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# Reflex-Percussive Grooves for Runways: Alternative to Saw-Cutting

SATISH K. AGRAWAL AND HECTOR DAIUTOLO

**The presence of transverse grooves in runway surfaces helps alleviate aircraft hydroplaning during landing operations. The Federal Aviation Administration has recommended installation of 0.25-in square-grooves spaced at 1.25 in center-to-center on runways where potential of hydroplaning exists. However, many runways remain nongrooved, primarily because the cost of grooving by the conventional saw-cutting method, currently in widespread use, is high. This paper describes the braking effectiveness of an aircraft tire on reflex-percussive grooves produced by a newly developed low-cost groove-installation technique called the reflex-percussive cutting process. This process is based on the principle of controlled removal of concrete. The cutting head causes the material directly under the area of impact to pass through a rapid compression-tension cycle. Because it is weak in tension, the concrete fractures in the localized area of impact without damaging the surrounding concrete. The braking effectiveness of an aircraft tire on these grooves is comparable to conventional saw-cut grooves under similar conditions of wetness, and both types of grooves alleviate hydroplaning. The cost of installation of the reflex-percussive grooves in portland cement concrete, however, can be as low as half the cost of installation of conventional saw-cut grooves at the recommended groove spacing.**

The braking performance of an aircraft during landings on water-covered runways depends on the level of friction developed in the contact area between the aircraft tire and the runway surface. The friction level developed in the contact area is affected by aircraft speed, design of the tire tread, runway finish and drainage capacity, characteristics of the braking system, and the amount of water on the runway. Under flooded runway conditions, aircraft may hydroplane whereby very low levels of friction are available and the braking capability is significantly reduced. Loss in braking capability can be considerable even if runways are covered with only a thin film of water.

During hydroplaning, the physical contact between the tire and the runway is lost, and the tires are supported on the intervening layer of water. Hydroplaning occurs as a result of rapid buildup of hydrodynamic and viscous pressures in the tire-runway contact area. Dynamic or viscous hydroplaning are identified according to whether inertial forces or viscous forces, respectively, are predominant. In all cases of hydroplaning, however, both effects are present to some degree. Dynamic hydroplaning can be minimized by a rapid removal of water from the tire-runway contact area; runway grooves accomplish this effectively by providing escape channels for water forced out of the contact area during tire passage over the grooves. Viscous hydroplaning can be alleviated by providing adequate microtexture in the runway surface.

The Federal Aviation Administration (FAA) has recommended (1) 0.25-in wide by 0.25-in deep grooves spaced at 1.25 in between centers and has encouraged airport managers, operators, and owners to groove runways where potential of hydroplaning or overrun exists. However, many runways have not been grooved. 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 grooved surfaces at the touchdown speeds of jet aircraft.

The objective of the research described in this paper is to evaluate the braking effectiveness of an aircraft tire on grooves produced by a new and less expensive reflex-percussive cutting process and to compare the performance of these grooves with the conventional saw-cut grooves.

## GROOVES PRODUCED BY REFLEX-PERCUSSIVE PROCESS

The reflex-percussive method of controlled removal of concrete was recognized by the Concrete Society of Great Britain in 1972. This method was first developed for providing a very rough finish in the runway surface. When the cutting head strikes the surface of the concrete, it causes the material directly under the area of impact to deflect downward and thus creates a momentary and localized compression. The compressive strain is primarily elastic, and almost immediately the concrete rebounds and passes into tension nearly equal to the initial compression. However, because it is very weak in tension, the concrete fractures and releases the elastic energy as the kinetic energy of the flying fragments. The great advantage of this method of cutting is its ability of not loosening the aggregate particles within the matrix or creating microfractures in the undamaged surrounding concrete.

Klarcrete Limited, of London, Canada, demonstrated that the reflex-percussive process can be readily adapted for installing grooves in the concrete surfaces. By tilting the cutting heads (three heads were used for this study) at 13°, the reflex-percussive grooving machine (Figure 1) provides nonsymmetrical V-shaped grooves. Figure 2 shows the reflex-percussive grooves in a portland cement concrete (PCC) test surface; Figure 3 shows the dimensions of these grooves and those of conventional saw-cut grooves.

## BRAKING EFFECTIVENESS OF REFLEX-PERCUSSIVE GROOVES

The experimental program was conducted at the Naval Air Engineering Center, Lakehurst, New Jersey. Test Track 1 at this facility was modified to accomplish the objectives of the research described in this paper.

### Test Facility and Equipment

The test track is 1 mile long and has guide rails spaced 52.5 in apart that run parallel to the track. Reinforced concrete strips extend beyond the guide rails to a width of 28 ft. The last 200 ft of the track were used for installing the test bed. The PCC test bed was 30 in wide and 5 in thick. 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 that supports the dynamometer and wheel assembly, and the measuring system. The jet car is powered with J48-P-8 aircraft engines that produce a total thrust of 24 000 lb•f and is used to propel the dynamometer and wheel assembly and the carriage from the launch end at a preselected speed. The jet car (Figure 4) is disengaged when 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 were jointly developed by the FAA and the U.S. Navy and have the capability of simulating a jet transport tire-wheel assembly under touchdown and rollout conditions. Test speeds of up to 150 knots were attained on the test track. Figure 5 shows the dynamometer and

Figure 1. Machine for installing reflex-percussive grooves.

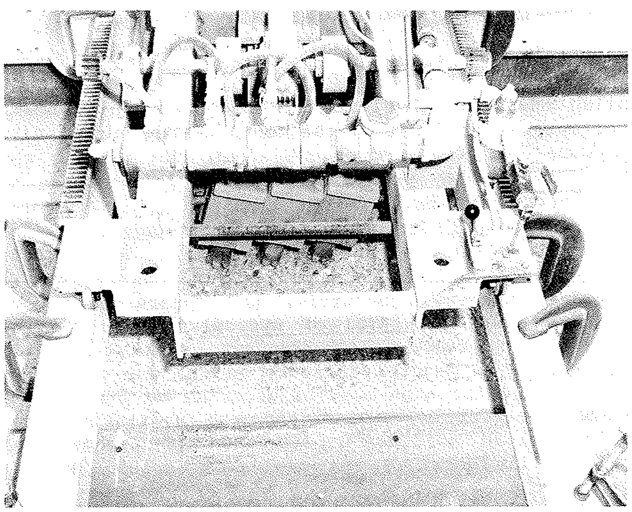


Figure 2. Reflex-percussive grooves in PCC surface.

Figure 3. Dimensions of reflex-percussive grooves and conventional saw-cut grooves.

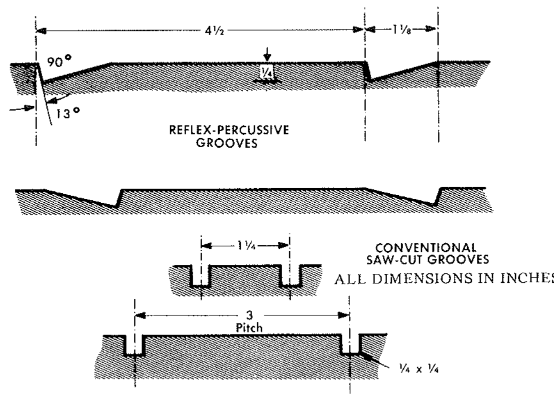



Figure 4. Jet-powered pusher car for providing preselected speeds to test equipment.

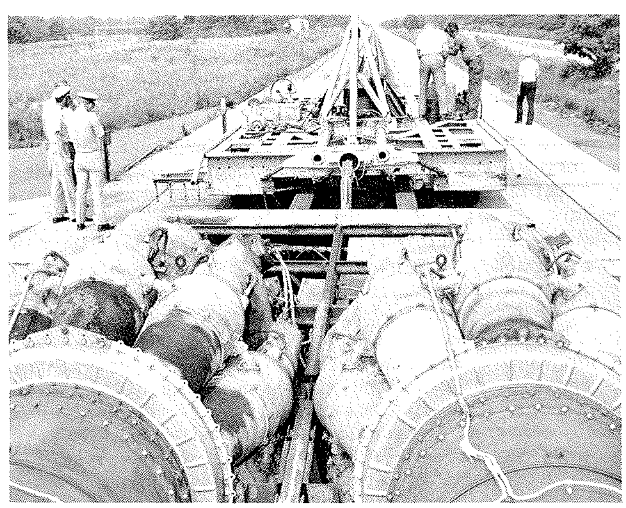


Figure 5. Dynamometer and wheel assembly showing vertical and horizontal load links.

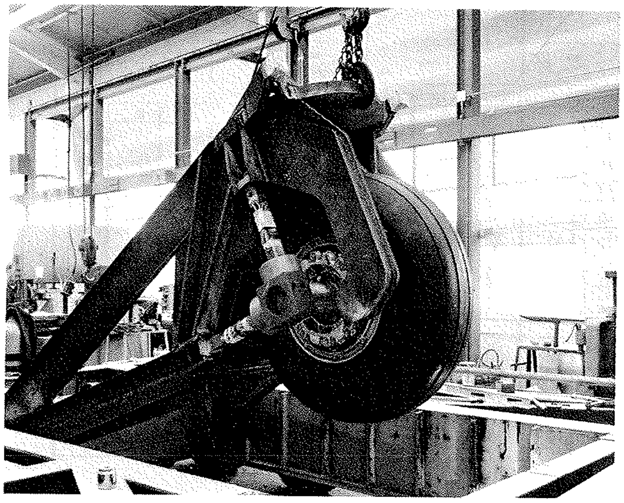
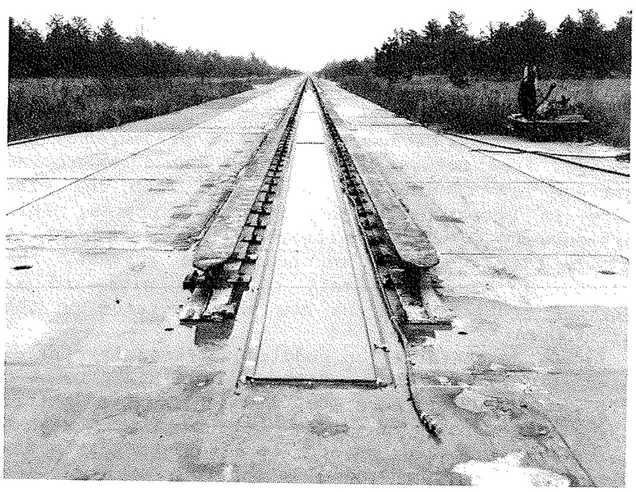


Figure 6. Four sections of 200-ft test bed.



wheel assembly and the details of the instrumentation.

The dynamometer is instrumented to measure the vertical load on the tire, the horizontal force developed at the tire-pavement interface, the angular velocity of the test tire, and the vertical motion of the dynamometer assembly relative to the dead load carriage. The water depth on the test bed was measured by the use of the National Aeronautical and Space Administration (NASA) water level depth gage.

## Test Sections

The 200-ft test bed (Figure 6) was divided into four 45-ft sections following a 20-ft section; the 20-ft section was intended to ensure proper approach of the test wheel into the test sections. The dimensional tolerance of the test surfaces was held within ±1/8 in from horizontal level in each test section. Figure 7 shows the schematic of grooved and nongrooved sections on each test bed. Testing on bed no. 4 is the subject matter of this paper;

Figure 7. Schematic of grooved and nongrooved sections.

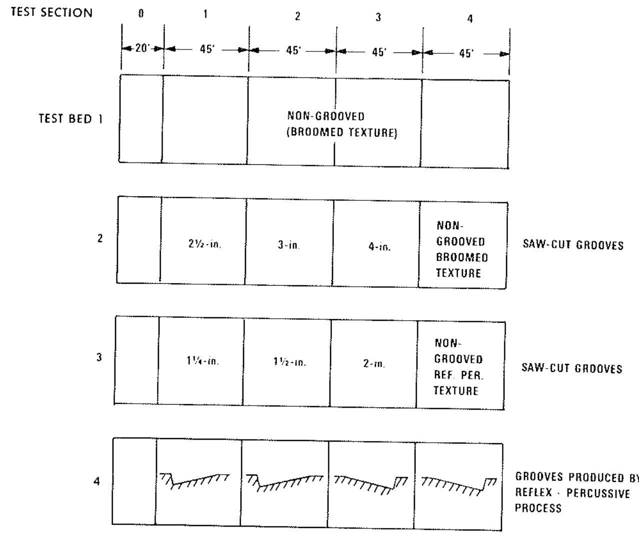



Table 1. Test parameters used in program.

| Parameter | Description |
|---|---|
| Tire | |
| Vertical load | 35 000 lb |
| Inflation pressure | 140 lb/in$^2$ |
| Tread design | Worn and fully treaded, six grooves |
| Size and type | 49x17, 26-ply, type 7 |
| Pavement | |
| Type of surface | PCC |
| Macrotexture | 0.021 in nongrooved, grease smear measure |
| Type of grooves | Reflex-percussive |
| Environmental | |
| Water depth | Under 0.02 in wet, 0.02-0.16 in puddled, 0.17-0.32 in flooded |
| Operational | |
| Wheel operation | Rolling to locked |
| Brake pressure | 300-1800 lb/in$^2$ |
| Speed | 70-150 knots |

testing on other beds is described in our other paper in this Record and elsewhere (2).

## Test Parameters

Four types of parameters were investigated in the test program. These are the tire parameters, the pavement parameters, the environmental parameters, and the operational parameters. The primary criterion was to choose a value for a given parameter such that it represented a value widely used by airlines and aircraft.

A summary of the test parameters included in the program is given in Table 1.

## Test Procedure

In order to obtain maximum available friction level for each set of operating conditions, multiple tests were conducted at a constant speed while the brake pressure was gradually increased in successive tests until wheel lock occurred. A wheel slip between 6-18 percent was recorded as the range in which maximum friction level occurred. A maximum of four data points were collected in each test. A complete test consisted of the following steps:

1. Test tire was selected and checked for inflation pressure;

Figure 8. Test on reflex-percussive grooves.

| TEST SPEED, KNOTS | COEFFICIENT OF FRICTION X 100 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WORN TIRE | | | | | | | NEW TIRE | | | | | | | | |
| | NON-GROOVED SURF. | GROOVE ORIENTATION | | | | | | NON-GROOVED SURFACE | | | GROOVE ORIENTATION | | | | | |
| | Average Water Depth, Inches | | | | | | | | | | | | | | | |
| | A* | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C |
| 70 | 18 | 49<br>41<br>40 | 15<br>24 | 19<br>19 | 41 | 32<br>29<br>27 | -<br>19<br>19 | 33 | 28<br>19 | 20<br>20 | 34<br>34 | 20<br>26 | 26 | 36 | 14<br>15<br>29 | 27<br>23 |
| 90 | - | 34<br>35<br>40 | 21<br>15 | 14 | 40 | 26<br>15 | -<br>13 | 26<br>20 | 10 | - | 31<br>25 | 24<br>20 | 11 | 30 | 26<br>27<br>15 | |
| 110 | 10 | 31<br>30 | 14<br>12<br>14 | 5 | 33 | 26<br>14 | -<br>13<br>5 | 23 | 4<br>6 | - | 24<br>26 | - | 6 | 28 | 19<br>18 | 10 |
| 130 | 9 | 22<br>21<br>25 | 17<br>10 | 10 | 25 | 19<br>14 | -<br>10 | 26 | 5 | - | 27<br>30 | 15 | 6 | 28 | 16<br>19<br>12<br>10 | 6<br>8 |
| 150 | - | - | - | - | - | - | - | 18 | - | - | - | - | - | - | - | - |

Notes: A = 0.0-0.02 in, wet; B = 0.02-0.16 in, puddled; and C = 0.17-0.32 in, flooded.
35 000 lb vertical load, 140 lb/in² inflation pressure.

2. Desired water depth was obtained on the test sections;
3. Jet engines were started at the launch end and set at the performance level to provide preselected speed in the test sections;
4. Jet car was released to propel the test equipment (dead load and dynamometer); test tire remained in free rolling state during this maneuver;
5. Jet car was braked and separated from the test equipment several hundred feet away from the test bed (This allowed the dead load and dynamometer to enter the first test section at the preselected speed. The test speeds in the remaining sections were within 1 or 2 knots of the speeds in the previous sections as computed from the analog traces.);
6. Before entering the first test section, the hydraulic systems were activated to apply the vertical load and the brake pressure on the tire (the magnitude of each was preselected), thus, the wheel entered the sections at preselected test conditions; and
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

Data were collected on oscillographs. Typical data collected in a test included horizontal force at the tire-pavement interface, vertical load on the tire, coefficient of friction developed at the interface, and wheel revolution. Water depth and brake pressure were recorded manually, and the test speed was computed from the distance-time trace on the oscillograph.

Figure 8 shows the test results. The values of the coefficient of friction in this figure represent the maximum available under each set of operating conditions. A least-square fit was obtained between speed and coefficient friction.

## Discussion of Results

Test results on reflex-percussive grooves and on nongrooved PCC are shown in Figures 9-11. The basic characteristics of the friction-speed relations in these figures indicate a drop in friction with increasing speed--a trend that is well documented in the past (3). These results verify the validity of the experimental procedures of this research and complement the findings of past research.

The improvement in available friction level as a result of grooving is shown in Figures 9 and 10. Under wet surface conditions (Figure 9), the braking performance of both new and worn tires is improved on the grooved surface compared with the nongrooved surface. The improvement in braking performance in going from a nongrooved to a grooved surface is larger for a worn tire than for a new tire. This may be expected because the viscous pressure in the contact area between a worn tire and a nongrooved surface are considerably high, and when the worn tire is operated on the grooved surfaces, this pressure is reduced significantly. For the case of a new tire operating on nongrooved surface, the viscous pressure is small to start with and is further reduced when the new tire operates on the grooved surface.

When the operation on puddled surfaces is considered (Figure 10), the performance of a new tire on a grooved surface (Figure 10c) is significantly better than on nongrooved surfaces. Note also that a worn tire performs better on a grooved surface than a new tire does on a nongrooved surface. Under flooded surface conditions (Figure 10), the occurrence of frequent wheel lock prevented accumulation of any meaningful data on nongrooved surfaces; the available friction levels were low even on the grooved surfaces.

The reflex-percussive grooves can be installed in two orientations (Figures 9-11) because the cross section of the grooves is nonsymmetrical. Depending on the direction of motion, the tire will encounter different flow conditions as it hits the groove. An attempt to isolate a preferred orientation of the grooves in terms of improved braking performance for one orientation compared with another was not successful; braking performance was comparable for both orientations. However, higher rubber deposits were observed for the orientation shown on the right in Figures 9-11.

## COMPARISON OF REFLEX-PERCUSSIVE GROOVES WITH CONVENTIONAL SAW-CUT GROOVES

The braking performance of conventional saw-cut grooves was evaluated in another investigation (2) and is reported in our other paper in this Record. Grooves of various pitches between 1.25 and 4 in (Figure 7) were included in the test program. The general conclusion from the study described in our other paper in this Record is that the conventional saw-cut grooves spaced at 3 in or less will provide an acceptable braking performance to an aircraft tire on water-covered surfaces.

A comparison of the braking performance of the reflex-percussive grooves with the conventional saw-cut grooves is shown in Figures 12 and 13. The results for the saw-cut grooves are from another report (2); the results for the reflex-percussive grooves are replotted from Figures 9-11 of this paper. Since the orientation of the reflex-percussive grooves did not show definitive trends, the data for these grooves, in Figures 12 and 13, are not separated by orientation. All the curves in Figures 12 and 13 show a least-square fit to the data.

It is evident from Figure 12 that the braking performance of an aircraft tire on the reflex-percussive grooves is comparable to that on the saw-cut grooves under puddled and flooded conditions. Figure 13 shows the performance comparison for wet surface conditions. Here again, the braking performance of the two types of grooves is comparable.

The cost of saw-cut grooves depends on the groove geometry, the groove spacing, and the hardness of the aggregate used in the PCC. An investigation by a construction cost consultant indicated that significant cost savings can result by increasing the groove spacing of the conventional saw-cut grooves. For example, by cutting grooves at 2-in spacing, the cost savings over 1.25-in groove spacing are 15 percent, and at 3- and 4-in spacings, the cost savings are 25 and 28 percent, respectively. Hardness of the aggregate influences the diamond blade life--softer aggregates require less frequent blade changes; harder aggregates require more frequent blade changes. Since the diamond-tipped blades are expensive, the total grooving cost increases for concrete by using harder aggregates.

Figure 9. Coefficient of friction as function of speed on reflex-percussive grooves under wet surface condition.

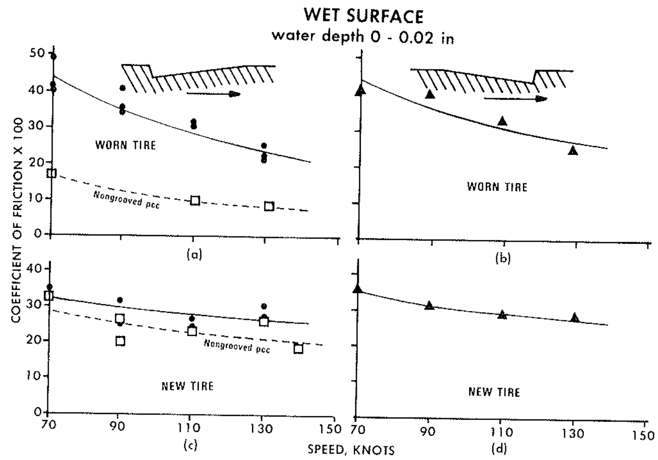



Figure 10. Coefficient of friction as function of speed on reflex-percussive grooves under puddled surface condition.

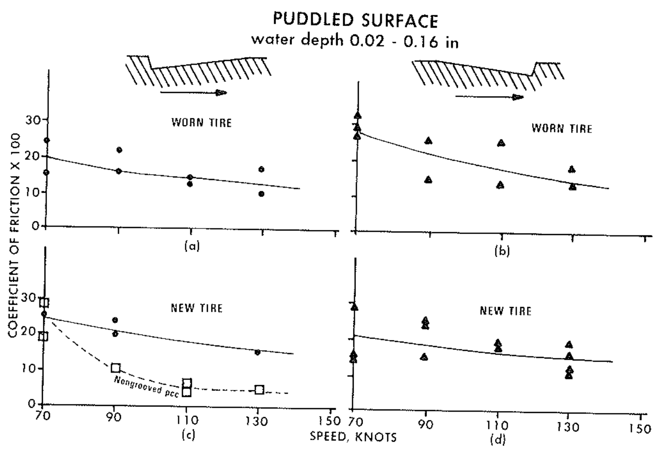



Figure 11. Coefficient of friction as function of speed on reflex-percussive grooves under flooded surface condition.

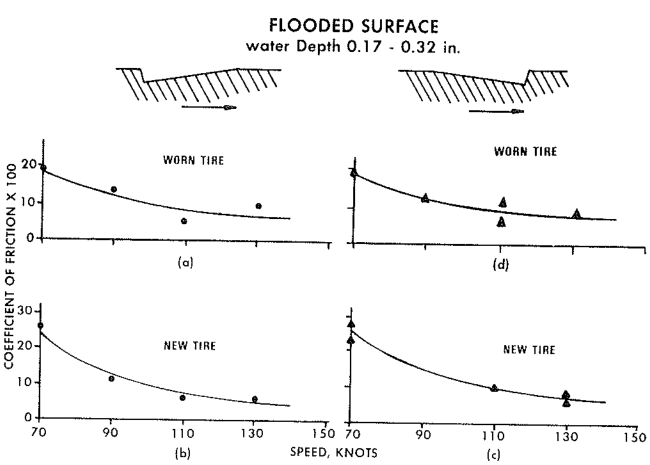



Figure 12. Comparison of braking performance of reflex-percussive and saw-cut grooves on puddled and flooded surfaces.

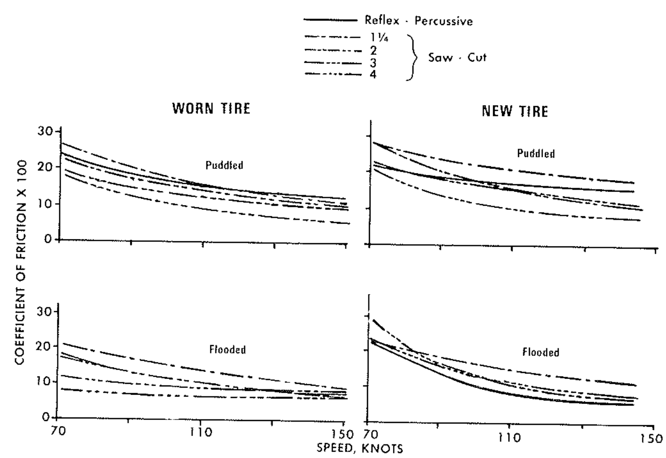



Figure 13. Comparison of braking performance of reflex-percussive and saw-cut grooves on wet surfaces.

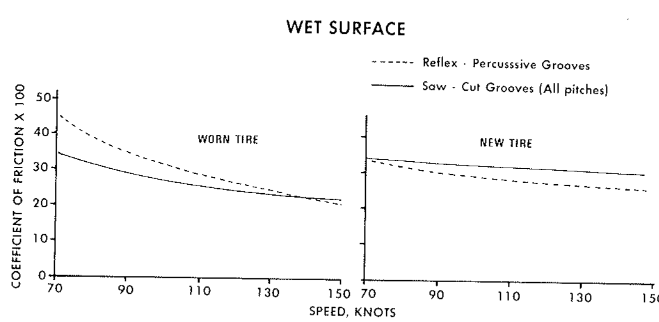
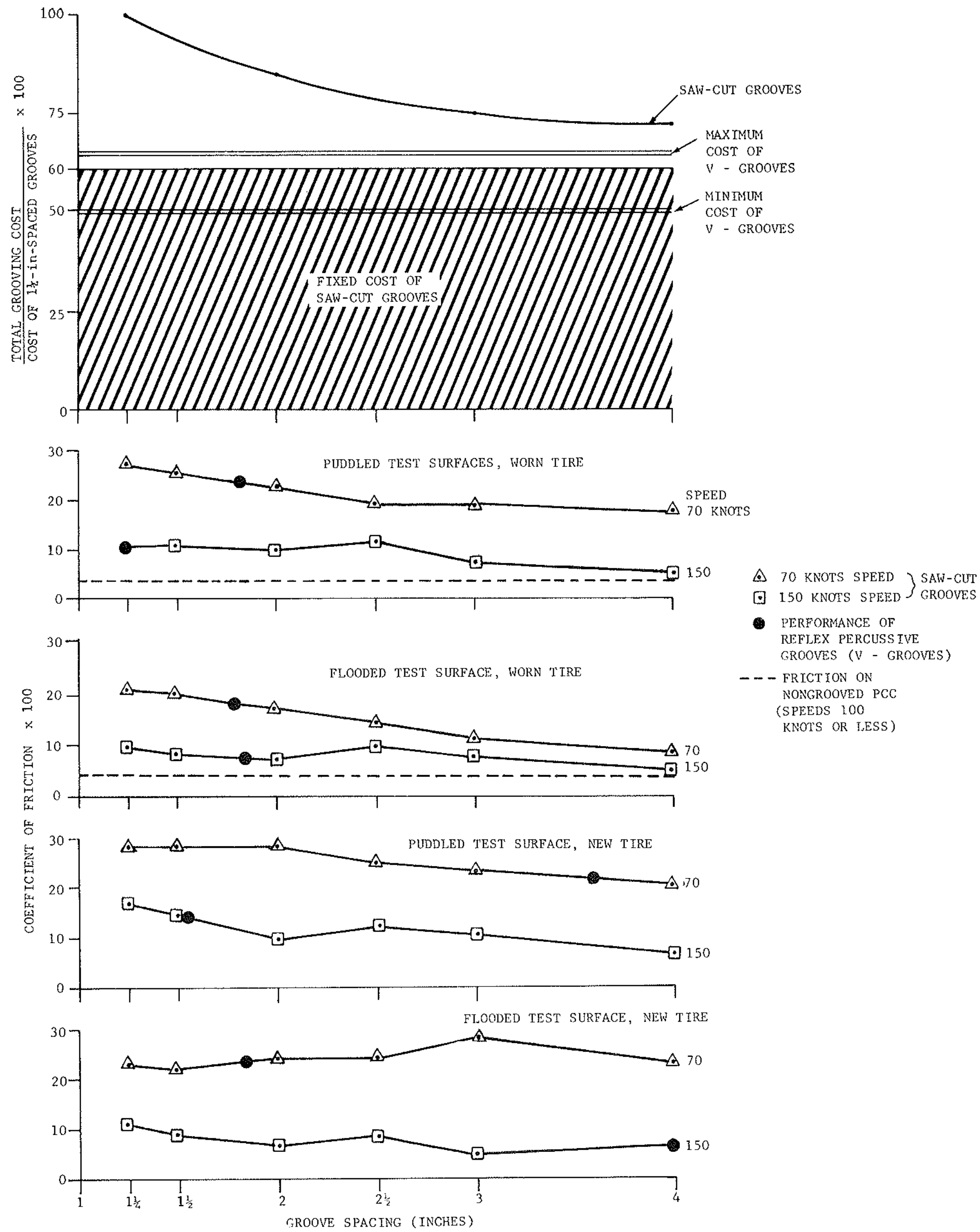


Figure 14. Braking performance and estimated cost as function of groove spacing.




The reflex-percussive grooving process is relatively insensitive to the hardness of the aggregates. This insensitivity coupled with the long life of cutting heads and high operating speed of the machine provide substantial savings to the total grooving cost. The Canadian manufacturer, who holds the patent for the application of this cutting process for grooving, has demonstrated the economics associated with the process during resurfacing of part of an operating runway. However, realistic cost estimates and full savings potential can only be realized after application of these grooves on an operating runway. Figure 14 shows a composite view of performance and estimated grooving costs for both the saw-cut grooves and the reflex-percussive grooves; the latter have the potential of costing only half as much as the 1.25-in spaced conventional saw-cut grooves.

Testing currently being conducted by FAA is directed toward finding a cost-effective groove configuration for the asphaltic concrete surfaces. As part of its engineering and development program (4), FAA expects to conduct a comprehensive evaluation of the grooves produced by the reflex-percussive process. The evaluation will include the optimization of the groove shape and size and the braking effectiveness of the grooves.

## CONCLUSIONS

The following conclusions are drawn from the findings of this research and are valid for PCC surfaces:

1. The reflex-percussive cutting process is an alternate groove-installation technique competitive with the conventional saw-cutting method;
2. The braking performance provided by the reflex-percussive grooves on water-covered surfaces is comparable to that provided by the 2-in pitch, conventional saw-cut grooves; and
3. The installation cost of the reflex-percussive grooves can be significantly less than that of the

conventional saw-cut grooves; a potential of costing as low as half as much as conventional saw-cut grooves at 1.25-in spacing exists.

ACKNOWLEDGMENT

This research was requested by the Office of Airport Standards, FAA. The Airport Development Division of the Systems Research and Development Service provided the program direction. Herman D'Aulerio provided helpful suggestions and critical reviews throughout the conduct of the research.

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# Effects of Groove Spacing on Braking Performance of An Aircraft Tire

SATISH K. AGRAWAL AND HECTOR DAIUTOLO

**The braking and cornering performance of an aircraft during operations on water-covered runways is improved by the introduction of transverse grooves on the runways. The Federal Aviation Administration has recommended 0.25-in wide x 0.25-in deep saw-cut grooves spaced at 1.25 in, to be installed on runways where the potential of hydroplaning exists. However, a large number of runways have not been grooved. The major reason for this is the high cost of groove installation and the availability of only limited evidence about the effectiveness of the grooved surfaces at the touchdown speeds of modern aircraft. The research reported here indicates that, by increasing the spacings of the conventional saw-cut grooves up to 3 in, the cost of groove installation can be reduced by up to 25 percent compared with the installation cost of grooves spaced at 1.25 in. The results further show that friction levels available on these grooves under wet operating conditions are not significantly below those attained on grooves spaced at 1.25 in. These results are valid for operating speeds up to 150 knots.**

The braking performance of an aircraft during landings on water-covered runways depends on the level of friction developed in the contact area between the aircraft tire and the runway surface. The friction level developed in the contact area is affected by aircraft speed, design of the tire tread, runway finish and drainage capacity, characteristics of the braking system, and the amount of water on the runway. Under flooded runway conditions, aircraft may hydroplane because very low friction levels are available and the braking capability is reduced significantly. Loss in braking capability can be considerable even if runways are covered with only a thin film of water.

During hydroplaning, the physical contact between the tire and the runway is lost and the tires are supported on the intervening layer of water. Hydroplaning occurs as a result of rapid buildup of hydrodynamic and viscous pressures in the tire-runway contact area. Dynamic or viscous hydroplaning is identified according to whether inertial or viscous forces, respectively, are predominant. In all cases of hydroplaning, however, both effects are present to some degree. Dynamic hydroplaning can be minimized by a rapid removal of water from the tire-runway contact area; runway grooves accomplish this very effectively by providing escape channels for water forced out of the contact area during tire passage over the grooves. Viscous hydroplaning can be alleviated by providing adequate microtexture in the runway surface.

The Federal Aviation Administration (FAA) has recommended (1) 0.25-in wide x 0.25-in deep grooves spaced at 1.25 in between centers and has encouraged airport managers, operators, and owners to groove runways where potential of hydroplaning or overruns exists. However, many runways have not been grooved. 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 about the effectiveness of grooved surfaces at the touchdown speeds of jet aircraft.

The objective of the research described in this paper is to determine a cost-effective groove configuration for portland cement concrete (PCC) surfaces.

## SCOPE OF INVESTIGATION

A cost-effective groove configuration was determined by investigating whether an increase in groove spacing beyond the FAA recommended value of 1.25 in can lower the total cost of grooving without adversely affecting the braking performance of an aircraft tire on these grooves under wet and flooded surface conditions.

Low grooving cost and acceptable braking performance are the two key factors used in the determination of a cost-effective configuration for the saw-cut grooves. The term acceptable braking performance is subjective and is defined as follows for