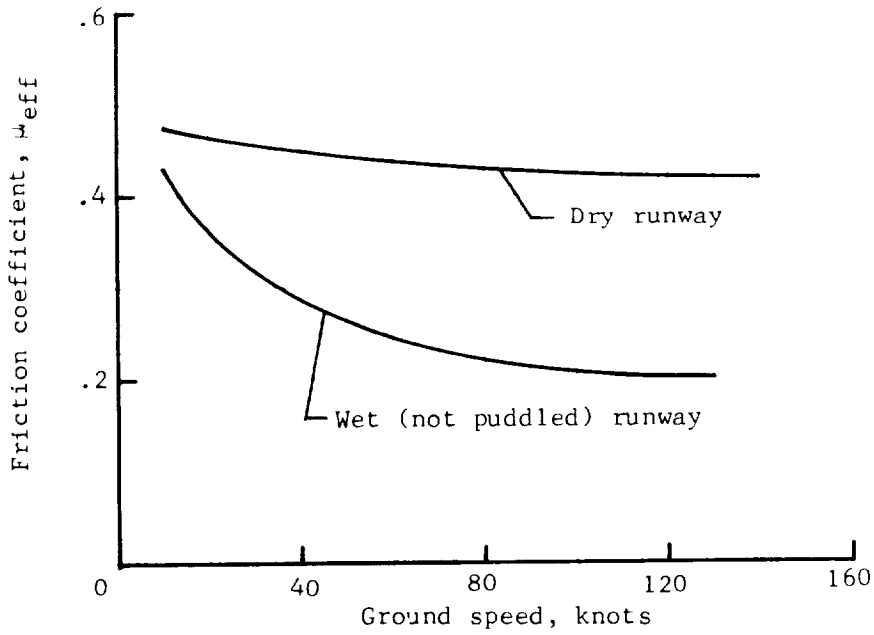


(a) Variation of drag parameter with ground speed.

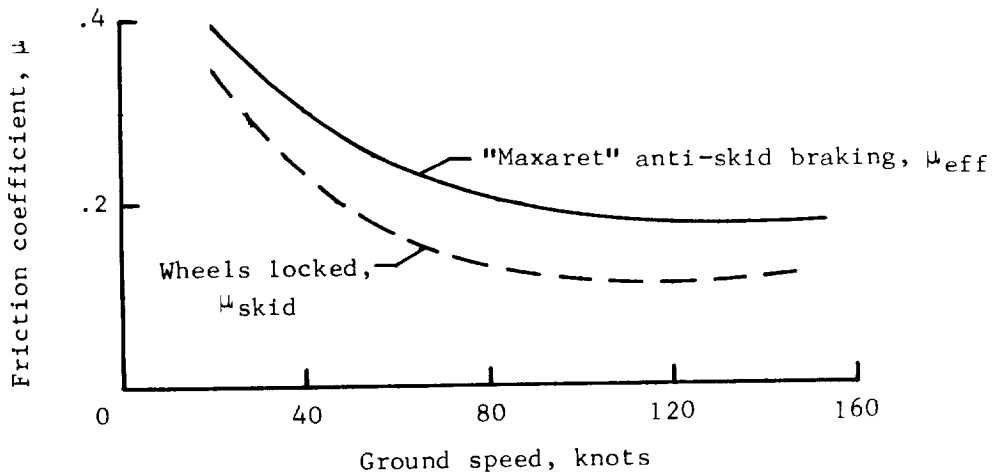


(b) Variation of drag parameter with velocity ratio.

Figure 17.- Effect of tire hydroplaning speed on the fluid drag developed by a dual-tandem landing gear on slush and water covered runways. $F_y = 22,300$ lb; water depth normalized to 1 inch.



(a) 880 jet transport aircraft (see ref. 10); concrete runway; anti-skid braking; $p = 150$ lb/sq in.; gross weight = 150,000 lb; rib tread tires.



(b) Swift fighter aircraft (see ref. 24); wet asphalt runway (water depth ≈ 2 mm); $p = 320$ lb/sq in.; gross weight $\approx 16,000$ lb; rib tread tires.

Figure 18.- Effect of wet but not flooded runways in anti-skid braking for two aircraft.

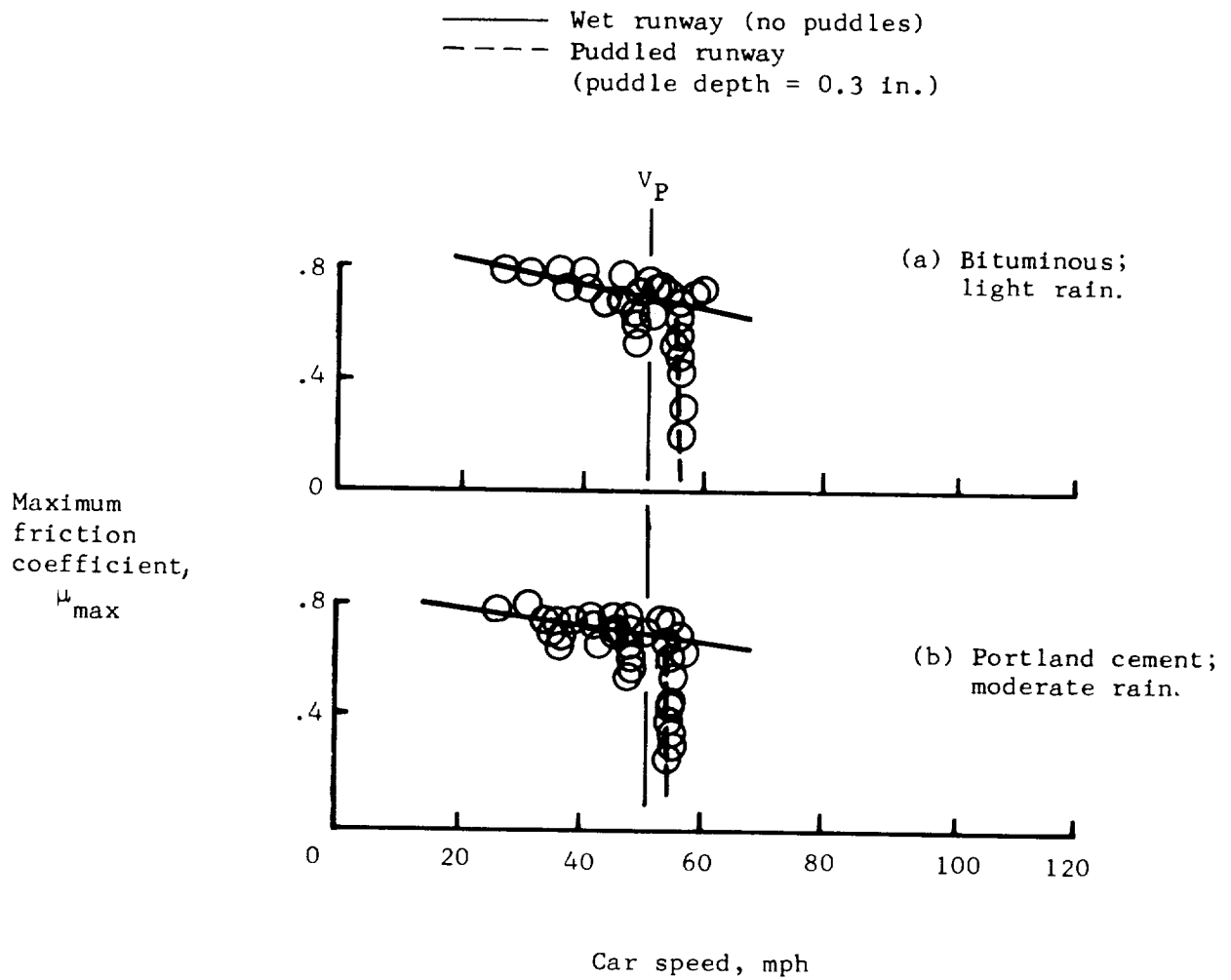


Figure 19.- Loss of braking traction in runway puddles due to hydroplaning. Data obtained from reference 5; 6.70-15 rib tread automobile tire; vertical load = 925 lb; $p = 24$ lb/sq in.

- C-123 aircraft; 17.00 - 20 Type III rib tread tire; heavy rain (ref. 4)
- - - - - NACA cart; 6.70 - 15 rib tread automobile tire; water depth = 0.3 inch (ref. 5)
- NASA track; 32 x 8.8 Type VII rib tread tire; water depth = 0 to 0.5 inch (ref. 11)
- - - - - 880 jet transport; 39 x 13 Type VII rib tread tire; slush depth \approx 0.5 inch (ref. 14)

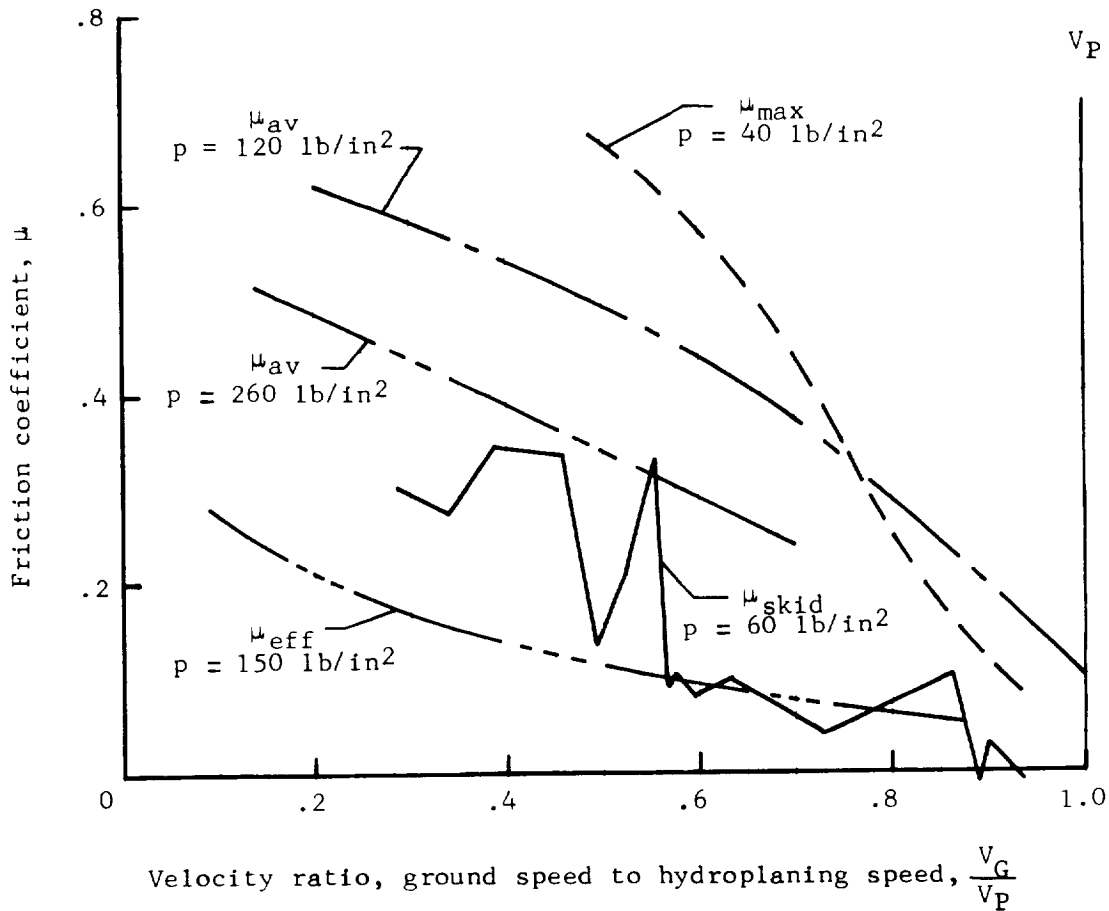


Figure 20.- Effect of hydroplaning on braking coefficients obtained on water and slush covered pavement surfaces.

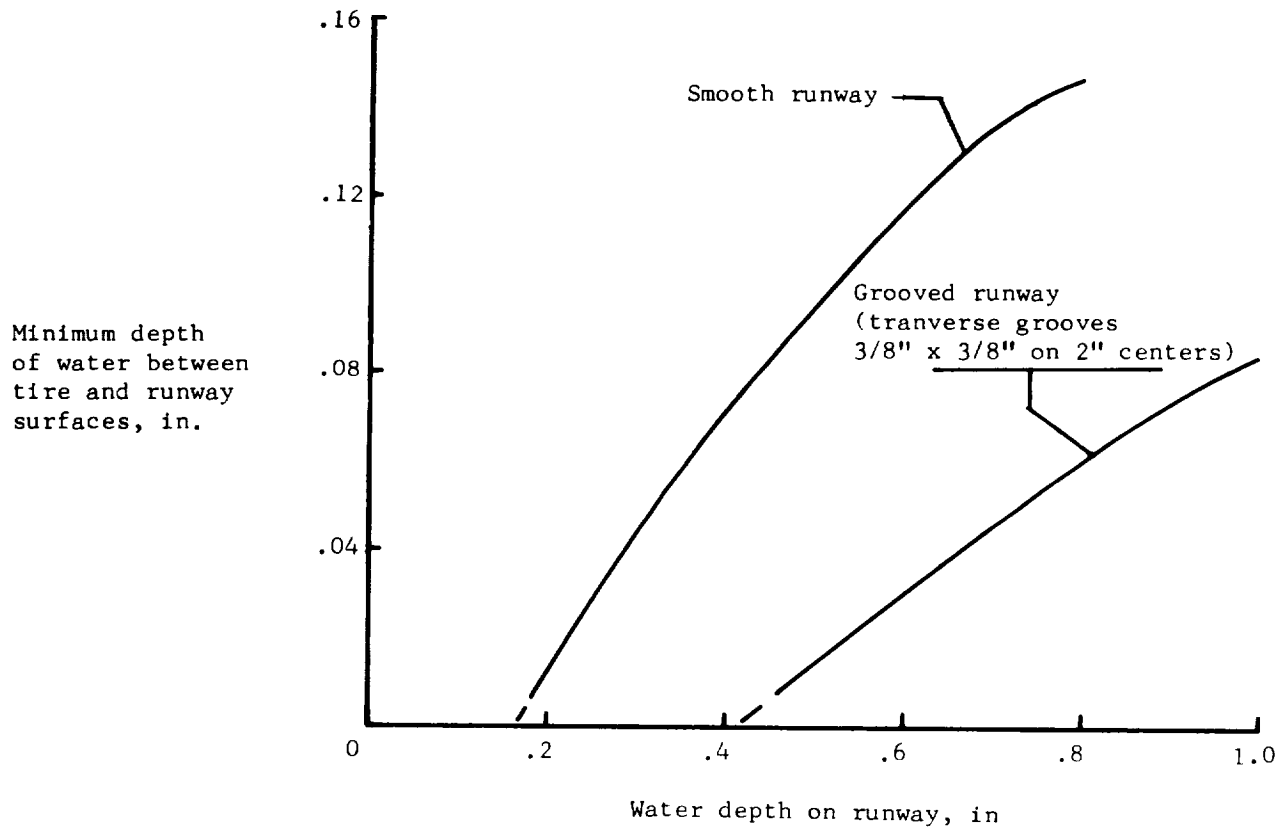


Figure 21.- Effect of runway water depth on tire displacement from runway under hydroplaning conditions. British Meteor fighter; ground speed, 87 knots; tire pressure, 60 lb/sq in.; $V_G/V_P = 1.25$. (Data from ref. 22.)

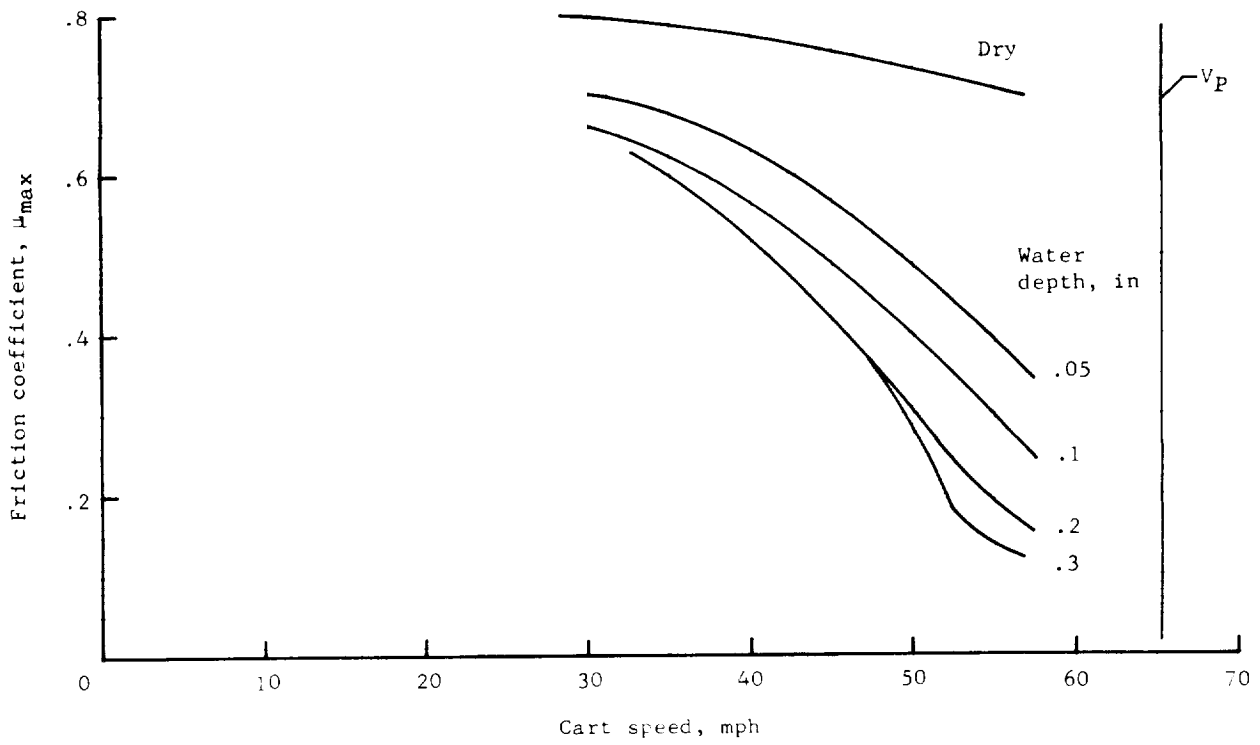


Figure 22.- Effect of water depth on runway on maximum braking friction coefficient. Langley landing loads cart test; 6.70-15 automobile rib tread tire; $p = 40$ lb/sq in.; slip, 0.125. (Data obtained from ref. 5.)

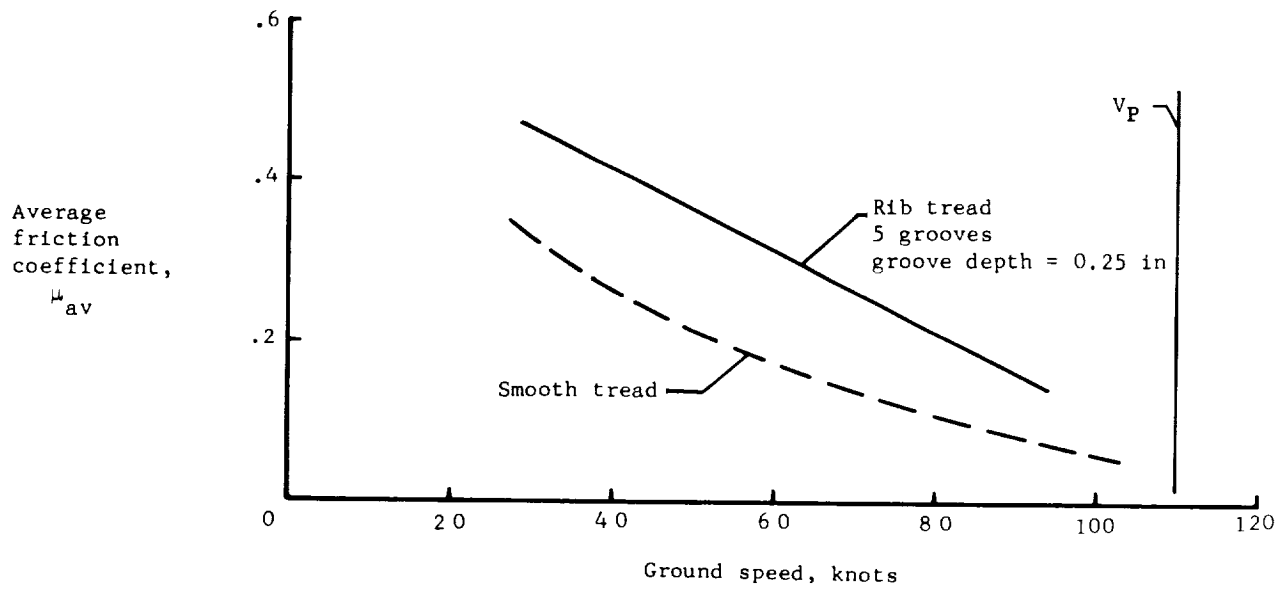


Figure 23.- Loss of aircraft tire traction under partial hydroplaning conditions. 32 x 8.8 aircraft tire; water depth \approx 0.3 inch (from Langley landing loads track tests); vertical load \approx 10,500 lb; $p = 150$ lb/sq in.

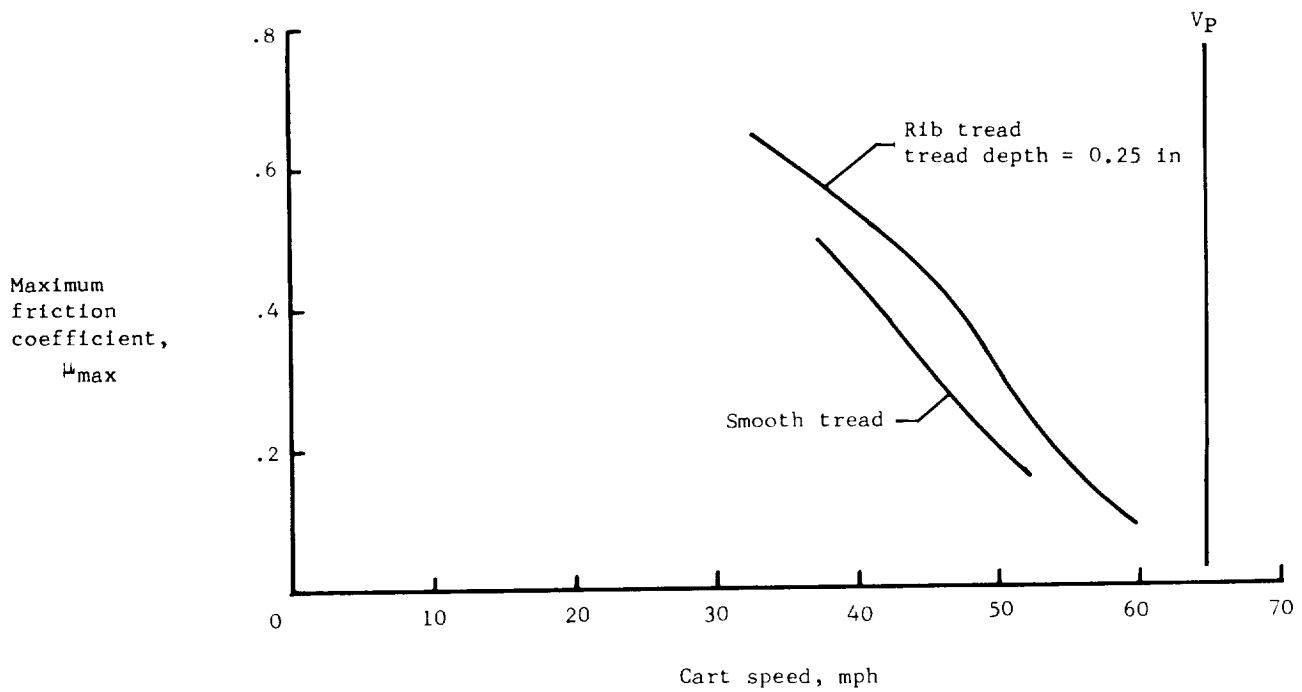


Figure 24.- Loss of automobile tire traction under partial hydroplaning conditions. 6.70-15 4-ply automobile tire; water depth = 0.3 inch (from braking trailer, ref. 5); vertical load = 925 lb; $p = 40$ lb/sq in.

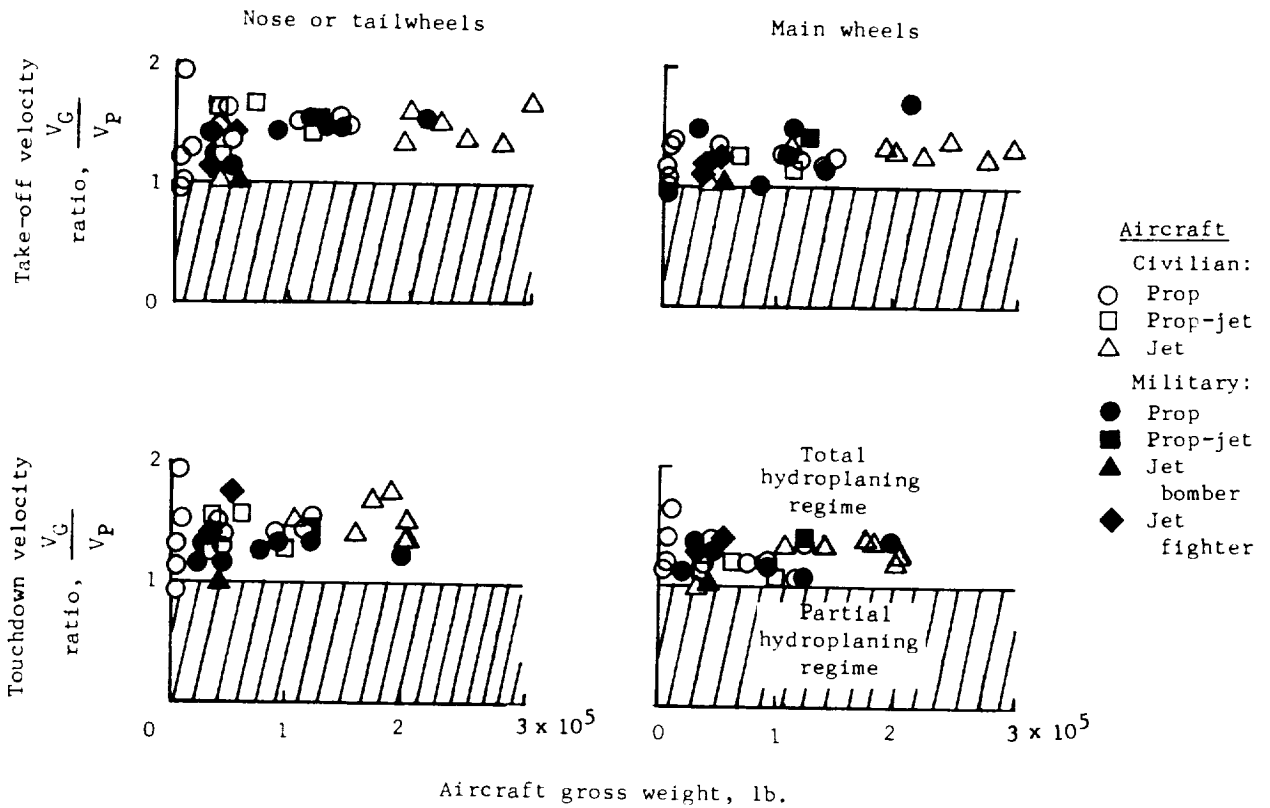


Figure 25.- Susceptibility of current aircraft to hydroplaning. (Data obtained from ref. 13.)

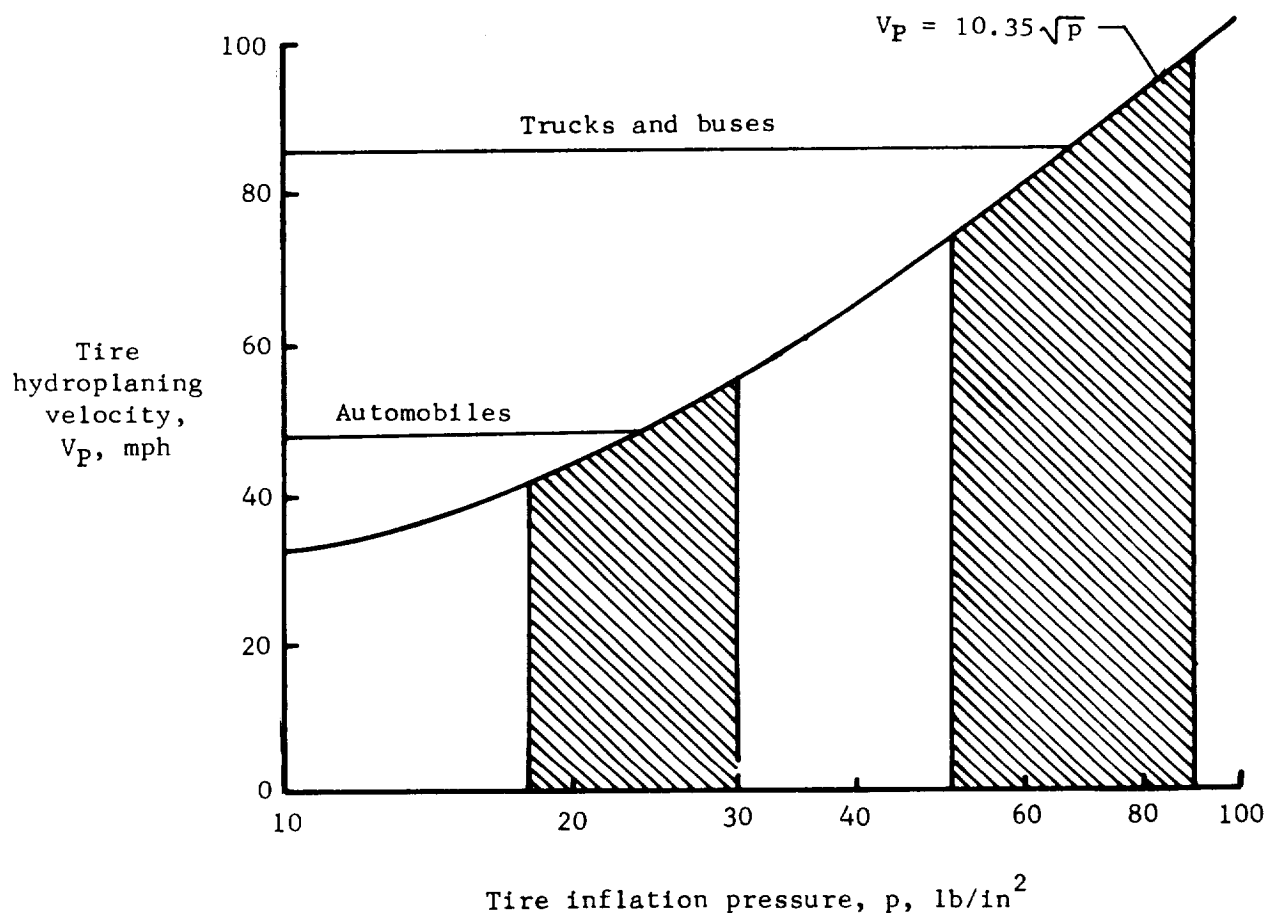


Figure 26.- Susceptibility of some ground vehicles to hydroplaning.

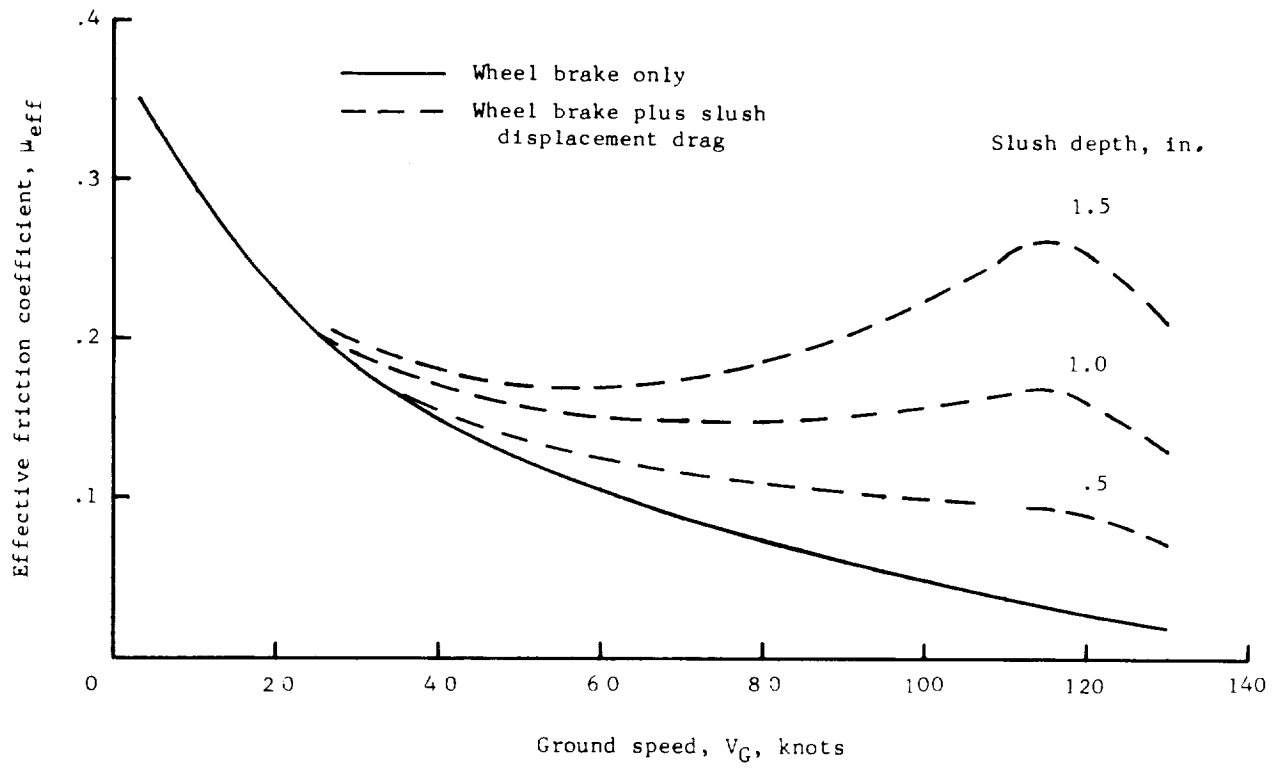


Figure 27.- Jet transport braking in slush. (Data obtained from ref. 10.)

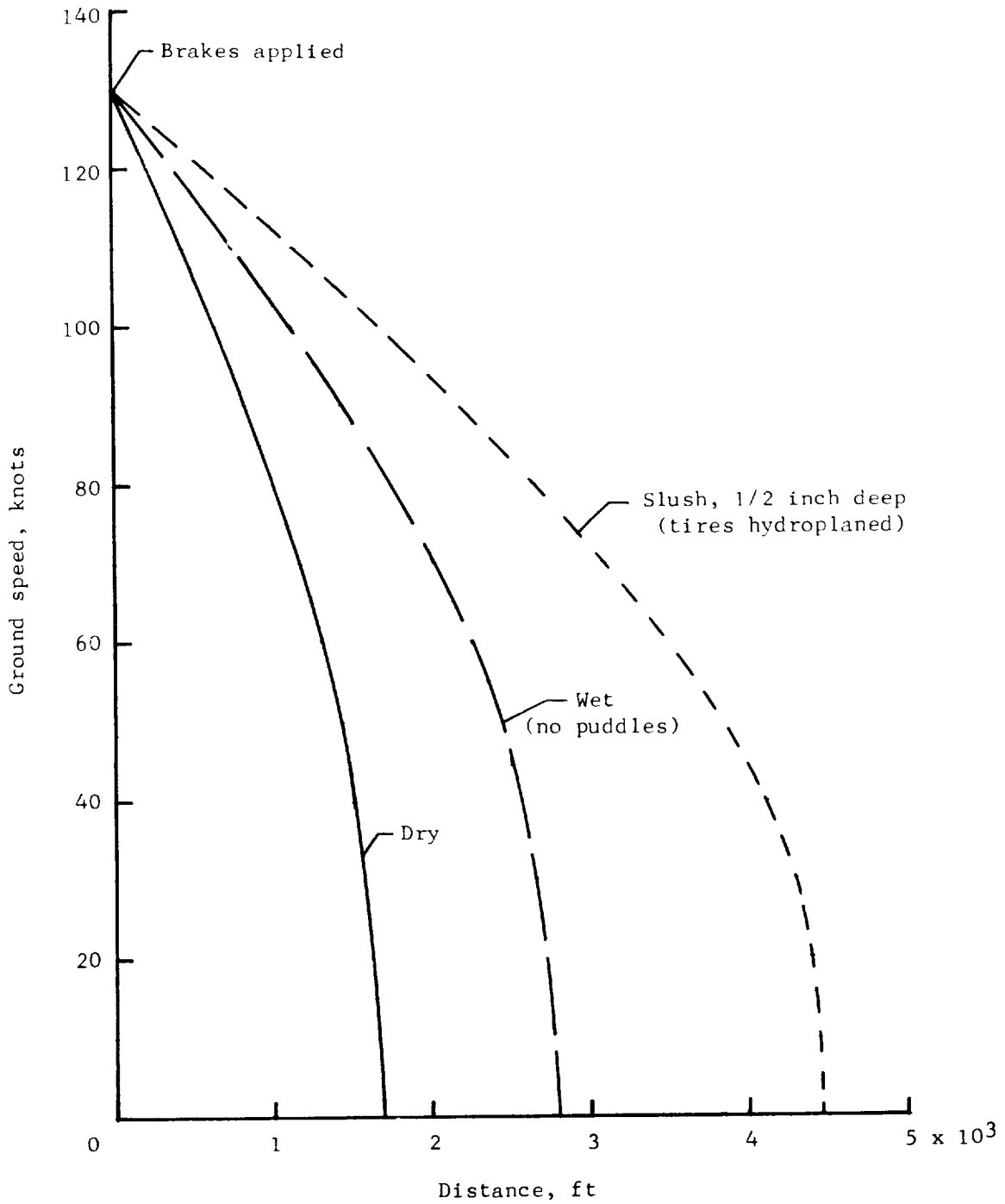
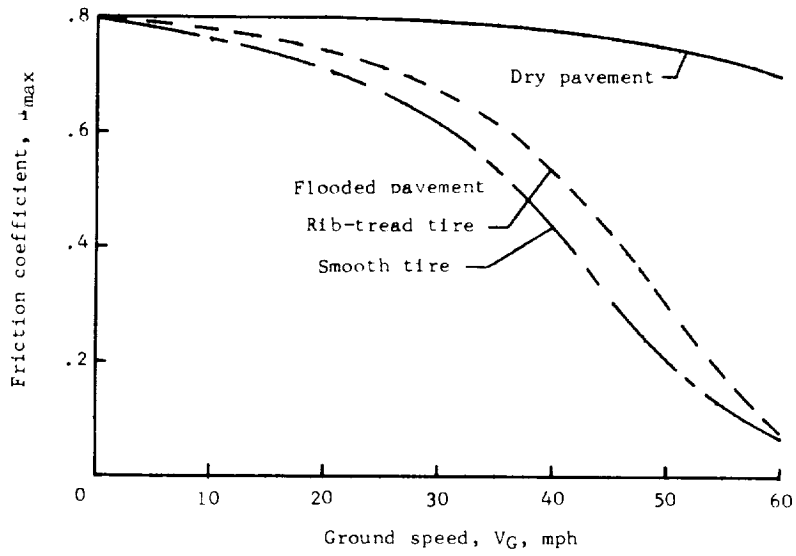
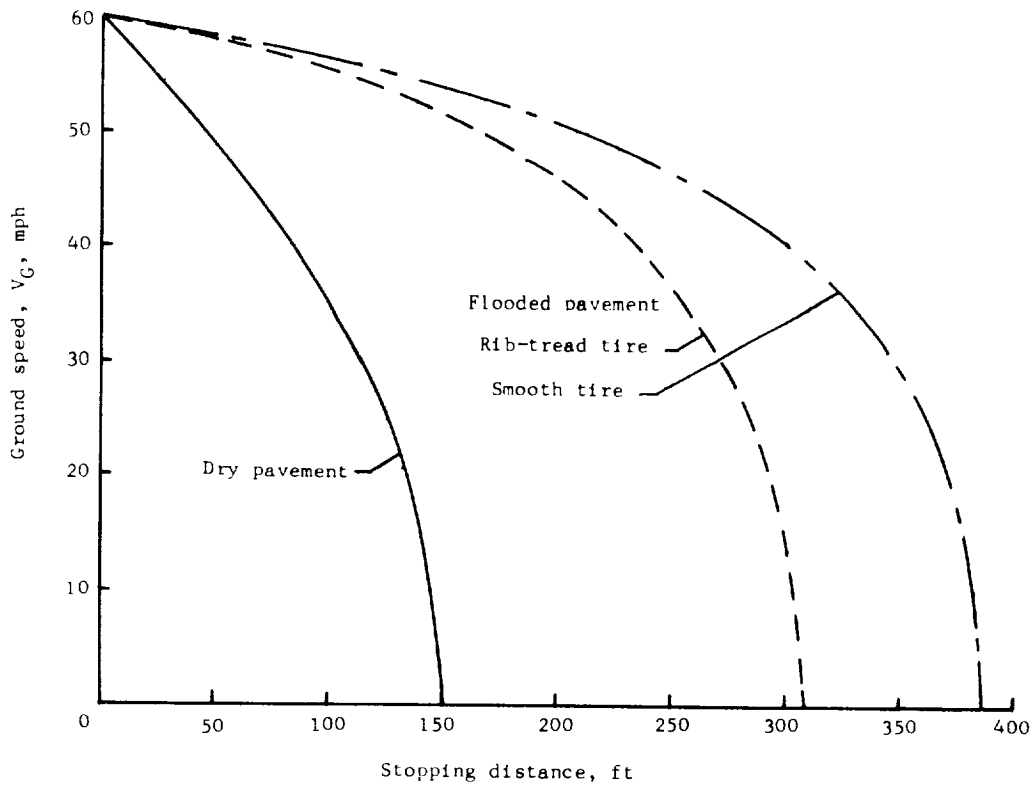


Figure 28.- Effect of concrete runway surface condition on stopping distance for a four-engine jet transport. Data obtained from reference 10; gross weight = 150,000 lb; tire pressure = 150 lb/sq in.; anti-skid braking; thrust reversers not used.



(a) Assumed friction-coefficient variation for stopping distance calculations.



(b) Calculated automobile stopping distance on dry and flooded pavements.

Figure 29.- Calculated increase in automobile stopping distance when tires hydroplane on flooded pavements based on assumed friction-coefficient variation.

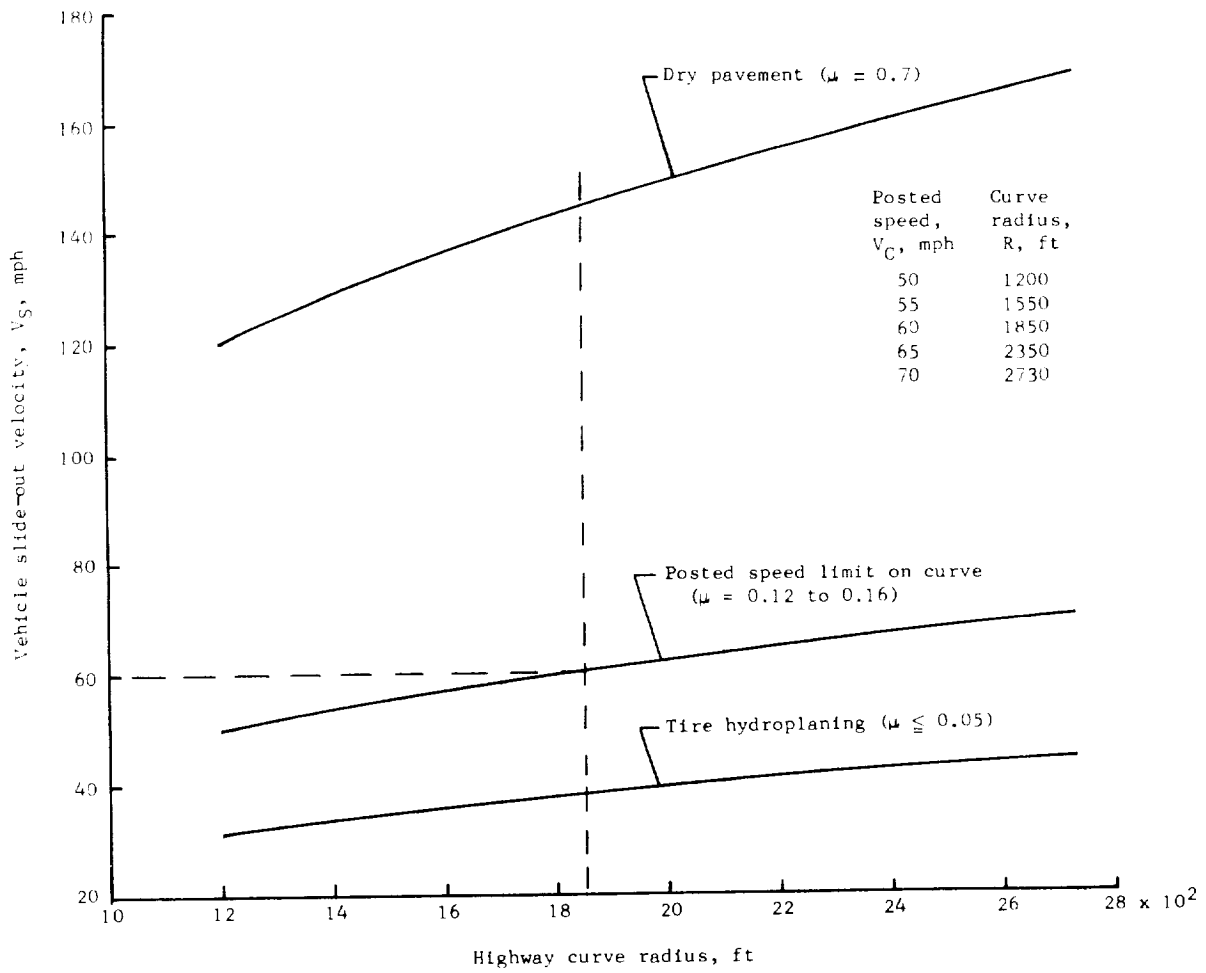
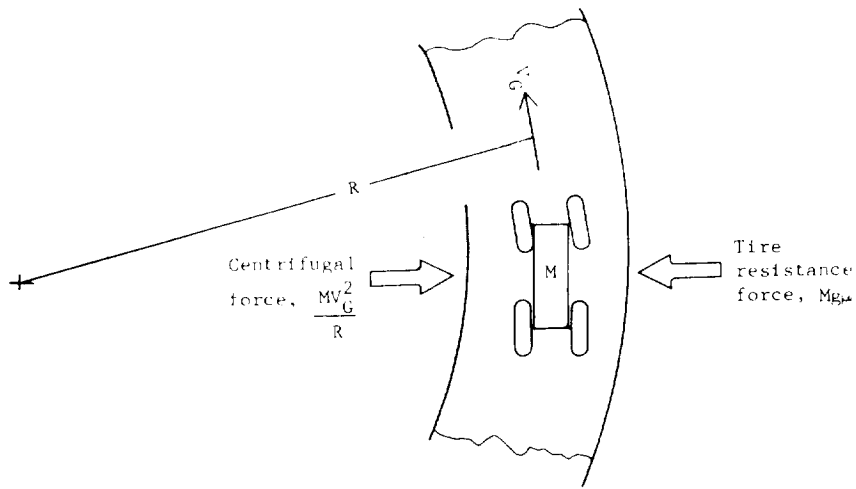
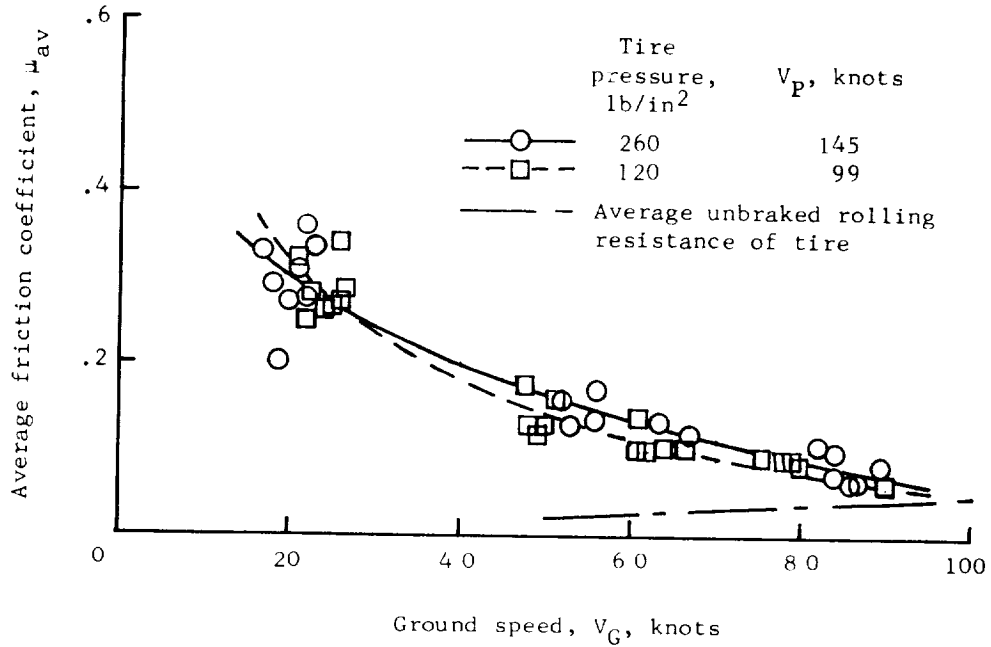
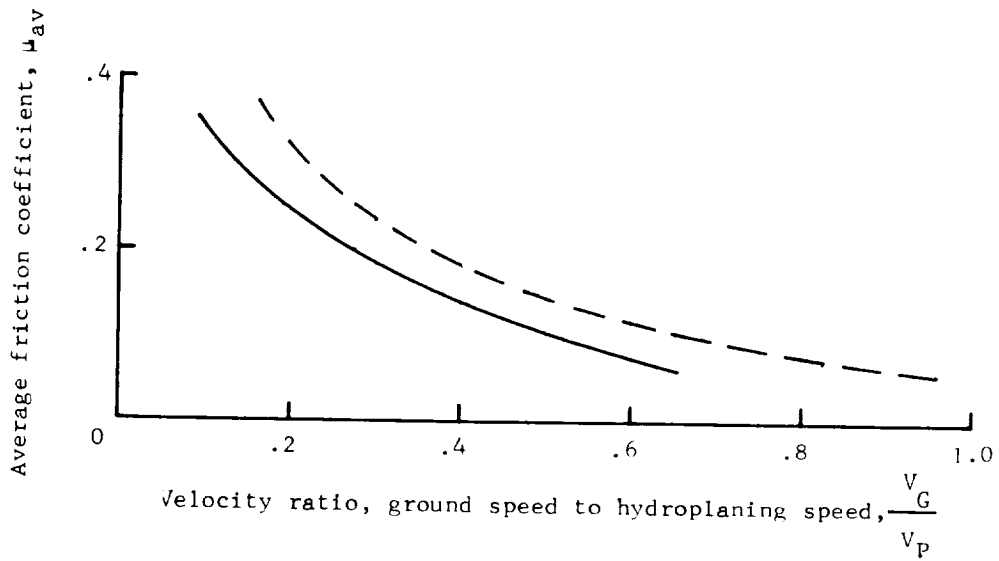


Figure 30.- Ability of ground vehicles to negotiate unbanked highway curves.

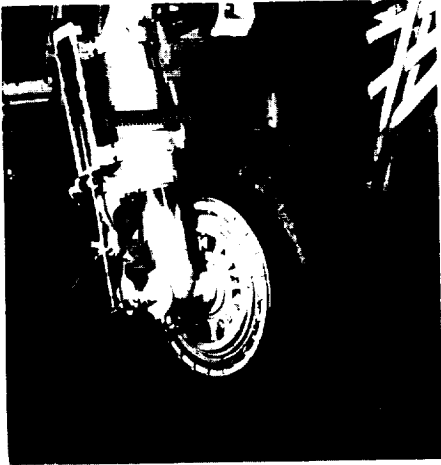


(a) Variation of average friction coefficient with ground speed.



(b) Variation of average friction coefficient with velocity ratio.

Figure 31.- Loss in braking traction occurring to smooth tread tire on smooth wet concrete runway. Data obtained from reference 11; 32 x 8.8 Type VII (Tire S1); F_V = 10,000 lb; water depth = 0 to 0.3 inch.



Test aircraft tire: 44x13 Type VII, rib tread.



Test membrane: T-12, nylon coated with neoprene, smooth surface; 0.048 inch thick

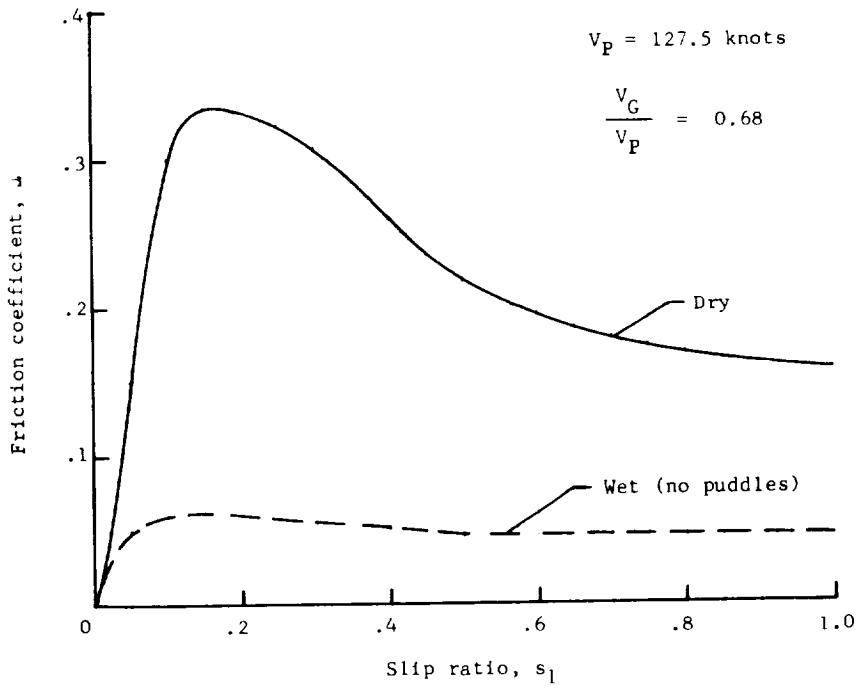


Figure 32.- Loss in braking traction suffered by rib tread tire on smooth wet membrane surface placed on top of concrete runway. Data obtained from reference 6; $V_G = 86$ knots; $F_V = 20,400$ lb; $p = 200$ lb/sq in. 63-9240

