Tire Hydroplaning and Its Effects on Tire Traction

WALTER B. HORNE, NASA Langley Research Center, Langley Station, Hampton, Va.

This paper first discusses the buildup of fluid pressures in the tire-ground footprint region of wet pavements that can lead to three distinct types of traction loss; namely, dynamic hydroplaning, viscous hydroplaning or thin-film lubrication, and the reverted rubber skid. The paper then discusses how pavement surface texture, pavement water depth, tire tread design, vertical load, and tire inflation pressure affect fluid pressure buildup in the footprint. Finally, two promising methods for alleviating fluid pressure buildup are discussed. These methods are pavement grooving and air jets placed in front of tires.

•WHY is it that skid-type accident rates of both highway vehicles and landing aircraft are much higher during operation on wet pavements than on dry? The answer is that traction characteristics are different and that wet pavements are more slippery than dry pavements. In the past, however, many wet skidding accidents of aircraft were blamed on faulty piloting techniques by the aircraft pilot concerned. Actually, recent research on wet skidding accidents points the main blame for these accidents on a little-understood wet pavement hazard called tire hydroplaning over which the pilot has little or no control. A similar situation faces the automobile driver. Although he does have more control over his speed, he still may be unaware of actual reductions in friction which may occur as a result of wet conditions, especially on smooth, curved pavements.

Tire hydroplaning is usually defined as the condition which exists when a film of water or other contaminant is present in the footprint and separates the tire from the pavement surface. The development of fluid pressures in this water film, which causes hydroplaning to occur, is extremely complicated and depends on many pavement, fluid, tire, and vehicle parameters. It is the purpose of this paper to discuss the effects and variations of fluid pressure which, acting separately or in concert, produce hydroplaning and to point out the parameters of importance. The paper also discusses certain vehicle, tire, and pavement design techniques which can be used to alleviate hydroplaning effects on vehicle traction.

THE ROLLING TIRE

When an unbraked freely rolling tire runs into stationary water on a flooded smooth-surfaced pavement, both viscous and dynamic water pressures can be produced in the tire-ground contact region (Fig. 1). The data in this figure were obtained by recording the water pressures generated in a tread groove and on an adjacent tread rib as an aircraft tire rolled across a water-covered smooth-surfaced pressure plate. The dynamic water pressure results from the stagnation pressure developed at the tire-water interface across the width of the tire at the operational speed. Its effect creates the initial pressure rise shown by both tread and groove water pressures in Figure 1.

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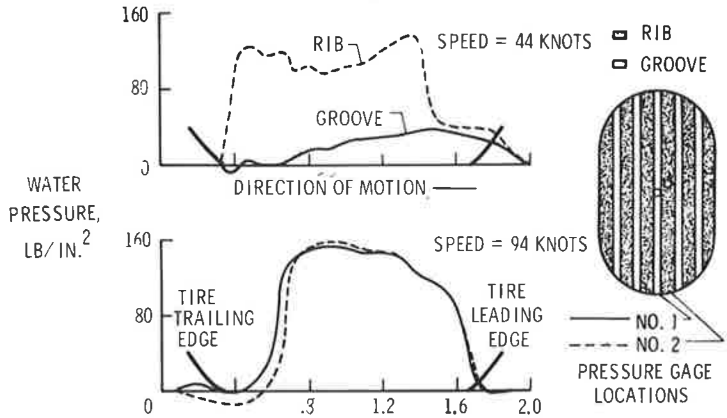

Figure 1. Fluid ground pressure signatures (water depth = 1.0 in.; tire pressure = 90 psi).

The viscous pressure is created by the inability of the rubber in the tread rib to puncture and displace the very thin and viscous residual film left on the smooth pavement after the majority of the water encountered has been displaced or squeezed out from under the tire. The pressure in the water film under the rib, in this case, must rise to the magnitude of the local tire-ground bearing pressure acting on the tread rib because of the tire vertical load. This effect is indicated by the much higher water pressures developed on the tread rib toward the rear of the footprint in Figure 1. Note that under these conditions, the pressure in the groove is correspondingly lower.

By definition, hydroplaning must occur at any speed where the combination of dynamic and viscous water pressures balance the tire-ground bearing pressure over the tire footprint. When this occurs, the tire is lifted off the pavement and rides on a water film. Research indicates that when dynamic water pressures predominate in the footprint, this speed is predicted by the simple relation $V_P = 9\sqrt{p}$, kts, or $V_P = 10\sqrt{p}$, mph, where V_P is the hydroplaning speed, and p is the inflation pressure in pounds per square inch.

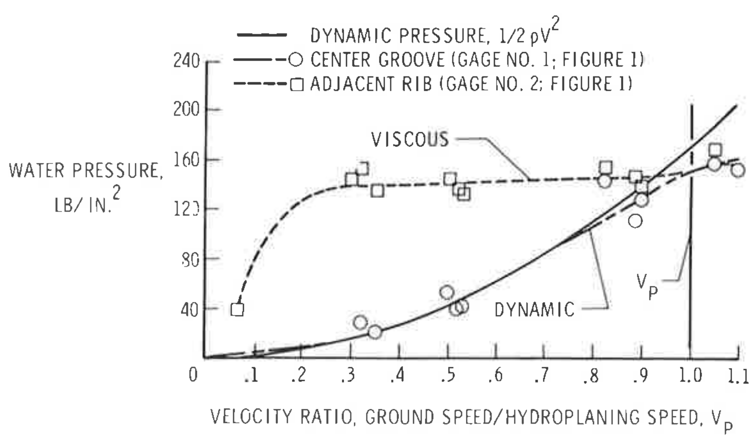

Figure 2. Variation of peak water pressures in rolling tire footprint (water depth = 1.0 in.; tire pressure = 90 psi).

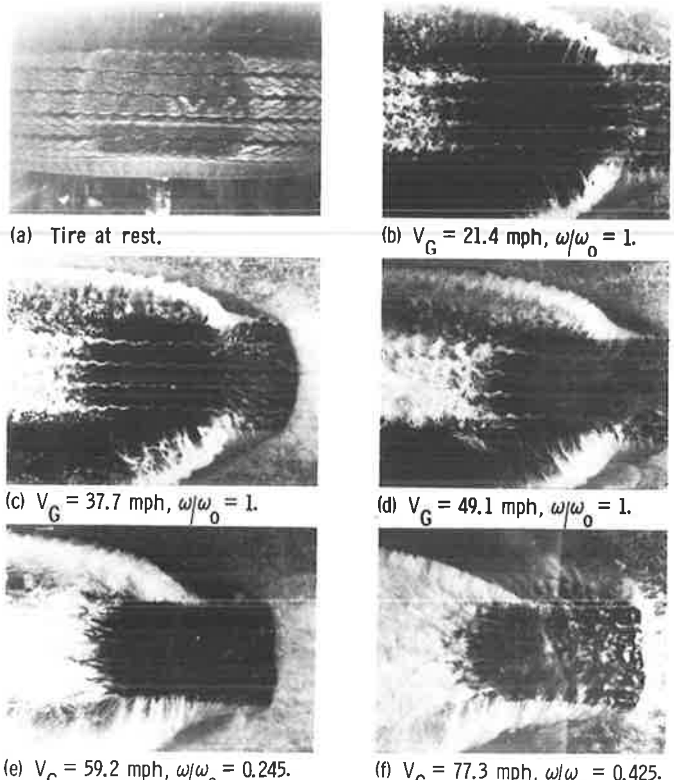

Figure 3. Photographs of typical production-type tire taken through glass plate (water depth = 0.4 in.; vertical load = 835 lb; yaw angle = 6°; direction of motion, left to right).

The data presented in Figure 2, which contrasts the viscous (rib) pressures with the dynamic (groove) pressures, show that the equation in the preceding paragraph is not appropriate for the case when viscous pressures predominate in the footprint (for example, a smooth tire on wet ice). These data show that viscous pressures build up much more rapidly with ground speed than dynamic pressures. Thus viscous hydroplaning will occur at much lower speeds than dynamic hydroplaning unless viscous pressures are alleviated by pavement texture or tire tread design.

The progressive development of hydroplaning with speed on an automobile tire rolling across a flooded glass runway surface is shown in Figure 3.

THE SKIDDING TIRE—DRY PAVEMENTS

The ability of a tire to develop traction on dry pavements depends to a great extent on whether the tire is rolling or sliding on the pavement. This is illustrated by the data presented in Figure 4 where braking and sideways friction coefficeints are plotted against slip ratio. (Slip ratio may be defined as the ratio of the difference between the vehicle speed and the braked-wheel speed to the vehicle speed.) In this figure, a freely rolling unbraked wheel has a slip ratio of zero while a fully skidding wheel (locked wheel) has a slip ratio of 1.0. These data were obtained by rolling an automobile tire at a yaw angle of 8° to develop a cornering or side force and then applying the wheel brake. The vehicle speed for the tests was 30 mph, and the tests were conducted on a dry concrete pavement.

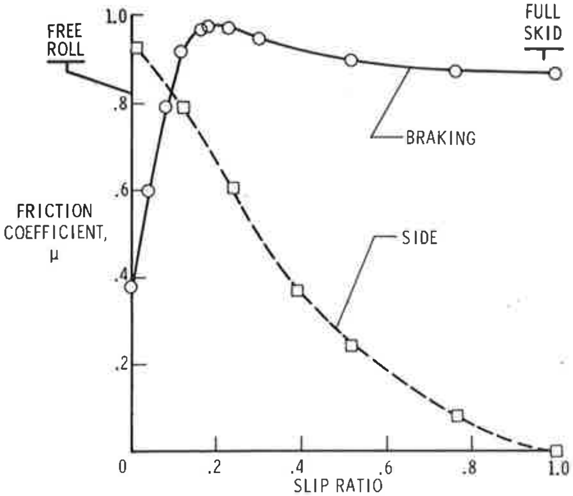

Figure 4. Effect of braking on tire side force capability (dry concrete; speed = 30 mph; yaw angle = 8°).

Consider the dry braking curve in Figure 4. The results show that, as the wheel brake is applied, the braking friction coefficient rises quickly to a peak value at 0.20 slip ratio and then decreases to a lower value at full skid or slip ratio of 1.0. It should be noted that the slip ratio indicated for braking friction to rise to peak value (0.20) is believed to be an apparent slip ratio caused by tire elasticity which allows the tire to windup torsionally about the wheel under the influence of the applied tire-ground drag load. Once the slip ratio for peak drag is exceeded, the tire starts to slip or slide on the pavement with increasing velocity until at slip ratio of 1.0, the relative skidding velocity between tire and ground equals the vehicle velocity.

Figure 4 also indicates that the capability of a tire to develop side or cornering forces is greatly affected by the condition of the tire, that is, whether it is rolling or sliding. For example, it will be noted in Figure 4 that side friction coefficient values decrease rapidly toward zero once the slip ratio for peak braking friction coefficient is exceeded. The lesson to be learned here is that a completely locked or full skidding wheel has no steering capability whatever, a tire cannot develop any side or cornering force if the wheel is locked, and drastic losses in side force can be expected if the wheel slip ratio substantially exceeds the incipient skidding (peak) value. These facts point with favor toward the use of anti-skid or anti-wheel-locking devices in vehicle braking systems to prevent total or partial wheel lockups and insure adequate tire cornering or side force capability during heavy wheel braking. Also, it is noted that cornering capability is preserved if the anti-skid system operates on the front side of the μ-slip curve rather than on the back side as is current practice with aircraft anti-skid systems.

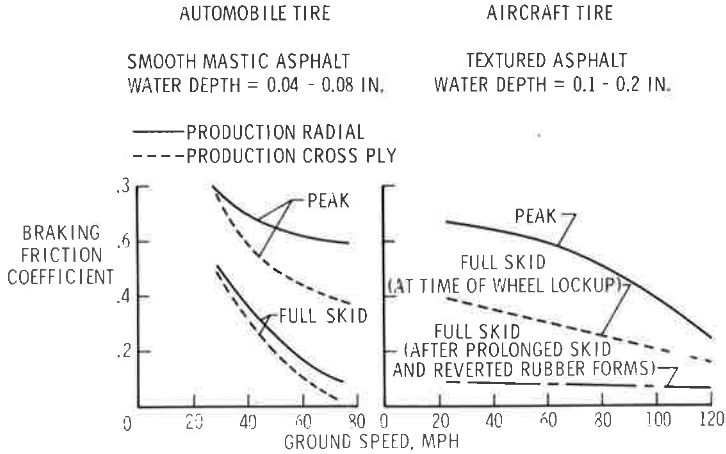

Figure 5. Comparison of tire rolling (peak) and tire locked (full skid) braking friction coefficients.

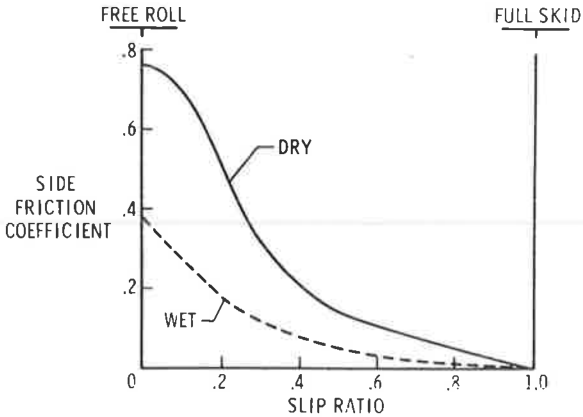

Figure 6. Effect of braking on tire side force capability (concrete surface; speed = 30 mph; yaw angle = 4°).

THE SKIDDING TIRE—WET PAVEMENTS

Results of tests have shown that when tires are allowed to skidunder partial or total locked-wheel conditions on wet pavements, the friction coefficients obtained are substantially lower than the peak values obtained when the braked rolling tire just starts to skid. This is illustrated by the braking friction coefficient curves shown in Figure 5 for both automobile and aircraft tires. Tire side force capability also is greatly reduced when the wheel operates in a partial or total slip condition on wet pavements (Fig. 6). The relative importance of the various factors which contribute to this decrease in friction coefficient with slip ratio on wet pavements is not yet fully understood. The very interesting study performed recently by the Royal Aircraft Establishment at Farnborough, England, of a tire rotating on the inside wetted surface of a transparent perspex drum illustrates a point which may be significant in this regard. Motion pictures taken of the tire footprint through the transparent drum surface in the RAE study show quite clearly that the rotating tire allows incoming water to readily pass through or drain from the rear of the footprint. On the other hand, when the tire stops rotating on the drum surface, water inflow and outflow from the tire footprint greatly diminishes. The water, now essentially trapped in the sliding footprint, tends to circulate in left- and right-hand vortices (Fig. 7).

It is also believed that the fact that water can be trapped and carried along in the skidding tire footprint as the locked wheel and tire slide across the wet pavement has a significant effect on the phenomenon called reverted rubber skid.

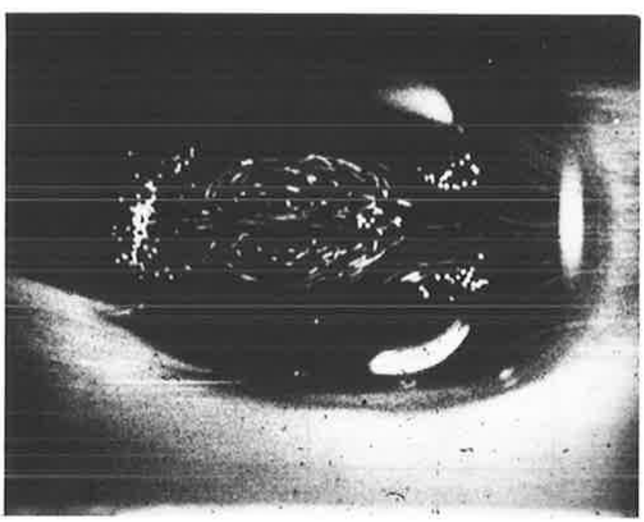

Figure 7. Trapped water circulating in the fully skidding footprint (tire pressure = 30 psi; water depth = 6 mm; drum speed ≈ 82 fps).

LEFT MAIN AND NOSE TIRE TRACKS

RIGHT MAIN TIRE TRACKS

MAIN LANDING GEAR TIRE WITH REVERTED RUBBER SKID PATCH

Figure 8. Hydroplaning accident—wet runway; 4-engine jet transport.

Reverted Rubber Skid

This phenomenon is named for the appearance of an aircraft tire after this type of skid occurs on wet pavements. The tire shows a patch of rubber that has the appearance of having been heated to the point that the surface rubber has melted and has reverted to the uncured state. This type of phenomenon occurs after a prolonged wheel skid, and once started, results in very low tire-ground braking friction which persists down to very low speeds (Fig. 5). It has been suggested that the braked tire's contact with the wet pavement may produce enough heat to turn the water, which is trapped and carried along in the tire footprint, into steam. Also, results of calculations show that, under the pressures involved, the steam would be hot enough to melt the rubber in the contact patch. It has also been suggested that this patch of soft, tacky rubber could produce a seal that would further entrap steam and water which would enable the tire to ride on a cushion of steam. Thus, the distinctive white marks left on wet pavements by reverted rubbers skids, in contrast to the black streak left on the pavement by dry skids, may be the result of the pavement in the tire path being steam-cleaned. Fortunately, as far as highway safety is concerned, this phenomenon has been noted thus far only during high-speed aircraft landings where the tire pressure is much higher than for automobile tires. An example of the white streak, reverted rubber, skid is shown in Figure 8.

TECHNIQUES FOR ALLEVIATING TIRE TRACTION LOSSES FROM TIRE HYDROPLANING

Viscous Pressures Predominating—Viscous Hydroplaning

Viscous fluid pressures in the tire-ground contact zone of rolling tires build up with speed to the dangerous levels required for hydroplaning only when water-covered pavements are smooth or smooth acting, when contaminants considerably more viscous than

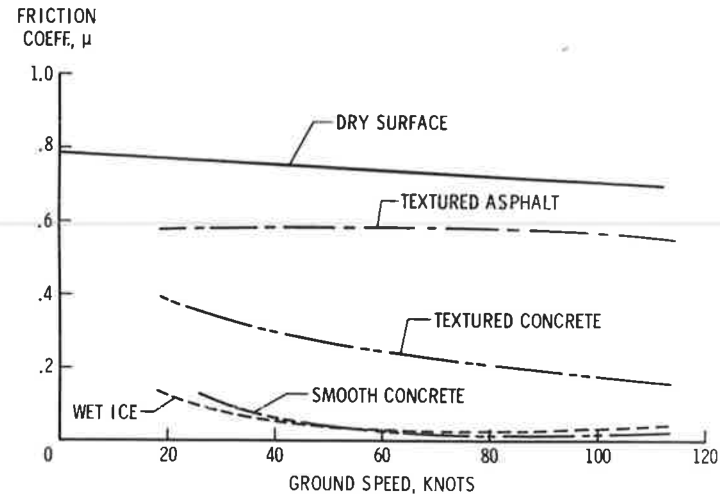

Figure 9. Thin film lubrication (damp runway; smooth tread; p = 140 psi).

water coat pavements, or when the tire enters a locked-wheel skid. It is important to point out that only slight amounts of precipitation, such as from a heavy dew which coats the pavement with a thin film of fluid, can produce this effect. This type of traction loss is illustrated by the very low peak braking coefficients developed by a smooth tread aircraft tire during braked rolling on damp smooth concrete and wet ice (Fig. 9). This figure also shows that providing the pavement with a surface texture is an excellent method for alleviating this condition. As previously mentioned, another effective method for alleviating viscous pressure buildup in the footprint is to provide the tire with an efficient tread design. The cornering data shown in Figure 10 for automobile tires having smooth, grooved, and grooved and siped tread designs illustrate this point, particularly at the low speeds where dynamic effects are small.

The large decrease in traction suffered when braked rolling tires enter a full skid on wet pavements was illustrated by the data presented in Figures 5 and 6. This type

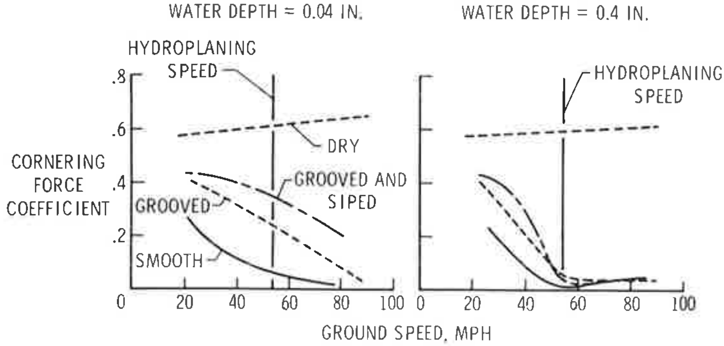

Figure 10. Viscous and dynamic pressures predominating (smooth concrete; yaw angle = 6°).

loss can be eliminated only by preventing the locked-wheel skid from occurring and suggests advantages to be gained from the use of anti-skid techniques or devices to prevent the wheel from locking up.

Dynamic Pressures Predominating—Dynamic Hydroplaning

Dynamic fluid pressures in the rolling tire-ground contact zone build up with speed to dangerous levels only when pavements are critically flooded. The depth of water on the pavement required can vary considerably depending on the particular combination of tire tread design and pavement surface treatment under consideration. Smooth tires operated on smooth pavements require the least water depth, while grooved tires operated on open-textured or grooved pavements require the greatest water depths for tires to dynamically hydroplane. Figure 10 shows that tread grooves improve tire traction when the water depth is less than the tread groove depth (0.04-in. water depth). This benefit is lost when the water depth exceeds the tread groove depth (0.4-in. water depth).

Several relatively new techniques offer great promise as a means of alleviating dynamic hydroplaning effects on tire traction by providing better fluid drainage in the tire-ground contact zone. For example, porous pavements are currently under study in England and elsewhere. A thin but porous wearing course is laid on top of an existing pavement. This construction allows the water trapped in the footprint to drain through the pavement itself as well as through the drainage channels provided by the tire and pavement surface texture.

Another very promising technique is to groove the pavement (Figs. 11 and 12). The pavement grooves provide additional drainage channels in the tire-ground contact zone and greatly increase water drainage from under the tire.

The use of air jets (Fig. 13) placed in front of aircraft tires to remove standing water on the pavement by means of an air blast also shows promise. Preliminary studies have been performed on automobile tires, aircraft tires, and full-scale aircraft. The results of these studies indicate that air jets are effective in removing standing water from the front of the tire and substantially increase tire traction on flooded textured pavements.

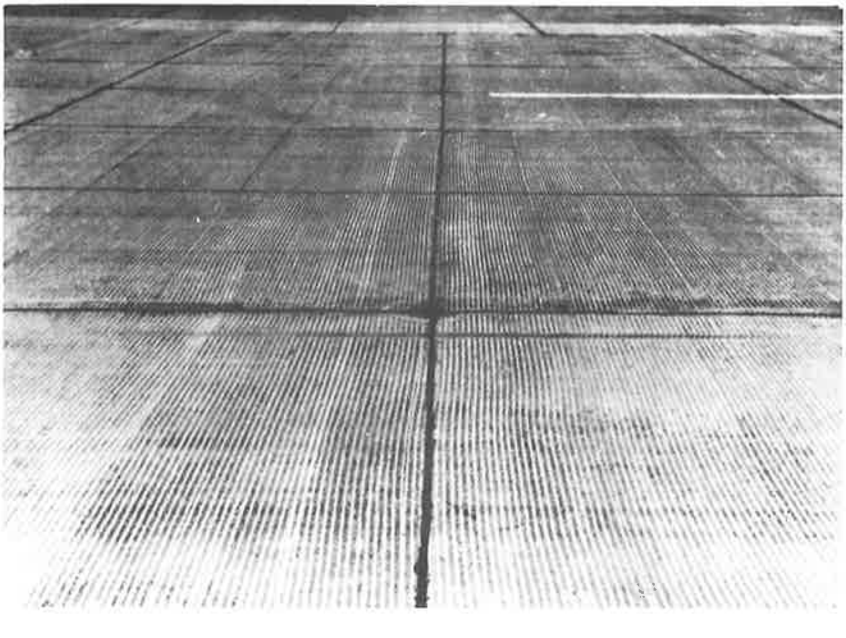

Figure 11. English grooved concrete runway (transverse grooves $\frac{1}{8}$ in. x $\frac{1}{8}$ in. on inch centers).

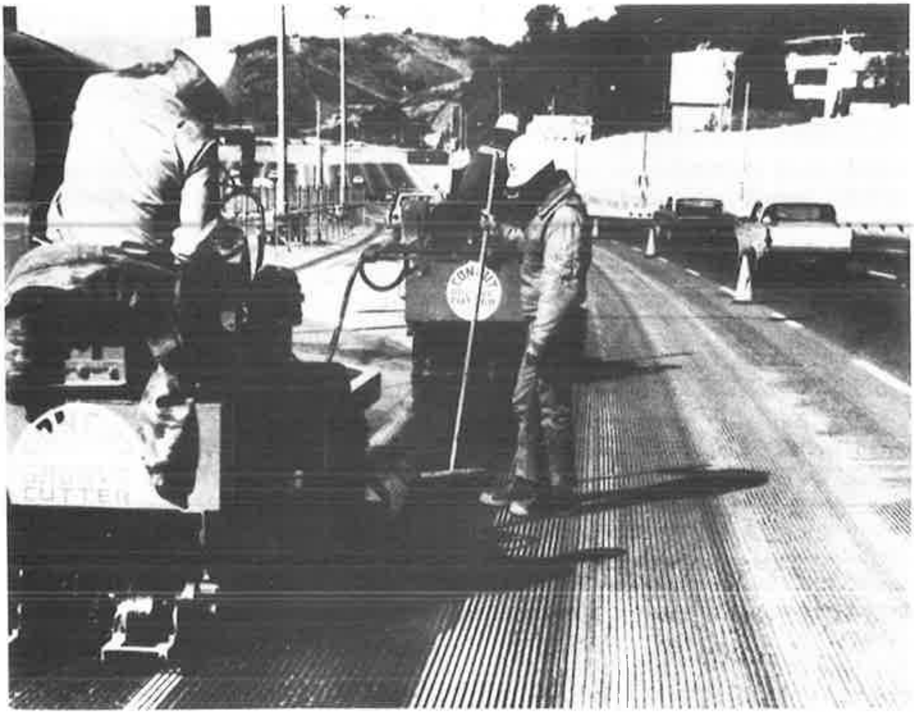

Figure 12. Longitudinal grooving—California highway.

Steam Pressures Predominating—Reverted Rubber Skid

Available results indicate that the extremely hazardous reverted rubber skid condition can be eliminated by preventing the tires from locking up. In this regard, the fact that many different aircraft equipped with anti-skid devices have suffered reverted rubber skid-type accidents points to the need for improving these devices for operation under low tire-ground friction conditions. At the present time, the only means

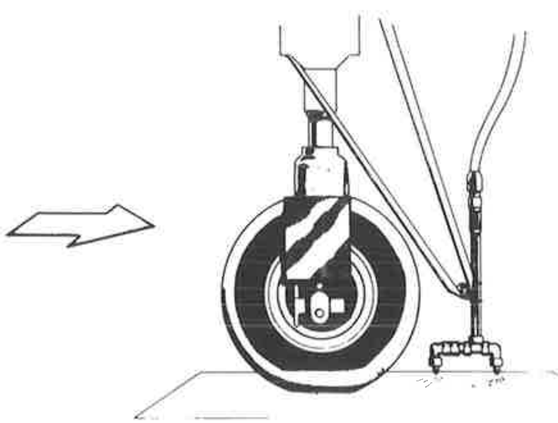

Figure 13. Arrangement of air jets.

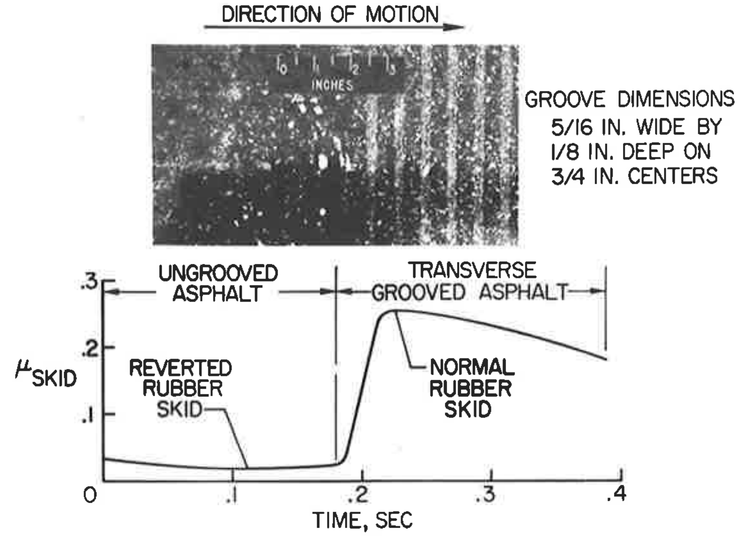

Figure 14. Effect of transverse grooves on reverted rubber skid (32 x 8.8 aircraft tire; ground speed = 77 knots; F_z = 16,000 lb; p = 250 psi; water depth = 0.1 to 0.2 in.).

known to alleviate the low friction conditions produced by a reverted rubber skid once it has fully developed on a tire is to substantially increase the effective pavement texture, such as by transverse pavement grooving. The effectiveness of pavement grooving in the alleviation of the reverted rubber skid condition is well demonstrated by comparing the friction coefficients for grooved and ungrooved asphalt shown in Figure 14.

CONCLUDING REMARKS

The research results described in this paper point out several tire, pavement, and vehicle operating conditions under which both aircraft and ground vehicle safety during operation on wet pavements are greatly degraded. The more important of these are the smooth or badly worn tire, pavements initially provided with too little texture or worn smooth or polished from traffic, the locked-wheel skid, and driver-pilot technique.

If highway safety is to be improved, then:

1. Smooth tire and smooth-acting pavements must be identified and rejected for vehicle and highway usage. For example, operation on highways with smooth tires can be controlled or prohibited as is presently being done in the State of New York and several European countries. Criteria and evaluation techniques are vitally needed to detect surfaces which are potentially slippery when wet so that the surface can be renovated by pavement grooving, surface additives, or resurfacing before skidding accidents start to occur.
2. Efforts should be made to reduce the catastrophic losses in tire cornering and braking ability that occur during partial or complete locked-wheel skids. Driver education can help in this regard, but the need to incorporate effective anti-skid or anti-wheel-locking devices in vehicle braking systems is clear.
3. It is believed that an educational program to alert the automotive public to important hazards of wet road driving will substantially reduce skidding accidents and improve safety.