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INTERACTIONS BETWEEN A PNEUMATIC TIRE AND A PAVEMENT SURFACE

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INTRODUCTION

The Supersonic Transport estimated to cost $30,000,000 and your family car have one common feature - the pneumatic tire. Both of these widely differing vehicles depend upon the pneumatic tire to perform three basic functions for safe and reliable ground operation. These functions are:

(1) To support the mass of the vehicle and its payload under all static and rolling conditions

(2) To develop cornering or side forces for vehicle steering and to oppose external side forces acting on a vehicle such as from crosswinds, centrifugal effects in curves or turns, and gravitational components due to pavement crowns

(3) To develop propulsive forces from driving wheels to maintain vehicle motion and to develop retarding forces from braking wheels to arrest vehicle motion

How well the pneumatic tire performs these three functions for the vehicle depends in turn upon the condition of the pavement the tire is rolling upon. It is all too true, that the interactions between tire and ground, and therefore vehicle safety, vary greatly with both tire and pavement conditions. It is the purpose of this paper to briefly describe the nature of some of these major tire-pavement interactions.

The portion of the vehicle mass supported by a flexible pneumatic tire causes the tire to deflect vertically and to distort so that the tire actually contacts the pavement over a well defined area called the tire footprint as shown in figure 1(a). The shape of a tire footprint is governed by tire design. For example, a bicycle tire will have a long but narrow footprint while a racing-car tire will have a wide but short footprint.

LOAD INTENSITY

The vertical load supported by the tire divided by the footprint area is the load intensity or the average ground bearing pressure. For both aircraft and automobile tires, the strength (stiffness) effects of the tire carcass are small, and therefore this bearing pressure is usually only slightly higher than the tire inflation pressure. The ground bearing- or tire inflation-pressure is very significant for tire-pavement interactions. This pressure is used by pavement designers to determine required pavement strength. This pressure also determines the maximum available friction coefficient that can be developed between tire and ground under dry conditions as shown in figure 2. The data show that the available friction coefficient decreases as the pressure increases. This figure also shows that some increase in friction may be obtained by appropriate tread rubber compounding, as indicated by the higher friction coefficient developed with synthetic rubber treads on auto tires as against that for the natural tread rubbers used on aircraft tires. Research results also show that pavement texture has but little effect on friction coefficients developed on dry surfaces as shown in figure 3. The data shown in this figure also indicate a speed effect in that the friction coefficient tends to decrease somewhat as vehicle speed increases. The effect of inflation pressure is also indicated, the upper curve is for 140 pounds per square inch and the lower curve for 290 pounds per square inch.

TIRE SLIP

The ability of a tire to develop friction on dry pavements depends to a great extent on whether the tire is rolling or sliding upon the pavement as shown in figure 4, where braking and sideways friction coefficients are plotted against slip ratio. (Slip ratio may be defined as the ratio of the vehicle speed minus the braked wheel speed to the vehicle speed.) In this figure a freely rolling unbraked wheel has a slip ratio of 0 while a fully skidding (locked) wheel has a slip ratio of 1.0. These particular data were obtained by rolling the tire at a yaw angle of eight degrees to develop a cornering or side force and then applying wheel brakes to the point that the tire locked up. The speed of the test was 30 miles per hour and the pavement was dry. Consider first the dashed curve for the sideways friction and note that the tire develops a steady state side force at slip ratio of 0. As the brake is applied, the braking friction (solid curve) increases to a maximum value at about a slip ratio of 0.18 and then decreases to a lower value at wheel lockup (slip ratio of 1.0). The sideways friction, however, rapidly decreases with increasing slip ratio and approaches zero at slip ratio of 1.0. The lesson to be learned here is that a completely locked or fully 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 tire slip ratio exceeds the incipient skidding value, which for this case is about 0.18. These facts point with favor toward the use of anti-skid or anti-wheel locking devices in vehicle braking systems to prevent wheel lockups and insure adequate tire cornering or side force capability during heavy wheel braking.

PAVEMENT CONTAMINATION

The most adverse tire-surface interactions occur when pavements become contaminated with water, snow, slush, ice, and combinations of road dust and water, or oil and water, and can under certain conditions result in almost complete loss of tire traction. Three physical phenomena chiefly responsible for these adverse effects are listed in figure 5. These phenomena are designated as dynamic hydroplaning, thin-film lubrication (or viscous hydroplaning), and reverted rubber skid.

Dynamic Hydroplaning

When a rotating or sliding tire runs into the stationary water on a flooded pavement, a stagnation pressure develops at the tire-water interface across the width of the tire. This dynamic water pressure builds up as the square of vehicle speed, and at a critical speed, called the hydroplaning speed, equals the average tire-ground bearing pressure or approximately, the tire inflation pressure. At vehicle speeds in excess of the hydroplaning speed, the dynamic water pressure balances the tire-ground bearing pressure over the tire footprint and the tire is held off from the pavement and rides on a water film. This is called hydroplaning and its progressive development with speed is shown in figure 1. The influence of dynamic hydroplaning on the braking friction produced by an aircraft tire is shown in figure 6 for various conditions of tread wear, where zero wear refers to a groove depth of 0.22 inch. Note that the tread grooves are effective at the lower speeds in raising friction coefficient but are ineffective at speeds near or above the hydroplaning speed. Research indicates that if the water depth is greater than the groove depth, even grooved tread tires lose their effectiveness at high speeds and behave as smooth tread tires.

Thin-Film Lubrication (or Viscous Hydroplaning)

This phenomenon results from the inability of the tire to puncture and disrupt the very thin residual fluid film left on the pavement in the tire footprint area after the majority of the trapped water has been displaced by the tire. The fluid pressure buildup in the footprint in this instance is due to viscous properties of the fluid, and test results indicate that the phenomenon is accentuated when fluids more viscous than water, such as oil or a mixture of road dust and water, contaminate the pavement. This problem is particularly hazardous for smooth tires operating on smooth pavements, and one outstanding method to eliminate or alleviate this problem is to provide a texture to the pavement as shown in figure 7. It should be emphasized that the data shown in this figure were obtained on test surfaces which were damp. They were not flooded and contained no standing water.

Another outstanding method to combat viscous hydroplaning is to provide sipes in the tire tread between the tread grooves (see tire in figure 1). The sharp edges of the sipes in contact with the pavement break through the fluid film and allow the tire to regain a portion of its dry grip on the pavement. This effect is shown in figure 8 where sideways or cornering coefficients of friction obtained on a wet, very smooth, concrete pavement are shown for automobile tires having smooth, grooved, and grooved and siped treads.

Reverted Rubber Skid

This phenomenon is named for the appearance of a tire after this type of skid occurs. 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 back to the uncured state. This type of skid happens after a prolonged wheel skid and once started, results in very low tire-ground friction that persists down to very low speeds.

Present thinking suggests that the braked tire's contact with the wet pavement may produce enough heat to turn the water trapped in the footprint into steam, which would be hot enough to change the rubber in the contact patch to reverted rubber. It has been suggested that this patch of soft and tacky rubber could produce a seal that keeps steam and water entrapped in which case the tire would ride on a cushion of steam. Thus the distinctive white mark left on a pavement by a reverted rubber skid may be the result of the pavement surface in the tire path being steam cleaned. Fortunately as far as highway safety is concerned, this phenomenon has been noted thus far only on high speed aircraft. An example of the white streak-reverted rubber skid is shown in figure 9.

Summary of Techniques for Improving Traction of Tires on Wet Pavements

A summary of techniques currently available for improving wet tire and wet pavement traction is shown in figure 10. This summary indicates that tried and true techniques of the past, such as tire tread design and texturing of pavement surfaces, while greatly beneficial, are unable to cope with all pavement contamination and vehicle speed conditions present on today's highways and airport runways. Relatively new concepts such as porous pavements, pavement grooving (figures 11 and 12), and air jets placed in front of tires (figure 13 (see reference 1 for further details)) offer promising results for improvement in traction, and research in these areas is currently underway at NASA and elsewhere.

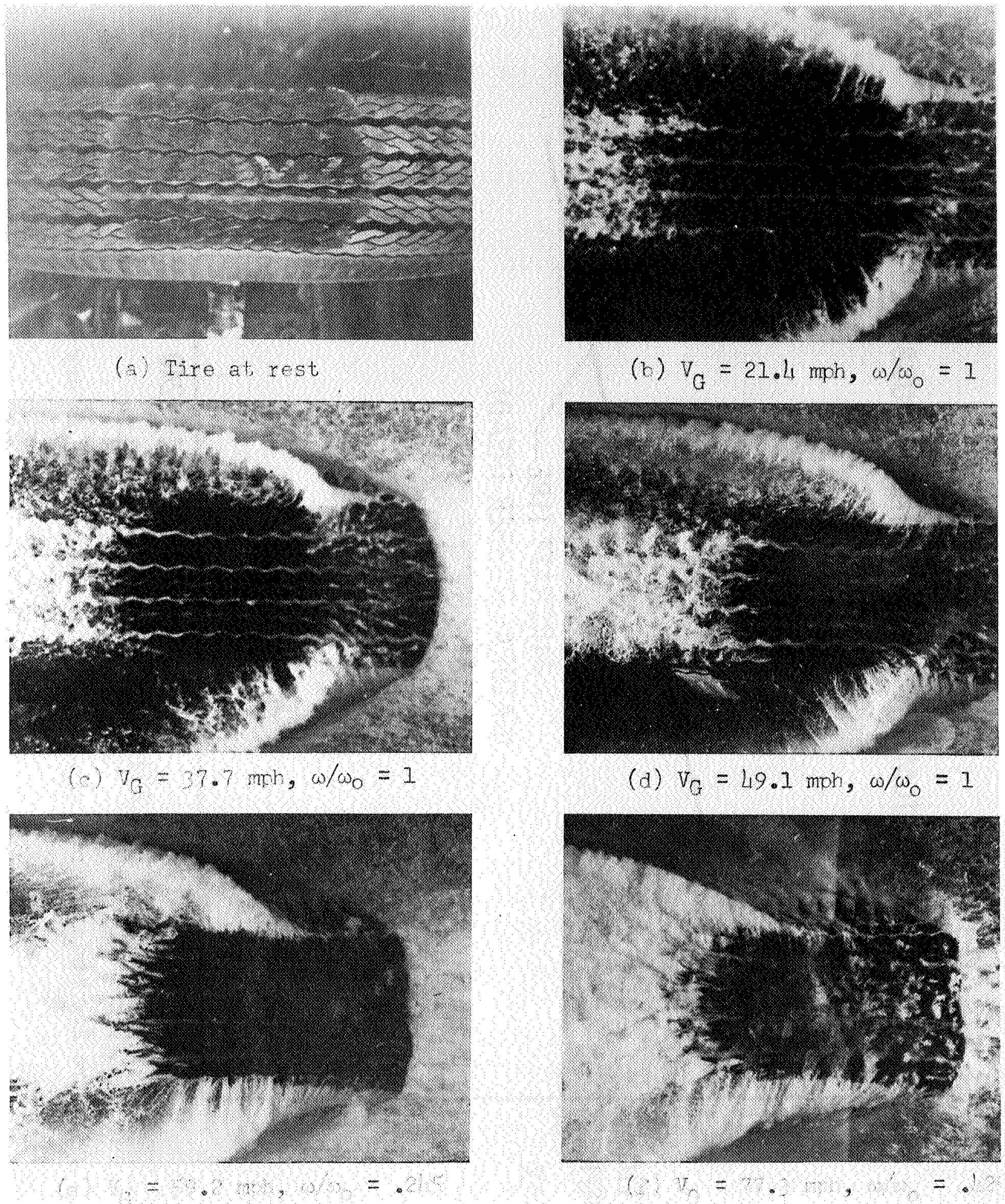
CONCLUDING REMARKS

Tire-pavement interactions on dry pavements are fairly simple and well understood, and provide adequate traction for vehicle braking and directional control on present highways and runways for normal operations. Locked wheel skidding or other abnormal vehicle operating procedures can produce problems which may not be subject to control even under ideal conditions.

Tire-pavement interactions on contaminated pavements are much more complicated than those occurring on dry pavements and are not nearly as well understood. Research results indicate that tires having smooth or badly worn treads, and pavements worn smooth or polished from traffic or initially provided with too little surface texture, must be identified and rejected for vehicle and for highway usage if highway safety is to be improved. For example, smooth tire operation on highways can be controlled or prohibited as is presently being done in New York State 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. An educational program to alert the automotive public on hazards of wet road driving is also required.

REFERENCE

1. Horne, Walter B.; Yager, Thomas J.; and Taylor, Glenn R.: Recent Research on Ways to Improve Tire Traction on Water, Slush or Ice. Presented at the AIAA Aircraft Design and Technology Meeting (Los Angeles, California), November 15-18, 1965.



(a) Tire at rest

(b) V_G = 21.4 mph, ω/ω_o = 1

(c) V_G = 37.7 mph, ω/ω_o = 1

(d) V_G = 49.1 mph, ω/ω_o = 1

(e) V_G = 59.2 mph, ω/ω_o = .215

(f) V_G = 77.[illegible] mph, ω/ω_o = .1[illegible]

Figure 1.- Photographs of typical production-type tire taken through glass plate. Water depth = 0.4 inch. Vertical load = 835 pounds. Yaw angle = 6°. Direction of motion left to right.

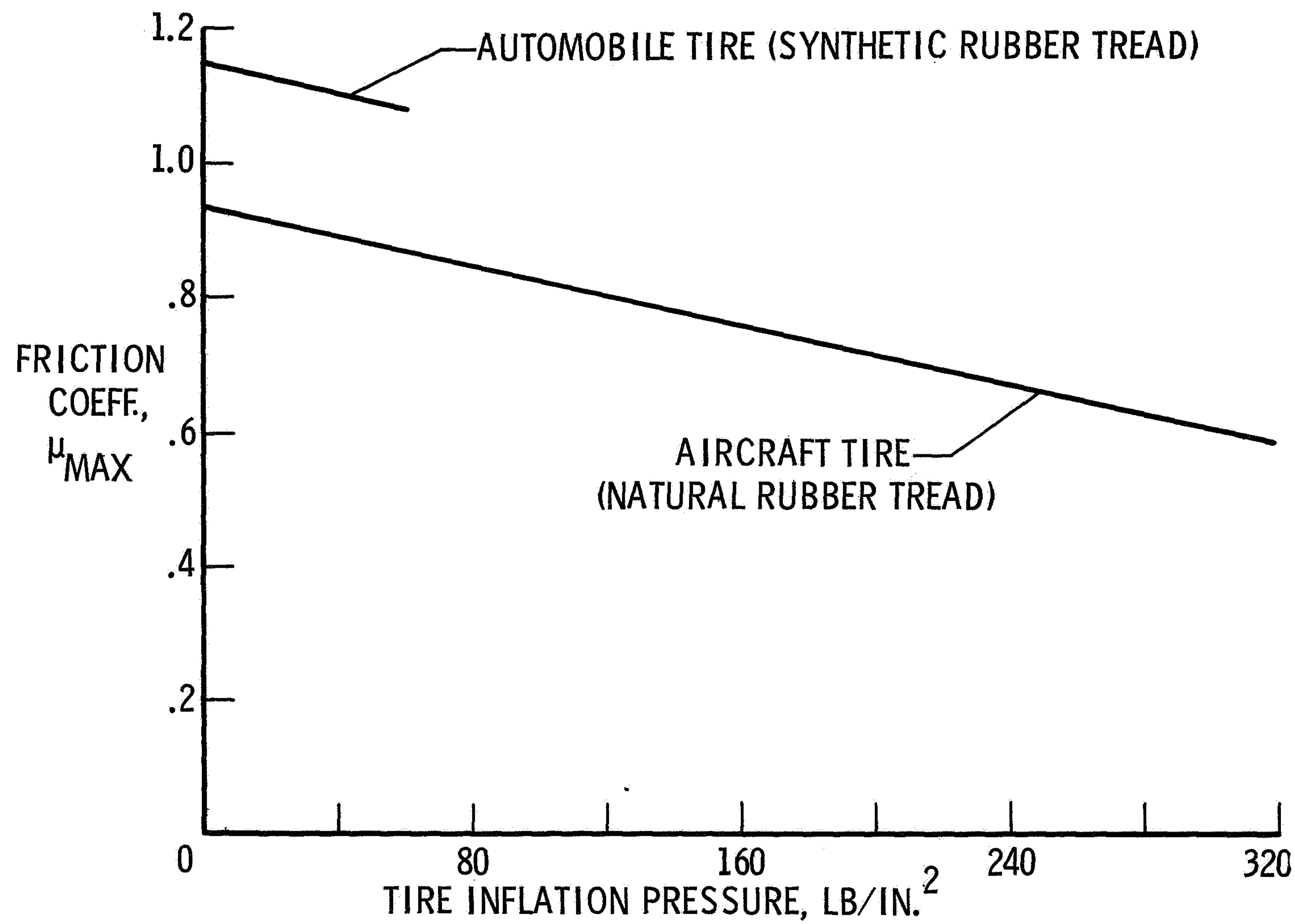


Figure 2.- Variation of μ_{max} with inflation pressure on dry pavements.

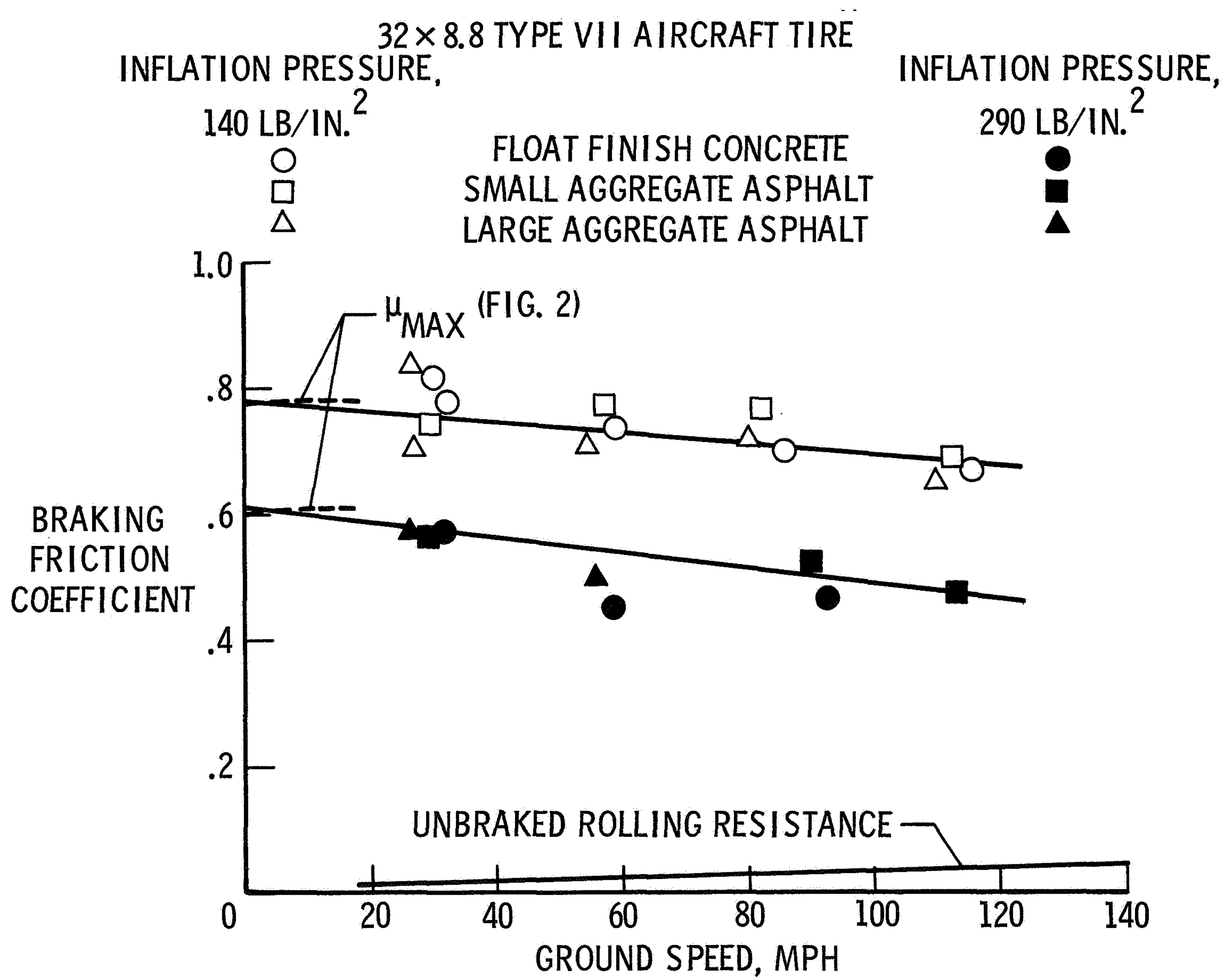


Figure 3.- Effect of surface texture and speed on dry runway braking.

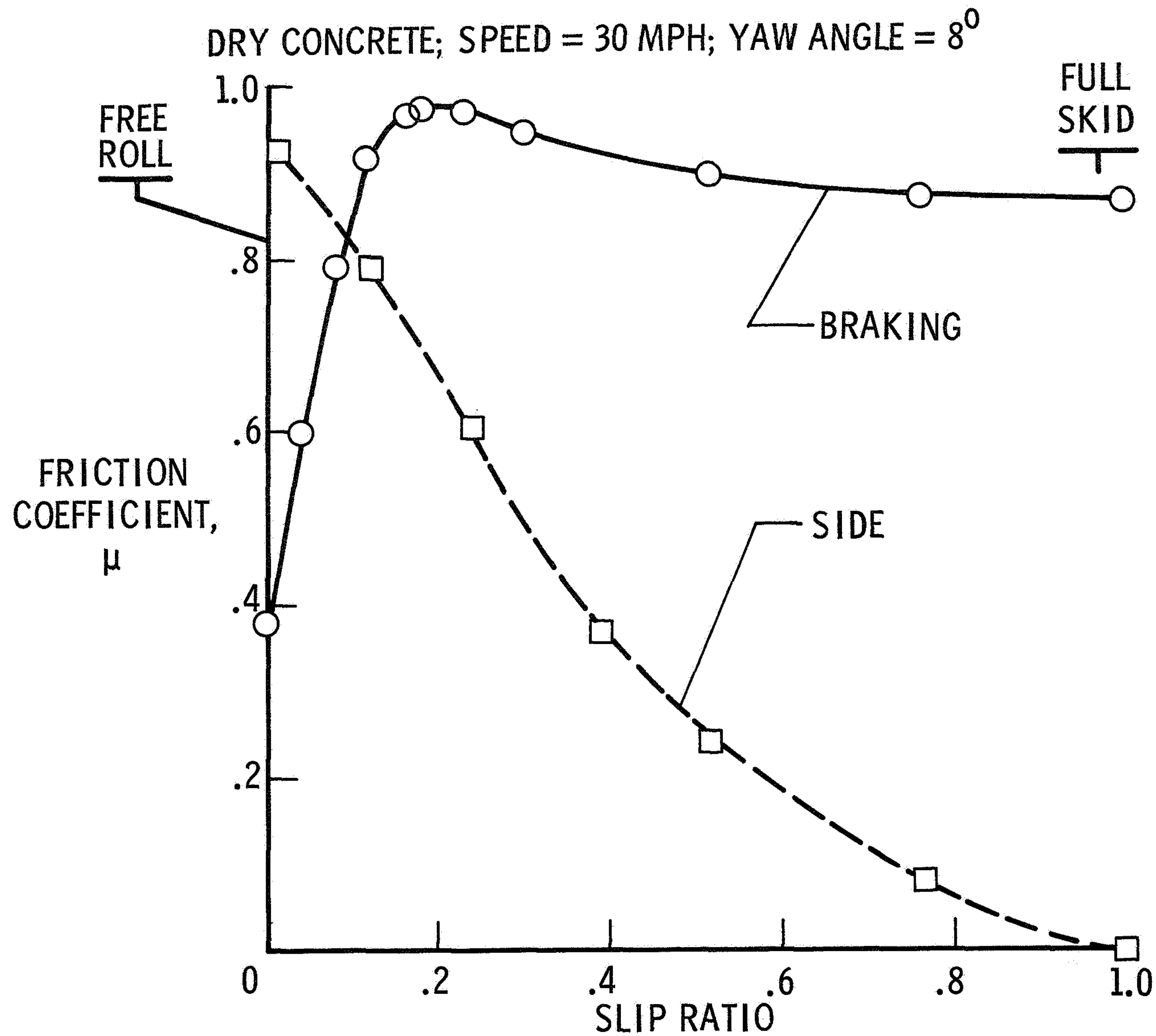


Figure 4.- Effect of braking on tire side force capability.

TYPE OF LOSS	AIRCRAFT WHEELS		CONDITIONS REQUIRED
	ROTATING	LOCKED	
DYNAMIC HYDROPLANING	YES	YES	HIGH SPEED FLOODED PAVEMENT TIRE PRESSURE DEPENDENT
THIN FILM LUBRICATION	YES	YES	MEDIUM TO HIGH SPEED DAMP TO FLOODED SMOOTH PAVEMENT TIRE PRESSURE INDEPENDENT
REVERTED RUBBER SKID	NO	YES	MAY PERSIST DOWN TO LOW SPEEDS DAMP TO FLOODED PAVEMENT TIRE PRESSURE EFFECTS NOT DEFINED

Figure 5.- Tire traction losses on wet runways.

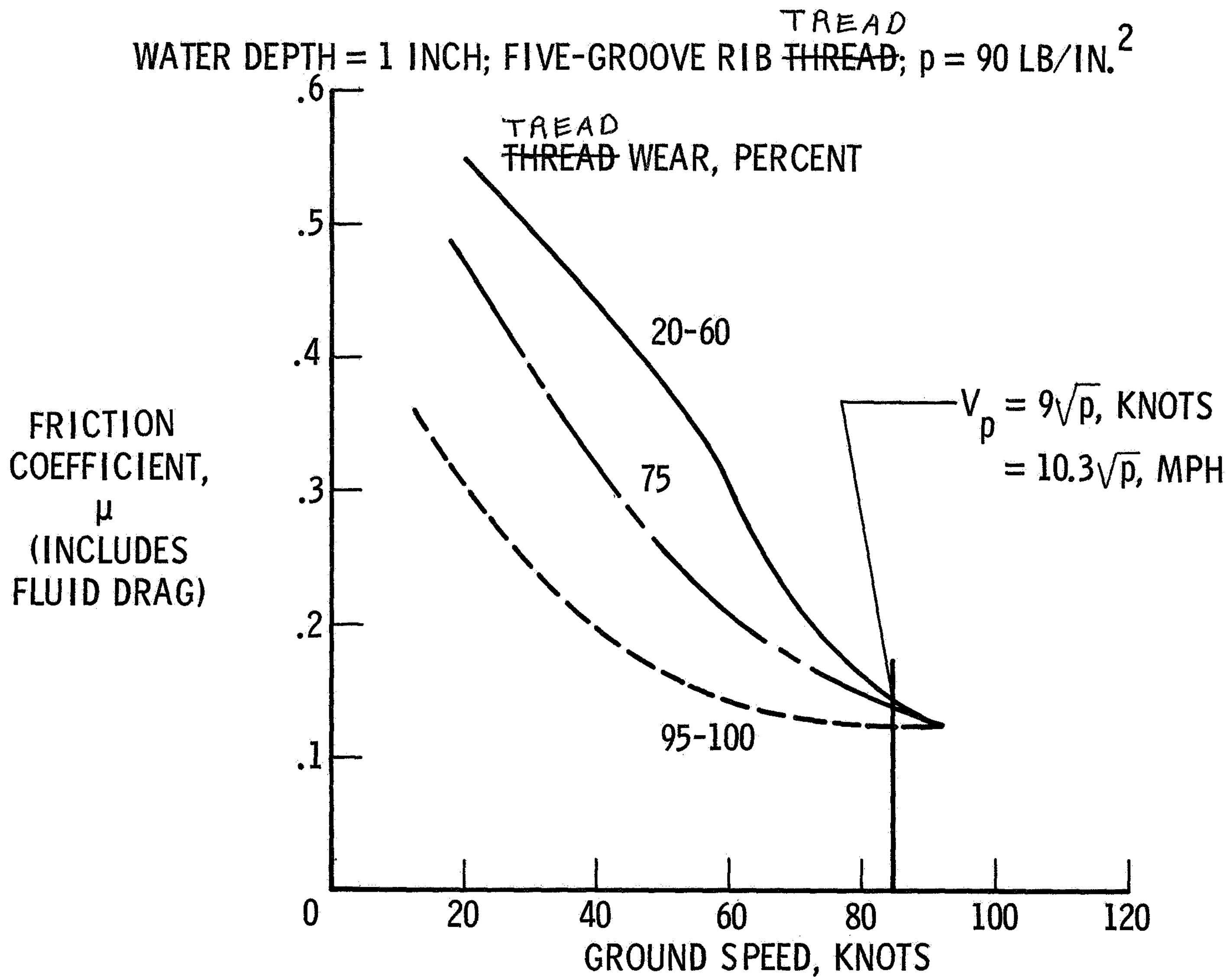


Figure 6.- Dynamic hydroplaning.

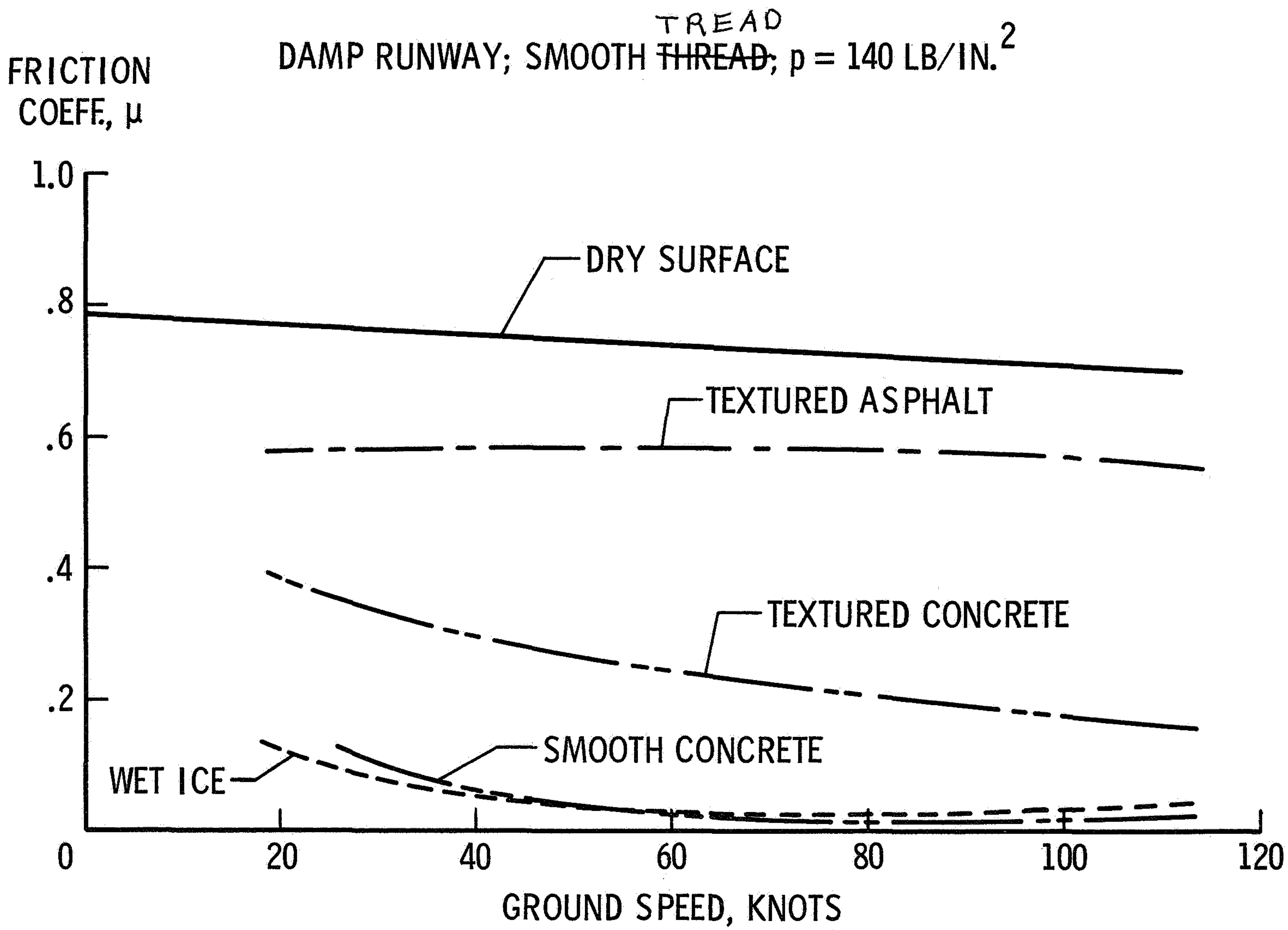


Figure 7.- Thin film lubrication.

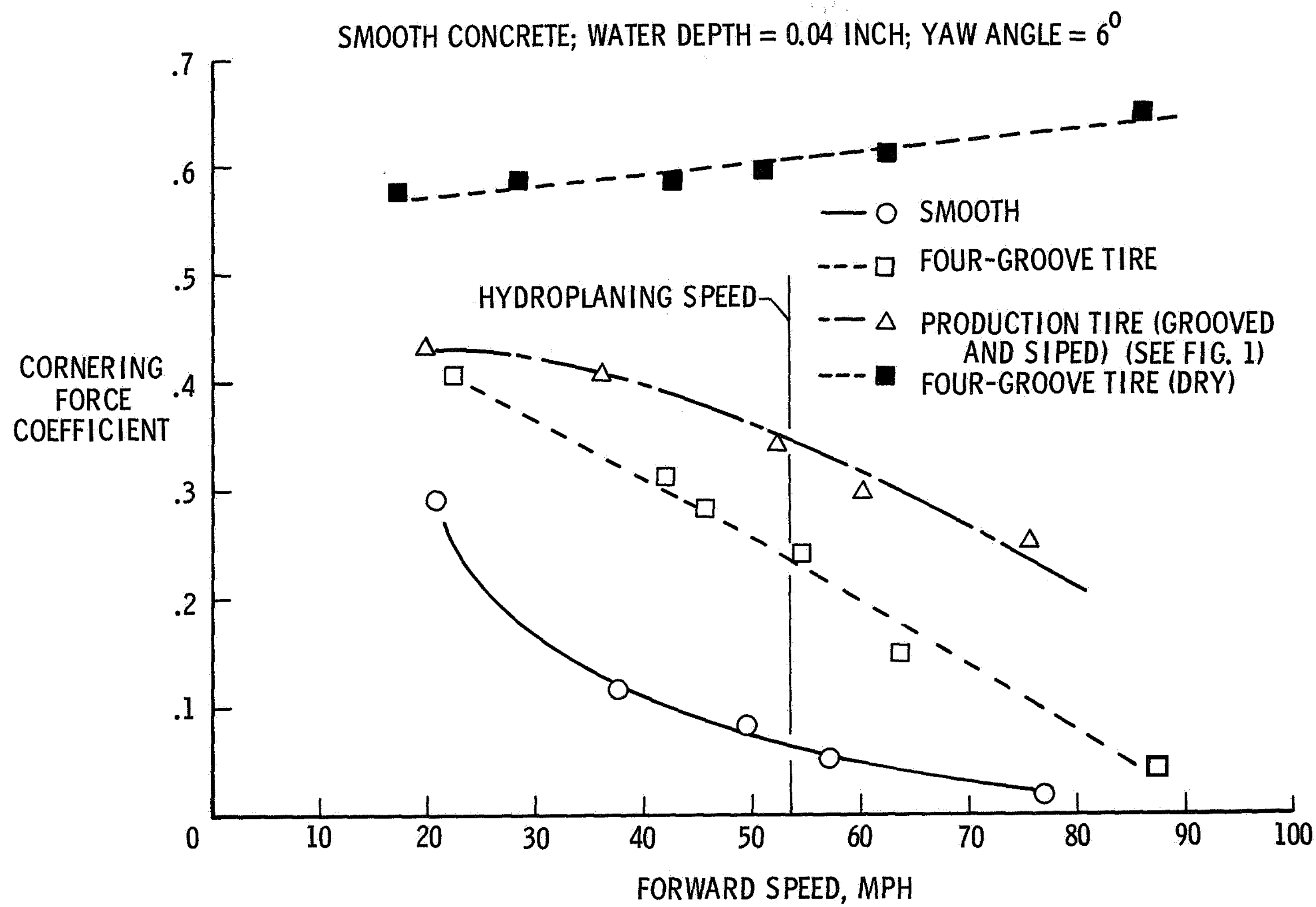


Figure 8.- Effect of tread design on automobile tire cornering capability.

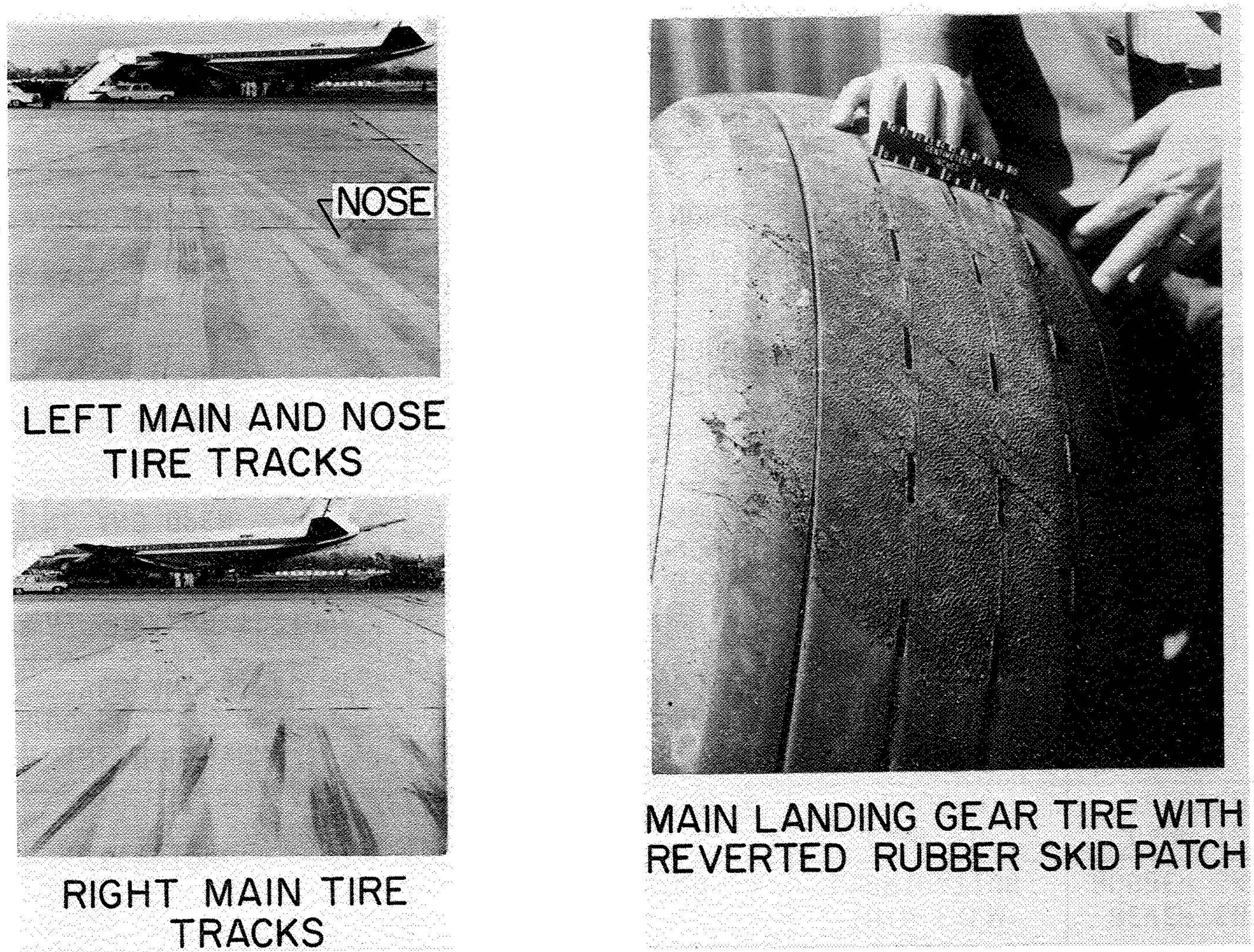


Figure 9.- Hydroplaning accident - wet runway 4 engine jet transport.

TECHNIQUE	EFFECTIVENESS FOR			
	DYNAMIC HYDROPLANING		THIN FILM LUBRICATION	REVERTED RUBBER SKID
	DAMP TO WET	FLOODED	DAMP TO FLOODED	DAMP TO FLOODED
TIRE TREAD DESIGN				
GROOVED	GOOD	NONE	FAIR	NONE
GROOVED AND SIPED	GOOD	NONE	GOOD	NONE
RUNWAY SURFACE TEXTURE				
SMOOTH	POOR	NONE	NONE	NONE
FINE (SAND PAPER)	FAIR	NONE	EXCELLENT	NONE
FINE AND OPEN	GOOD	NONE	EXCELLENT	NONE
POROUS	←	←	UNKNOWN	→
PAVEMENT GROOVING				
LONGITUDINAL*	GOOD	GOOD	GOOD	UNKNOWN
TRANSVERSE	EXCELLENT	GOOD	GOOD	EXCELLENT
AIR JETS	EXCELLENT	GOOD	POOR	UNKNOWN
ADVANCED WHEEL BRAKING SYSTEMS	UNKNOWN **	NONE	UNKNOWN **	UNKNOWN **

*TRACK TESTS SHOWED TIRE DAMAGE UNDER YAWED ROLLING CONDITIONS

**INITIAL ANALYSIS INDICATES IMPROVEMENTS FEASIBLE

Figure 10.- Summary of techniques for improving tire-runway traction.

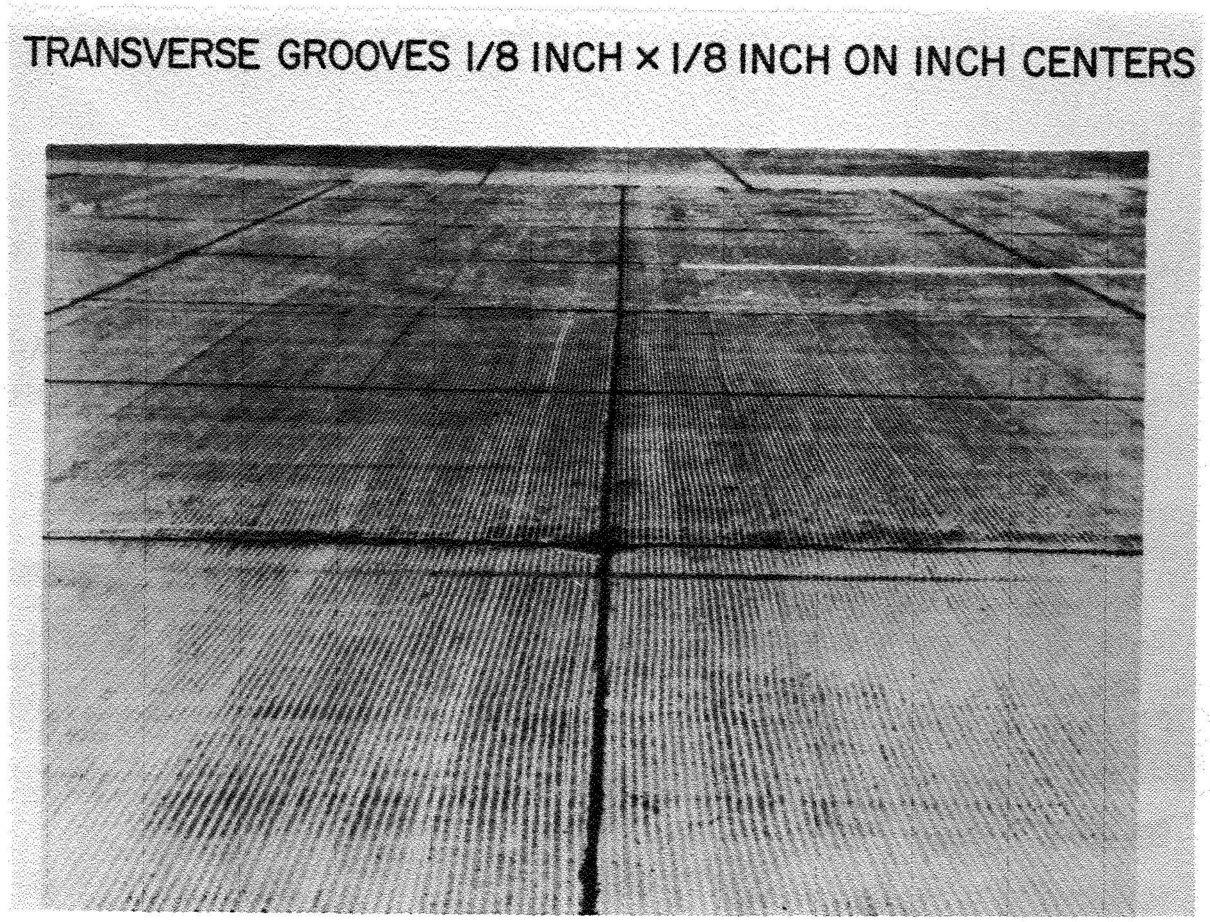


Figure 11.- Grooved concrete runway (England).

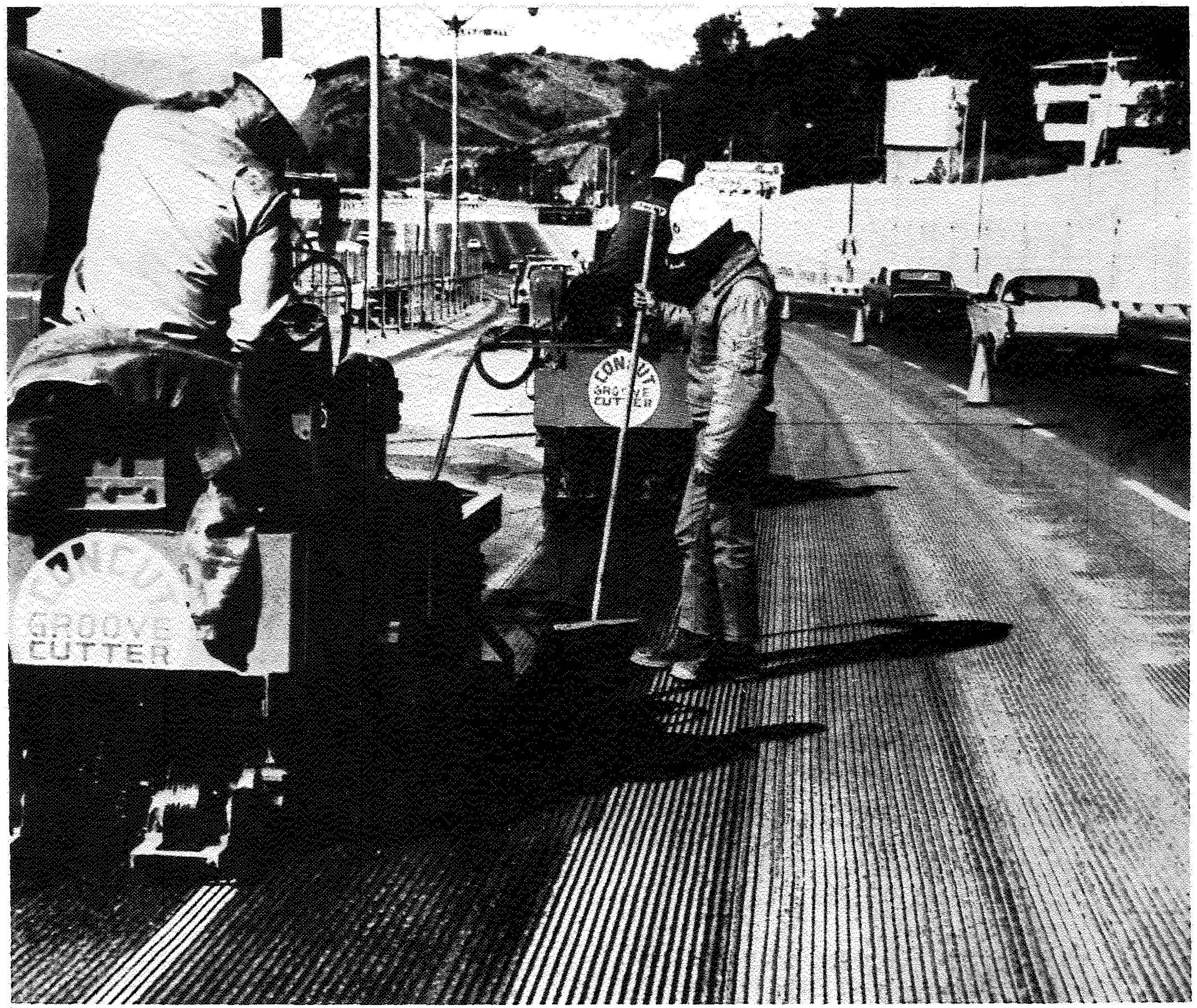


Figure 12.- Longitudinal grooving - California highway.

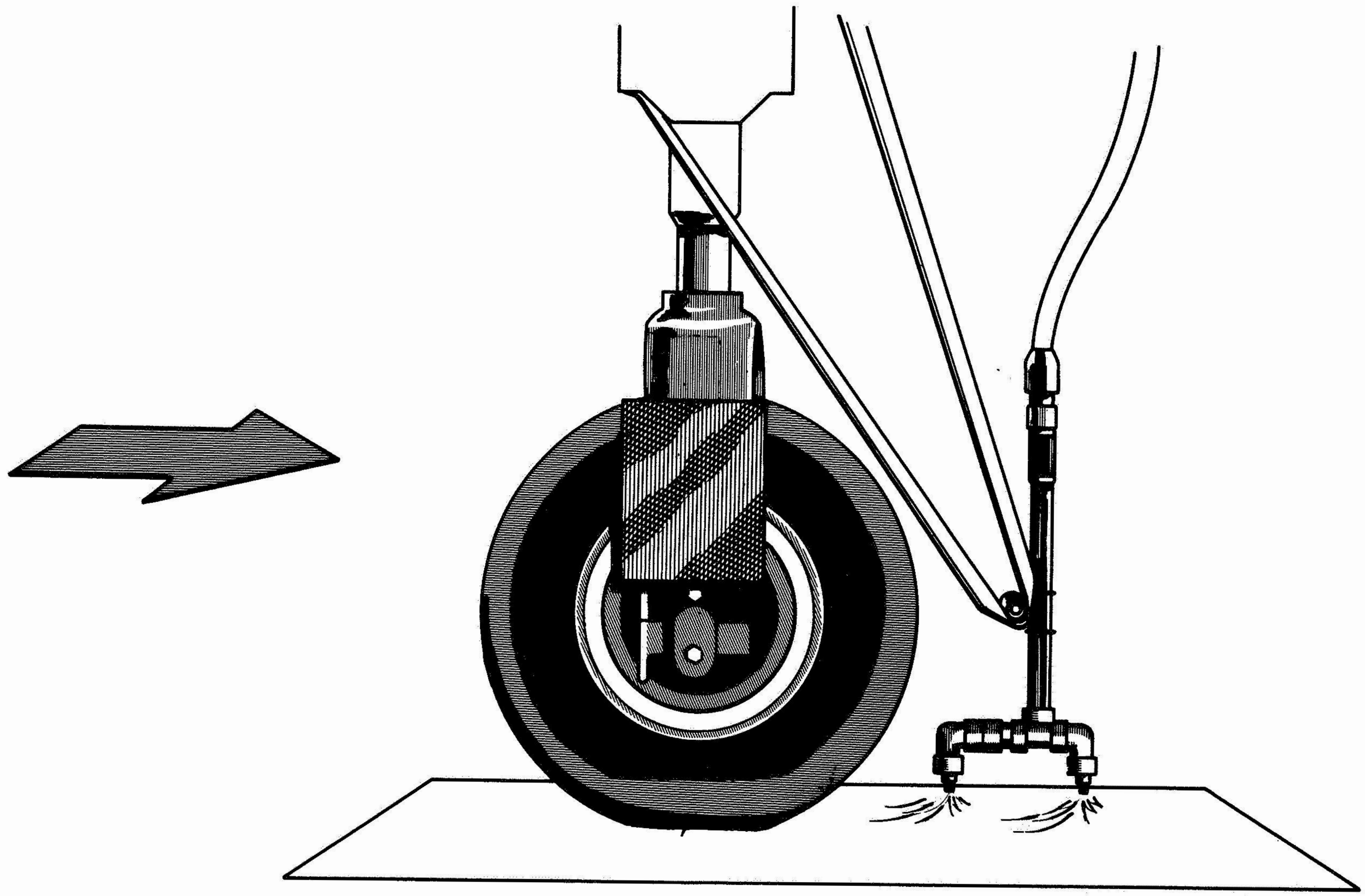


Figure 13.- Schematic of air jet arrangement on automobile tire tests. Airflow at jet nozzle ≈ 2.7 lb/sec. Nozzle pressure ≈ 390 psi.

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