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

Figure 1. Grooving machine used for cutting 0.25-in x 0.25-in deep grooves at various pitches in test sections.

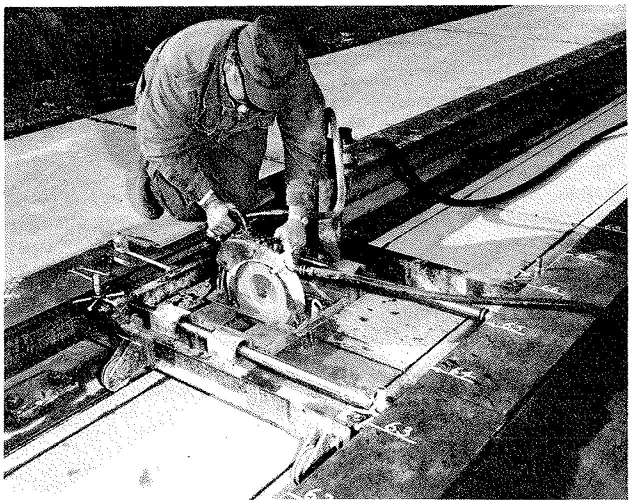


Table 1. Test parameters used in program.

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	Conventional saw-cut grooves, 0.25 x 0.25 in
Groove spacing	1.25, 1.50, 2, 2.50, 3, and 4 in
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

the purposes of this study: The available friction level on water-covered surfaces that have grooves installed at spacings in excess of 1.25 in is significantly higher than on nongrooved surfaces and is not significantly lower than grooves spaced at currently recommended values.

The groove spacing was chosen as the only variable to be included in the test program after an investigation (2) showed that increases in the groove spacing has significantly more potential for cost saving than changes in the groove size. This investigation was conducted by sampling the grooving costs in the northeastern, midwestern, and southwestern United States and included both the PCC and the asphaltic concrete surfaces. This paper describes the results on PCC surfaces only. The saw-cut grooves were installed by a machine (Figure 1) developed by the U.S. Navy.

EXPERIMENTAL PROGRAM

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 objective of the research. The descriptions of the test facility and equipment, test sections, and the test procedure are given elsewhere (3) and also in our other paper in this Record.

Test Parameters

Four types of parameters were investigated in the test program: tire parameters, pavement parameters, environmental parameters, and 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.

Table 1 summarizes the test parameters included in the program.

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 revolutions. Water depth and brake pressure were recorded manually, and the test speed was computed from the distance-time trace on the oscillograph.

Tables 2 and 3 show the test results. The values of the coefficient of friction in these tables represent the maximum available under each set of operating conditions. A least-square fit was obtained between speed and coefficient of friction.

DISCUSSION OF RESULTS

Test results on the conventional saw-cut grooves are shown in Figures 2-4. The basic characteristics of the friction-speed relation in these figures indicate a drop in friction coefficient with increasing speed--a well-documented trend (4). These results verify the validity of the experimental procedures of this research and complement the findings of past research.

Wet runway surfaces are normally encountered during or after a light or moderate rain; these surfaces may be saturated with water but would not have measurable water depth. A worn tire operating on a wet, nongrooved surface represents a situation where predominantly viscous hydroplaning may occur. Even when hydroplaning does not occur, the viscous pressures in the contact area are high and remain high at a relatively low speed. The result is low levels of available friction. The broken-line curve in Figure 4a shows the friction levels obtained under these conditions.

When a new tire is operated on wet, nongrooved surfaces, a more complex phenomenon takes place under the tire. The viscous pressure under the tire grooves is smaller than under the ribs. This results in a lower integrated pressure under the tire and provides more contact between the tire and the concrete surface. The friction levels available are increased significantly (over those obtained with a worn tire), as shown by the broken-line curve in Figure 4b.

When the surfaces are grooved, the performance of a worn tire under wet conditions improves significantly, when compared with nongrooved surfaces, as shown in Figure 4a; the performance of a new tire is also improved under similar conditions. However, the introduction of grooves on the surfaces renders the performance of a worn tire comparable to that of a new tire, as shown by the solid-line curves in Figures 4a and b.

The data scatter around the solid-line curves in Figure 4 is not indicative of the effect of groove pitch or shape on the available friction levels. Rather, it shows the sensitivity of the coefficient of friction to changes in the water depth; it is relatively more difficult to control small water depths (0.0-0.02 in) precisely; therefore, it is likely that the water depths are varying from these limits.

The puddled surfaces are representative of conditions that can be expected right after heavy rains of short durations. Puddles can also be formed on poorly drained runways or where large variations in temperature produce undulations in the runway surface. In any event, the water-filled puddles are generally not continuous in either the longitudinal or the lateral direction. The flooded runway conditions can be expected as a result of continuous, heavy rainfall. Braking performances on grooved and nongrooved surfaces when puddled and flooded conditions are encountered are shown in Figure 5.

Comparison of Figures 5a and b shows that, for all groove spacings, the braking performance on puddled surfaces is improved by the use of a new tire rather than a worn tire. This improvement is available over the entire range of operating speeds. On the other hand, when flooded conditions are present, the new tire provides gradually improving braking performances as operating speeds are reduced. Tire wear is thus an important factor during low-speed operations on grooved, flooded surfaces.

The braking performance on nongrooved surfaces is poor under puddled and flooded conditions, and the probability that hydroplaning may occur is always high. The results on nongrooved surfaces under puddled and flooded conditions with the use of a worn tire are shown in Figures 5a and c. A coeffi-

Table 2. Test results on PCC surfaces with worn tire.

Test Speed (knots)	Coefficient of Friction x 100: Nongrooved Surface, Broomed			Groove Spacings: 1.25 in			1.50 in			2 in			2.50 in			3 in			4 in		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
70	26	4	4	38	29 29	21 24	36	27 28	19 23	36	27 25	18 22	31	19 19 19	16 18	31	20 19 19	15 10	33	20 19 19	13 8
90	17	4		37	24 19	17 15	34	24 18	15 17	37	19 15	12 14	29	19 22	13 11	29	15 20	9 10	29	10 18	7 6
100	14	4	4																		
110	9			18 19	15 9	14 15	19 21	16 9	8 12	19 21	13 7	9 5	28	13 14	13 6	27	9 8	11 6	20	8 10	6 4
130	7			18 19	15	14 11	19 22	18 13	12 9	20 22	16 12	9 7	30	9 12	13 10	30	9 10	10 6	26	7 8	9 4
140				25	15	12 8	26	15	11 8	25	14	12 8			14			11			9
150	9												27	16 12		24	10 8		24	11	

Notes: Average water depths are as follows: A = 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·f/in² tire inflation pressure.

Table 3. Test results on PCC surfaces with new tire.

Test Speed (knots)	Coefficient of Friction x 100: Nongrooved Surface, Broomed			Grooved Spacings: 1.25 in			1.50 in			2 in			2.50 in			3 in			4 in		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
70	30	29 19 31		41	30 28 24	20 24	43	29 29 24 24	24 19	39	32 29 24	25 21	31	22	21	32	24	24	32	23	24
90	26			32	29 25 24	24 19	31	29 22 23	24 21	35	25 22 19	20 21		17 24 24	24 11		23 15	17 20 24	35	24 15 15 10	14 15 16
110	29 28	17		23	25 19 20	15 11	24	18 21 18	14 9	26	13 17 12	9 8		16 18 19 12	9 17 13		16 14 15 11	6 13 11	34	17 11 8 12 7	10 12 5
130	26 28			37	22 21 15 15 13	13 11	36	13 17 18 14 10 15	8 8	33	16 13 14 14 9 11	7 9	29	17 14 12 11 12	10 12	33	16 11 11 10	11 5	30	13 10 10 8	10 15 4
140	28 28			37	26	16 10	39	17	12 12	34	10	8 8	33	15		28	17	7	24	11	4
150	26																				

Notes: Average water depths are as follows: A = 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; 1 40 lb·f² tire inflation pressure.

cient of friction of only 0.05 is available when operating speeds were below 100 knots; above 100-knot operating speeds, the wheel was locked at all of the braking pressures. A friction coefficient of 0.05 is generally accepted as a level that represents hydroplaning. The friction force that corresponds to a coefficient of friction of 0.05 is 5 percent of the vertical load on the tire. The introduction of grooves on the surface has increased the available friction from 0.05 to a maximum of 0.29; the smallest increase occurs for the worn tire in operation on flooded surface; the largest increase occurs for a new tire in operation on puddled surface.

Although the use of newer tires and grooved runways will shift the onset of hydroplaning to a higher speed, they cannot, in all cases, completely eliminate it. As the operating speeds increase, the time available for the fluid particles to escape from the tire-runway contact area decreases. Any increase in number of escape paths, either by providing patterns in the tire tread or grooves in the runway surface, cannot totally compensate for the reduction in available time brought about by higher operating speeds. Closer spacings between the grooves, however, will provide more discharge outlets to the water entrapped in the contact area. Although the number of discharge outlets will be increased, the reduction in time available for a fluid particle to go from one discharge outlet to another when the groove spacing is reduced from, for example, 3 in down to 1.25 in will be 0.000 87 s at 100-knots operating speed. The question, therefore, arises as to whether the entrapped mass of water, because of its inertia, can respond fast enough to show any significant changes in braking performance on the two spacings used in the above example. Clearly, much larger spacings will have adverse effects on the braking performance; Figure 5 seems to support this argument. It shows a large drop in coefficient of friction for 4-in groove spacing over 1.25-in groove spacing. However, no consistent trend is identifiable regarding the direction in which the friction force is changing when the entire spectrum of groove-spacings is considered.

Figure 2. Coefficient of friction as function of speed under puddled and flooded surface conditions on saw-cut grooves for 1.25- and 1.50-in pitch.

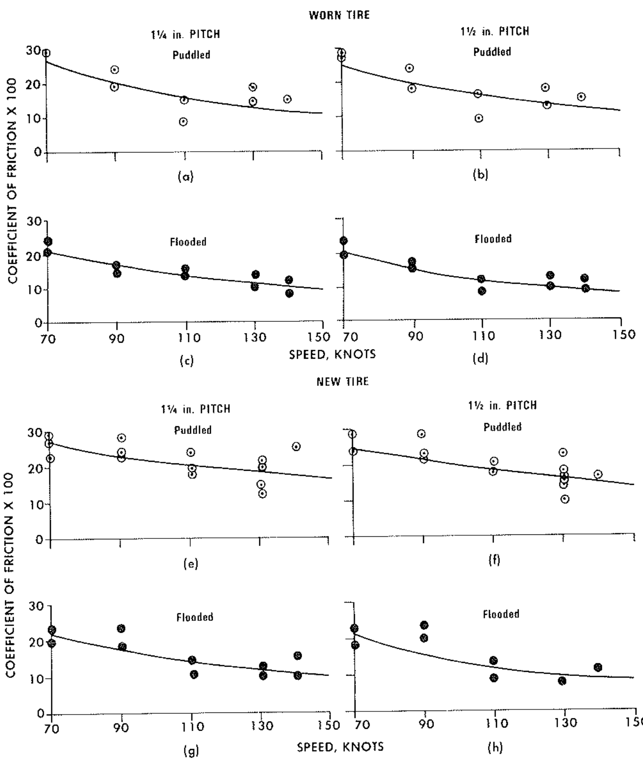


Figure 3. Coefficient of friction as function of speed under puddled and surface conditions on saw-cut grooves for 3- and 4-in pitch.

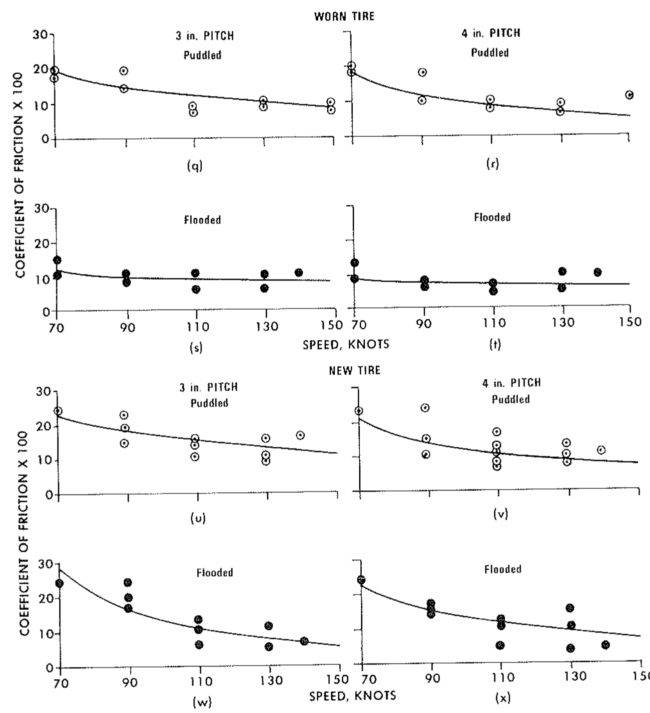
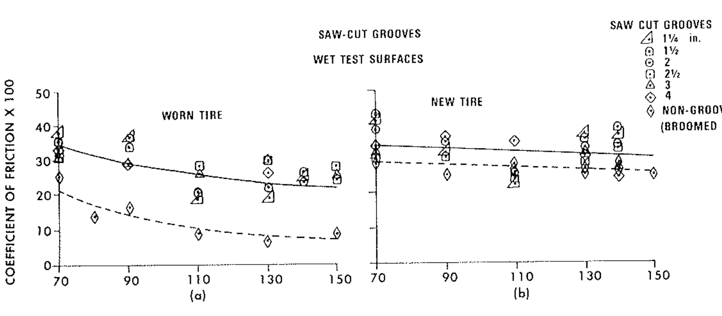


Figure 4. Coefficient of friction as function of speed under wet surface conditions on saw-cut grooves.



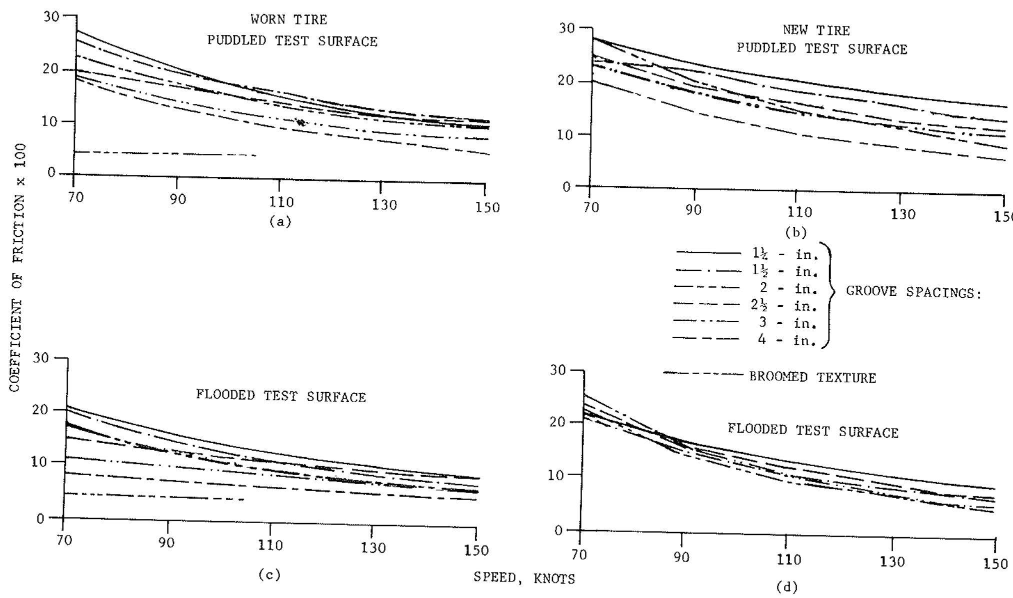
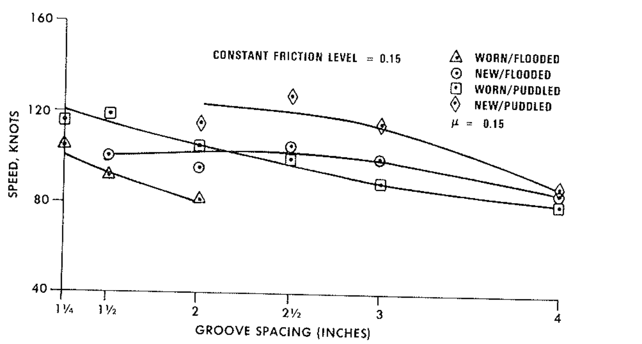


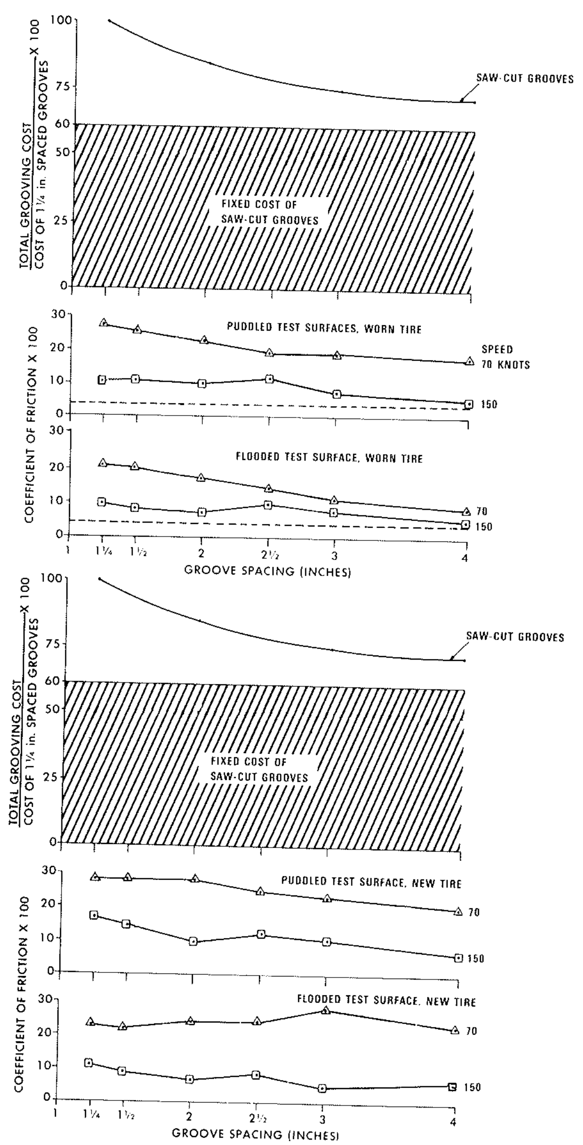
Figure 5. Comparison of relative braking performance of worn and new tires.

Figure 6. Comparison of attainable speed for constant friction level on saw-cut grooves.



If a coefficient of friction (μ) of 0.15 is arbitrarily chosen as a performance level that is expected from any of the groove configurations included in the test program, it is possible to compare the braking performance on these grooves in terms of attainable speeds under various operating conditions. The data from Figure 5 are replotted in Figure 6 for a constant friction level of 0.15. Certain observations can be made from a review of Figure 6. Under flooded conditions, the grooves spaced beyond 2 in cannot provide a μ of 0.15 with worn tires even at low operating speeds. This can be expected because the only channels for water to escape from the contact area are the grooves, and there are not enough of them. In this situation, the smaller the groove spacing, the better the braking performance. However, the consequence that groove spacing beyond 2 in cannot sustain a friction level of 0.15 is of little importance. The completely worn tire and the flooded surface represent two extremes of tire wear and runway contamination, respectively; the likelihood of this combination being present at the runways is very small. If the grooved surfaces were puddled, the same worn tire can now attain a friction level of 0.15 under an operating speed range of 120-80 knots between the groove spacings of 1.25 and 4 in, respectively. In general, as the groove spacing is increased, the operating speed to maintain a constant friction

Figure 7. Braking performance and estimated grooving cost as function of groove spacing.



level of 0.15 decreases. The rate of decrease is smaller with a new tire.

The effect of groove spacing on the braking performance of a worn or a new tire on puddled and flooded surfaces can also be evaluated from Figure 7. This figure shows the data from Figure 5 re-plotted in an alternate manner; the effect of groove spacing is compared in terms of maximum available coefficient of friction under various other test conditions.

In all cases, the friction coefficient decreases as the speed increases for all the groove spacings. The friction levels attainable on nongrooved surfaces approach the hydroplaning level ($\mu = 0.05$) at operating speeds of 100 knots or less; the introduction of grooves increases both the level of friction available and attainable speeds; the lower the operating speeds, the higher the available level of friction.

When comparing the effects of increased groove spacings under constant operating conditions, note that, although the overall effect is a decrease in friction level with increased spacings, the decrease cannot be classified as significant. If the operation with new tires is considered, by increasing the spacing from 2 to 3 in, the friction force remains unchanged at 150 knots. In fact, the decrease in friction force, when the groove spacing is increased from the current standard value of 1.25 to 2 or 3 in, is a maximum of 0.06 with new tires operated on puddled or flooded surfaces. A slightly higher decrease occurs with a worn tire under similar operating conditions.

Cost Analysis

The total cost of grooving is a function of many variables; groove spacing is one of them. The investigation by a Washington, D.C., firm concluded that fixed and variable construction costs for grooving runways are 60 and 40 percent, respectively, of total cost and that the variable cost savings increase nonlinearly with groove spacing. For example, by cutting grooves at 2-in spacing, the cost savings over 1.25-in groove spacing are 15 percent (out of the total available of 40 percent). The cost saving for 3- and 4-in spacings over 1.25-in spacing are 25 and 28 percent, respectively (Figure 7).

Cost-Effective Groove Configuration

As pointed out earlier in this paper, the cost-effective groove configuration must meet certain criteria. We showed in Figure 5 that the overall effect of an increase in the groove spacings is a decrease in available friction. However, the decrease is not significant. In addition, the braking performance on all the grooved surfaces tested is significantly higher than on nongrooved surfaces; friction levels that represent hydroplaning condition were observed on both puddled and flooded, nongrooved surfaces (Figures 5a and c). If performance alone were a factor for selecting a groove configuration, 1.25-in spaced grooved runways will provide maximum friction levels under all operating conditions included in this study. However, in the majority of cases, both the cost and performance are considered to be important when installing grooves on runways. In these cases the groove spacings of 2 or 3 in will provide sufficient braking to allow a gradual reduction in the speed of an aircraft and thus develop further braking. In addition, savings of up to 25 percent in the cost of groove installation (compared with installation cost of 1.25-in spaced grooves) are available.

CONCLUSIONS

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

1. The conventional saw-cut grooves spaced at 3 in or less will provide acceptable braking performance to an aircraft on water-covered surfaces. Installation cost of these grooves is up to 25 percent less than that of the grooves spaced at 1.25 in.
2. Conventional saw-cut grooves spaced at 1.25 in provide maximum friction levels under all operating conditions included in this study.

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