Modified Reflex-Percussive Grooves for Runways

SATISH K. AGRAWAL and HECTOR DAIUTOLO

ABSTRACT

Runway surface treatments, such as grooving, can minimize the danger of aircraft hydroplaning by reducing the water buildup on the runway and by facilitating forced water escape from the tire-runway interface. Square saw-cut 1/4-in. grooves spaced between 1 and 2 1/2 in. have been widely used; the former provide a higher resistance to hydroplaning. Other surface treatments that have been reported as being effective in minimizing aircraft hydroplaning include porous friction overlay and reflex-percussive grooves; the latter are offered as a cost-effective alternative to square saw-cut grooves. As the title of this paper suggests, the modified reflex-percussive grooves are a derivative of reflex-percussive grooves in that the cutting heads for the latter were modified to produce smoother groove edges, which tend to improve water flow through the groove channels. Comparative dynamic tests showed that the braking action of an aircraft tire on modified reflex-percussive grooves is equivalent to that on square saw-cut grooves spaced between 1 1/4 and 2 in. Results also showed that hydroplaning was not initiated at speeds of up to 150 knots. The lower cost of the modified grooves makes them a viable cost-competitive method; however, realistic cost estimates and full savings potential can only be affirmed after application of these grooves in an operational environment.

A rain-soaked runway poses a problem unique to a landing aircraft: if sufficient water is accumulated on the runway as a result of rainfall, the aircraft may hydroplane. In hydroplaning, a thin layer of water separates the aircraft tire from the runway surface. The net result is a severe degradation of the braking action of the aircraft and of the ability to bring the aircraft to a stop. Adequate slope and proper runway surface treatments help reduce the accumulation of large amounts of water. Commonly used surface treatments include grooving and porous friction overlays. Although grooves can be installed on both portland cement concrete (PCC) and asphaltic concrete surfaces, the porous friction overlays are limited to the latter.

In its efforts to determine low-cost surface treatments that provide adequate braking action to aircraft, the Federal Aviation Administration (FAA) has identified (1) a reflex-percussive grooving process as a viable cost-effective alternative to square saw-cut grooves. The process, which is based on the principle of controlled removal of concrete, was first developed in Great Britain to provide a rough finish on the pavement. The great advantage of the cutting process is its ability to not loosen the aggregate particles within the matrix and not create microfractures in the surrounding concrete. When the cutting head strikes the surface of the concrete it causes the material directly under the area of impact to deflect downward, thus creating momentary and localized compression. The compressive strain is mainly elastic and is almost immediately given up in generating a rebound that causes the concrete to attempt to pass through its relaxed state into one of tension nearly equal to the initial compression. However, because it is very weak in tension, the concrete fractures, and elastic energy is given up as kinetic energy of the flying fragments.

Klarcrete Limited of Canada demonstrated that the reflex-percussive process can be readily adapted for grooving in PCC surfaces. However, the cutting heads that performed successfully in PCC (1) were unsatisfactory in cutting smooth grooves in asphaltic concrete surfaces (2); the primary reason is the decrease in the reflex action of the percussive process in viscoelastic asphaltic concrete. The developer of the cutting heads, therefore, designed new heads that produced significantly improved grooves in asphaltic concrete surfaces. Consequently, the research described herein was undertaken to determine if the grooves produced by these modified cutting heads will provide "acceptable braking action" to an aircraft tire and be cost competitive with the square saw-cut grooves.

MODIFIED REFLEX-PERCUSSIVE GROOVES AND SQUARE SAW-CUT GROOVES

The cutting heads for the original and modified reflex-percussive grooves are shown in Figure 1. When installed on the machine shown in Figure 2, the cutting head rotates about its axis in a random manner as it strikes the concrete surface. The speeds of forward motion and cutting stroke are pneumatically controlled. It is believed that the continuous cutting edge of the modified head provides overlapping strokes that tend to produce a smooth groove channel. The square saw-cut grooves are installed by a rotary saw equipped with diamond-tipped blades. The rotary saw, shown in Figure 3, is also pneumatically powered.

Figures 4 and 5 show the asphaltic concrete test sections and groove dimensions. The program included square saw-cut grooves at spacings of 1 1/4 and 2 in.; the former spacing provides higher resistance to hydroplaning (1,3).

HYDROPLANING

When an aircraft lands on a water-covered runway, the tires first contact the top of the water layer and then descend through this layer. The descent is relatively simple until the aircraft weight is transferred to the tires. During this transfer, a

FIGURE 1 Original and modified cutting heads for installing reflex-percussive grooves.

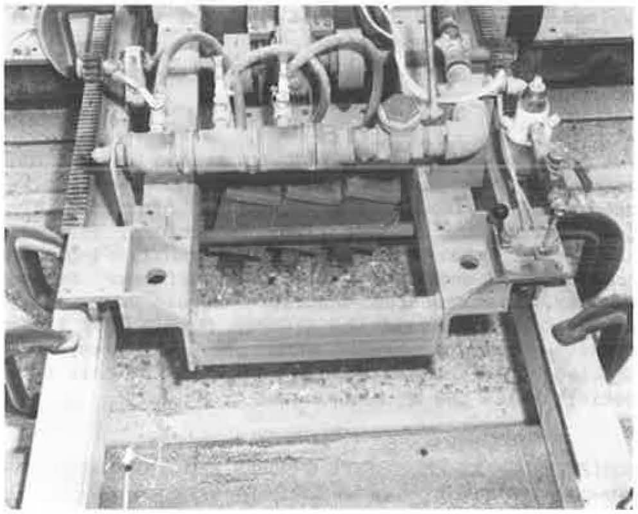

FIGURE 2 Machine for installing reflex-percussive grooves in the test sections.

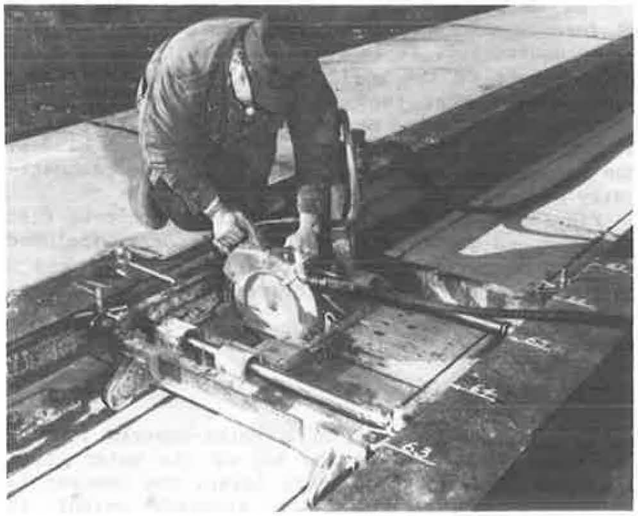

FIGURE 3 Machine for installing saw-cut grooves in the test sections.

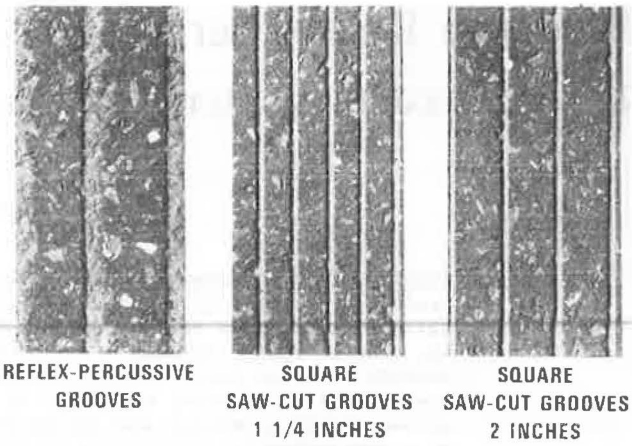

FIGURE 4 Various test sections of asphaltic concrete test bed (each section is 40 ft long).

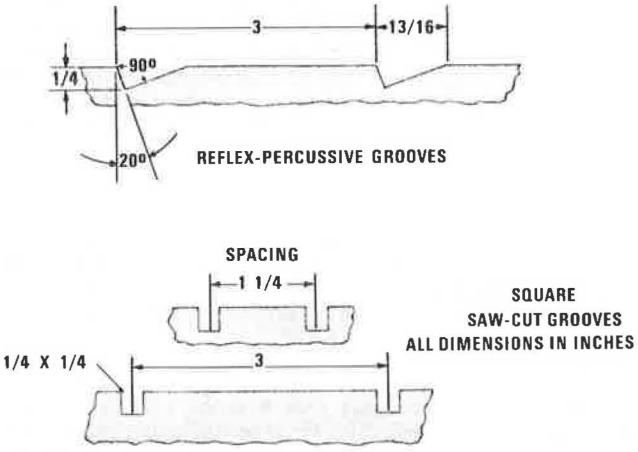

FIGURE 5 Dimensions of reflex-percussive grooves and saw-cut grooves.

complex water flow exists in the space bounded by the tire at the upper end and the runway at the lower end. Water enclosed in the bounded space undergoes rapid change of momentum and generates large forces. These forces act on the tire surface and deform it radially; if the forces exceed aircraft weight, the tire surface will be lifted and supported entirely by the water layer. This condition is called hydroplaning. Friction forces in the tire-runway contact area approach zero during hydroplaning and aircraft braking and directional control are essentially nil. It is important to note that the time elapsed between the initial contact of the tire with the top of the water layer and eventual hydroplaning (should the conditions be sufficient to induce hydroplaning) is on the order of a fraction of a second (4).

Hydroplaning is not always imminent; operational and environmental conditions determine the nature of water flow under the tire. Water depth on the runway and aircraft speed are the two important parameters that share the most responsibility for inducing hydroplaning. However, because aircraft landing speeds are limited by aerodynamic considerations and cannot be varied much beyond those limits, water accumulation alone becomes the critical parameter for inducing hydroplaning. Efforts are therefore expended in reducing water accumulation on the runway.

Near elimination of aircraft hydroplaning on a grooved runway is believed to be the result of a dual process of water removal from the tire-runway contact area. First, the grooves facilitate free flow of water through the channels during rainfall; except in cases of continuous rainfall of high intensity, this channel flow reduces average water depth compared to that on a nongrooved runway under similar rainfall conditions. Second, water is forced out from under the tire when the aircraft travels on a water-covered grooved runway. In contrast, the forced water escape is much more difficult on a nongrooved runway.

MEASUREMENT OF BRAKING ACTION

The braking action of an aircraft tire is a function of the frictional forces developed in the tire-runway contact area. These forces are developed as a result of relative motion between the tire surface and the runway. The braking action can be represented by a coefficient of friction that is the ratio of the friction forces developed in the contact area to the vertical load on the tire. As the coefficient of friction decreases, so does the braking action.

In theory, the coefficient of friction approaches zero at the onset of hydroplaning; however, small viscous and mechanical drags are always present. For a direct measure of hydroplaning speed, various drag forces must be separated. This is generally difficult if only because of the need for highly sensitive instrumentation for measuring small quantities. Various indirect methods have been used in the past (5) to identify the onset of hydroplaning. In the present study, incipient hydroplaning is indicated when the computed coefficient of friction is 0.05 or lower. In comparison, the average coefficient of friction between an aircraft tire and a dry runway is approximately 0.70 during landing.

There are two methods by which a meaningful comparison of the braking action of an aircraft tire on 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 value of the available coefficient of friction on each test surface. This study employs the second method.

The maximum value of the available friction coefficient can be obtained by conducting a series of tests in which applied braking effort is gradually increased, other operational conditions of the tire and runway being identical during the series. Because precise duplication of operational conditions is difficult, care should be taken in controlling and monitoring the test conditions. Under ideal conditions, the friction coefficient will initially increase, then reach a maximum value, and finally drop as the braking effort is gradually increased.

Clearly, this method of comparing braking action of an aircraft tire on various surfaces involves a large number of tests. However, it represents a realistic reproduction of the aircraft braking process. The disadvantage of the first method is accelerated treadwear of the tire, which may require frequent tire changes; danger of tire blowout is also present in the first method.

EXPERIMENTAL PROGRAM

The experimental program was conducted at Track 3 of the Naval Air Engineering Center, Lakehurst, New Jersey. The track is 1 1/4 mi long and has guide rails spaced 52 1/4 in. apart and running parallel to the track centerline. Reinforced concrete strips extending beyond the guide rails to a width of 28 ft also run parallel to the track. The last 144 ft of the track contained the test bed. The test bed was 2 1/2 in. thick and 30 in. wide and was made of asphaltic concrete.

The major components of the test equipment are (a) a four-wheeled jet car, (b) a dead-loaded carriage that supports the dynamometer and wheel assembly, and (c) the measurement system. The jet car (Figure 6) is powered with four J48-P-8 aircraft engines that develop a total thrust of 24,000 lb. The jet car is used to propel the dynamometer, the wheel assembly, and the carriage from the launch end at a preselected speed. The 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.

FIGURE 6 Jet-powered pusher car for providing preselected speeds to test equipment.

The dynamometer and wheel assembly were designed and fabricated by the FAA and have the capability of simulating a jet transport tire-wheel assembly under touchdown and rollout conditions. The dynamometer is similar in design to one developed by the National Aeronautics and Space Administration (NASA) for the Langley Test Facility (6). Figure 7 shows the dynamometer and wheel assembly and the details of the instrumentation for measuring vertical and horizontal loads at the axle. The assembly is pivoted about an axis contained in the dead-load carriage.

Test Section

The 144-ft test bed was divided into four 36-ft sections (Figure 8). The dimensional tolerance of the asphaltic test bed was held within ±3/32 in. from horizontal. The first two sections contained the reflex-percussive grooves produced by the modified cutting heads; the other two contained 1/4-in. square grooves at spacings of 1 1/4 and 2 in.

Test Parameters

The operational parameters were selected to represent main landing gear assembly values typical of heavy jet aircraft during landing and rollout. The environmental parameters included water accumulation

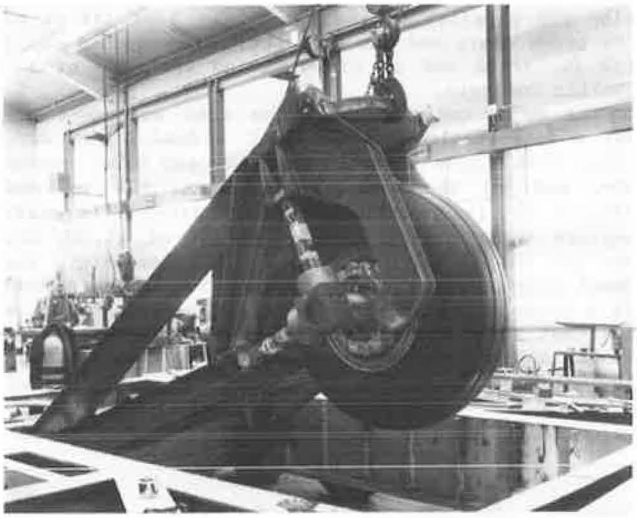

FIGURE 7 Dynamometer and wheel assembly showing vertical and horizontal load links.

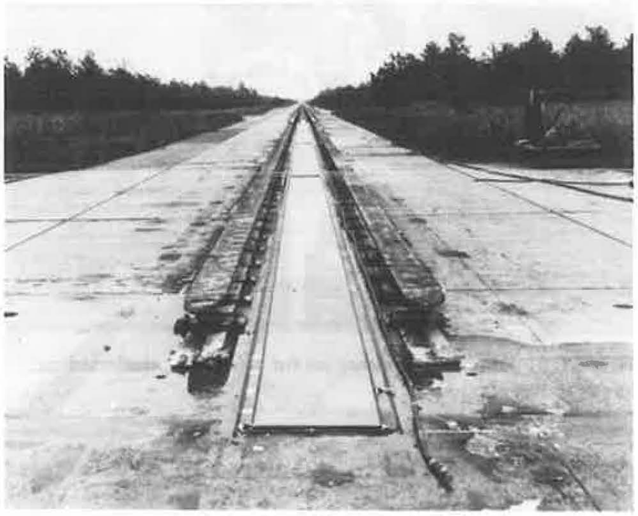

FIGURE 8 Test bed at the end of the test track.

representative of light to moderate rain. A summary of the test parameters follows.

Operational Parameters

Tire	
Vertical load	35,000 lb
Inflation pressure	140 lb per square inch
Tread design	Worn
Size/type	49 x 17, 26-ply, Type VII
Pavement	
Type	Asphaltic concrete
Texture	0.015 (nongrooved)
Surface treatments	Reflex-percussive grooves with 20-degree groove angle and 3-in. spacing Square saw-cut grooves, 1/4-in. size at 1 1/4- and 2-in. spacings
Aircraft	
Speed	70 to 150 knots
Wheel operation	Rolling to locked wheel
Brake pressure (braking effort)	200 to 2,200 lb per square inch

Environmental Parameters

Light rain	Wet: water depth less than 0.01 in.
Moderate rain	Puddled: water depth of 0.10 in. or more

This investigation included the rainfall conditions that will represent "wet" and "puddled" water conditions on the runway. Wet conditions are normally encountered during or after a light rain. The surfaces may be saturated with water but do not have measurable water depth present on them. The puddled surfaces are representative of conditions that can be expected immediately after heavy rains of short duration.

Test Procedure

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

1. Water depth was set on the test sections at the recovery end.
2. Jet engines were started at the launch end and set at a performance level to provide the preselected speed in the test section.
3. The jet car was released to propel the test equipment (dead-load carriage and dynamometer assembly). The test tire remained in free-rolling mode.
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 carriage and dynamometer assembly to enter the first test section at the preselected speed. The speed decayed by 1 to 2 knots in the remaining sections.
5. Before the dynamometer assembly entered the first section, the hydraulic systems were activated to apply the vertical load and brake pressure on the tire.
6. The wheel entered the test sections under 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.

The automatic data handling system is a multichannel analog recording system. It uses standard FM/FM telemetry for transmission of data from the mobile dead load. Both low- and high-level signals are frequency multiplexed for recording on a single magnetic tape. Recovery of these data in analog form permits early validation and review of the data for further testing purposes.

Tables 1 and 2 give the results on the asphaltic concrete sections. The coefficients of friction in these tables are the maximum developed under each set of operating conditions; many more tests were conducted to obtain the maximums. A least squares fit was obtained between speed and coefficient of friction.

DISCUSSION

The relevant figures show the results of the braking tests. The curves show the variation of the maximum friction coefficient with speed under wet or puddled water conditions. The data show the well-established trend that friction coefficient decreases with increasing speed.

Under wet water conditions, the friction coeffi-

TABLE 1 Least Squares Problem—Worn Tire on Wet Surface

```
NO. OBSERVATIONS         14
POLY. DEGREE              2
                                                 TREATMENTS:
           COEFFICIENTS                          A - 1 1/4 INCH SPACING

 0           0.36780E 02                         B - 2 INCH SPACING
 1           0.53487E-01
 2          -0.76476E-03                         C - MODIFIED REFLEX
                                                     PERCUSSIVE GROOVES

                         COEFFICIENT OF FRICTION X 100

POINT  SPEED, KNOTS   MEASURED       CALCULATED     DIFFERENCE    TREATMENT
    1  0.70000E 02   0.33000E 02   0.36777E 02  -0.37769E 01        C
    2  0.70000E 02   0.35000E 02   0.36777E 02  -0.17769E 01        C
    3  0.70000E 02   0.39000E 02   0.36777E 02   0.22231E 01        B
    4  0.70000E 02   0.40000E 02   0.36777E 02   0.32231E 01        A
    5  0.10900E 03   0.34000E 02   0.33524E 02   0.47589E 00        A
    6  0.10900E 03   0.34000E 02   0.33524E 02   0.47589E 00        B
    7  0.10900E 03   0.36000E 02   0.33524E 02   0.24759E 01        B
    8  0.11100E 03   0.30000E 02   0.33295E 02  -0.32946E 01        C
    9  0.13900E 03   0.29000E 02   0.29439E 02  -0.43890E 00        B
   10  0.14000E 03   0.28000E 02   0.29279E 02  -0.12790E 01        A
   11  0.14100E 03   0.29000E 02   0.29118E 02  -0.11761E 00        C
   12  0.14100E 03   0.29000E 02   0.29118E 02  -0.11761E 00        C
   13  0.14100E 03   0.30000E 02   0.29118E 02   0.88239E 00        B
   14  0.14200E 03   0.30000E 02   0.28955E 02   0.10453E 01        C

ERR**2 =  0.53918E 02               STD-ERR =  0.22140E 01
```

TABLE 2 Least Squares Problem—Worn Tire on Puddled Surface

```
NO. OBSERVATIONS         16
POLY. DEGREE              2
                                                 TREATMENTS:
           COEFFICIENTS                          A - 1 1/4 INCH SPACING

 0           0.93076E 02                         B - 2 INCH SPACING
 1          -0.12521E 01
 2           0.47055E-02                         C - MODIFIED REFLEX
                                                     PERCUSSIVE GROOVES

                         COEFFICIENT OF FRICTION X 100

POINT  SPEED, KNOTS   MEASURED       CALCULATED     DIFFERENCE    TREATMENT
    1  0.70000E 02   0.25000E 02   0.28486E 02  -0.34861E 01        C
    2  0.71000E 02   0.31500E 02   0.27898E 02   0.36025E 01        A
    3  0.72000E 02   0.25000E 02   0.27318E 02  -0.23183E 01        C
    4  0.72000E 02   0.33000E 02   0.27318E 02   0.56817E 01        B
    5  0.74000E 02   0.24000E 02   0.26188E 02  -0.21881E 01        C
    6  0.89000E 02   0.18000E 02   0.18912E 02  -0.91159E 00        C
    7  0.89000E 02   0.17000E 02   0.18912E 02  -0.19116E 01        C
    8  0.10800E 03   0.12500E 02   0.12734E 02  -0.23445E 00        C
    9  0.10900E 03   0.11000E 02   0.12503E 02  -0.15035E 01        B
   10  0.11000E 03   0.14500E 02   0.12282E 02   0.22181E 01        A
   11  0.11100E 03   0.13000E 02   0.12070E 02   0.93032E 00        C
   12  0.12900E 03   0.11000E 02   0.98597E 01   0.11403E 01        A
   13  0.13400E 03   0.10000E 02   0.97870E 01   0.21300E 00        C
   14  0.13600E 03   0.11000E 02   0.98238E 01   0.11762E 01        A
   15  0.13800E 03   0.85000E 01   0.98982E 01  -0.13982E 01        C
   16  0.14000E 03   0.90000E 01   0.10010E 02  -0.10103E 01        B

ERR**2 =  0.85866E 02               STD-ERR =  0.25700E 01
```

cients are "relatively high" throughout the speed range (Figure 9). A single curve can adequately represent the braking action of an aircraft tire on both the square saw-cut grooves and the modified reflex-percussive grooves.

When the wetness on the surface is representative of puddled conditions, the spacing of the saw-cut grooves starts to influence the maximum friction coefficient (Figure 10) available in the tire-runway contact area. The separation of the two solid lines in Figure 10 is not large; however, the grooves spaced at 1 1/4 in. provide higher friction coefficients than do the grooves spaced at 2 in. The performance of modified reflex-percussive grooves falls between the curves for saw-cut grooves spaced at 1 1/4 and 2 in. for speeds above 90 knots.

The improvement provided by the modified cutting heads (Figure 1) over the standard cutting heads (Figure 1) can be best evaluated by comparing the results obtained with both heads. Figure 11 shows the data [from Agrawal (2)] using the standard cutting heads for reflex-percussive grooves; the data for square saw-cut grooves are also included. The most distinct feature in Figures 10 and 11 is the shift in the coefficient-of-friction curve for the reflex-percussive grooves: the coefficient curve resulting from the use of modified cutting head lies above the curve for saw-cut grooves spaced at 2 in.; the coefficient curve resulting from the use of standard cutting heads lies below the curve for saw-cut grooves spaced at 2 in.

Though the data on the puddled surface are repre-

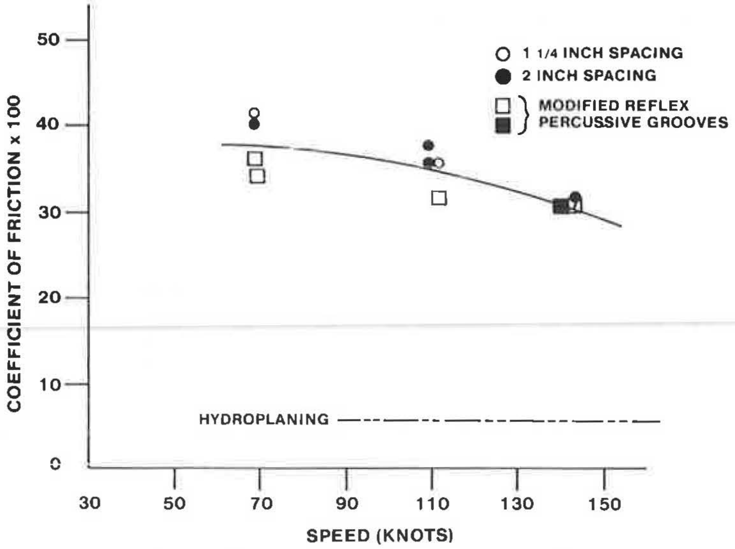

FIGURE 9 Braking performance of a worn tire on wet surfaces.

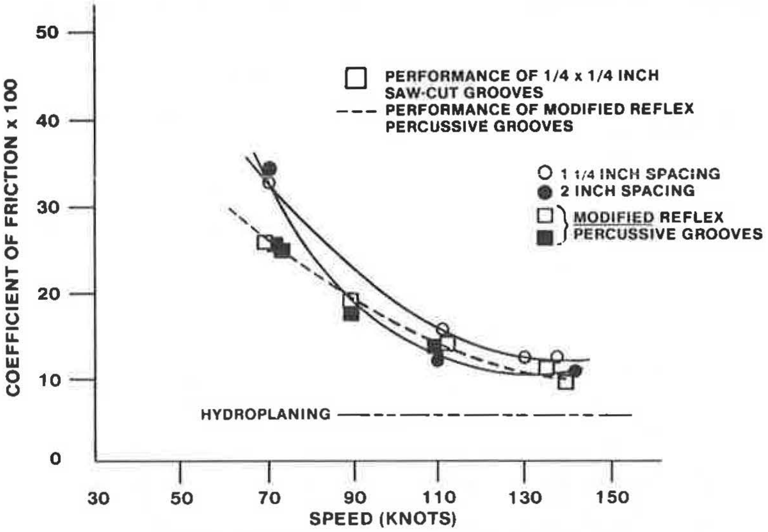

FIGURE 10 Braking performance of a worn tire on puddled surfaces.

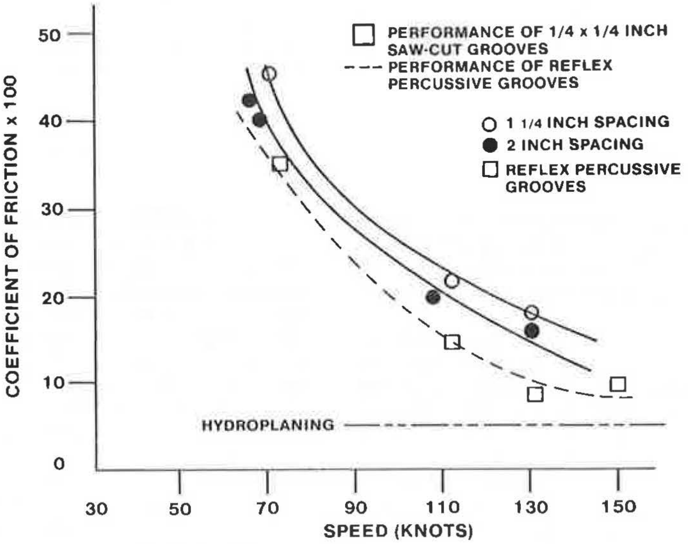

FIGURE 11 Braking performance of a worn tire on puddled surfaces *(2)*.

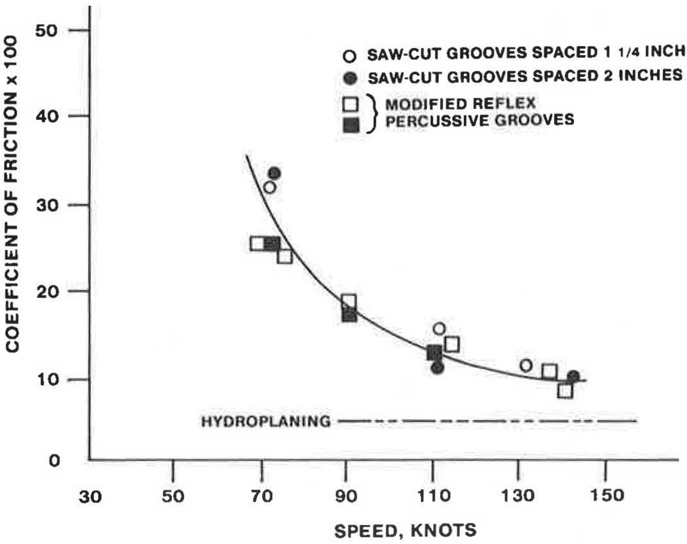

FIGURE 12 Combined braking performance of a worn tire on puddled surfaces.

sented by individual curves for various surface treatment (Figure 10), it may be reasonable to draw a single curve (Figure 12) to show the performance on the two types of grooves, particularly because the data scatter is small in the high-speed range. It can also be observed that in both wetness conditions (Figures 9 and 12) the friction coefficients are above the hydroplaning level (coefficient = 0.05).

A previous study (1) has concluded from cost analysis of various grooving methods that the cost of installing reflex-percussive grooves could be as low as half the cost of saw-cut grooves spaced at 1-1/4 in. This study has shown that with the use of the modified cutting heads, the performance tradeoff is minimized: modified reflex-percussive grooves provide braking action nearly equivalent to that provided by saw-cut grooves spaced between 1 1/4 and 2 in.

CONCLUSION

It can be concluded from the findings of this research that the modified reflex-percussive grooves are a viable cost-effective alternative to square saw-cut grooves. However, realistic cost estimates and full savings potential can only be affirmed after these grooves have been applied in an operational environment.

REFERENCES

1. S.K. Agrawal and H. Daiutolo. Reflex-Percussive Grooves for Runways: Alternative to Saw-Cutting. In Transportation Research Record 836, TRB, National Research Council, Washington, D.C., 1981, pp. 49-55.
2. S.K. Agrawal. Braking of an Aircraft Tire on Grooved and Porous Asphaltic Concrete. Report DOT/FAA/RD-82-77. Federal Aviation Administration Technical Center, Atlantic City, N.J., Jan. 1983.
3. T.J. Yager. Comparative Braking Performance of Various Aircraft on Grooved and Ungrooved Pavements at the Landing Research Runway, NASA Wallops Station. Paper 3, NASA SP-5073. Conference on Pavement Grooving and Traction Studies, Langley Research Center, Hampton, Va., Nov. 1968.
4. S.K. Agrawal and J.J. Henry. A Simple Tire Deformation Model for the Transient Aspects of Hydroplaning. Tire Science and Technology, Vol. 8, Nos. 3-4, July, Dec. 1980.
5. S.K. Agrawal, W.E. Meyer, and J.J. Henry. Measurement of Hydroplaning Potential. Report PTI-7701. Pennsylvania State University, University Park, Pa., Feb. 1977.
6. U.T. Joyner, W.B. Horn, and T.J.W. Leland. Investigation on the Ground Performance of Aircraft Relating to Wet Runway Braking and Slush Drag. Report 429. Advisory Group for Aeronautical Research and Development, Paris, France, Jan. 1963.

Publication of this paper sponsored by Committee on Surface Properties-Vehicle Interaction.