Traction of an Aircraft Tire on Grooved and Porous Asphaltic Concrete

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ABSTRACT

The Federal Aviation Administration is engaged in an experimental program to determine the effectiveness of various surface treatments to eliminate aircraft hydroplaning when landing on wet runways. The surface treatments included saw-cut grooves, reflex-percussive grooves, and porous friction overlays in the asphaltic concrete runways. Experiments were conducted on a 1.25-mile long track that included a 300-ft test bed containing concrete with 40-ft sections of various surface treatments. Test speeds between 70 and 150 knots were achieved by the use of a jet-powered pusher car that also supported a dynamometer and tire-wheel assembly. The test tire was similar to one that is used on a Boeing-727 aircraft. The results showed that the porous friction overlay, the reflex-percussive grooves, and the saw-cut grooves of various spacing provided similar friction levels under wetness conditions that were either "wet" or "flooded." However, for the "puddled" condition (intermediate wetness between wet and flooded), the saw-cut grooves spaced at 1.25 in. provided the maximum improvement in friction level over a nongrooved or nontreated surface. Thus, although hydroplaning is delayed to a speed higher than 150 knots for all the surface treatments included in the program, the selection of a particular type of surface treatment can be based on whether the rainfall intensities in a region create predominantly wet, puddled, or flooded water conditions on the runway.

The total distance required for bringing a landing aircraft to a complete stop can fluctuate widely, depending upon the friction level available at the tire-runway interface. When this interface is dry, the friction level is high and the aircraft can be brought to a stop quickly; however, the presence of water at the interface reduces the available friction level significantly, and results in hazardous conditions that can cause overrun and hydroplaning.

Runway grooving has been recognized as an effective means of minimizing the danger of hydroplaning. The grooves provide escape paths for water from the tire-runway interface during the passage of the tire over the runway. Runway grooves are usually cut by diamond-tipped rotary blades. Various groove configurations have been used on the runways; however, square grooves of 0.25 in. at groove-spacing between 1 and 1.5 in. have been widely used. Recently, a few runways have been grooved at a spacing of 3 in. Other reportedly effective methods of surface treatment include porous friction overlays and grooving by the reflex-percussive cutting process.

The grooves provided by the reflex-percussive cutting process are still in an experimental stage; however, their cost-effectiveness has been demonstrated by the Federal Aviation Administration (FAA) in the portland cement concrete (PCC) surface by full-scale tire tests under controlled dynamic conditions (1). Because 80 percent of all the runways in the United States are of asphaltic concrete construction, it is important to evaluate the effectiveness of these experimental grooves cut in asphaltic concrete. It is also necessary to determine the relative braking performance of an aircraft tire, under controlled dynamic conditions, on saw-cut grooves cut in the asphaltic concrete surface, particularly in the absence of any such investigation in the past. Full-scale aircraft tests have been conducted on asphaltic concrete surfaces by the National Aeronautics and Space Administration (NASA); however, groove-spacing was not a variable in that study. A direct comparison of the reflex-percussive grooves, saw-cut grooves, and porous friction overlay in asphaltic concrete is the primary objective of this paper. It is expected that such a comparison will provide information about a cost-effective surface treatment for asphaltic concrete runways.

HYDROPLANING AND GROOVING

Aircraft Tire Hydroplaning

The magnitude of the coefficient of friction is influenced by many parameters. The important ones are: speed of operation, water depth, runway surface texture and drainage capacity, condition of tire tread, and the characteristics of the braking system. In general, an aircraft experiences an increase in available friction on a water-covered runway as it is decelerated by the action of brakes. A high level of available friction at the start of the deceleration process will provide better braking and directional control; a low level of available friction at the start of the deceleration process will adversely affect the braking and directional control of the aircraft. A complete loss of braking and directional control results when the available friction at the tire-runway interface approaches zero. Such a condition exists when the aircraft encounters the state of hydroplaning.

Hyroplaning is a peculiar tire-to-runway condition where the aircraft tire is physically separated from the runway surface by a layer of water that supports the aircraft weight by developing hydrodynamic and viscous pressure within the water layer. Hydrodynamic and viscous pressures are associated with fluid density and fluid viscosity, respectively. Thus, when runways are flooded with water, fluid density effects cause predominantly dynamic hydroplaning, whereas the fluid viscosity effects that cause viscous hydroplaning are predominant when smooth runways are covered with only a thin film of water. In all cases of water-covered runways, however, both effects are present to some degree.

In dynamic hydroplaning, the buildup of hydrodynamic pressures in the tire-runway interface causes inward buckling of the tire surface. The space so created between the tire and the runway is filled with water. A relief in fluid pressures is necessary to regain contact between the aircraft tire and the runway surface for developing higher friction forces for effective braking action and directional control of the aircraft. Partial relief in the hydrodynamic pressures can be obtained by cutting circumferential grooves on the aircraft tire and transverse grooves in the runway surface; grooves of various shapes and sizes can be designed for optimum braking performance. Transverse runway grooves provide a longer-lasting solution to alleviating hydroplaning than the circumferential grooves on the aircraft tire.

In viscous hydroplaning, a thin film of water separates the tread rubber from the aggregate and binder of the runway surface. The deformation of the tire surface within the tire-runway interface is not as large as in dynamic hydroplaning. For an intimate contact to occur between the tire tread rubber and aggregate material, fine-scale asperities (or microtexture) in the aggregate material are desirable. These asperities can break through the thin water film and relieve the viscous pressures.

Runway Grooving

Grooves are small channels of geometrical cross-section cut into the runway surfaces usually by means of diamond-tipped rotary blades. A square cross-section is the most widely used shape for the grooves; however, other promising designs have been investigated by researchers (1).

Pavement grooves were introduced by the British (2) and have been investigated by NASA (3) and the FAA (4). The basic objective of the NASA investigation had been to determine the groove configuration that provided the best cornering and braking performance under wet operating conditions. Investigating various groove widths and depths and three groove spacings (1 in., 1.5 in., and 2 in.), NASA concluded that all groove configurations provided improved cornering and braking performances relative to nongrooved surfaces; however, 0.25-in. square grooves spaced 1 in. apart provided the greatest increase in available friction (3). Based on these and further tests by NASA (5), the FAA has recommended (6) a standard groove configuration of 0.25-in. depth x 0.25-in. width x 1.5-in. spacing and has encouraged airport operators, managers, and owners to groove runways where the possibility of hydroplaning exists. However, many runways remain nongrooved. The major deterrents to the use of runway grooves are the high cost of grooving by the conventional saw-cutting method and the availability of only limited evidence as to the effectiveness of the grooved surfaces at the touchdown speeds of jet aircraft.

In its efforts to find a cost-effective groove configuration for the runways, the FAA completed a test program on PCC in 1981 (4). The study compared the braking performance of an aircraft tire on the reflex-percussive grooves and on the conventional saw-cut grooves. The general conclusion was that the conventional saw-cut grooves, spaced up to 3 in., will provide acceptable braking performance to an aircraft on water-covered runways, and that the cost of installation of grooves at 3-in. spacing can be up to 25 percent less than that of the grooves spaced at 1.25 in. (7). It also concluded that the braking performance on reflex-percussive grooves (spaced at 4.5 in.) was equivalent to that on conventional saw-cut grooves spaced at 2 in., and that the installation cost of the reflex-percussive grooves could be as low as one-half the cost of conventional saw-cut grooves spaced at 1.25 in. However, this information requires verification on asphaltic concrete surfaces. In addition, other promising methods of groove installation or surface treatments should be continuously investigated.

Grooving, Drainage, and Hydroplaning

The improved braking performance of an aircraft on a grooved runway is the result of a dual process of water removal from the tire-runway interface. First, the grooves influence the surface water drainage (runoff) by providing channels through which water can flow freely. How an increase or decrease in the groove-spacing influences the drainage is a subject not clearly understood. However, results from an analytical study (8) show that a decrease in water depth occurs with decreasing spacing for the saw-cut grooves of square cross section. Second, the grooves provide forced water escape from the tire-runway interface when the aircraft travels on a water-covered runway. Because the maximum amount of water that can be removed from the runway in a given time 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 interface. Being laminar in nature, the free flow is enhanced if the groove channels are smooth; forced water escape is essentially turbulent and requires 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 interface.

Effectiveness of grooving in providing forced water escape is influenced by the amount of water on the runway and the speed of the aircraft. As mentioned earlier, runway grooves can provide relief in the hydrodynamic pressure developed within the tire-runway interface. Because fluid pressures are predominantly hydrodynamic when runways are flooded, grooves will be very effective on these runways. On the other hand, when the runways are covered with only a thin film of water, where predominantly viscous pressures are developed within the tire-runway interface, grooves are less effective than the sharp-textured aggregates in the runway surface because the pressure relief is accomplished by sharp aggregates breaking the thin water film between the tire and the runway. In the intermediate condition, between thin film and flooding, both grooves and sharp-microtexture aggregates are desirable.

TESTING APPROACH

The measurement of hydroplaning of an aircraft tire is a complex problem that involves simulating the braking operation of an aircraft tire on a wet or flooded runway. The coefficient of friction, as computed by dividing the tangential forces developed at the tire-runway interface by the vertical load on the tire, determines the relative performances of the surfaces tested. As the coefficient of friction decreases, so does the braking capability. In the limiting case, when the coefficient approaches zero, hydroplaning is said to occur. However, the friction coefficient cannot be equal to zero because of the presence of small viscous and hydrodynamic drag forces (at the tire-runway interface), which are difficult to measure accurately. Thus, a direct measurement of the speed at which hydroplaning occurs is difficult. Various indirect methods have been used in the past (9) to identify the onset of hydroplaning. In the present study, incipient hydroplaning is indicated when the measured coefficient of friction is 0.05 or lower. In comparison, the average coefficient of friction between the aircraft tire and the dry runway is approximately 0.7.

Fractional forces are developed as a result of relative motion between two surfaces; the tire-runway combination is no exception. It is well-documented that as the tire slips in the contact area, a progressively increasing friction coefficient is developed. Tire slip is an indication of the departure of the angular velocity of the braked tire from the free-rolling velocity. Thus, a locked tire represents 100 percent slip whereas a free-rolling tire is under no slip. A slip of between 10 and 20 percent has been identified as the value beyond which the coefficient of friction starts to decrease. This behavior is more pronounced when the tire-runway interface is dry. For wet interfaces, the coefficient of friction remains level over a wide range of slip value; this makes it more difficult to determine the maximum value of friction coefficient under wet interface conditions. There are two methods by which a meaningful comparison of various surface treatments can be accomplished: (a) measurement of coefficient of friction when the tire is locked and slides over the test surfaces, or (b) measurement of maximum available value of the coefficient of friction on each test surface. The present study uses the second method, even though it requires many more tests than the first method.

The disadvantage with the first method is an accelerated treadwear of the tire that may require frequent tire changes; danger of tire blowout is also present in the first method. The advantage with the second method is that it represents a realistic simulation of the braking process of an aircraft. To obtain the maximum coefficient of friction available for a given set of speed, water depth, and surface type (treatment), multiple tests were performed. The first test was conducted at a relatively low brake pressure to assure that wheel lock would not occur. Subsequent tests were conducted at gradually increasing brake pressures. In each test, the magnitudes of the coefficient of friction and tire slip were monitored. Initially, both the coefficient and the slip increased with increasing brake pressure. Later on, a drop in the coefficient or sudden increase in the slip indicated that the maximum value of the coefficient of friction had been obtained in the previous test. This procedure was followed throughout the test program. To eliminate undesired sliding of the test tire, automatic brake release was initiated just beyond the test section in question.

EXPERIMENTAL PROGRAM

Test Facility and Equipment

The experimental program was conducted at track No. 3 of the Naval Air Engineering Center, Lakehurst, New Jersey. The track is 1.25 miles long and has guide rails spaced 52.25 inches apart running parallel to the track centerline. The last 300 feet of the track were used for installing the test bed over the existing PCC surface. The test bed was 2.25 in. thick and 30 in. wide and was made of asphaltic concrete. An aircraft arresting system is located beyond the test track to recover the test equipment at the completion of a test run.

The major components of the test equipment are: the four-wheeled jet car, the dead-load carriage, which supports the dynamometer and wheel assembly, and the measuring system. The jet car (Figure 1) is powered with four J48-P-8 aircraft engines developing a total thrust of 24,000 pounds. The jet car is used to propel the dynamometer and wheel assembly and the carriage from the launch end at a preselected speed. The jet car is disengaged after the test speed is attained, and the dynamometer assembly and the carriage are allowed to coast at this speed into the test bed.

The dynamometer and wheel assembly was designed and fabricated by the FAA and is capable of simulat-

FIGURE 1 Jet-powered pusher car for providing preselected speed to test equipment.

ing a jet transport tire-wheel assembly under touchdown and rollout conditions. The dynamometer is similar in design to one developed by NASA for the Langley Test Facility (10). Figure 2 shows the dynamometer and wheel assembly and the details of the instrumentation for measuring vertical and horizontal loads at the axle. The dynamometer is instrumented to measure the vertical load on the tire, the horizontal force developed at the tire-runway interface, the angular velocity of the test tire, and the vertical motion of the dynamometer assembly relative to the dead-load carriage.

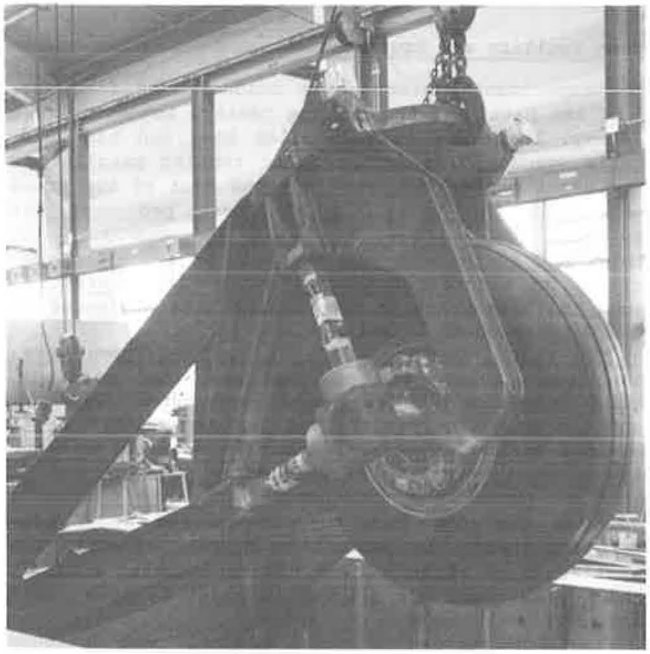

FIGURE 2 Dynamometer and wheel assembly showing vertical and horizontal load links.

FIGURE 3 300-ft test bed at the end of the test track.

Test Sections

The 300-ft test bed (Figure 3) at the end of the track was divided into seven 40-ft sections following a 20-ft section. The 20-ft section was intended for ensuring proper approach of the test wheel into the test section. The dimensional tolerance of the test surface was held within 0.031 in. from horizontal level throughout the test bed.

Various surface treatments installed in the test bed are shown in Figure 4. Section 2, which is not shown in the figure, contained reflex-percussive grooves having the same dimensions as those in the PCC surface that was tested earlier (1); section 1 contains reflex-percussive grooves with different dimensions (Figure 5).

The original grooves have a V-angle of 13 degrees and a groove spacing of 4.25 in. The new configuration has a 20-degree V-angle and the spacing is reduced to 3 in. The flow area per unit length for the two configurations is approximately equal. This is the first improvement to the reflex-percussive grooves originally developed by Klarcrete Limited, London, England and Ontario, Canada; however, other changes may be required to develop an optimized geometry. The square grooves of 0.25-in. size were spaced at 1.25 in., 2 in., and 3 in. between centers. Typical dimensions of the saw-cut grooves are shown in Figure 5.

The plastic state grooving technique refers to grooving PCC while it is still in an uncured plastic state. Use of a ribbed vibrating float constructed on a bridge spanning the pavement width, and use of a roller with protrusions, or ribs, which form the grooves in the plastic concrete are two methods used in the United Kingdom and the United States (6). Another method uses steel combs of various dimensions and tine spacing to form a groove-like texture in the plastic concrete pavement. The grooves are approximately 0.125 x 0.125 in., spaced at 0.5-in. intervals center-to-center. The configuration provided in section 6 (Figure 4) has the groove dimensions of the wire comb technique.

The porous friction course was installed in section 7 (Figure 4). Porous friction course is a thin asphaltic concrete overlay about 0.75-in. thick characterized by its open-graded matrix. It consisted of a 0.5-in. maximum size aggregate mix.

Test Parameters

The following is a summary of the test parameters investigated in this research:

Tire Parameters	
Vertical load	: 35,000 lb
Inflation pressure	: 140 lb/sq in.
Tread design	: Worn and treaded 6-in. groove
Tire size and type	: 49 x 17, 26 ply, type VII
Pavement Parameters	
Type of surface	: Asphaltic concrete
Microtexture	: 0.014 nongrooved surface; grease smear test
Types of surface	: Saw-cut grooves, reflex-percussive

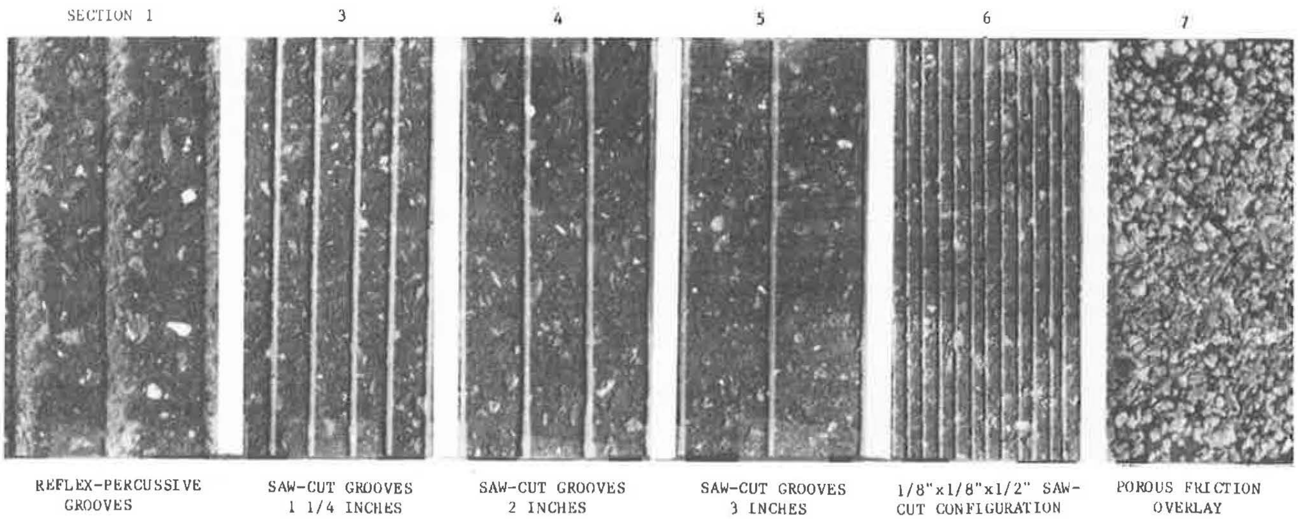

FIGURE 4 Various test sections of the 300-ft asphaltic concrete test bed (each section is 40 ft long).

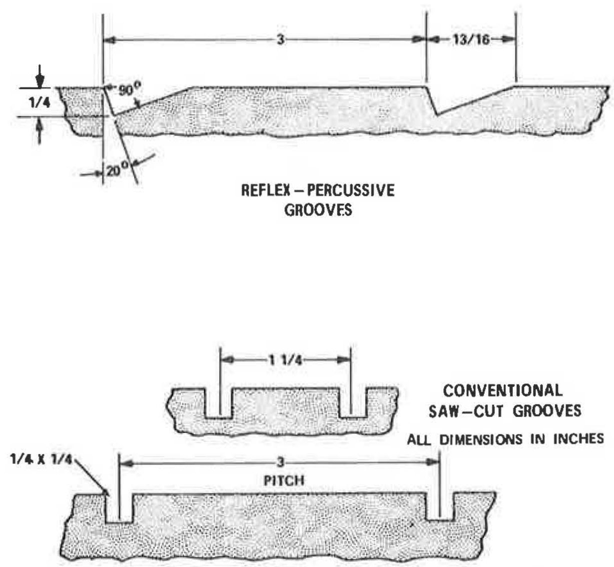

FIGURE 5 Dimensions of reflex-percussive grooves and conventional saw-cut grooves.

Treatment	: V-grooves, porous friction overlay
Groove spacing	: Saw-cut grooves 0.25-in. square: 1.25-in., 2-in., 3-in. spacing 0.125-in. square: 0.5-in. spacing Reflex-percussive V-grooves: 20° groove angle, 3-in. spacing
Environmental Parameters	
Average water depths	: Less than 0.01 in.-wet 0.10 0.01 in.-puddled 0.25 0.01 in.-flooded
Operational Parameters	
Wheel operation	: Rolling to locked
Brake pressure	: 200 lb/sq in.-2,200 lb/sq in.
Speeds	: 70 knots to 150 knots

Test Procedure

The dynamometer assembly, with mounted tire, was positioned at the launch end for the tests. A complete braking test consisted of the following steps:

1. Desired water depth was obtained on the test sections at the recovery end.
2. The jet engines were started at the launch end and set at the performance level to provide the preselected speed in the test section.
3. The jet car was released to propel the test equipment (dead load and dynamometer carriage). The test tire remained in a free rolling state during this maneuver.
4. The jet car was braked and separated from the test equipment several hundred feet ahead of the test bed. This allowed the dead load and dynamometer to enter the first test section at the preselected speed. The test speed in the remaining sections were within 1 to 2 knots of the speed in the first section as computed from the analog traces.
5. Before the dynamometer assembly entered the first test section, the hydraulic systems were activated to apply the vertical load and brake pressure on the tire. (The magnitude of each was preselected.)
6. The wheel entered the test sections at preselected test conditions. The instrumentation was activated and the data were recorded.
7. As the wheel left the test bed, unloading and brake release were initiated and the test equipment was recovered by the use of arresting cables.

Data Collection and Analysis

The results on the asphaltic concrete surfaces are given in Table 1. The coefficients of friction in this table represent the maximum available under each set of operating conditions; many more tests were conducted to obtain this maximum. A least-square fit was obtained between speed and coefficient of friction. A second order fit was found satisfactory because of a small scatter of data.

DISCUSSION

Braking Performance

Wet runway surfaces are normally encountered during or after a light or moderate rain. These surfaces

TABLE 1 Coefficient of Friction–Speed Relationships

Surface Treatment	Wet Surface Speed, Knots	Wet Surface Friction Level μ x 100	Puddled Surface Speed, Knots	Puddled Surface Friction Level μ x 100	Flooded Surface Speed, Knots	Flooded Surface Friction Level μ x 100
Nongrooved	44	34	33	31	33	32
(worn tire)	54	31	55	23	57	22
	90	26	70	18	68	16
	125	20	90	14	90	12
	151	18	110	11	110	10
			130	8	133	8
			143	5	143	4
Nongrooved	54	40	42	38	42	40
(new tire)	70	37	54	29	54	30
	90	33	72	25	72	26
	108	30	90	24	90	16
	131	24	108	16	110	13
	149	27	131	12	131	11
			149	6	149	5
Conventional saw-cut						
grooves	71	48	70	44	71	39
(worn tire)	109	49	110	21	90	24
	144	45	128	17	90	25
1.25-in. spacing	147	44			110	13
					128	10
					130	10
					147	10
2-in. spacing	72	46	66	41	70	39
	111	44	68	39	89	19
	144	40	106	19	90	20
			128	15	108	10
					110	10
					110	10
					128	8
					148	8
3-in. spacing	72	42	67	35	68	33
	112	39	72	35	70	33
	146	40	106	15	85	20
			128	9	86	20
			147	10	110	8
					128	8
					147	8
Reflex-percussive						
grooves	70	44	70	33	70	33
(worn tire)	90	41	111	15	86	20
	144	38	129	10	107	10
			147	9	129	8
					145	9
Plastic state grooves (0.125 x 0.125 x 0.5	73	48	72	34	72	30
in.)	109	39	110	14	90	23
	147	40	128	8	110	8
			147	9	130	9
(worn tire)					148	9
Porous friction course	73	49	—[a]	—[a]	72	33
	109	40			72	33
	147	43			90	19
(worn tire)					91	19
					130	9
					148	9

[a]No data.

may be saturated with water but would not have measurable water depth present on them. The puddled and flooded surfaces are representative of conditions that can be expected immediately after heavy rains of short and long durations, respectively.

On the wet nongrooved surface, a new tire performs better than a worn tire. Although predominantly viscous pressures are developed in the entire contact area of a worn tire, a more complex pressure distribution develops under a new tire; the viscous pressure under the tire groove is lower than under the rib. In addition, the water particles that try to escape (from the contact area of the worn tire) and cannot do so because of high tire side-wall pressures, find immediate relief in the circumferential grooves of the new tire. This results in a "drier" contact area and correspondingly a higher friction coefficient for the new tire (top solid line curve in Figure 6).

The data for the puddled and flooded conditions on a nongrooved surface (two bottom curves) show that the braking performance is significantly lower than for the wet surface (upper curves). The reduction in performance on puddled and flooded surfaces is due to the presence of hydrodynamic forces in the contact area, which along with the viscous forces have forced a partial separation of the tire from the runway surface. This effect is more pronounced at speeds in excess of 140 knots where conditions of imminent hydroplaning exist for both the new and worn tire.

When the wet runway surface is subjected to treatments included in this study, the braking performance of a worn tire is significantly better than

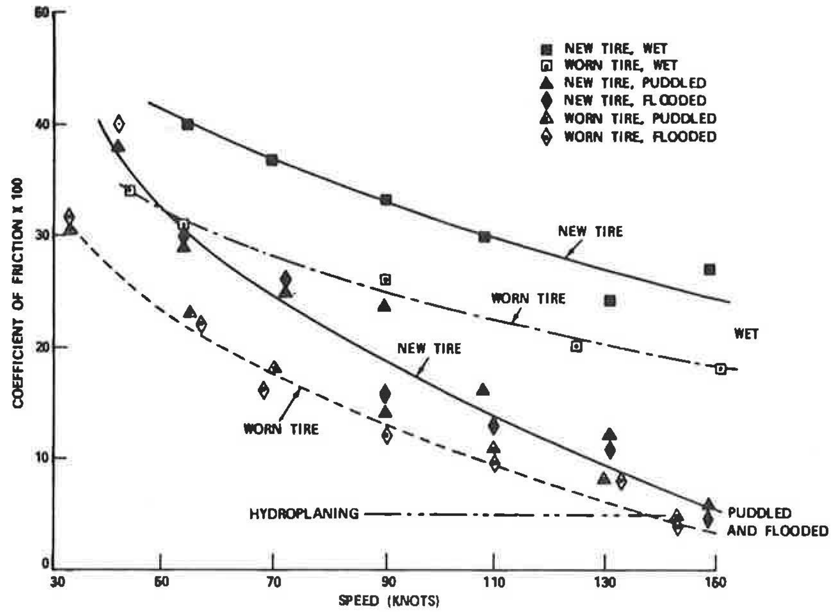

FIGURE 6 Braking test on nongrooved surfaces with new and worn tires.

on a nongrooved surface as shown in Figure 7. Even the performance of the new tire on a nongrooved surface is lower than that of the worn tire on treated surfaces. It should be pointed out that a single curve has been drawn for the performance of worn tires on all the treated surfaces. This choice is based on the high available friction level for all the treated surfaces for the entire range of test speeds.

The braking performance of the worn tire on puddled surfaces with saw-cut grooves is shown in Figure 8. Figure 8 shows that for the 0.25-in. square grooves, the spacing has a distinct effect on the available friction level: for a given speed, the larger the spacing, the smaller the value of available friction level. However, even with the largest groove spacing included in the test program (3 in.), the condition of hydroplaning is not reached within the speed range tested (70 to 150 knots).

The performance on the reflex-percussive grooves, and on 0.125-in. square saw-cut grooves is shown in Figure 9. A single curve adequately represents the average performance of the two treatments.

Figures 10 and 11 show the braking performance of a worn tire on flooded surfaces. In each case, a single curve shows the average performance on the surfaces tested.

Friction Coefficient and Stopping Capability

An interesting characteristic of the friction speed curve--its slope--in Figures 6, 8, 10, and 11 can provide additional information about the overall improvement the surface treatments have over nongrooved surfaces. The slope of the friction-speed curve is continuously decreasing for all the sur-

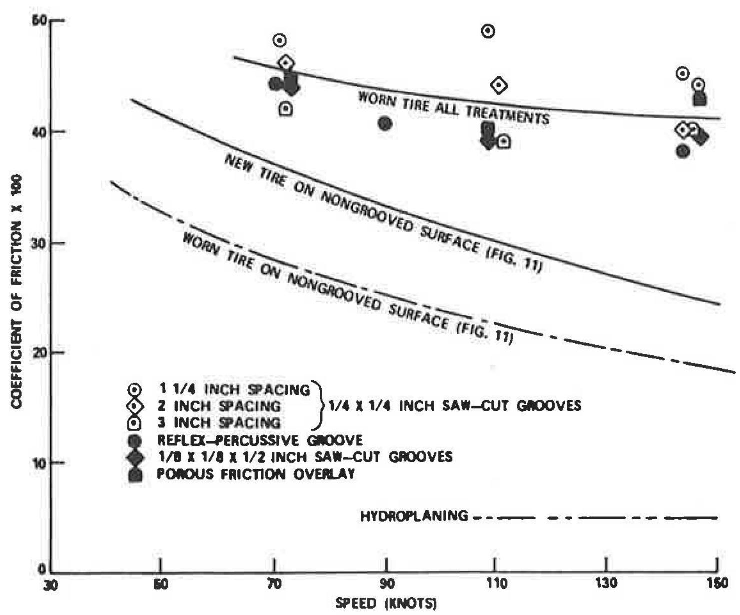

FIGURE 7 Braking performance of worn tire on wet surface.

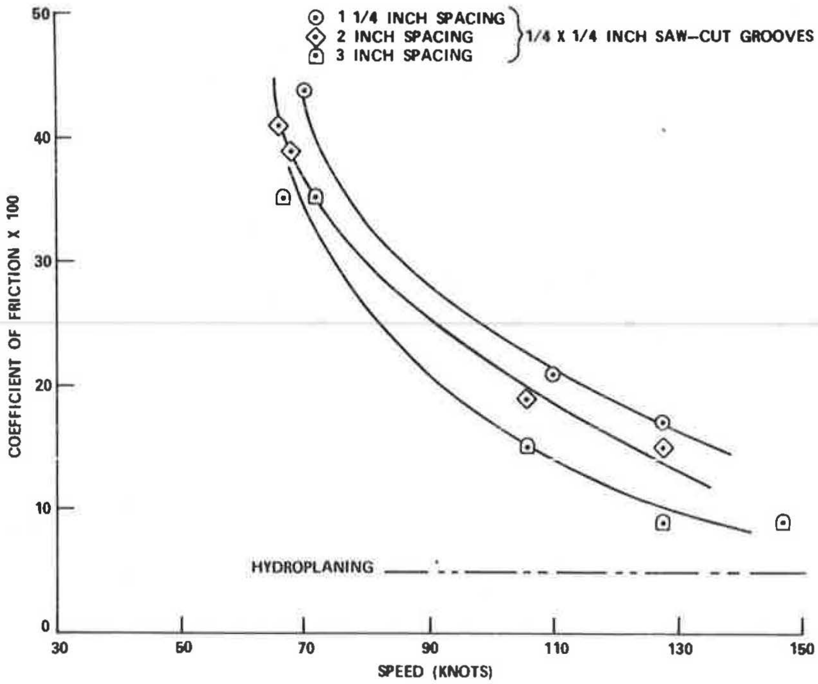

FIGURE 8 Braking performance of a worn tire on saw-cut grooves under puddled conditions.

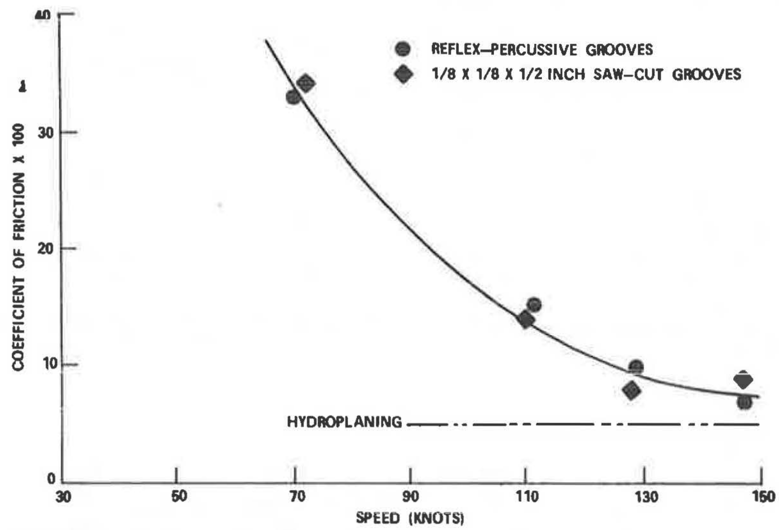

FIGURE 9 Braking performance of a worn tire on reflex-percussive grooves under puddled conditions.

faces--treated or nongrooved. However, although not enough data are available, Figures 8, 10, and 11 indicate that the slope is changing asymptotically beyond 140 knots and below 70 knots for treated surfaces. Thus, in a situation where a landing is attempted at a speed higher than normal, the wheel will not immediately experience friction levels corresponding to hydroplaning. Also, as the aircraft is being braked and going through successively lower speeds, it is encountering a gradually increasing rate of friction level change. This enables a shorter overall stopping distance. In comparison, the friction-speed curve for the nongrooved surfaces (Figure 6) uniformly decreases near the high speed end and a state of hydroplaing will exist should the landing speed be higher than normal.

Forced Water Escape

Water is forced out of the tire-runway interface when the tire travels on the runway. Escape of water takes place in all directions; however, a large amount of water escapes from the rear and the sides of the contact area between the tire and the runway.

Although this research did not include instrumentation to measure the water escape paths or the amount of water escaped, an attempt is made here to explain how the grooves help water escape. When a worn tire travels over a wet (0.01-in. depth) surface having grooves, the pressures in the contact area are predominantly viscous. Because only a small amount of water is present in the contact area, all

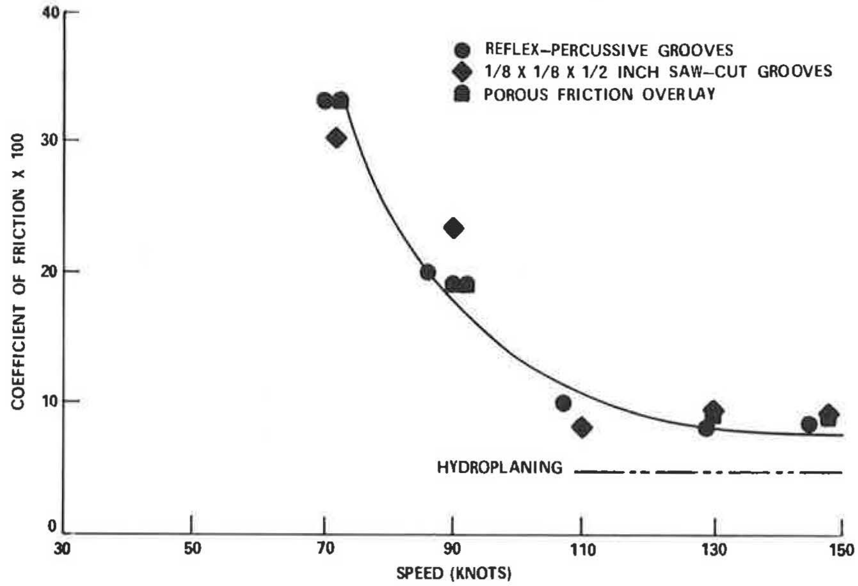

FIGURE 10 Braking performance of worn tire on saw-cut grooves under flooded conditions.

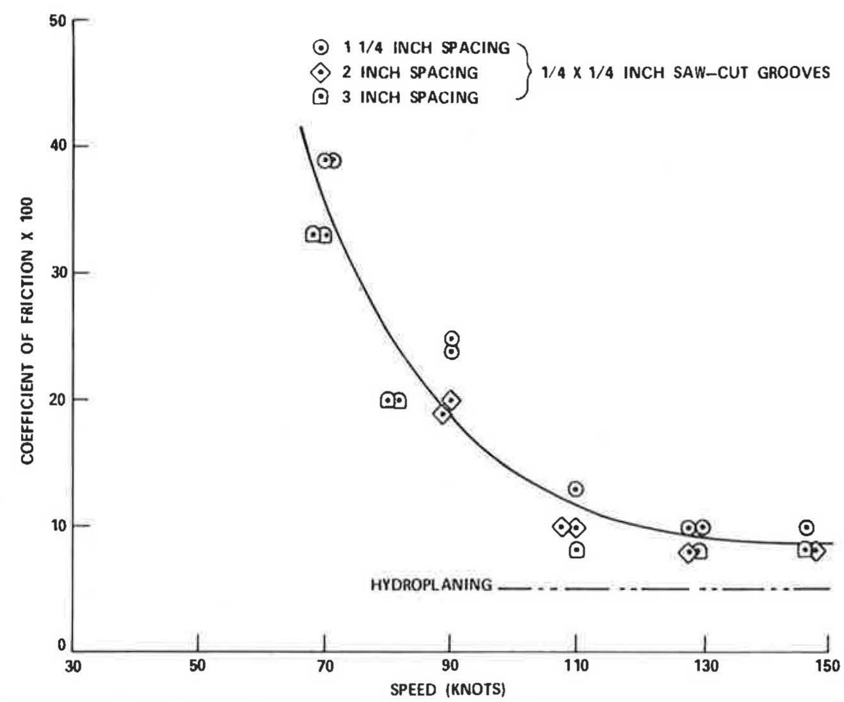

FIGURE 11 Braking performance of worn tire on reflex-percussive grooves and porous-friction course under flooded conditions.

of it is expelled through grooves. Thus, all the surfaces provide high friction levels as shown by the solid-line curve in Figure 12 (curve 1). The data scatter can be seen in Figure 7. But because the friction levels are high for the entire range of test speed, data scatter is irrelevant and all surface treatments (included in this study) will provide adequate safety in terms of stopping the aircraft quickly.

When the grooved surfaces are puddled, the hydrodynamic pressures become important. The additional water in the contact area must be removed to reduce the buildup of hydrodynamic pressures and to ensure high friction levels. When the grooves are spaced closer, water particles trying to escape through the rear of the contact area will find it easier to escape through the grooves and develop a drier contact area. However, a large spacing will be completely ineffective in forcing the water out of the contact area because it will simulate a nongrooved surface and the friction forces will approach a hydroplaning level as shown by curve No. 5 in Figure 12. An optimum condition would be when all the water is expelled from the contact area in such a way that the water-carrying capacity of the grooves is fully exhausted. This condition could be obtained by a certain combination of groove-spacing and the amount of water. Thus, for the same amount of wetness for

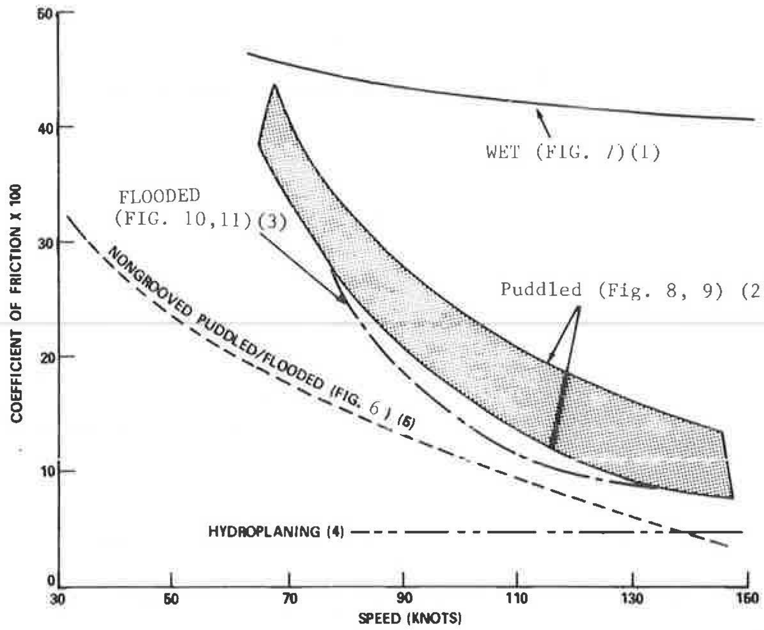

FIGURE 12 Comparison of all surface treatments under wet, puddled, and flooded conditions.

which the capacity of 3-in. spaced grooves is exhausted, the capacity of 1.25-in. spaced grooves will not be and these grooves will provide a drier contact. The results on puddled surfaces with grooves verify this phenomenon: curve No. 2 shows these results. The shaded area bounded by two lines shows the extent of the forced water escape as a function of groove spacing: The top boundary represents the 1.25-in. groove spacing and the bottom boundary represents the grooves spaced at 3 in.

The puddled condition in this study (water depth 0.10 in.) represents a water condition where groove-spacing is a factor in determining the maximum friction levels available. Clearly, the grooves at 1.25-in. spacing provide better braking action. However, the spacing of 3 in. will provide sufficient braking to allow a gradual reduction in speed to develop further braking. It should be noted that hydroplaning is avoided for all spacings.

When the grooved surfaces are flooded, the reduced groove spacing does not improve the available friction levels. It can be seen from curve No. 3 (Figure 12) that the available friction levels are slightly below the bottom of the shaded area for the puddled condition. Also, only a single curve represents the performance on all treated surfaces. For the flooded surfaces, the grooves are filled with water even before the passage of tire over them. Then, the inertia of water particles retards the escape of water in all directions when the tire does travel over the grooves. The result is that the available friction levels are insensitive to the groove spacing.

Saw-Cut Grooves, Reflex Percussive Grooves, and Porous Friction Overlay

For the asphaltic concrete surface under wet and flooded conditions, the reflex-percussive grooves, the porous friction overlay, the 0.125-in. x 0.125-in. x 0.5-in. saw-cut grooves, and the 0.25-in. square saw-cut grooves of various spacings perform alike in terms of available friction levels when a full-scale aircraft tire is braked on these surfaces. However, the spacing of the 0.25-in. square saw-cut grooves influence the available friction levels on "puddled" surfaces: The smaller spacing provides higher friction levels. The reflex-percussive grooves, the 0.125-in. x 0.125-in. x 0.5-in. saw-cut grooves and the 3-in. spaced saw-cut grooves provide similar results on puddled surfaces.

Because a previous study (4) has included the cost analysis of various grooving methods, it would be necessary in this study to accept those results. However, another cost analysis would be desirable to reflect new developments during the past several years. The previous study had shown that the saw-cut grooves spaced 3 in. apart in PCC could provide a cost savings of approximately 25 percent over the grooves spaced 1.25 in. apart. It also showed that the reflex-percussive grooves in PCC offer even higher cost savings: these grooves could cost as low as half the cost of saw-cut grooves at 1.25-in. spacing.

The reflex-percussive grooves need refinements to offer a cut as clean as in PCC. This may require a modified cutting head and a different impact frequency for the head. These changes may be necessary to compensate for the viscoelastic nature of asphaltic concrete surface. With proper modifications, the reflex-percussive cutting process would be a viable cost-competitive method to the saw-cut grooves. But, realistic cost estimates and full savings potential can only be affirmed after application of these grooves on an operating airport.

CONCLUSIONS

The following conclusions are drawn from the findings of this research. These conclusions are valid for asphaltic concrete surfaces and for the operating parameters included in the test program.

1. Where the seasonal and topographical conditions consistently produce puddled water conditions on the runways, the type of surface treatment has a significant influence on the braking performance of an aircraft tire. Although all the surface treat-

ments alleviate hydroplaning, the saw-cut grooves spaced at 1.25 in. provide the maximum values of friction levels.

2. Where the seasonal and topographical conditions consistently produce either wet or flooded water conditions on the runways, the type of surface treatment has an insignificant effect on the braking performance of an aircraft tire.

3. The reflex-percussive grooves (spaced at 3 in.), the porous friction overlay, and the saw-cut grooves spaced at 3 in. perform comparably at all wetness conditions, and all alleviate hydroplaning.

4. If performance were the only criterion for the selection of a surface treatment, it is only at those airports where seasonal and topographical conditions produce puddled water conditions that the choice of one treatment will be more beneficial than another. However, if performance were not the only criterion, any surface treatment could be selected based on cost, because all the treatments provide sufficient braking to allow a gradual reduction in the speed of the aircraft and thus develop further braking.

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