ICAS-84-5.3.2

HIGH SPEED BRAKING OF AN AIRCRAFT TIRE ON GROOVED WET SURFACES

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ABSTRACT

The United States' Federal Aviation Administration is engaged in an experimental program to determine the effectiveness of grooves and other low-cost surface treatments that alleviate hydroplaning. Ground test facility provides speeds of up to 150 knots by the use of a jet-powered pusher car that also supports a tire-wheel assembly. Boeing 727 aircraft tire is inflated to 140 pounds per square inch, and loaded vertically to 35,000 pounds. The tire-runway braking is measured by the use of proper instrumentation. High-speed braking tests show that low-cost surface treatment can be provided in two ways: (1) by increasing the spacing of the square saw-cut grooves beyond 1 1/4 inch, and (2) by installing V-shaped grooves using a reflex-percussive cutting process. In both cases, the braking effectiveness of an aircraft tire was found to be "acceptable" and hydroplaning was not experienced at speeds of up to 150 knots.

INTRODUCTION

An aircraft is brought to a complete stop on a runway by the combined forces of aerodynamic drag, reverse engine thrust, and wheel braking. The effectiveness of wheel braking deteriorates as the wetness on the runway surface increases. In an extreme case where a runway becomes flooded with water, an airplane can hydroplane during landing or takeoff and its braking and cornering capability is significantly reduced. Runway surface treatments, such as grooves, can minimize the danger of hydroplaning by reducing the water buildup on the runway and by facilitating forced water escape from the tire-runway interface.

The Federal Aviation Administration (FAA) is engaged in an experimental program to determine low-cost surface treatments that are effective at high landing speeds of jet aircraft. Surface treatments included in the program were: square grooves cut by rotary saws with diamond-tipped blades, V-shaped grooves installed by pneumatically-driven hammer type cutters, and porous friction course which is characterized by its open-graded matrix. The effectiveness of these surface treatments was quantified in terms of maximum braking action available under a variety of test conditions. The basic parameter measuring the braking action is the coefficient of friction developed at the tire-runway interface.

TEST APPROACH

MEASUREMENT OF INCIPIENT HYDROPLANING

The coefficient of friction is computed by dividing the frictional forces developed at the tire-runway interface by the vertical load on the aircraft tire. During hydroplaning, the coefficient of friction is theoretically zero; however, because of the presence of viscous and mechanical drags, the measured friction coefficient is not zero. Thus, for a direct measurement of the speed at which hydroplaning occurs, the viscous and mechanical drags must be subtracted from the measured friction coefficient. This is generally not practical, if only because of the necessity of complex instrumentation system. Many indirect methods have been used in the past(1) 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.

MEASUREMENT OF MAXIMUM BRAKING ACTION

Frictional forces at the tire-runway interface are developed as a result of relative motion between the tire surface and the runway. This relative motion is also known as circumferential tire slip; tire slip is an indication of the departure of the angular velocity of the braked tire from the free-rolling velocity. Frictional forces initially increase with slip, then reach a maximum value, and finally decrease as the tire slip increases beyond 20 percent. Tire slip is a complex function of speed, brake pressure, wetness of the runway, runway surface texture, and type of tire. For a given set of speed, wetness, tire, and runway type, the friction coefficient can be measured by varying the brake pressure in successive tests. By closely monitoring the magnitude of friction coefficient and tire slip, the maximum available friction coefficient is obtained.

EXPERIMENTAL PROGRAM

TEST FACILITY AND SYSTEM

The high speed braking action of an aircraft was duplicated at the ground test facilities of the Naval Air Engineering Center, Lakehurst, New Jersey. Powered with four J48-P-8 aircraft engines, a vehicle (figure 1) pushes a carriage containing aircraft tire-wheel assembly (figure 2) on steel guide rails; little over a mile of the track is available to achieve test speeds in excess of 150 knots. The jet vehicle is separated from the carriage after achieving the predetermined speed, and the carriage coasts into the test bed (figure 3) which is located at the end of the track.

The tire-wheel assembly is subjected to operational conditions representative of values used by airlines and aircraft. The test system provides adequate control of the variables and good reproducibility of the measured data.

SURFACE TREATMENTS

Grooves and porous friction overlay were installed in concrete sections (figure 4). Dimensions of the reflex-percussive grooves and square saw-cut grooves are shown in figure 5. Each test section was approximately 40 feet long; longer sections were not necessary because earlier research(2) has shown that the tire-pavement interface friction is fully developed in 1 to 6 feet, depending upon the speed of operation.

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FIGURE 1. JET-POWERED VEHICLE AND ASSOCIATED SYSTEM

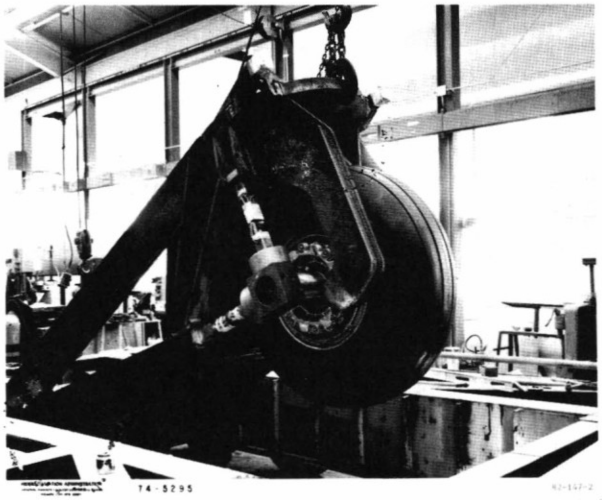

FIGURE 2. TIRE/WHEEL ASSEMBLY

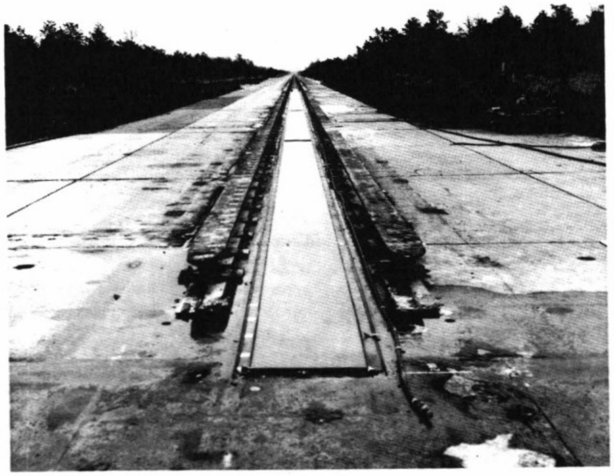

FIGURE 3. TEST BED AT THE END OF THE TRACK

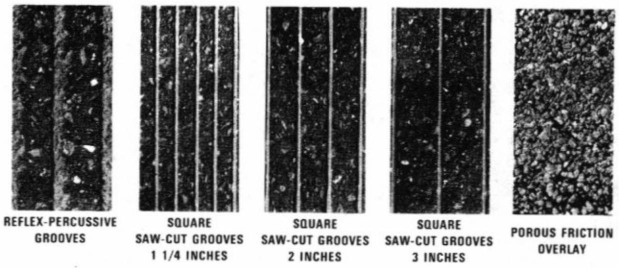

FIGURE 4. VARIOUS SURFACE TREATMENTS

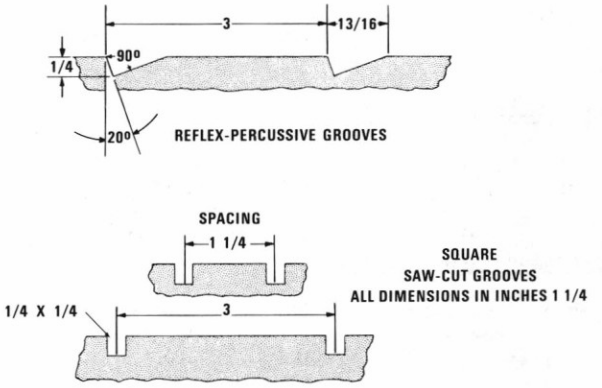

FIGURE 5. DIMENSIONS OF GROOVES

Square grooves are widely used for runways since they were first introduced by the British in 1956 on several airfields in England. The National Aeronautics and Space Administration (NASA) has studied the saw-cut grooves in the middle 1960's(3) and early 1970's(4). The FAA test program complements the NASA program by extending the speed range to 150 knots.

The V-shaped grooves are produced by a cutting process derived from the reflex-percussive method of controlled concrete removal. This method was recognized by the Concrete Society of Great Britain in 1972 and was first employed to obtain a rough finish on the pavement. The cutting process to provide the "reflex-percussive grooves" is patented by a Canadian manufacturer. Performance results of these grooves on portland cement concrete (pcc) are detailed elswhere(5). Although still in experimental stage, the reflex-percussive grooves offer a cost-competitive alternative to the square saw-cut grooves.

Low-cost groove pattern can also be provided by increasing the spacing of the saw-cut grooves(6). Therefore, the program included saw-cut grooves spaced between 1 1/4 inches and 3 inches. A few runways with saw-cut grooves spaced 3 to 4 inches can be found in the United States and Europe(7).

TEST PARAMETERS

The following is a summary of the test parameters employed in the program:

Tire Parameters

Vertical Load:	35,000 pounds
Inflation Pressure:	140 $\mathrm{lbf/in^2}$
Tread Design:	worn tire
Size/Type:	49X17, 26 ply, type VII

Surface Parameters

Type:	Asphaltic Concrete
Texture:	0.014-inch nongrooved
Treatment:	square saw-cut grooves of 1/4-inch size with spacing 1 1/4 inches to 3 inches, V-grooves with 20° groove angle and 3 inches spacing, and porous friction overlay with 1/2-inch maximum size aggregate.

Environmental Parameters

Wetness or Water Depth:	0.01 inch (wet) 0.10 inch (puddled) 0.25 inch (flooded)

Operational Parameters

Wheel Operation:	Rolling to braked
Brake Pressure:	200 to 2500 $\mathrm{lbf/in^2}$
Antiskid System:	Not operative
Speeds:	70 to 150 knots

TEST PROCEDURE

Desired wetness was achieved in the test sections.
Operational parameters were set on the jet vehicle and tire-wheel assembly.
Jet vehicle and assembly were released from the launch end.
Jet vehicle was braked and separated when the desired test speed was achieved.
The tire-wheel assembly entered the test sections.

DISCUSSION OF RESULTS

Before discussing the results, it may be worthwhile to explain the relationships among some of the parameters of the interface. The improved braking action of an aircraft tire on 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. Second, the grooves provide forced water escape from the tire-runway interface when the aircraft travels on a water covered runway. Both the free flow and the forced flow are important, because together they comprise the total flow.

Groove roughness and spacing play important roles 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, while the forced water escape is essentially turbulent and requires rough groove channels 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.

An increase in number of escape paths, resulting from closely-spaced grooves, promotes water runoff(8); however, since at higher operating speeds of the aircraft the time available for water to escape from the interface is reduced, the amount of water that can be expelled from the interface is limited by inertia of water.

Thus, the optimum removal of water from the aircraft path on the runway results from a complex relationship between groove roughness, groove spacing, and speed of tire.

BRAKING ACTION

A wet surface represents a condition encountered during or after a light rain. Puddled and flooded surfaces are representative of conditions prevailing immediately after heavy rains of short or long durations, respectively. When nongrooved, the wet surface provides adequate braking action to a worn tire (figure 6); however, installation of grooves in the surface or application of porous friction overlay improves the braking action significantly as shown in figure 6.

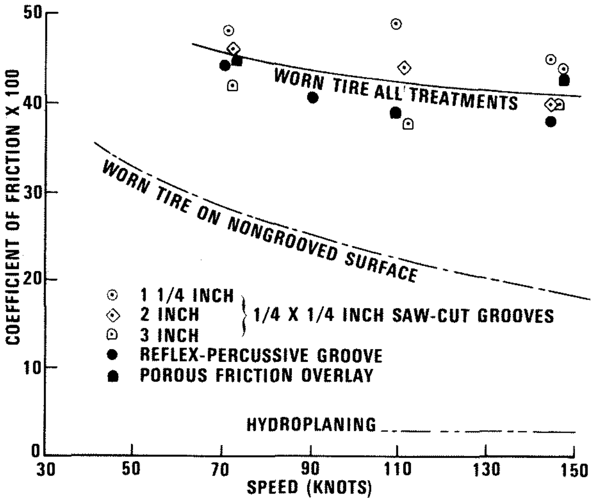

FIGURE 6. BRAKING PERFORMANCE OF A WORN TIRE ON WET SURFACE

Figure 7 shows the results on a flooded surface containing all the treatments. In each case, incipient hydroplaning is delayed beyond 150 knots. All the treatments provide similar braking action as represented by a single curve. The braking action on a puddled surface is shown in figure 8. The sensitivity of the friction coefficient to the spacing of square saw-cut grooves is obvious: 1 1/4-inch spacing provides the highest braking action. The reflex-percussive grooves provide braking action equivalent to saw-cut grooves spaced btween 2 and 3 inches.

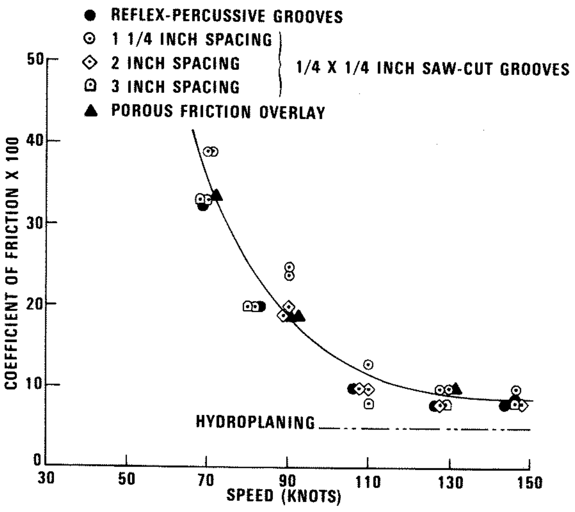

FIGURE 7. BRAKING PERFORMANCE OF A WORN TIRE ON FLOODED SURFACE

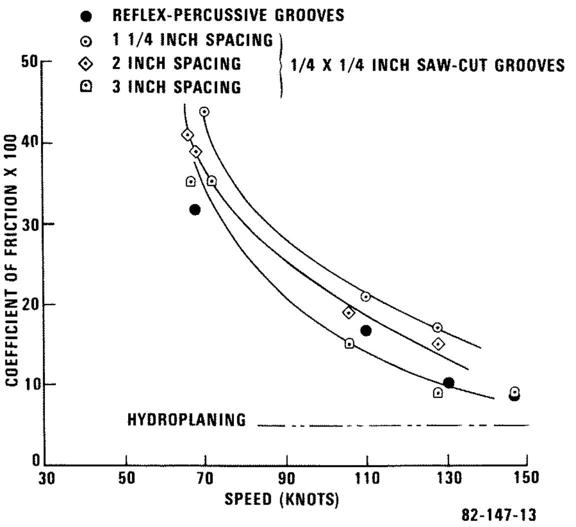

FIGURE 8. BRAKING PERFORMANCE OF A WORN TIRE ON PUDDLED SURFACE

A comparison of all the surface treatments under various water depth conditions is shown in figure 9. The observed behavior can be explained by physical interpretation of the data. Although, this research did not include instrumentation to measure the water escape paths or amount of water escaped, an attempt is made to explain how grooves help water escape. When a worn tire travels over a wet surface with grooves, predominantly viscous pressures are developed in the interface; viscous pressures alone are not sufficient to lift the tire off the ground. Because only a small amount of water is present in the interface, most of it is expelled through grooves and all the surfaces provide high friction levels as shown by the curve marked wet (figure 9).

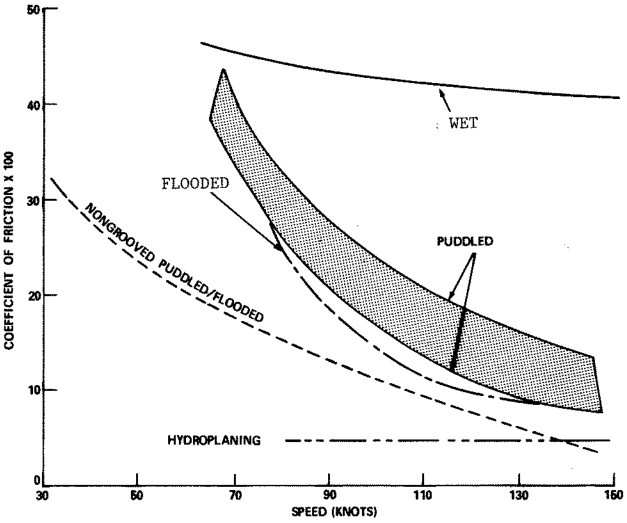

FIGURE 9. COMPARISON OF ALL SURFACE TREATMENTS UNDER WET, PUDDLED, AND FLOODED CONDITIONS (DATA POINTS REMOVED)

When the grooved surfaces are puddled, hydrodynamic pressures become important. The additional water in the interface must be removed to reduce the buildup of hydrodynamic pressures to ensure contact between the tire and the runway. When the grooves are spaced closer, water particles trying to escape through the rear of the contact will find it easier to escape through the grooves and develop a "drier" interface. However, a very large spacing will be ineffective in forcing the water out of the interface because it simulates a nongrooved surface and the friction coefficient will approach hydroplaning level, as shown in figure 9. An optimum condition would be when all the water is expelled from the interface in such a way that the water carrying capacity of the grooves is fully exhausted. This condition could be obtained by a certain combinatin of groove spacing and amount of water on the runway surface. Thus, for the wetness for which groove capacity of 3-inch spaced grooves is exhausted, the capacity of 1 1/4 inch spaced grooves will not and these grooves will provide a "drier" contact. The results on the puddled surfaces with grooves verify this phenomenon; the shaded area shows the extent of the water carrying capacity as a function of groove spacing: the top boundary represents the 1 1/4-inch spaced grooves and the bottom boundary represents the grooves spaced at 3 inches.

When the grooved surfaces are flooded, the available friction levels are insensitive to groove spacing. The dotted curve below the shaded area represents results on all surface treatments. For the flooded surfaces, the grooves are filled with water even before the passage of the tire over them. Then, the inertia of the water particles retards the escape of water in all directions when the tire does travel over the surfaces.

The reflex-percussive grooves and the porous friction overlay perform alike under wet and flooded conditions. The braking action is equivalent to square saw-cut grooves spaced at 3 inches.

AIRCRAFT TESTS ON A GROOVED RUNWAY

A joint FAA/NASA test program, currently underway, included testing with the NASA Boeing 737 airplane. The testing was conducted at the NASA Wallops test facility and the FAA Technical Center runway 13-31. The 10,000-foot runway at the Technical Center has a unique grooving configuration ideal for full-scale testing: it includes square saw-cut grooves at 1 1/2 inches and 3 inches and small nongrooved sections. A direct performance comparison of the grooves is possible. Preliminary results from the joint program on runway 13-31 are shown in figure 10. Superimposed on the aircraft data points is a curve showing the results from the jet vehicle track test(9). It can be seen that the performance of square saw-cut grooves spaced between 1 1/4 inches and 3 inches is similar in the speed range of 90 to 150 knots.

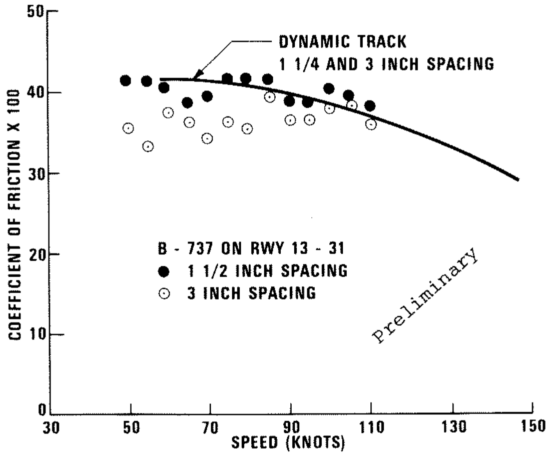

FIGURE 10. BRAKING PERFORMANCE OF AN AIRCRAFT ON GROOVED RUNWAY

COST COMPARISON

The cost of square saw-cut grooves is influenced by groove spacing. A study(6) shows that the fixed and variable construction costs for grooving the runways are 60 percent and 40 percent, respectively, of the total cost. Figure 11 shows the relative cost savings as a result of increasing the spacing of the square saw-cut grooves or the installation of reflex-percussive groves. The latter offers a viable cost competitive alternative to saw-cut grooves; however, cost estimates and full savings potential can only be affirmed after application of these grooves in an operational environment.

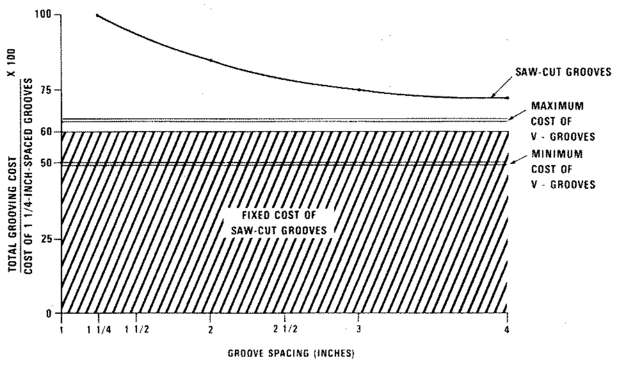

FIGURE 11. ESTIMATED GROOVING COST AS A FUNCTION OF GROOVE SPACING

CONCLUSIONS

The following conclusions are drawn from the findings of this research. These conclusions are valid for the operational parameters included in the study.

1. High-speed braking tests show that low-cost surface treatments can be provided either by increasing the spacing of the square saw-cut grooves beyond 1 1/4 inches or by installing the V-shaped grooves using a reflex-percussive cutting process.

2. When predominantly puddled water conditions are encountered on a runway surface, the closely-spaced saw-cut grooves are preferable, although, all treatments included in the test program will delay aircraft hydroplaning beyond 150 knots.

3. Selection of a particular treatment on a runway can be based on seasonal rainfall conditions and cost of installation of the treatment.

4. Under all conditions of operation, square saw-cut grooves spaced at 1 1/4 inches provide maximum braking action to an aircraft tire.

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