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Technical Report

**FRICTION COEFFICIENTS BETWEEN
TIRES AND PAVEMENTS SURFACES**

15 June 1964



U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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FRICION COEFFICIENTS BETWEEN TIRES AND PAVEMENT SURFACES

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Type C Final Report

by

H. Tomita

ABSTRACT

A review of the problem of aircraft skidding on Naval airfields during landings and a thorough literature search on the work conducted on friction coefficient were made. The literature search revealed that much work has been conducted on basic theoretical studies of friction coefficient, on development of friction measuring devices, and on investigations to determine the factors which affect the friction coefficient between tires and pavement surfaces.

It was found that low friction coefficients were responsible for some aircraft accidents on Naval airfields. Basic studies indicated that the actual friction coefficients between tires and pavement surfaces did not follow the basic laws of friction. The total frictional force included, in addition to the basic frictional force, a mechanical force resulting from the interlocking of the rubber with the aggregate particles protruding above the pavement surfaces.

Various field-testing devices have been developed by others, used, and compared in an effort to locate low-friction pavements and to standardize the method of measurement. One device still in the development stage showed promise of measuring friction coefficient under simulated conditions of landing aircraft.

Many factors affecting the friction coefficient between tires and pavement surfaces have been found through laboratory and field investigations. These factors were related to vehicle and aircraft operation, to tire design, and to types of pavement surfaces. The effect of these factors on the friction coefficients were varied. The individual effects of each factor were not found since many of the factors worked in combination.

The review of the problem and of the work conducted on friction coefficient is summarized. A recommendation is given to the effect that no effort be made at this time to develop a friction measuring device.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

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INTRODUCTION

Since the beginning of overland transportation, man has searched for better highway pavement surfaces. The goal has been to have surfaces that are firm, stable, and smooth, and that will withstand the loads and abrasive actions of moving vehicles as well as resist the effects of inclement weather and climate for long periods of time. Progress in reaching the desired goal has been made through research, development, and experience on highway pavements and by improvements to the vehicles using them. This progress has made highway traveling comfortable at today's relatively high speeds. Technological advances and a continual rise in the standard of living have resulted in a tremendous increase in the number of highway travelers in the United States. Unfortunately, accidents have increased in number with the increase in traffic until they have become a major problem on many highways. The study of accident causes indicated that some accidents happened because braking forces were insufficient to decelerate or maneuver the vehicles. The lack of sufficient braking force was often caused by low friction coefficients between vehicle tires and many pavement surfaces, especially when the surfaces were wet or icy. Thus, efforts were begun to improve unsafe pavement surfaces by devising and testing equipment to measure friction coefficients and by developing paving materials which yield high skid-resistance. Along with these studies on pavement surfaces, vehicle and tire manufacturers have made efforts to increase the operational safety of their products. These efforts were directed towards helping the motorists avoid skidding accidents on highways.

Progress towards better airfield pavements has also been made, especially in recent years, to handle today's heavier and higher-performance civil and military jet aircraft. As on highways, the lack of braking force caused by low friction coefficients between aircraft tires and pavement surfaces during the last phase of landing became a matter of concern from the standpoint of safety. In the last two or three years, the Navy has experienced a number of incidents involving skidding aircraft. As a result, a standard test procedure was suggested to determine the friction coefficients of airfield pavement surfaces used by the Navy. The U. S. Naval Civil Engineering Laboratory (NCEL) at Port Hueneme, California, was requested to study the problem. The plan was to review the skidding problems encountered at Navy airfields and to conduct a thorough study of the work done by highway engineers and others. It is anticipated that a set of criteria will evolve from this study which can be used to create a reliable method or field device for accurately measuring friction coefficients under simulated dynamic conditions of landing aircraft. It is anticipated also that this method or device will permit all Navy airfield pavement surfaces to be accurately rated according to their slipperiness.

REVIEW OF SKIDDING PROBLEMS AT NAVY AIRFIELDS

To review the skidding problem encountered at Navy airfields during aircraft landings, information was obtained through correspondence with the U. S. Naval Aviation Safety Center (NASC), Norfolk, Virginia. NASC compiles all data on aircraft accidents reported by Navy airfield activities, as well as other information.

The information from NASC indicates that approximately 170 field landing accidents occurred during the calendar years of 1961 and 1962. Wet, slippery runways were a contributory cause in 27 of the 170 accidents. The following are some typical examples, obtained from NASC, of accidents that occurred on wet runways:

1. F8U1. WET RUNWAY. AIRCRAFT TOUCHDOWN AT 300 FT. POINT ON CENTER-LINE. BRAKING INEFFECTIVE; AIRCRAFT DRIFTED LEFT. PILOT DROPPED HOOK. MADE ANGLE ARRESTMENT 50 FT. LEFT OF CENTER. SWERVED OFF RUNWAY. SHEARED PORT GEAR.
2. A3D2. DRAG CHUTE FAILED TO DEPLOY. WET RUNWAY. HYDROL MALFUNCTIONED. AIRCRAFT RAN OFF RUNWAY.
3. F8U2N. TOUCHDOWN ON WET RUNWAY. TIRE BLEW. AIRCRAFT RAN OFF RUNWAY. PILOT LANDING LONG AND FAST USED IMPROPER BRAKING TECHNIQUE.
4. F9F8T. GROUND CONTROL APPROACH TO WET CROSS DOWNWIND RUNWAY. AERODYNAMIC BRAKING ATTEMPTED BUT AIRCRAFT STARTED SKID. NOSE LOWERED. MAXIMUM BRAKING ATTEMPTED. TIRE BLEW AND AIRCRAFT RAN OFF RUNWAY END ACROSS DRAIN DITCH.

These occurrences indicate that many factors are involved in the landing and stopping of aircraft on Navy airfields. The ineffective braking of Example 1 indicates that braking force was insufficient because the friction coefficient was low between the pavement surface and the tires. Example 2 can be attributed to faulty equipment on the A3D2 aircraft. Pilot error, specifically in not using the correct landing point, touchdown speed, or braking technique, was responsible for the accident described in Example 3. Example 4 indicates that a bad wind condition was a contributory cause. Although these examples indicate that a low friction coefficient was not responsible for all of the accidents, it was responsible for some, and it presented an unsafe landing condition which must be avoided as much as possible.

REVIEW OF WORK CONDUCTED ON FRICTION COEFFICIENT

A great amount of work has been conducted and published on the subject of friction coefficients. The work includes the basic theoretical studies on friction coefficient, the development of devices to accurately measure the friction coefficients between tires and pavement surfaces, and various experiments to determine the factors that affect the friction coefficients. In addition, experiments were conducted to find means to restore slick pavement surfaces to safe or high-friction levels. Most of the work was conducted by state highway departments, research organizations, and vehicle and tire manufacturers in the interest of highway safety.

Basic Laws of Friction and Theory of Skidding

Moyer (1959) reported that two basic laws of solid friction were established many years ago by Leonardo da Vinci and verified by Charles Coulomb. The laws state (1) that the frictional force is proportional to the normal force, and (2) that the frictional force is independent of the contact area of the sliding surfaces. These laws are primarily laws of solid friction and are based on test results of materials having comparable rigidity. The sliding of a pneumatic rubber tire on a rigid pavement surface, however, is an interaction of two materials at the extreme range of rigidity. The pavement, especially portland-cement-concrete pavement, is rigid, whereas rubber has properties of flexibility, toughness, elasticity, and plasticity. Consequently, the total frictional force of a rubber tire on a pavement surface involves not only the basic frictional force, but, in addition, the mechanical force which results from the interlocking of the tire tread with the aggregate particles. The basic frictional force is proportional to the normal force between the two surfaces as previously stated. The ratio of frictional force to normal force is defined as the friction coefficient or the coefficient of friction. The mechanical force is dependent not only on the normal force, but also on the contact area. A high normal force on a large contact area will result in a higher mechanical frictional force on a given surface than that obtained with the same load on a smaller contact area.

The mechanical force is brought about in the following manner: When a tire is in contact with the pavement surface, the rubber is in elastic and plastic types of deformation and envelops the protruding aggregates. Upon braking, accelerating, or cornering, this enveloping causes an interlocking effect or shearing force between the rubber and the aggregates which is similar in principle to the rack-and-pinion gear design. This interlocking or "gearing" of the tire to the protruding aggregates plays an important part in developing high skid-resistance on both dry and wet pavement surfaces.

The measured friction coefficient on dry pavement is generally very high if a sufficient amount of protruding aggregates are present. The formation of melted rubber due to high temperatures during skidding at high speeds introduces certain effects which will vary the test results, but not to a great extent. An analysis made by Milwitzky, Lindquist, and Potter (1955) with some simplifying assumptions showed that the friction coefficient decreased with increasing tire-surface temperature or decreased with increasing skidding energy per unit of surface area.

In the wet pavement tests, the presence of water introduces many new factors and conditions at the contact area of skidding. Water functions as a lubricant and reduces the friction coefficient. When water is present in films thick enough to cover the protruding aggregates, it must be ejected by the pressure of the rolling tire before contact can be made with the pavement surface. This process takes time because of the inertia and viscous forces of the water. As speed increases, the time for ejection of the water decreases, and a greater portion of the tire contact area is supported by water. Therefore, if the speed is sufficiently high, the entire contact area will be supported by water alone, and the tire may stop rotating and plane along the wet surface. This is known as "aquaplaning." When this condition occurs, braking effectiveness and sidewise stability are almost entirely lost. The degree of surface wetness required to produce these conditions has apparently been encountered on airport runways during heavy rain, and it appears likely to occur, at least occasionally, on highways.

When a braking torque is applied to the wheel, the angular velocity is reduced, but the axle velocity may be held constant. This reduction in angular velocity under torque gives rise to the concept of slip ratio. Slip ratio is normally defined as the ratio of change in the angular velocity of a wheel, under application of torque, to the angular velocity of a freely rolling wheel at the same axle velocity. That is:

$$S = \frac{\dot{\theta}_f - \dot{\theta}}{\dot{\theta}_f}$$

where S = slip ratio

$\dot{\theta}_f$ = angular velocity of freely rolling wheel

$\dot{\theta}$ = angular velocity of wheel under torque

The slip ratio can also be expressed as the ratio of the apparent skidding velocity of the tire to the actual translational velocity of the axle. That is:

$$S = \frac{V_s}{V_a}$$

where V_s = apparent skidding velocity

V_a = actual translational velocity of axle

The apparent skidding velocity, V_s , is the difference between the actual translational velocity of the axle, V_a , and the translational velocity of the axle in free rolling with the same angular velocity. Thus, another way in which slip ratio can be expressed is:

$$S = \frac{V_a - r\dot{\theta}}{V_a}$$

where r = rolling radius, (approximately equal to the outside radius of the tire, less 1/3 of the tire deflection).

As shown in Figure 1, given by Kullberg (1962), the friction coefficient varies with the slip ratio. As the slip ratio is increased from free rotation, the friction coefficient increases to a maximum and decreases to a lower value at the full-skid or locked-wheel condition. The point of maximum friction coefficient in Figure 1 is known as the point of incipient skid. Clearly, if braking can be maintained at the point of incipient skid, a vehicle will have the highest deceleration and shortest stopping distance possible. However, a sudden, hard application of brakes, which usually occurs in an emergency, causes the wheels to lock, and the vehicle requires more distance to stop than under the incipient-skid condition.

The path of a skidding 4-wheel vehicle may not be straight because the wheels on one axle may slide first, depending on the brakes and the load distributions. Stonex (1959) reported that for a given brake distribution, there was only one load distribution which provided simultaneous sliding of all wheels on a surface with uniform friction coefficient. The behavior of a vehicle with either the front or rear wheels skidding was demonstrated by Stonex (1959) with a fixed-steering model car on a slippery floor. When the model car had freely rolling rear wheels and locked front wheels, it traveled in the direction it was headed at the onset of the skid. Stonex (1959) explained that this stable condition occurred because the cornering forces (forces parallel to the wheel axle) were developed by the rear wheels as soon as the vehicle yawed or turned slightly (Figure 2). The skidding front wheels developed no cornering forces, but did develop frictional forces in a direction opposite to the direction of motion. Consequently, the rear wheels had a tendency to reduce the yaw and to permit the vehicle to continue in the original direction.

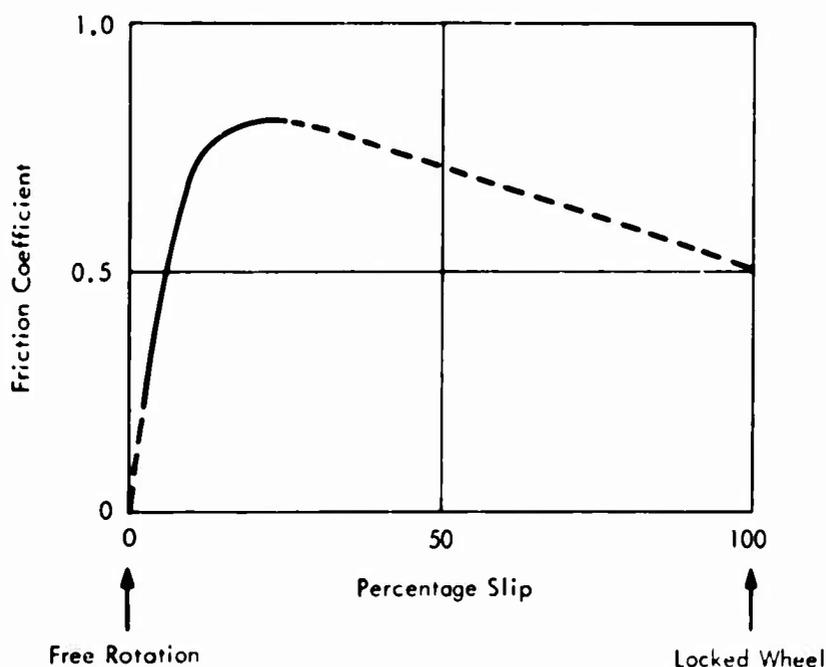


Figure 1. Characteristic curve of friction coefficient and slip.

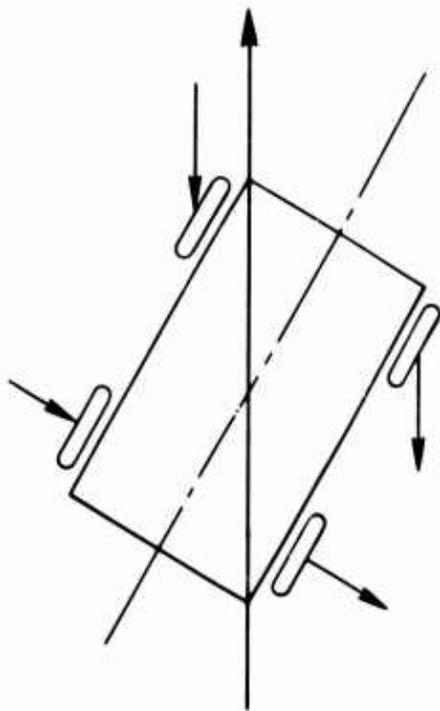


Figure 2. Front wheels slide.
(Stonex, 1959.)

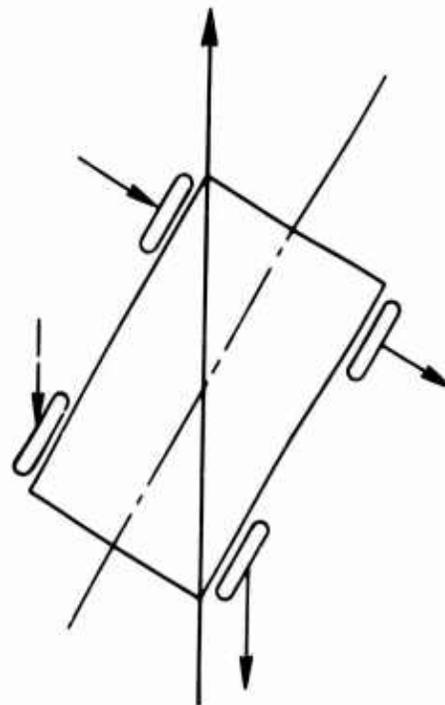


Figure 3. Rear wheels slide.
(Stonex, 1959.)

When the model car had locked rear wheels and freely rolling front wheels, it invariably turned through 180 degrees and continued in that direction with the rear end foremost. This unstable condition is shown in Figure 3. Stonex (1959) explained that this condition was the opposite of the stable condition. That is, the cornering forces developed in the front wheels had a tendency to increase the yaw and turned the vehicle through a half-circle. At this turned position, the behavior of the vehicle reverted back to that of the vehicle with locked front wheels and freely rolling rear wheels.

In a full-scale vehicle which can be steered, the condition of instability still exists. A skilled and alert operator may be able to delay or possibly avoid the half-circle spin, but he is dealing with an unstable condition. Therefore, in many situations, it appears that efforts must be directed toward reducing the skid by proper application of brakes rather than by controlling the path of full skid with steering.

Friction Measuring Devices

Various field methods or devices have been developed to measure the friction coefficients between tires and pavement surfaces. Most of the devices were designed and fabricated by highway departments and organizations primarily interested in the skid resistance of vehicles on highways rather than the skid resistance of aircraft on airfield pavements. The following paragraphs describe the various devices and discuss the results of some comparative tests conducted in an effort to standardize the method of measuring friction coefficients.

Stopping-Distance Method. In the stopping-distance method, a passenger automobile, usually equipped with ordinary tires and some instrumentation, was used as a test vehicle to measure the friction coefficient. The early tests by this method were conducted in the following manner: For a wet-surface test, the test section was wetted down by spraying from a water truck, by soak hoses, or by other means. The vehicle was then brought to an initial speed,

and the brakes were jammed to lock the wheels. The point of brake application was marked by a chalk pellet fired from a .22 caliber blank cartridge set off by an electrical connection to the brake pedal. The distance between the point of brake application and the final stopping point of the vehicle was measured to calculate the average friction coefficient by the following stopping-distance formula:

$$F = \frac{V^2}{30S}$$

where F = average friction coefficient

V = initial speed in mph at the instant of brake application

S = measured length of skid in feet

After some experience, several shortcomings were realized and modifications were made to improve the method. Mahone (1962) used a special speedometer, which locked in place upon application of the brakes, and a "feet-to-stop" meter attached to a fifth wheel. A motion picture camera in the vehicle photographed the dial movements during the test. Michael and Grunau (1956) installed a vacuum braking system, a special speedometer, and an odometer which eliminated the human variables and simplified the operation. To make a test with the modified test vehicle, the driver merely pressed a microswitch at the desired speed as indicated by the special speedometer. This action locked the wheels, held the speedometer at the test speed, and activated the odometer. At the end of the skid, the initial speed from the speedometer and the skid distance from the odometer were recorded. Michael and Grunau (1956) indicated that these modifications permitted the method to be extremely consistent.

State highway departments in Virginia, Indiana, Michigan, Florida, California, Mississippi, Ohio, North Carolina, Tennessee, and others, have used and relied on the stopping-distance method to determine the friction coefficient. The initial speeds used for the tests varied from 20 to 70 mph on dry pavements, but were limited to a range of 20 to 40 mph on wet pavements for safety reasons.

Wherever possible, the skid tests were conducted on pavement surfaces where the grade was practically zero. Occasionally, when such a location was not found, tests were made on grades, and a correction was made to get the final result. Nicholas, Dillard, and Alwood (1956) have used the following modified form of the formula for computing the friction coefficient:

$$F \pm \frac{\text{percent grade}}{100} = \frac{V^2}{30S}$$

An alternate method was to perform tests both downgrade and upgrade and average the results. Although the occasion seldom arises, Nicholas, Dillard, and Alwood (1956) reported that averaging of results is now being used in Virginia.

Deceleration Method. In conjunction with the stopping-distance method, decelerometers mounted on the floors of the stopping-distance test vehicles have been used to measure the friction coefficient. The most popular and simple device, known as the Tapley decelerometer, was used by Dillard (1962), Marshall and Gartner (1962), and others. It was designed originally for the primary purpose of testing brakes. The device worked on the principle of a damped pendulum which swung forward in an arc from its normally level position. The angle of the arc was proportional to the rate of deceleration. The ratio of the rate of deceleration at any given speed in the test to the deceleration of gravity was the friction coefficient.

In using this simple device, some difficulties were encountered. Nicholas, Dillard, and Alwood (1956) reported that the deceleration rate increased and the dial readings crept higher and higher below the speed of 25 mph. However, fairly constant readings were obtained at speeds from 40 to 25 mph. In addition, Dillard (1962) pointed out three factors of the Tapley decelerometer which were potential sources of error:

1. The "dive" of the test vehicle upon braking meant that the pendulum was not perpendicular to the vehicle. Hence, the actual deceleration was less than the apparent deceleration by the amount of the angle of dive of the vehicle. To compensate for this error, Dillard (1962) used a value equal to 0.94 of the actual reading as the true deceleration for a 1958 Chevrolet and 0.96 for a 1957 Ford.

2. Vertical accelerations developed because the pavement surface was not smooth. Once the pendulum was out of horizontal plane, the vertical accelerations developed forces on the pendulum which acted both upward and downward. However, Dillard (1962) indicated that these forces were negligible from a practical standpoint. The relatively smooth surfaces of most pavements were not likely to generate vertical accelerations of any magnitude at most test speeds.

3. The true deceleration at a given moment was not recorded by the decelerometer because of the damping of the pendulum with a viscous fluid. This meant merely a delay in the response of the instrument and had relatively little significance. Dillard (1962) indicated that the damping of the pendulum resulted in a lag of about 0.8 second between the actual deceleration and the response of the instrument.

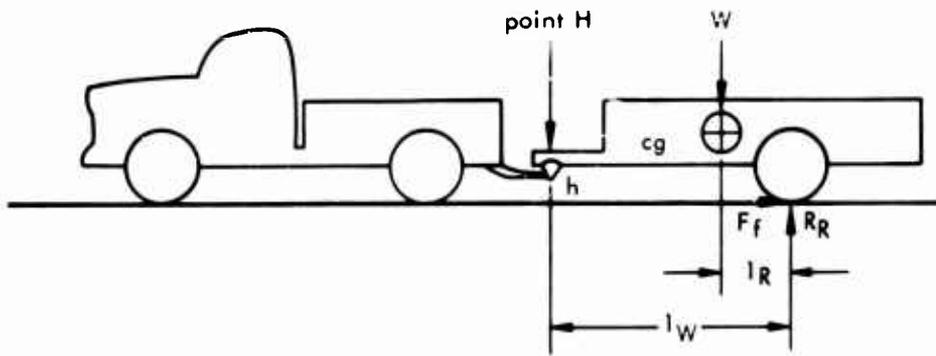
Trailer or Friction Cart Method. In the trailer or friction cart method, the equipment mainly consisted of a towing vehicle and a 2-wheel trailer or cart. The trailer with locked wheels was towed over the pavement surface with a towing vehicle, usually a truck. The braking force or the draw-bar pull was measured by a dynamometer. This value, divided by the vertical load on the wheels during the test, gave the friction coefficient.

Various designs of carts have been used, but the most economical construction was to use an existing automobile chassis obtained from a junk yard. For the trailer constructed by the General Motors Proving Grounds, Skeels (1958) reported that the complete rear running gear of the original chassis was retained. The only modification made was in the method of applying the brakes by using a truck-type power-brake unit from the towing vehicle. The remainder of the construction consisted mainly of fabricating a body to supply weight to the wheels of the cart and a system to wet the road surface. For some carts, brakes to only one wheel were used, leaving the other free to rotate. This tended to eliminate sideways sliding on curves or on crowned-pavement surfaces and to conserve water.

The operation was automatic on the General Motors (GM) trailer as well as on most of the other trailers. A switch or lever controlled a timer which opened the water valves, turned on a direct reading recorder, and applied the brakes.

Calibration of the GM trailer and other trailer devices was rather straightforward, but it was necessary to consider the weight transfer from the trailer wheels to the truck hitch caused by the application of brakes to the trailer wheels. Skeels (1958) explained that when the braking torque developed, it applied a downward pressure on the truck hitch. This downward force resulted in a decrease in the weight on the trailer wheels, since the weight of the trailer was constant. This is a simplified explanation of the weight-transfer problem. A more detailed explanation is provided by the diagram and formulas shown in Figure 4.

Since the friction force, F_f , in Figure 4 was measured and recorded, it was possible to calculate the friction coefficient for any frictional force when the values were known for the static weight on the trailer wheels, W_S , the height of the hitch above ground, h , and the distance from the axle centerline to the trailer hitch, l_w .



$$1. M = \frac{F_f}{R_R}$$

$$2. \Sigma M_N = W(l_W - l_R) - R_R l_W - h F_f = 0$$

$$3. R_R = \frac{W(l_W - l_R)}{l_W} - \frac{h}{l_W} F_f$$

$$4. M = \frac{F_f}{W(l - \frac{l_R}{l_W}) - \frac{h}{l_W} F_f}$$

With no braking

$$5. F_f = 0 \text{ and the total trailer wheel reaction force, } R_R, \text{ becomes:}$$

$$6. R_R = W(1 - \frac{l_R}{l_W}) = \text{static weight on trailer wheels.}$$

Therefore

$$7. M = \frac{F_f}{W_S - \frac{h}{l_W} F_f}$$

Where:

M = Friction Coefficient

F_f = Friction Force

W_S = Static Weight on Trailer Wheels

h = Trailer Hitch Height

l_W = Trailer Hitch to Axle Distance

Figure 4. Determination of friction coefficient for towed trailer.

In calibrating the device, a drawbar was inserted as a connecting link between the towing truck and the trailer. The trailer wheels were locked by applying the brakes, and a pulling force was applied to the trailer by the truck. The drawbar and recorder readings were then taken simultaneously at several points from the minimum to the maximum drawbar reading obtainable before sliding. These drawbar readings were the friction forces, F_f , in Equation 7 of Figure 4. With the other factors of Equation 7 known, the friction coefficients were calculated, and a calibration curve of friction coefficient versus the recorder reading was then prepared.

Skeels (1958) reported that continuous, all-day measurement was possible with the GM trailer. As many as 500 individual tests have been made during one day of operation. The GM trailer has been used satisfactorily up to 70 mph. However, it was difficult to maintain a constant speed with the trailer wheels sliding at speeds over 40 mph. The measuring system was designed so that it was virtually unaffected by gravity components, and it was possible to readily use the trailer on hills or curves.

Besides General Motors Proving Grounds, various organizations, state highway departments, and foreign countries have designed, constructed and used the trailer type of friction measuring device. These have been the Portland Cement Association; Bureau of Public Roads; Cornell Aeronautical Laboratory; National Aeronautics and Space Administration (NASA); British Road Research Laboratory; and highway departments of California, Michigan, Ohio, Oregon, Tennessee, Germany, France, Holland, Sweden, Spain, Italy, and others.

Most of the trailer devices measured the friction force with one or both wheels locked. The NASA trailer used gears to transmit torque from one wheel to the other and consequently fixed the velocity ratio between the wheels. When the cart was being towed, one wheel was forced to operate with positive slip and developed a braking force while the other operated at negative slip and developed a driving force. The gearing was arranged so that replacing one of the gears with another of a different size changed the gear ratio, the speed ratio of the wheels, and, hence, the slip ratio. Four interchangeable gears provided slip ratios of 0.125, 0.175, 0.240, and 0.500; thus, it was possible to measure the friction coefficients at these slip ratios with the NASA trailer.

The Federal Aviation Agency (FAA) is currently developing, under contract, a trailer-type, or a single-unit, surface-friction measuring device. Since it is in the development stage, no definite results on the device are available. However, information received from FAA through correspondence indicated that this device is being designed to measure the friction coefficient of airfield pavement surfaces under simulated conditions of high velocities, high tire pressures, and heavy loads of modern civil aircraft. The aircraft factors being considered in the design of this device are:

1. Wheel loads up to 30,000 pounds each
2. Tire pressures up to 170 psi
3. Velocities up to 80 mph

The detail requirements are such that the device will:

1. Measure the friction coefficient between the pavement surface and the aircraft tire
2. Indicate the friction coefficient available from a condition of zero to 80 percent slip and produce a permanent record that can be read immediately
3. Measure and record the friction coefficient slip curve at intervals of approximately five seconds

4. Be a trailer-type unit, or a single unit, capable of independent operation scaled down from the aircraft parameters to a minimum reasonable size and weight
5. Pre-wet the pavement as the measurements are being taken
6. Be roadworthy or easily transportable

It appears from the detailed requirements that this device will be expensive. The FAA plans to use the device in research rather than in routine measurements of the frictional properties of pavement surfaces. Since this device will hopefully duplicate the action of aircraft during landing and will be expensive, the FAA anticipates a study to correlate the device with other, simpler devices which are less expensive to operate and maintain for routine friction measurements of pavement surfaces.

Other Friction Measuring Devices. Various devices other than those described previously have been developed. For the most part, these devices were developed to determine the friction coefficients between surfaces of laboratory-size pavement specimens and small sections of tire or rubber. These devices are not described herein except for the bicycle-wheel apparatus of the National Crushed Stone Association and the British portable skid-resistance tester, both of which appear to show some promise as field-testing devices.

The National Crushed Stone Association device described by Dillard and Allen (1959) consisted of a bicycle mounted on a stationary frame and an eccentric weight mounted on the rim to drive the wheel. The tread was removed in the portion of the tire which preceded the zero reading, and friction was created as the treaded portion came in contact with the pavement surface. The central angle through which the wheel passed was considered as an empirical measure of slipperiness. This device was very inexpensive, costing less than \$100 to build.

Mahone (1962) described the British portable skid tester as a pendulum device which measured the friction resistance of a wetted surface to the passage of a wetted, rubber slider. The slider, a spring-loaded 3- by 1-inch block of rubber, contacted the surface along one edge of its 3-inch length. After proper adjustment, the pendulum and pointer were cocked in a horizontal position. Upon release, the pendulum and pointer swung through an arc. The pendulum returned, but the pointer stayed at the farthest point of the arc. At this point, a measurement was recorded from a scale numbered from 0 to 150 which was calibrated to give readings that were 100 times the effective friction coefficient. A similar device has been developed in France.

Comparison of Friction Measuring Devices

A considerable amount of controversy over the relative merits of various skid-testing devices and methods resulted in an attempt to establish a standard method for determining the friction coefficient between pavement surfaces and tires. In this attempt, several organizations conducted skid tests for the purpose of comparing the results obtained with the different devices.

A number of skid tests using the stopping-distance method simultaneously with the deceleration method were conducted by Nichols, Dillard, and Alwood (1956) and Dillard (1962) in Virginia. Similar tests were also conducted by Whitehurst (1956) in Tennessee and by Marshall and Gartner (1962) in Florida.

A 1954 Ford, equipped with rib-tread tires, and a Tapley decelerometer were used in Virginia. It was found that the decelerometer readings remained fairly constant as the test vehicle skidded from 40 to 25 mph at which time the readings began to increase. The Tennessee tests were performed on 20 different pavement sections from initial speeds of 20, 30, and 40 mph using a similar decelerometer, but the test vehicle had tires which were capped with smooth treads. In Florida, Tapley decelerometer tests were conducted on 25 asphaltic-concrete pavement surfaces with the test vehicle traveling at the initial speed of 40 mph and using tires with standard treads.

The results of the tests conducted in Virginia, Tennessee, and Florida are shown in Figure 5. A comparison of the curves established by these tests shows an appreciable difference in the slopes of the curves. Marshall and Gartner (1962) indicated that this difference was apparently caused by the difference in the tread design of the tires. Florida's results were in between the other two and gave the best correlation between the decelerometer and stopping-distance methods of measuring the friction coefficient.

The results of the stopping-distance method of measuring the friction coefficient were compared with those of the trailer method by Dillard (1958) in Virginia, and Whitehurst and Goodwin (1955) in Tennessee. In Virginia, only a limited amount of time was available for the tests with the trailer borrowed from General Motors. The results given in Figure 6 show that only a few measurements were made in Virginia where the friction coefficient was above 0.50. The results suggest that at friction values below 0.50 the friction coefficients obtained by the stopping-distance method were higher than those obtained by the GM trailer.

In Tennessee, the results of the two test methods were compared at speeds of 10 to 40 mph on asphaltic-concrete pavements made with different aggregates such as slag, gravel, and limestone. Figure 7 shows the curves developed by Finney and Brown (1959) from the data obtained in Tennessee. Curve A in Figure 7 shows that at similar speeds, the stopping-distance method gave friction values 40 to 50 percent higher than those for the trailer method. Curve B shows an approximate relationship between the stopping-distance tests at 20 mph and the trailer tests at 40 mph. In this case, the trailer method gave results which were approximately 60 percent less than those obtained on the same surface by the stopping-distance method.

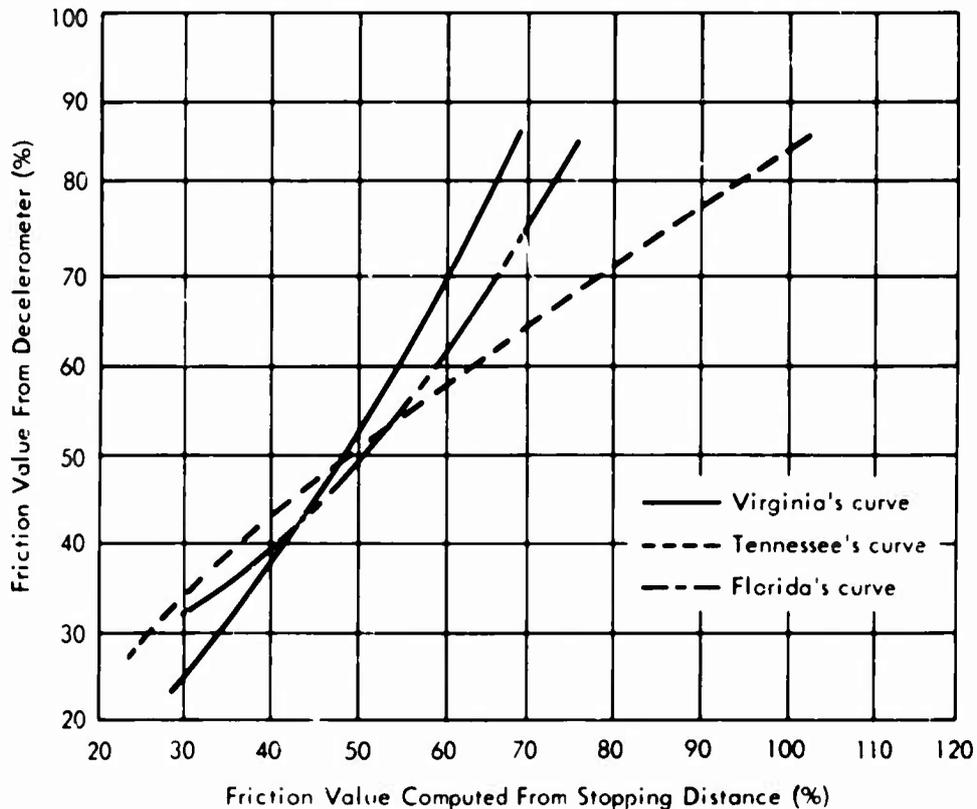


Figure 5. Friction value versus decelerometer readings (apparent effect of tread design).

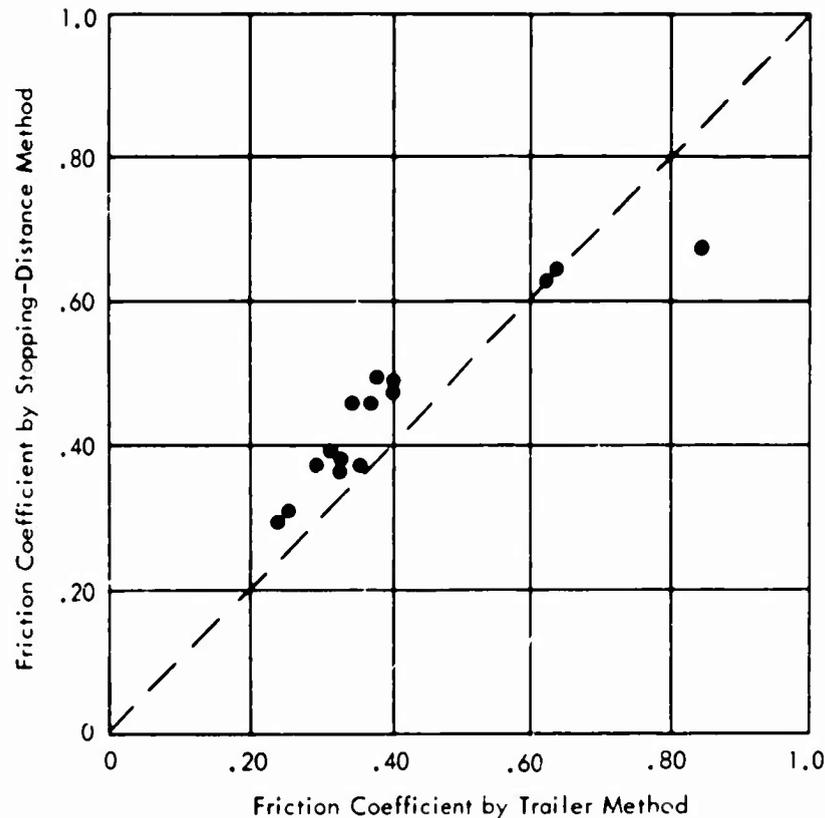


Figure 6. Comparison of friction coefficient determined by tests in Virginia, using General Motors' trailer and stopping-distance test car.

Moyer and Shupe (1951) compared the results of tests made by the deceleration method using a Statham instrument, the stopping-distance method, and the trailer method. The tests were conducted on portland-cement concrete, fog seal-coat, and two open-graded asphalt surfaces. The results shown in Figures 8 and 9 indicate that the friction values measured by the deceleration and trailer methods were nearly the same at corresponding speeds. However, the values from the stopping-distance method plotted in terms of initial speed were approximately 25 percent higher than the values obtained by the other two methods. Moyer and Shupe (1951) gave two possible explanations for the difference in the friction values. One was that the friction values from the stopping-distance method were average values over the entire stopping distances, and were considered as friction values for the average speed instead of the initial speed. Using the average speed in the stopping-distance formula, however, still yielded friction values higher than those yielded by the other two methods. The other explanation was that the stopping-distance method combined the effect of incipient-skid and sliding friction whereas the trailer method measured only the sliding friction. Since the incipient-skid friction values are supposedly higher than the sliding-friction values, it appeared that this accounted for the differences in the results given in Figures 8 and 9.

Mahone (1962) made an extensive comparison of the British portable tester and the stopping-distance method of measuring friction coefficients. Fourteen pavements ranging in friction levels from dangerously low to very high, and providing a wide range of surface textures, were tested. The test data was statistically analyzed. From this study it was found that the friction coefficients obtained by the two methods were significantly different on approximately 50 percent of the surfaces. Mahone (1962), therefore, concluded that the values from the two methods were not directly interchangeable, but that it was possible to predict the friction coefficient for the stopping-distance method from measurements with the portable tester by use of estimating equations.

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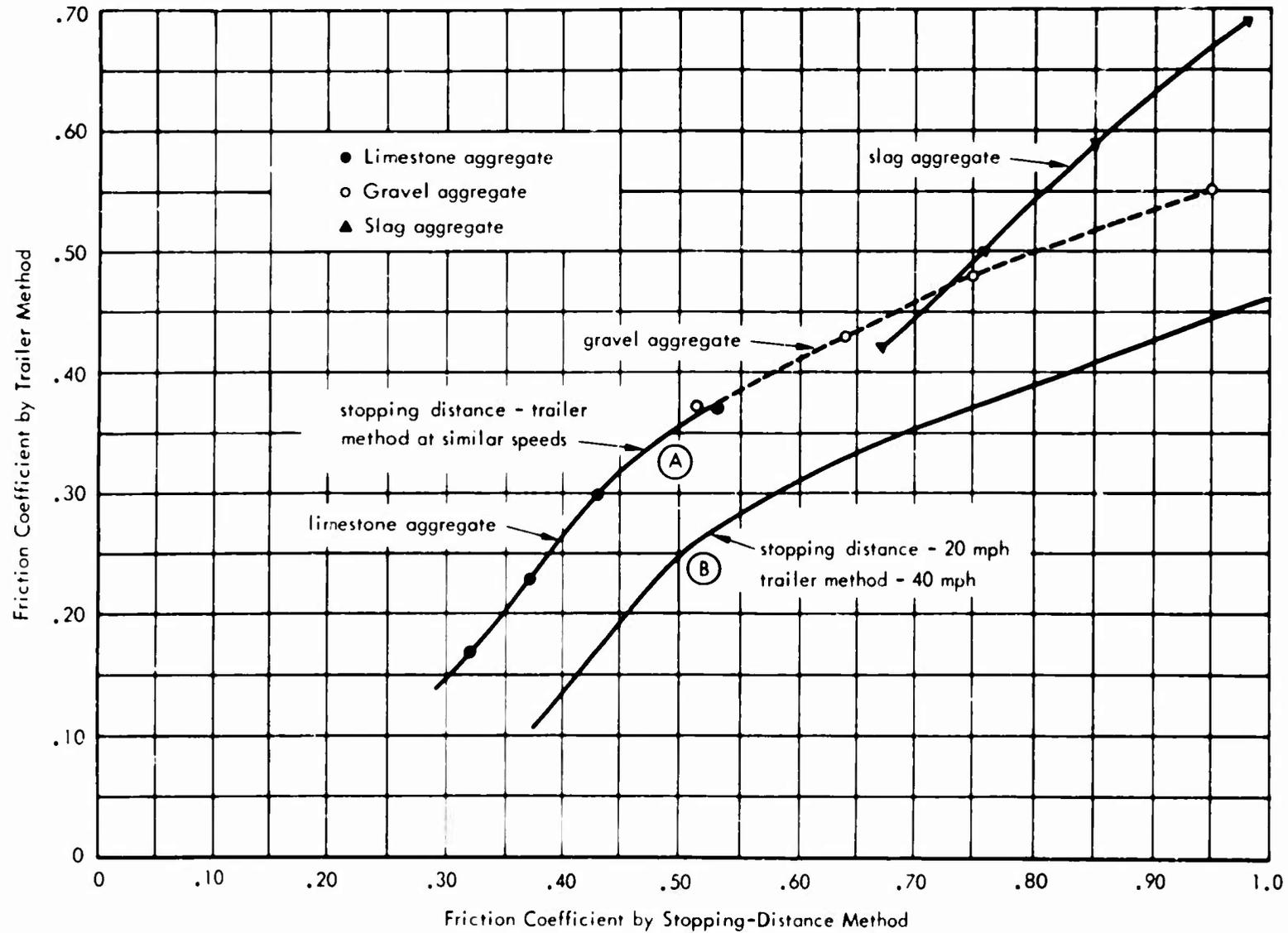


Figure 7. Friction relationships: Trailer and stopping-distance methods at different speeds. (Finney and Brown, 1959.)

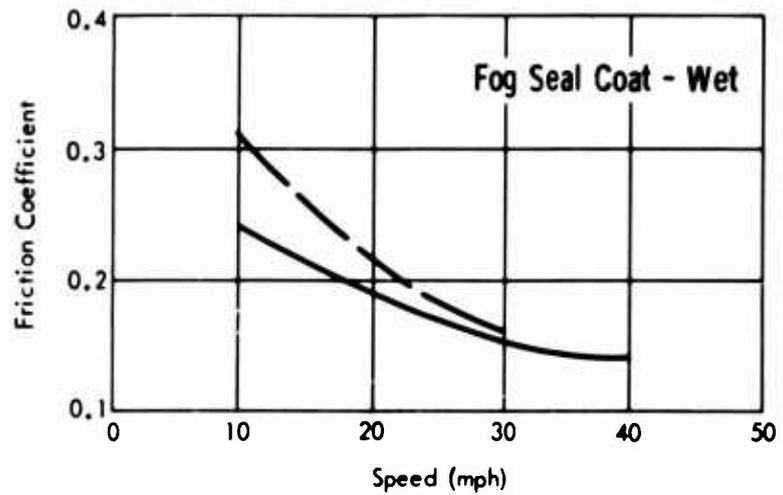
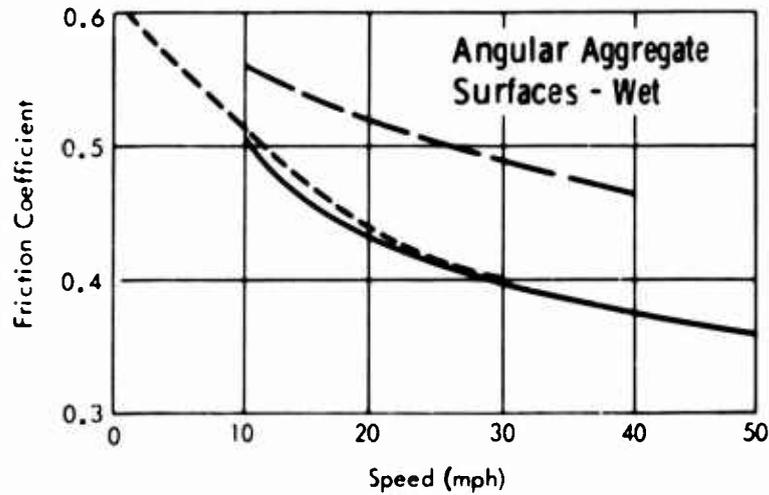
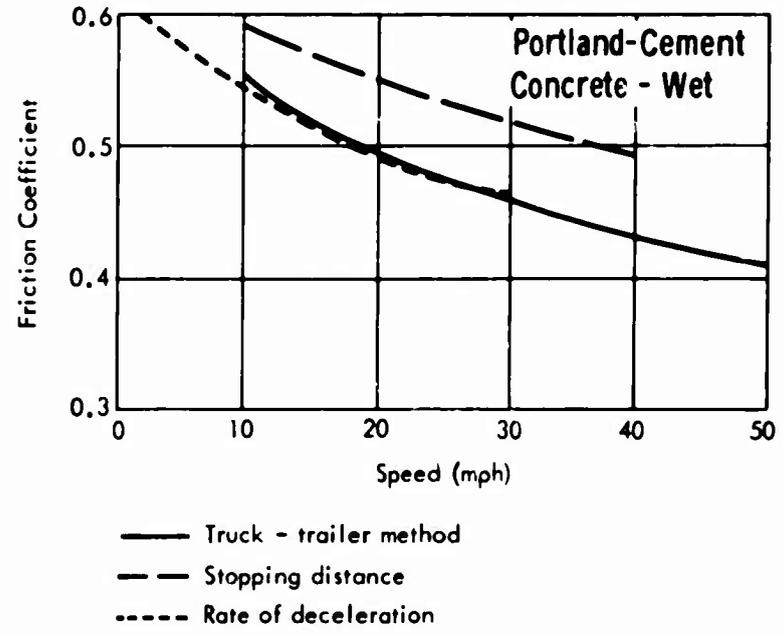
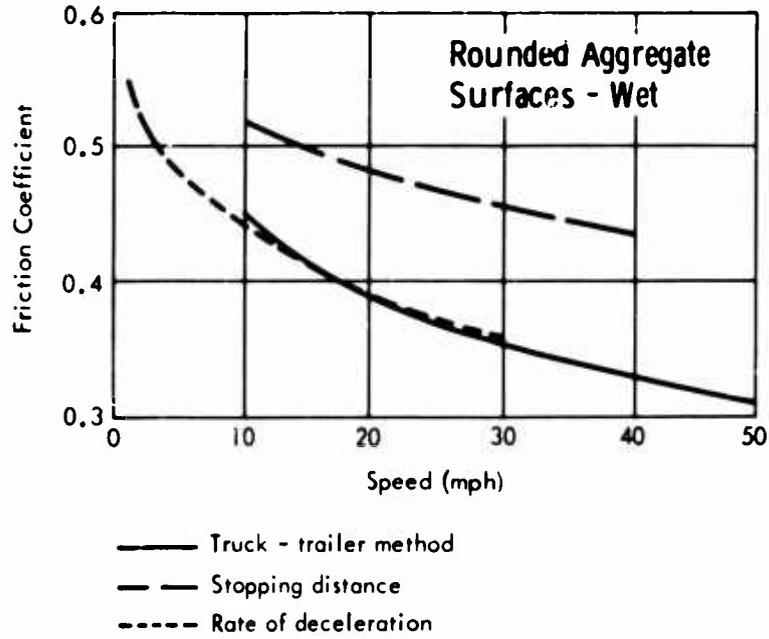


Figure 8. Comparison of results obtained by different methods of testing skid resistance of open-graded asphalt surfaces. Meyer and Shupe, National Academy of Sciences, National Research Council, 1951.

Figure 9. Comparison of results obtained by different methods of testing skid resistance. Meyer and Shupe, National Academy of Sciences, National Research Council, 1951.

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Dillard and Allen (1959) reported that an extensive study on the comparison of several devices for measuring the friction coefficient was made during the planning of the First International Skid Prevention Conference held in August 1958. The purposes of the study were to:

1. Compare the results obtained by the various devices as they were normally used by the respective organizations. These tests were designated as Series X tests.
2. Compare the test results using the same kind of tire (standard tire) on each device. These tests were designated as Series Y tests.
3. Conduct a group of miscellaneous sub-experiments to obtain information on other important aspects of measurement. These tests were designated as Series Z tests.

The experiment was designed so that all factors affecting the results were controlled as much as possible, and a sound statistical analysis of the results was possible. The devices which participated in the study are summarized in Table I.

Four test sites were selected for the study. Three of the sites were dense-graded asphaltic concrete made with 1/2-inch maximum size aggregate, and the other was a fine plant-made sand deslicking mix. The friction levels of the four test sites ranged from dangerously low to very high. The designations of the levels were based on the mean values of the friction coefficients as measured by all the devices when the pavements were wet. The designations were as follows:

<u>Designation</u>	<u>Friction Coefficient</u>
Poor	0.25
Fair	0.38
Good	0.51
Excellent	0.62

The results of Series X and Series Y tests are shown in Figures 10 and 11, respectively. In the Series X tests, which were conducted with the regular tires, the results of the stopping-distance method of Purdue and Virginia were close to those of the trailer method of the General Motors Proving Grounds, the Portland Cement Association, and the Cornell Aeronautical Laboratory. However, the incipient-skid friction coefficients measured by the NASA trailer were well above the others, and the Tennessee trailer, using smooth-tread tires, had sliding-friction values well below the others. These divergences were expected since the friction values were supposedly highest at the incipient-skid condition and smooth-tread tires gave low friction values on wet pavements. Some differences in the results of the Series X tests were also expected since the devices used different types of tires. Figure 11 shows that the differences were substantial even when the devices were equipped with the standard tires.

For the Cornell device, the mean of the results on the good site was disregarded, since it was evident from visual inspection that the test wheel was not locking. For this reason, a straight dotted line was drawn for the results of the Cornell device from the "fair" to "excellent" site in both Figures 10 and 11.

Figures 10 and 11 show that the stopping-distance methods gave friction coefficients on the "good" and "excellent" sites which were not appreciably higher than those measured by the trailers. Dillard and Allen (1959) anticipated higher results from the stopping-distance method than those from the trailer method.

Table 1. Summary of Characteristics of Devices Participating in Study

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Machine No.	Agency	Type	Braking Conditions	Tire Size	Normal Static Load per Wheel (pounds)	Force Measuring System
1	Bureau of Public Roads	1-wheel trailer	1 wheel locked	6.70-15	1110	Drawbar force
2	Portland Cement Association	2-wheel trailer	2 wheels locked	6.70-15	925	Beam deflection
3	Cornell Aeronautical Laboratory	1-wheel trailer	1 wheel locked	6.70-15	970	Brake torque
4	General Motors Proving Grounds	2-wheel trailer	2 wheels locked	7.60-15	967	Torque tube deflection
5	National Aeronautics and Space Administration, Langley Field	2-wheel trailer	2 wheels slipping	6.70-15	932	Gear box torque
6	Joint Highway Research Project, Purdue University	Skid car	4 wheels locked	6.70-15	905 (approximate)	Length of skid
7	Tennessee Highway Research Project	2-wheel trailer	Inside wheel locked	6.70-15	871	Drawbar force
8	Virginia Council of Highway Investigation and Research, University of Virginia	Skid car	4 wheels locked	7.40-14	1015	Length of skid
9	Virginia Council of Highway Investigation and Research, University of Virginia	Tapley decelerometer mounted in Machine No. 8				
10	Bureau of Public Roads	An alteration of Machine No. 1 to measure sideway force coefficient				
11	Cornell Aeronautical Laboratory	An alteration of Machine No. 3 to measure sideway force coefficient				
12	National Crushed Stone Association	Bicycle wheel apparatus				

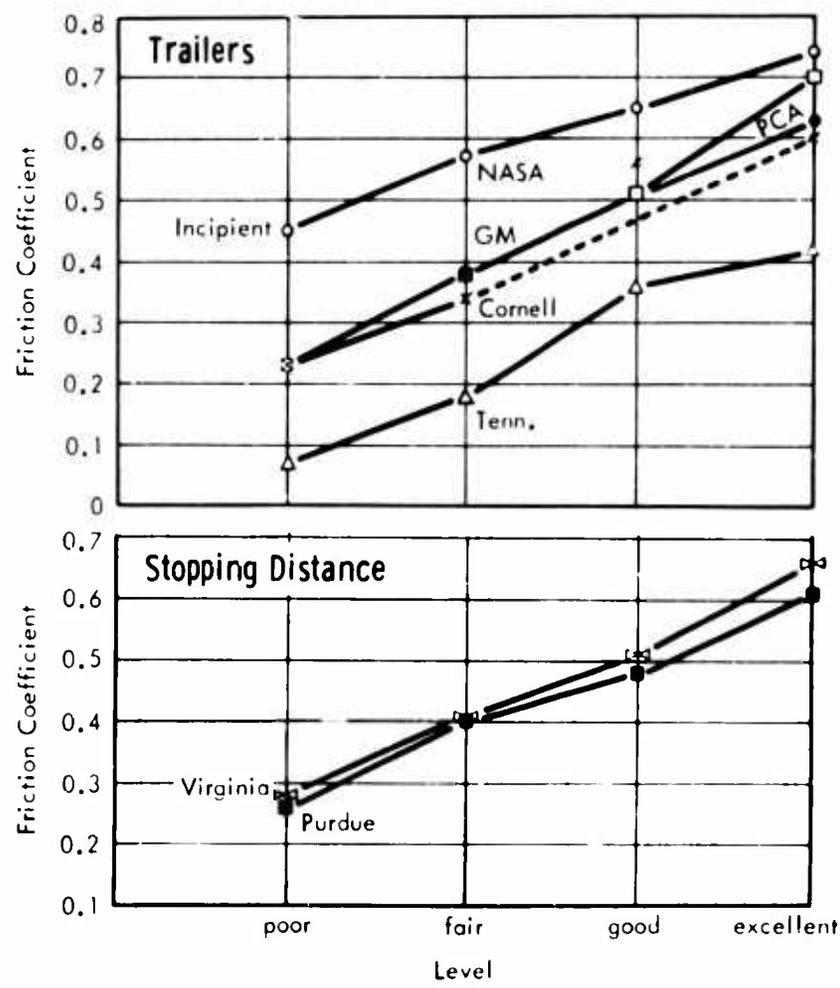


Figure 10. Measurements with regular tires (Series X).

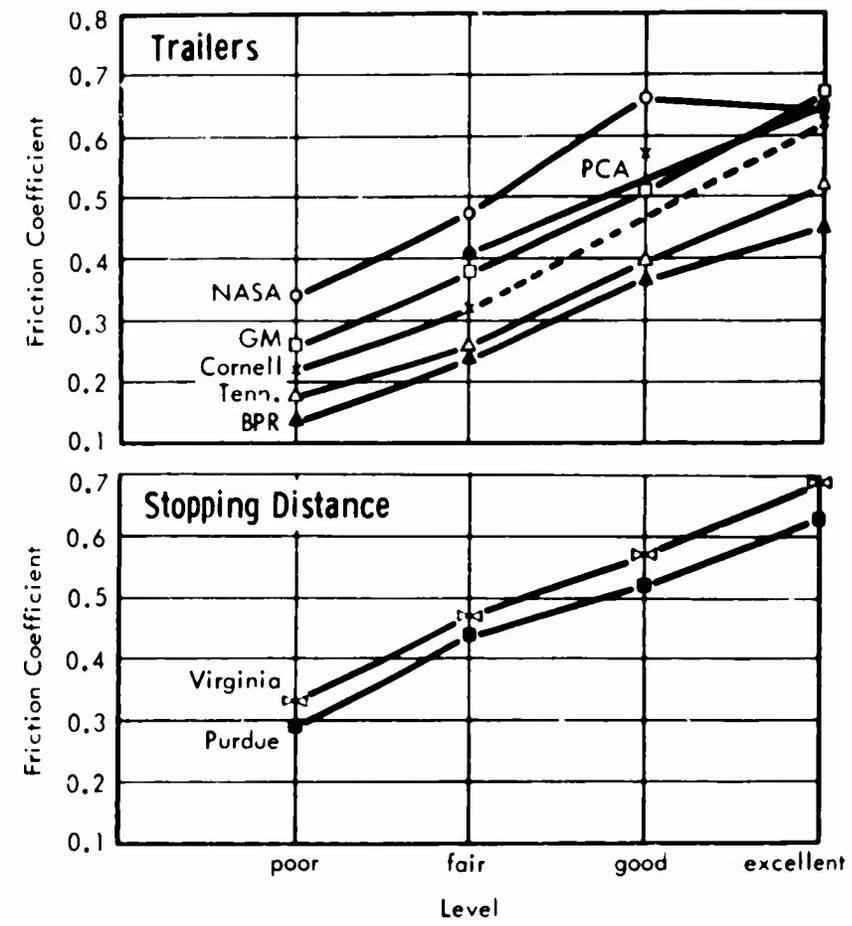


Figure 11. Measurements with standard tires (Series Y).

From the results of the Series X and Y tests, Dillard and Allen (1959) made the following conclusions:

1. The friction coefficients measured by the various devices were different. The differences were such that comparison of the results by use of an additive factor was not possible.
2. No definite relationships were established between the measurements made by the trailers and those made by the stopping-distance methods.
3. It was possible to correlate the results from different tires by an additive factor. This factor differed from tire-to-tire but appeared to be nearly the same across the different levels of friction.
4. The devices differed in terms of the variations of the results during successive measurements of the same pavement. The variations were not affected by the level of friction which indicated that the friction level had little influence on the precision of measurement.

As previously indicated, Series Z was a group of miscellaneous sub-experiments. The Series Z measurements were taken after completion of Series X and Series Y; therefore, the pavement surfaces had been subjected to considerable wear. All measurements were taken with standard tires on wet surfaces. The following sub-experiments were conducted in Series Z:

1. Comparison of friction coefficients from a stopping-distance method and a deceleration method
2. Comparison of the incipient-skid, locked-wheel, and sideway-force coefficients
3. Comparison of the effect of speed on the incipient-skid and locked-wheel friction coefficients
4. Correlation of a bicycle-wheel method with a stopping-distance method

The average test results from the stopping-distance method and the Tapley decelerometer indicated a quite favorable comparison. The Virginia vehicle, after being corrected for tilt, was used in the stopping-distance tests. The maximum deviation of the average results at the four sites was only 0.04.

The results shown in Figure 12 provide a comparison between the incipient-skid, locked-wheel, and sideway-force coefficients. The comparison indicates that the sideway-force coefficients measured by the Cornell device were considerably higher than the incipient-skid or locked-wheel friction values. Figure 12 also shows that the incipient-skid friction values were higher than those of the locked wheel.

The effect of speed on the incipient-skid and locked-wheel friction coefficients is shown in Figure 13 for the four levels of friction. In Figure 13, the GM trailer measured the locked-wheel coefficients, and the NASA trailer measured the incipient-skid coefficients. At 10 mph, the locked-wheel coefficients were greater than the incipient-skid coefficients. However, at 40 and 55 mph the friction values were reversed, indicating the effectiveness of the incipient-skid condition over the locked-wheel condition at high speeds. The incipient-skid condition will therefore contribute appreciably to safety during emergency stops from high speeds.

The slipperiness readings of the bicycle-wheel device made by the National Crushed Stone Association (NCSA) were the central angles through which the wheel passed and gave empirical indications of skid resistance. For the correlation study, a minimum of 100 readings were taken over the entire length of each test site. The friction coefficients and

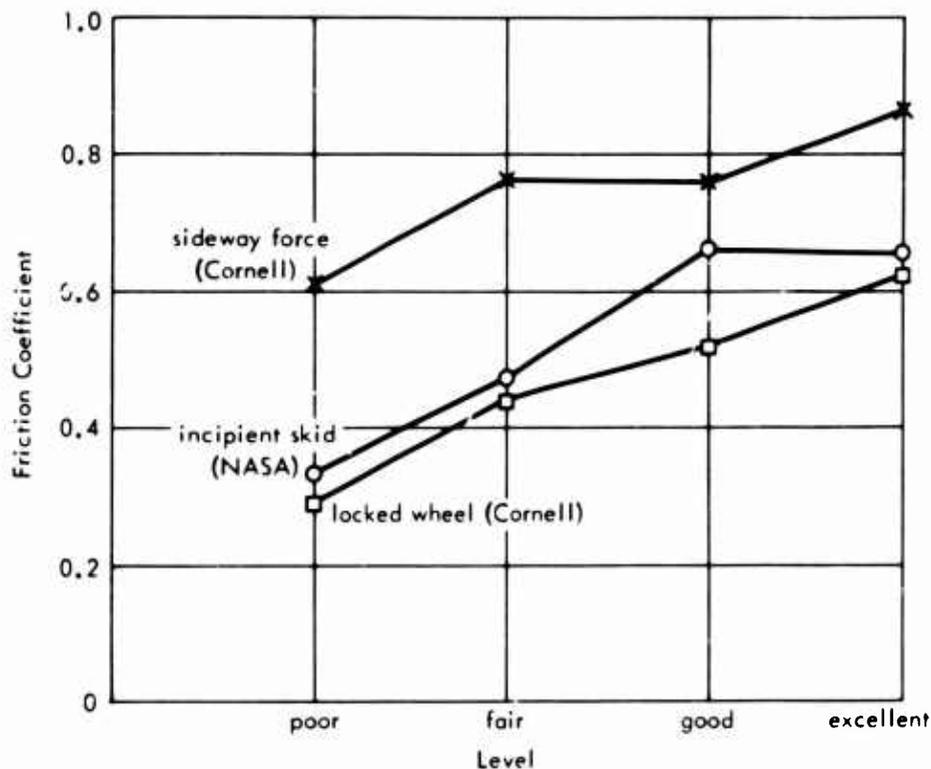


Figure 12. Comparison of the sideways-force, incipient-skid, and locked-wheel friction coefficients. *Quoted from National Academy of Sciences, National Research Council, 1959.*

stopping distances determined by the Virginia test vehicle are plotted in Figure 14 against the slipperiness readings of the bicycle-wheel device. Figure 14 shows that as the friction coefficients decreased, the stopping distances and the slipperiness readings increased. Dillard and Allen (1959) reported that the bicycle-wheel device showed promise as a laboratory device and may provide a valuable link between laboratory and field measurements if further comparisons show good correlations.

Advantages and Disadvantages of Friction Measuring Devices

Many experienced investigators concerned with the measurement of friction coefficients have stated the advantages and disadvantages of the available friction measuring devices. The advantages and disadvantages of the devices which have been used mostly by the investigators in the United States are summarized in the following paragraphs.

Stopping-Distance and Deceleration Methods. The advantages of the stopping-distance and deceleration methods are as follows:

1. The stopping-distance method is realistic for friction coefficients between pavements and vehicle tires. A standard vehicle is involved in an emergency skid and the consequences are observed.
2. Late model cars can be used for the tests; consequently, the results reflect the vehicular and tire design changes made by the automobile industry.
3. Results obtained by the stopping-distance method are more consistent than those measured by the trailer method.

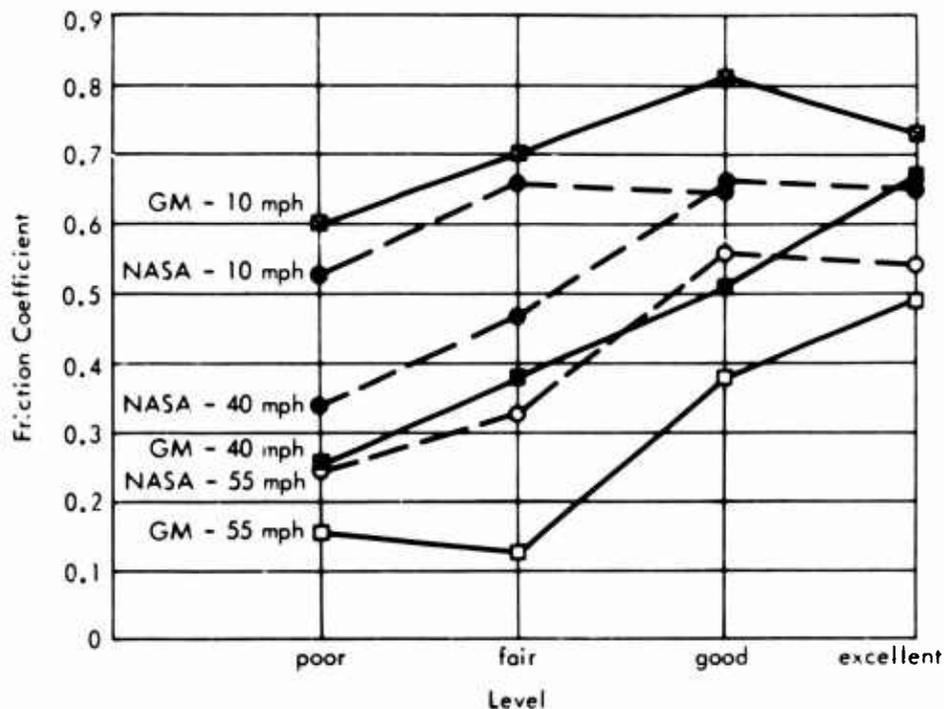


Figure 13. Influence of speed on locked-wheel and incipient-skid friction coefficients.

Chandler and Allen, National Academy of Sciences, National Research Council, 1969

4. Results can compare favorably with those of the Tapley decelerometer.
5. The deceleration method is simple.

The disadvantages of the stopping-distance and the deceleration methods are as follows:

1. Older vehicles are placed with newer models; it becomes difficult to compare the new data with the old.
2. Data obtained by different test vehicles are not easily compared.
3. Tests are more time consuming and more costly than for the trailer method.
4. Tests at grades and dangerous curves must be avoided.
5. Tests over the entire length of a section are not practical.
6. Tests require use of a water-truck and special traffic-control measures such as flagmen and warning signs.

Trailer or Friction Cart Method. The advantages of the trailer or friction cart method are as follows:

1. The method is very rapid; tests can be run with a minimum of interference with traffic.
2. The method permits testing of sections throughout their entire length rather than in segments.

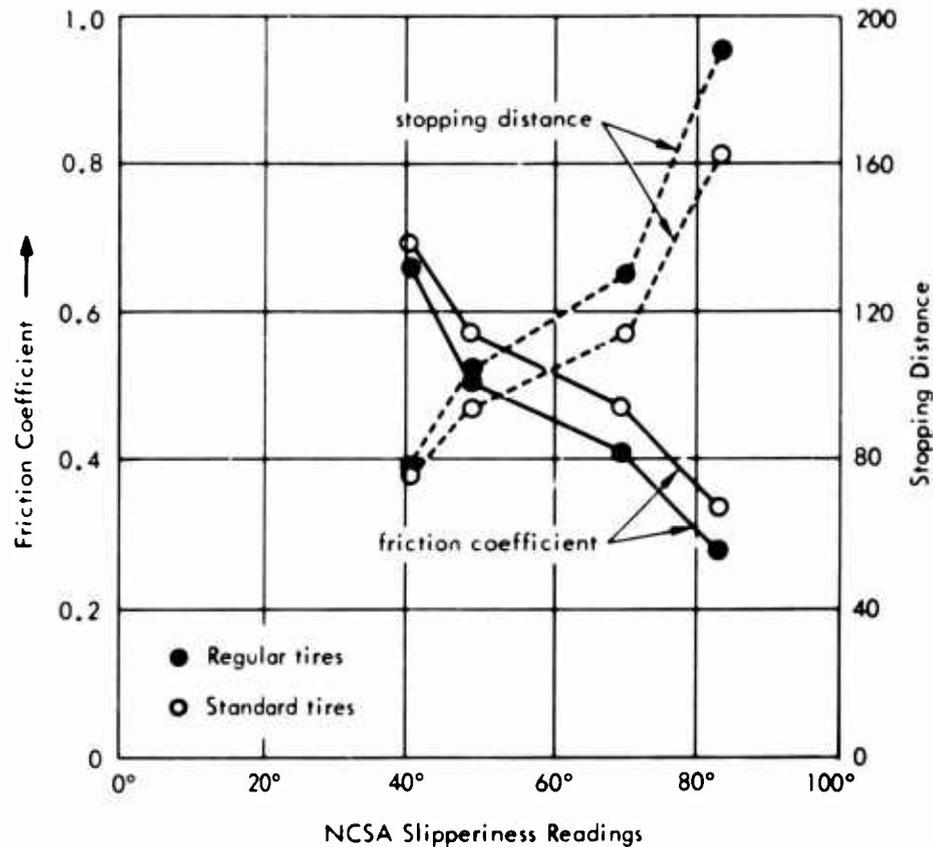


Figure 14. Friction coefficient and stopping distance versus slipperiness.

© Dillard et al., National Academy of Sciences, National Research Council, 1959

3. The cost of conducting the test is low. Dillard (1958) estimated that the cost of testing with the GM trailer is approximately one-fourth that required for the Virginia stopping-distance test.
4. There is practically no hazard as far as loss of control of the towing vehicle is concerned.
5. The wet tests do not require an auxiliary water-truck.

The disadvantages are as follows:

1. The sideways on some trailers is rather severe.
2. The sliding friction at constant speed is measured; consequently, it is not as realistic as the stopping-distance method.
3. The initial cost is high when the cost of all equipment and the towing vehicle is considered.

Factors Affecting Friction Coefficient

Many factors affecting the friction coefficient between tires and pavement surfaces have been identified through investigations. In general, the factors were considered to fall in three categories: (1) vehicle and aircraft operation factors, (2) tire factors, and (3) pavement factors. Although the interest of this task is primarily concerned with the friction

coefficients of aircraft tires on airfield pavement surfaces, the following paragraphs mainly describe the factors concerned with friction coefficients of vehicle tires on highway pavement surfaces since most of the work was done in the interest of highway safety.

Vehicle and Aircraft Operation Factors. Speed and braking techniques used in operation of vehicles and aircraft are major factors affecting the friction coefficient.

1. Speed. Of all the factors, the high speed of vehicles on the highways has been cited as the major cause of skidding when braking, accelerating, or rounding a curve. Through the years, speed has increased primarily because of wider, multilane highways and higher horsepower engines. Normann (1959) reported that in 1941 vehicles were traveling at an average speed of 48 mph on highways considered, at that time, to be of modern design. In 1959 the average speed reached 64 mph. Unfortunately, many motorists were not aware that this increase in average speed of 16 mph represented a 78 percent increase in the kinetic energy of the vehicle and required a 78 percent longer stopping distance, assuming that the vehicles in 1941 and 1959 had brakes capable of using the full friction coefficient available between the tires and pavement surfaces. It is probable that the average speed on highways will continue to increase, especially as more sections of the Interstate Highway Systems are opened to traffic. If this is true, the average speed in time will be 80 mph or more at some locations of these super highways.

Fortunately, it was found that the friction coefficient between tires and dry pavement surfaces varied little with change in speed. This finding was reported by Moyer (1959), Mercer (1958), and many others. Figures 15 through 18 show the effect of speed on the friction coefficient for a portland-cement-concrete pavement and for three asphalt-pavement surfaces under both dry and wet conditions. All of the curves for the dry surfaces, except for the bleeding-asphalt surface in Figure 16, indicate that the friction coefficient was nearly constant from 10 to 50 mph. The small variations in friction coefficient were probably caused by changes in temperatures at the tire-pavement interface. Figures 15 through 18 also show that there were definite decreases in the friction coefficients with increases in speed on wet pavement surfaces. Consequently, speed must be reduced on wet pavements to minimize skidding; however, Stohner (1956) reported that speeds of passenger cars on wet asphaltic-concrete and portland-cement-concrete pavements were not appreciably lower than those on the same pavements when dry. This study was conducted on level, 2- and 4-lane rural highways with horizontal curvatures of 2-1/2 to 9 degrees. Motorists appeared to be unconcerned or ignorant of skidding hazards on wet pavement surfaces.

Studies of aircraft landings showed that airspeeds at touchdown varied even for a given aircraft and pilot. The two extremes of airspeed were touchdown at full stall, and "spiking" at high airspeed to allow early braking. Results of some statistical studies on aircraft landing characteristics conducted by Stickle (1961), Silsby (1956), and Silsby and Harrin (1955) showed that the mean airspeeds at touchdown for some civil transports and military fighters and bombers were anywhere from 19 to 29 percent above stalling speeds. The mean airspeeds ranged from 110 to 147 mph. Results of studies conducted by Stillwell (1955) and Szaniawski (1955) showed that airspeeds at touchdown were as high as 185 mph for a military jet-fighter and 255 mph for a research aircraft. These touchdown airspeeds were measured under actual landing conditions and were considered to be normal, except for a few which were under emergency-landing conditions. High touchdown airspeeds were attributed to the types of aircraft, the type of operation, and the wind conditions. For jet aircraft, thrust was required to maintain safe rates of descent during the landing approaches. In some cases, gusty wind conditions forced the pilots to land at higher airspeeds than under normal wind conditions. All in all, the studies indicated that the speeds of aircraft at touchdown and during the initial phase of braking were much higher than those of vehicles on highways.

Some studies showed that the relationship between friction coefficient and speed for aircraft tires on airfield pavements was similar to that for vehicle tires on highway pavements. That is, the friction coefficients varied little with speed on dry pavements, but they decreased with an increase in speed on wet pavements. This relationship was found to be

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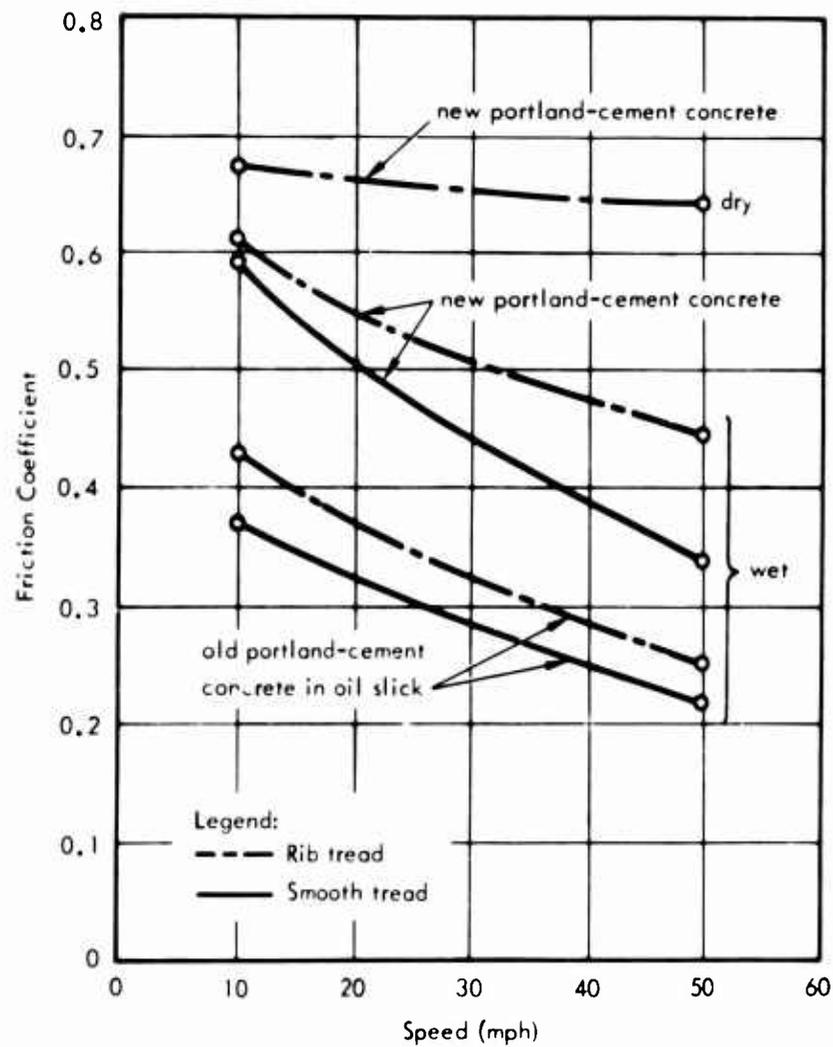


Figure 15. Friction values on new portland-cement concrete and in a heavy oil slick on old portland-cement concrete. Average daily traffic - 9,000 vehicles. (Moyer, 1959A.)

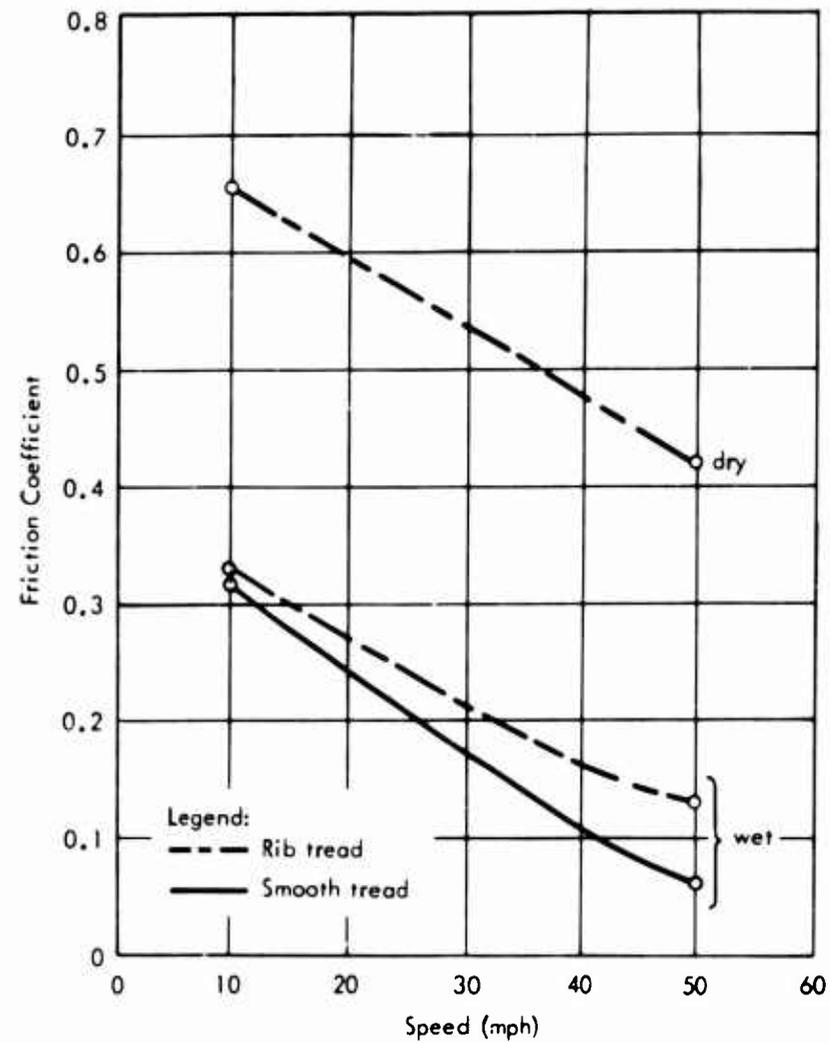


Figure 16. Friction values on an asphalt seal-coat surface with excess asphalt contributing to bleeding in hot weather. (Moyer, 1959.)

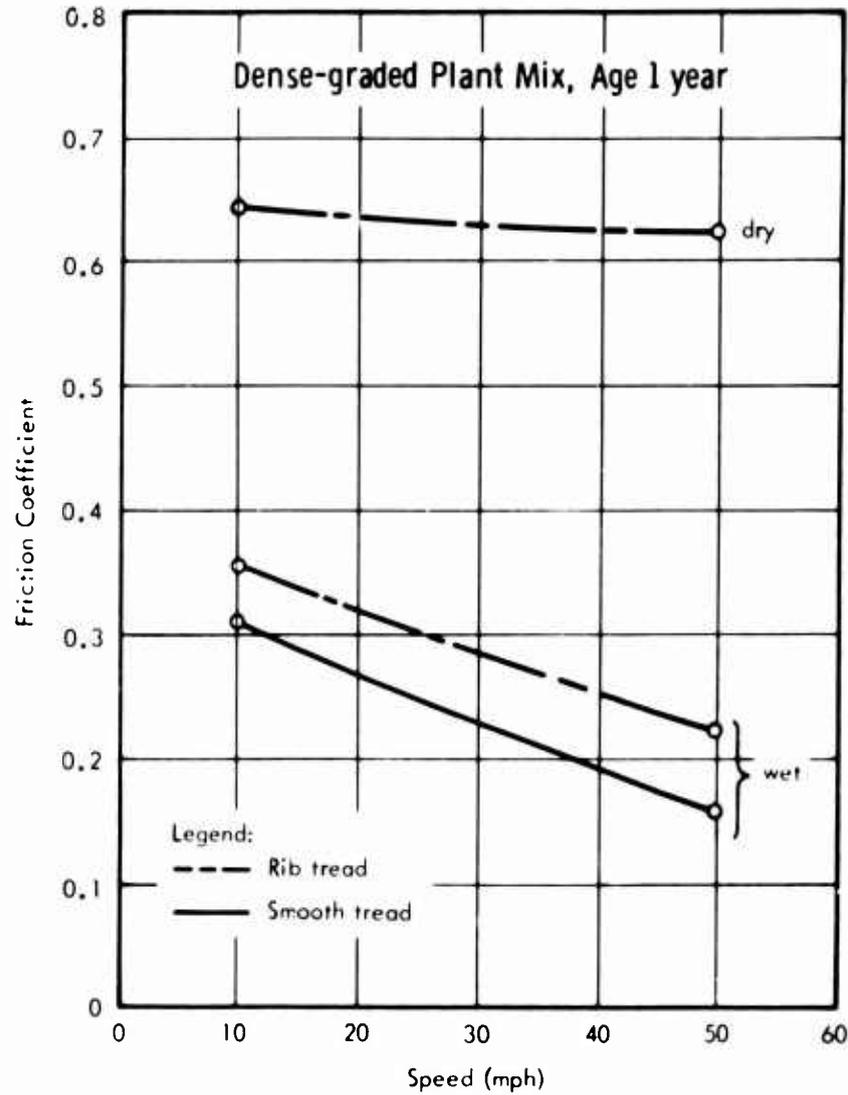


Figure 17. Friction values on a dense-graded plant-mix asphaltic surface constructed with partly crushed gravel aggregate. Average daily traffic - 15,000 vehicles. (Moyer, 1959.)

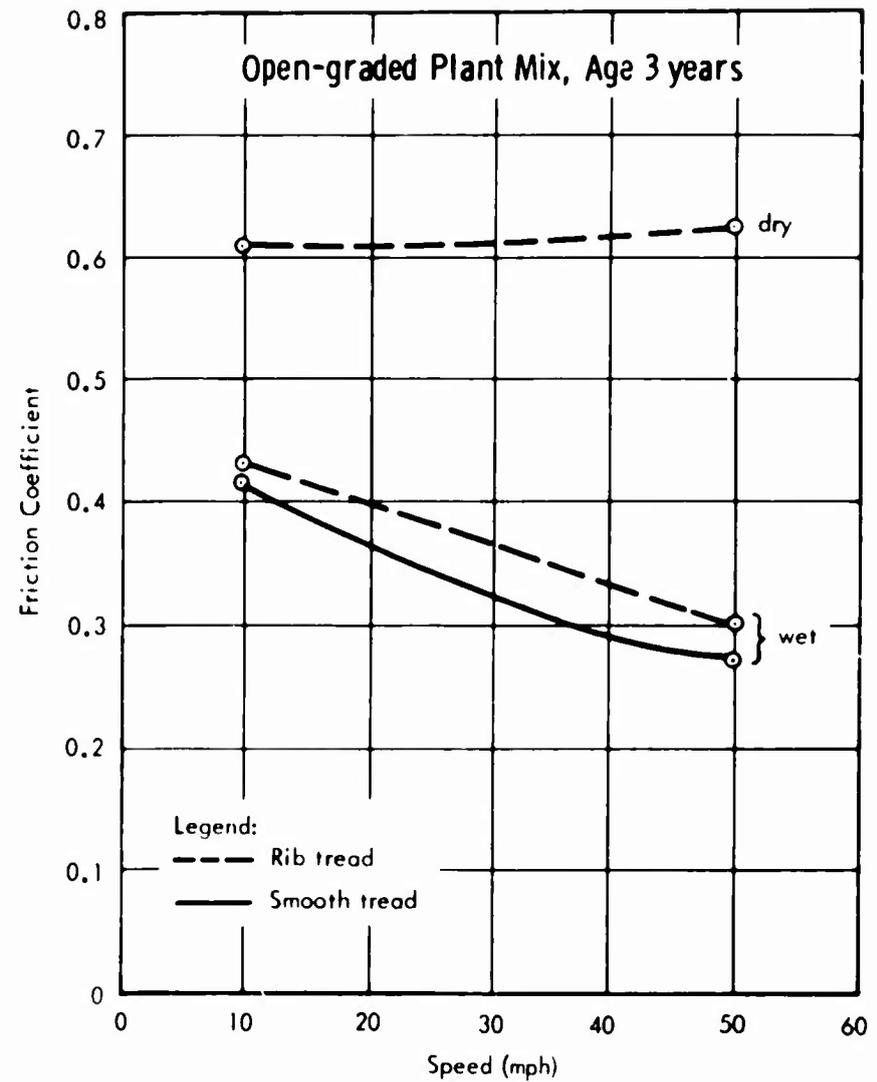


Figure 18. Friction values on an open-graded plant-mix asphaltic surface constructed with crushed gravel aggregate. Average daily traffic - 8,000 vehicles. (Moyer, 1959.)

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true by Trant (1959) at speeds up to 60 mph and by Giles and Lander (1955) at speeds up to 100 mph. The results found by the Ministry of Aviation (1960) showed that the friction coefficients on wet concrete pavement decreased rapidly with increasing speed from zero to about 50 or 60 knots (57.5 to 69 mph). However, at speeds above 80 to 100 knots (92 to 115 mph), the friction coefficients tended to increase slightly with increase in speed. This increase was not found by Trant (1959), nor by Giles and Lander (1955), probably because the test speeds used by them were too low to indicate the increasing trend. The method of measurement also differed. Trant (1959) and Giles and Lander (1955) used the trailer method while the Ministry of Aviation (1960) used an instrumented jet aircraft. The wing lift created by the speeds of 80 to 100 knots (92 to 115 mph) probably caused the increasing trend. Thus, there were differences in the vertical loads and tire pressures in the measuring techniques employed.

2. Braking Techniques. Vehicles have been decelerated mainly by means of brakes. On most modern American vehicles, brake systems were designed so that hydraulic, vacuum, or air pressure forced the brake linings against the wheel drums to create torque against the spinning wheels. The systems were generally designed to have sufficient heat capacity to dissipate the heat created at the lining-drum interface under normal use. The brakes were capable of creating sufficient torque to lock the wheels of the vehicles. As previously discussed, the locked-wheel friction was found to be lower than the incipient-skid friction. Thus, judicious use of the brakes, such as intermittent braking, in some situations resulted in shorter stopping distances than did locked-wheel braking, especially on wet or icy pavements, and thereby helped in avoiding dangerous skids.

Studies on deceleration of vehicles indicated that retarders, other than brakes, such as engine drag, wind resistance, and rolling resistance helped in decelerating vehicles. For a typical passenger vehicle, Oetzel (1959) reported that these retarders were able to balance an 8-percent grade at 60 to 65 mph, but braking was the best known method for stopping and holding a vehicle.

A combination of air drag and brakes has been used to decelerate landing aircraft. Some investigations on the techniques of handling landing aircraft indicated that aircraft were generally positioned in nose-high attitudes with flaps down at touchdown. At this position, air drag was high and was the primary means of deceleration. However, the resulting lift created by the nose-high attitude considerably reduced braking effectiveness. Thus, for some aircraft, the nose was lowered immediately for early braking while for others the nose-high attitude was maintained for a considerable portion of the entire landing rollout to decelerate primarily by air drag. The choice between the two landing techniques was influenced by the friction coefficient and by the drag and lift coefficients with respect to the attitude of the aircraft, known as the aircraft polar. An analytical study conducted by Hanks (1955) showed that aircraft should be nosed down immediately after touchdown to utilize braking when the ratio of the drag-to-lift coefficient was less than the friction coefficient. An analytical study conducted by Zalovich (1957) showed that there was no reduction in landing rollout distance by maintaining a nose-high attitude for a swept-wing transport, for an unswept-wing fighter, and for one type of swept-wing fighter when the braking coefficient or the friction coefficient utilized by braking was equal to the maximum available friction coefficient of 0.3. A nose-high attitude in the neighborhood of the stall angle for a delta-wing fighter resulted in considerable reduction in the landing rollout distance when the braking coefficient was 50 percent of the maximum friction coefficient of 0.4. However, no reduction in the landing rollout distance resulted for the delta-wing fighter if the attitude angle was limited to about one-half the stall angle by tailpipe clearance, or by other factors.

Zalovich (1957) also showed that retraction of flaps at the instant of touchdown resulted in a reduction of the landing rollout distance for the swept-wing transport for friction coefficients as low as 0.05. For the unswept- and swept-wing fighters, flap retraction resulted in an appreciable increase in landing rollout distance at maximum friction coefficients of less than 0.2.

Thus, the decision to keep the nose-high attitude during the landing rollout or to lower the nose of aircraft immediately after touchdown for early braking depended on the design of the aircraft, on the friction coefficient between the tires and the runway surface, and on the ability of the pilot to make full use of the available friction coefficient with the brakes.

Since high speeds were involved during landing of aircraft, a considerable emphasis has been placed on the design and proper use of brakes. The space, weight, and high heat dissipation requirements led to the disc type of brake design for aircraft. As discussed previously, the locked-wheel condition resulted in the skidding of vehicles. For landing aircraft, it was found that even 1 second of wheel lock resulted not only in skidding, but also in excessive tire wear and sometimes damage and blowout. During some landings, quick disintegration of the tires resulted from the locked-wheel condition and left the metallic rims skidding on the pavement surfaces. The rims had a friction coefficient lower than rubber on the pavement surfaces. Pilots were therefore instructed to avoid the locked-wheel condition, or slip ratio of 1, either by intermittent braking or by light application of brakes. However, these techniques generally resulted in average constant-braking coefficients that were much lower than the maximum available friction coefficient. Hanks (1955) reported that an average braking coefficient of 0.15 was a representative value for the entire braking phase of the landing distance.

Efforts were made to improve aircraft braking by developing skid-control systems that increased the braking coefficient and at the same time avoided wheel lock. Some of the newer civil and military aircraft are equipped with such devices of several types. It is anticipated that more aircraft will be equipped with these devices in the future. Some experiments, apparently with great success, have been conducted with skid-control systems installed on highway vehicles.

With one type of skid-control system, known as the anti-skid system, the pilot controls the actual brake pressure until just prior to the locked-wheel condition. The system detects the approaching skid and instantly signals a dump valve to release the brake pressure. The pressure is released until the approaching skid condition is corrected and is applied again just before the wheels recover normal speed. This on-off system prevents wheel lock and applies sufficient torque to the wheels to take advantage of the high friction coefficient near the incipient-skid condition. Another system, similar to the on-off system, operates a buzzer located on the brake pedals instead of releasing the brake pressure. The pilot, feeling the vibration through the brake pedal, releases the brake pressure. A third type of system maintains brake pressure slightly below the skid point whenever the pilot pushes the brake pedals hard enough to otherwise cause wheel lock.

Devices other than brakes and brake-control systems have been developed to help decelerate landing aircraft. Some types of military aircraft are equipped with a drag chute which is released immediately after touchdown. Since the drag force created by the chute is a function of the square of velocity, the drag force drops off rapidly after touchdown. The chute is, therefore, effective only during the early part of the landing rollout. One of the newest Navy jet aircraft is equipped with what is known as the boundary-layer control system. This system directs high-temperature and high-velocity laminar air, bled from the engine, over the wings and flaps to delay flow separation over the airfoil. This reduces turbulence and drag, and results in a lower stall speed. Consequently, a reduction in touchdown speed is possible.

Tire Factors. The effects of various factors related to tires on friction coefficient were investigated to improve the traction, reliability, and wear of tires for vehicles and aircraft. The tire factors investigated were tread design, thread composition, inflation, vertical load, and temperature.

1. Tread Design. One feature of tread design investigated was the effect of circumferential ribs or grooves in the tire. Figure 19 shows the effect of the number of ribs in the tire on the friction coefficient for highway-type passenger tires on a dry pavement, on common wet

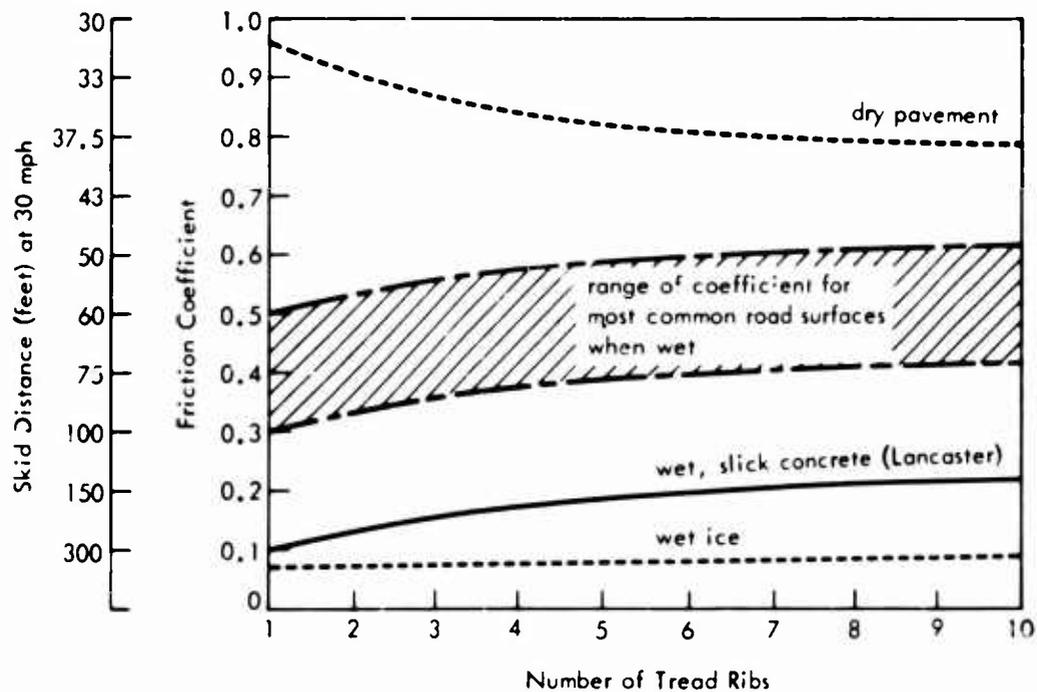


Figure 19. Coefficient versus number of tread ribs; highway-type passenger tires, comparisons at 30 mph. (The Subcommittee on Tire Factors, 1959.)

road surfaces, and on wet ice. Figure 19 shows that the friction coefficient decreased on dry pavement with an increase in the number of ribs in the tire. This indicates that a bald tire which had no groove and, consequently, had the maximum contact area, gave the highest friction coefficient on dry pavement.

For most of the common wet road surfaces, as shown in Figure 19, the increase in the number of ribs increased the friction coefficient. The Subcommittee on Tire Factors (1959) to the First International Skid Prevention Conference reported that the ribs improved the skid resistance from 20 to 100 percent on wet surfaces depending on the friction coefficient. Giles and Lander (1955) and Trant (1959) also reported that tires with ribs gave higher friction coefficient than smooth tires on wet pavement surfaces. Marick (1959) explained this phenomenon in the following manner: Ribs or grooves in tires decreased the net contact area which lowered the friction coefficient. However, the grooves provided vents or voids through which the water at the tire-pavement interface was displaced by the pressure between them and thus increased the friction coefficient. The net result was a gain in friction coefficient. The corresponding penalty in friction coefficients on dry pavements by the decreased net contact area was evidently accepted to minimize the hazards of long skids on wet pavements.

Figure 19 also shows that the friction coefficients on wet, slick, concrete surfaces and wet ice were extremely low. Some increase in the friction coefficient was observed on slick concrete with an increase in the number of ribs in the tire. However, no such influence was observed on wet ice. In other words, the bald tire had just as much traction as the ribbed tire on wet ice.

Another feature of tread design was lateral edges made with molded slots and cut slits which provided a wiping action over wet pavement surfaces. This wiping action was effective in removing water between the tire and pavement surface. The Subcommittee on Tire Factors (1959) to the First International Skid Prevention Conference reported that the molded slots and cut slits improved skid resistance up to 100 percent on surfaces with extremely low

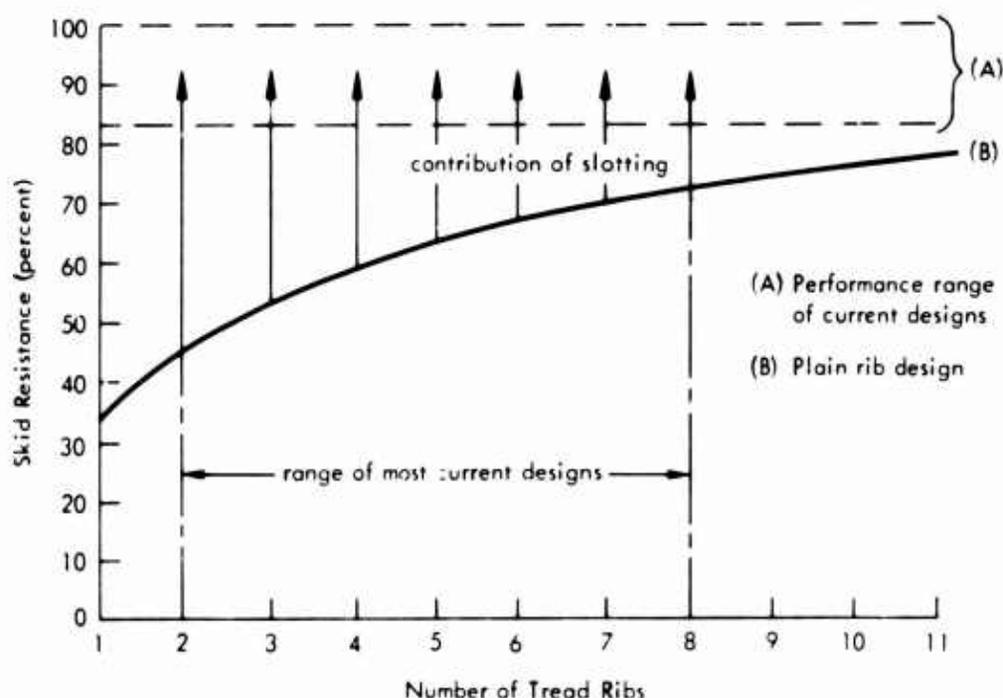


Figure 20. Skid resistance of passenger tires: effect of tread ribs combined with slotting, on wet, slick concrete (Lancaster test surface). (The Subcommittee on Tire Factors, 1959.)

friction coefficients. Marick (1959) reported that, in general, the slitting of tire treads was effective in improving the friction coefficient by as much as 20 to 25 percent. Figure 20 shows the contribution of slotting of passenger vehicle tires on wet, slick concrete. The slotting improved skid resistance by 30 to 100 percent, depending on the number of ribs.

Some mud- and snow-tire treads have been designed with a combination of angular ribs and lug-type elements. The depth and width of the tread pattern were usually greater for these tires than for ordinary vehicle tires, and gave additional traction through the force required to shear the snow trapped between the ribs and lug elements. Marick (1959) reported that on winter surfaces, the mud and snow treads were about 25 percent superior to the ordinary passenger-tire tread and 3 percent superior on wet, slick concrete. Marick (1959) also reported that other surface treatments of mud and snow tires increased the skid performance on winter surfaces by approximately 10 percent. One treatment known as "tractionizing" consisted of perforating the tread surface by running the tire for a short time against a wheel having sharp, tack-like projections. The multiplicity of holes permitted the entrance of snow into the tread face, and the force required to shear the snow provided increased resistance to sliding. Lateral cuts on the tread face and the incorporation of nonadhering material such as corn grits, nut shells, salt, and similar materials in the tread compound also provided additional resistance to sliding.

The improvement in skid resistance by means of tread design of tires was generally limited by the shear strength or tearing resistance of the rubber compound. Most treads of aircraft tires were designed without slots, slits, or lateral edges because they are subjected to speeds and impact loads higher than those experienced by vehicle tires. The advantage of having tear-resistant tires during landing more than compensates for the decreased friction coefficient because torn or damaged tires quickly disintegrate.

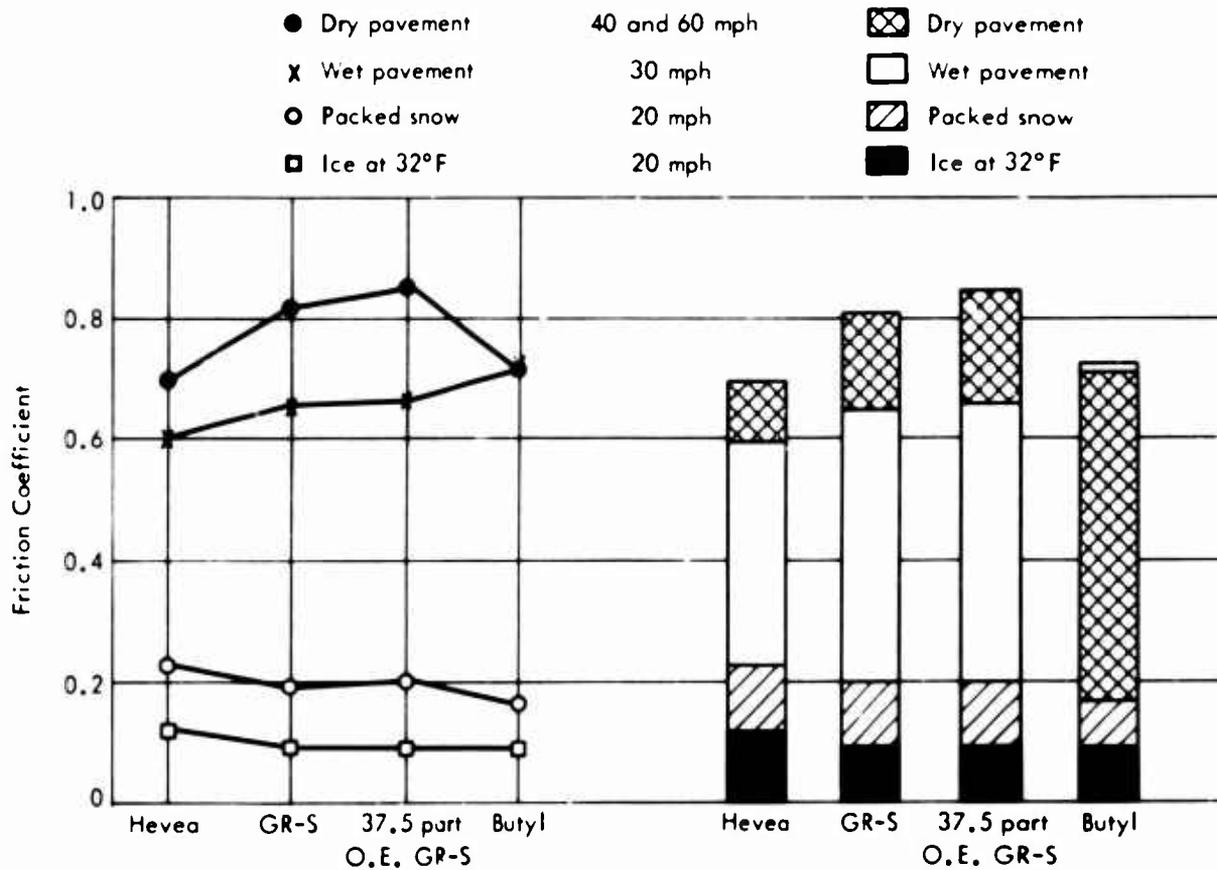


Figure 21. Four-wheel-skid tire tests. (Reinhart, 1959.)

2. **Tread Composition.** Studies on tread composition indicated that the friction coefficient was only one of a number of essential service characteristics of rubbers used in tires. In addition to the friction coefficient, the essential service characteristics of tread composition were abrasion resistance, weather and ozone resistance, hysteresis and heat build-up, cornering noise, steering ability, and resistance to groove cracking. Alterations in tread composition which improved one or more of these essential service characteristics adversely affected some of the others. The final selection of tread composition, therefore, was a compromise to suit all of the essential characteristics.

Figure 21 shows the effect of tread compositions made from four different rubbers on the friction coefficient. As shown on Figure 21, the greatest difference in friction coefficients occurred on dry pavement surfaces. The difference continued on wet surfaces, but on low friction coefficient surfaces of packed snow and ice, the difference was quite small.

Reinhart (1959) indicated that the high friction coefficient of both oil-extended and non-oil-extended GR-S rubber, shown in Figure 21, for a dry pavement surface was due to their excellent resistance to melting. The initial melting and degradation temperature for GR-S rubber was about 100°F higher than that for hevea (natural rubber) and approximately 70°F higher than that for butyl rubber. Furthermore, the rate of melting of GR-S rubber was appreciably lower at temperatures of 400 to 1,000°F developed during skidding. Since melted rubber acted as a lubricant to reduce the friction coefficient, the GR-S rubber, with the highest resistance to melting, gave the highest friction coefficient.

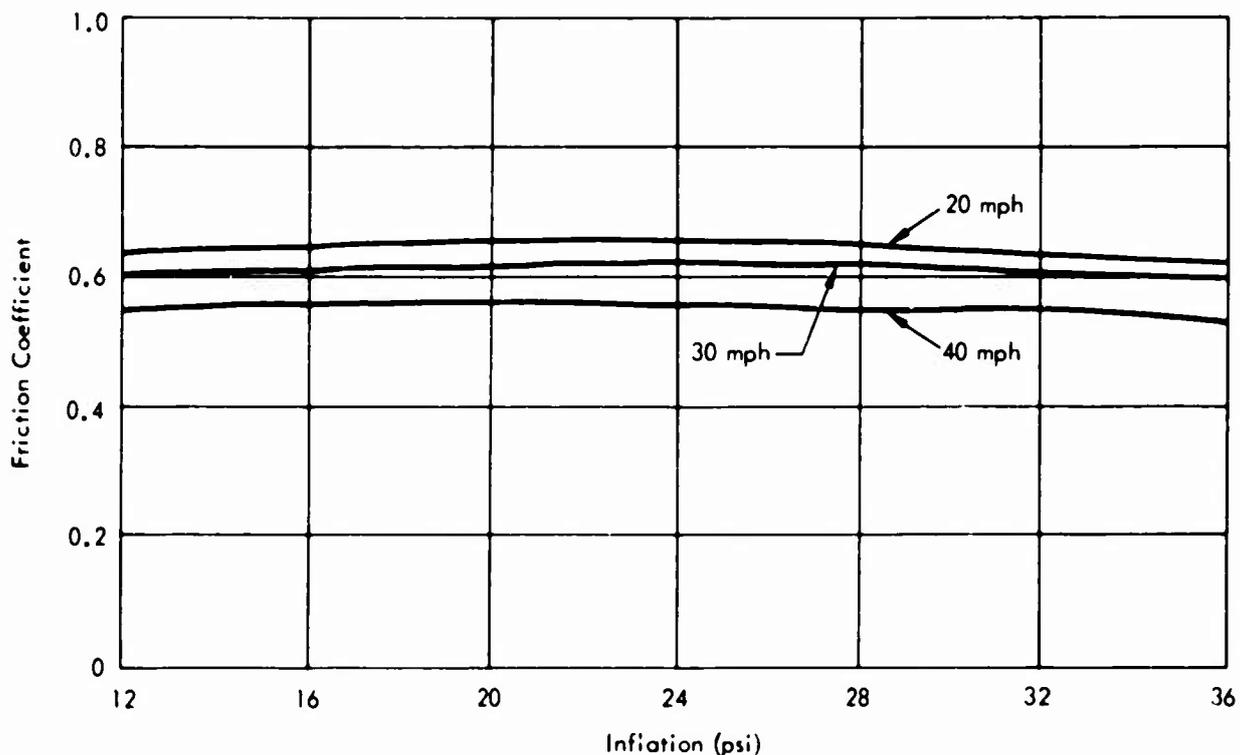


Figure 22. Effect of inflation upon friction coefficient. (Hofelt, 1959.)

3. Inflation. Hofelt (1959) reported on the effect of inflation on the friction coefficient. Since inflation pressure was the pressure contained in the tire and prestressed the tire, it supported much of the load. For a constant load, changes in inflation pressure changed the contact area of the tire and thus affected the friction coefficient. Figure 22 shows the relationship between inflation pressure and friction coefficient at 20, 30, and 40 mph. The results shown on Figure 22 were determined by the stopping-distance method with 7.50-14, 4-ply, rayon tubeless tires on a wet hand-troweled-concrete surface. Figure 22 indicates that there was only a slight decrease in friction coefficient with an increase in inflation. Hofelt (1959) reported that other investigators found similar results. Consequently, there was little advantage in decreasing the inflation pressure to increase skid resistance, particularly since operation at inflation pressures other than those recommended, in some occasions, has caused carcass damage and premature tire failure. In addition, Hofelt (1959) also reported that varying tire pressures from those recommended had an insignificant effect on braking distance, traction, and cornering ability on smooth ice.

Inflation pressures as high as 400 psi have been used in some Naval aircraft to obtain high loads without bottoming of the tires. Momentary or short duration loads which caused high deflections were experienced in carrier operations. During carrier takeoffs, the catapult bridle applied a strong downward component of force which added to the static load to produce extreme tire deflections. Arrested landings also produced momentarily high loadings which were aggravated when tire impact occurred directly upon an arresting cable.

The effect of inflation on the friction coefficient was also studied with high pressures similar to those used in aircraft tires. Figure 23 shows the friction coefficient versus instantaneous skidding velocity immediately after touchdown and during spin-up of aircraft tires with 35, 70, 140, and 210 psi inflation pressures. Figure 23 shows that high inflation pressures gave lower friction coefficients than low inflation pressures at high skidding velocities. Batterson (1957) indicated that this relationship was primarily caused by differences in temperature of the tire contact region. When the inflation pressure was

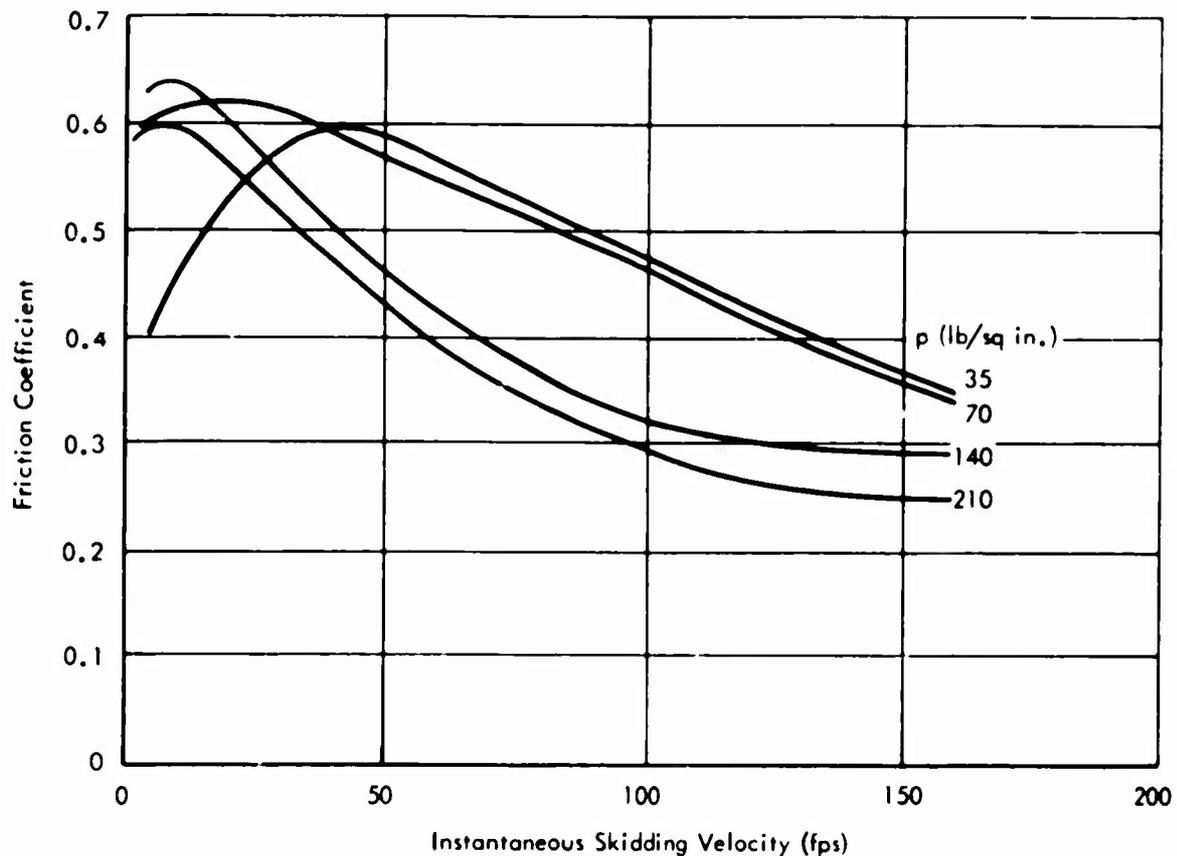


Figure 23. Effect of tire pressure on friction coefficient; horizontal velocity, 160 fps; vertical velocity, 7 fps. (Batterson, 1957.)

increased, the tire contact areas decreased; the heat generated during skidding was distributed over a smaller area. Thus, the rubber was hot, primarily molten, and exhibited a low friction coefficient. However, at a low inflation pressure, the heat was distributed over a greater area; the rubber was cooler and primarily in a solid state and exhibited a high friction coefficient.

Horne (1960) indicated that the variation in friction coefficient with inflation on wet runway surfaces was somewhat obscured during wheel spin-up by the surface wetness. A noted trend was for the friction coefficient to decrease very slightly with increasing tire-inflation pressure for portland-cement-concrete and non-skid carrier-deck surfaces. However, experimental data apparently indicated, in general, that the friction coefficient during wheel spin-up was relatively independent of tire inflation pressures in the range of 260 to 400 psi.

Figure 24 from the Ministry of Aviation (1962) shows the friction coefficient versus the ground speed after completion of spin-up and during deceleration of an aircraft by anti-skid braking. Measurements were made with an instrumented jet aircraft on a wet, portland-cement-concrete runway with inflation pressures of 120 to 300 psi and on a dry, concrete runway with an inflation pressure of 120 psi. Figure 24 shows that the wet friction coefficient was lower for tires inflated up to 300 psi than for tires inflated to 120 psi throughout the speed range of 40 to 145 knots.

4. Vertical Load. In general, the distribution of vertical load or weight for a passenger vehicle is considered to be nearly 50 percent to the front axle and 50 percent to the rear axle. During cornering, acceleration, or deceleration, transfer of the weight occurs from one wheel

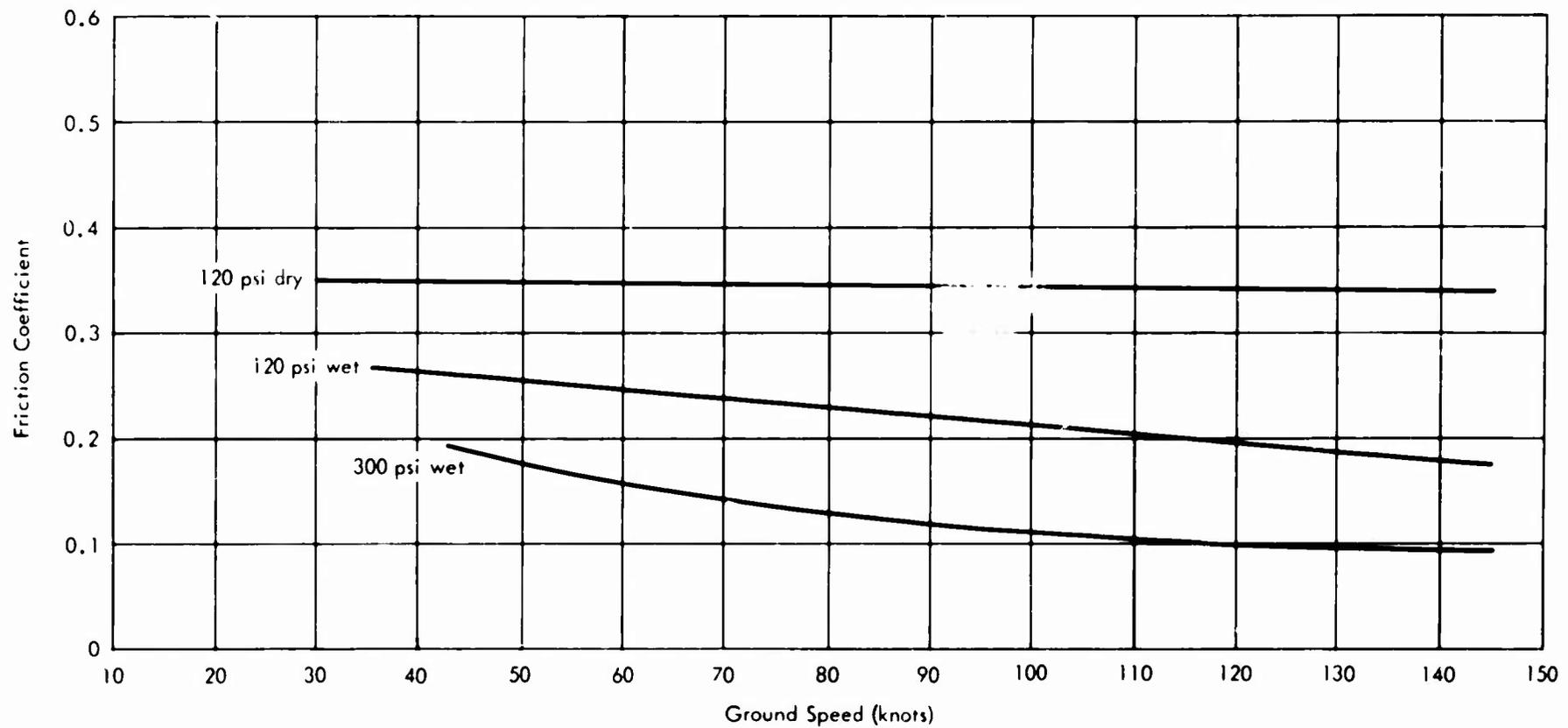


Figure 24. Comparison of friction coefficient for two tyre pressures on a wet surface and one tyre pressure on a dry surface. Portland-cement-concrete runway. Anti-skid braking throughout. Gross weight 18,350 lbs. Ministry of Aviation, 1962

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to another or from one axle to the other. Hofelt (1959) reported that it was possible to cause a momentary weight transfer in the order of 65 percent to the front axle and 35 percent to the rear axle during braking.

Moyer and Shupe (1951) investigated the effect of vertical load or wheel load of vehicles on friction coefficient. Figure 25 shows that a wheel load of 460 pounds gave friction coefficients from 10 to 20 percent higher than those given by a wheel load of 875 pounds for a speed range of 10 to 50 mph on wet, portland-cement-concrete and plant-mix-asphalt surfaces. Hofelt (1959) and Mercer (1958) reported similar results with wheel loads ranging from approximately 800 to 1,500 pounds. Hofelt (1959) explained that the decrease in friction coefficient was due to a decrease in the tire contact area per unit load as the load was increased. This provided less opportunity for the tire to grip the road surface and resulted in a decrease in the friction coefficient.

Hofelt (1959) reported that the results of stopping-distance tests of automobiles, commercial vehicles, and other types of vehicles when unloaded showed higher friction coefficients than when loaded. The difference was about 20 percent. These tests were primarily conducted to test brakes. Consequently, the differences in friction coefficients were probably due to the brake efficiencies as well as the vertical load. In contrast to these results, Hofelt (1959) reported that tests on ice made in 1957 by the National Safety Council Committee on Winter Driving Hazards gave a slight increase in friction coefficient as the rear axle static load was increased.

During landing of an aircraft, the net load on the pavement is given by the difference between the aircraft weight and the lifting force. Since the aircraft weight is constant and the lifting force varies with the square of the forward velocity, the load on the pavement depends on the forward velocity. If a high decrease in forward velocity occurs, the load on the pavement will approach the static weight of the aircraft rather quickly. For some Naval aircraft, the static load on the pavement through a main landing gear wheel is as high as 25,000 pounds.

The variation of the friction coefficient with velocity is shown in Figure 26 for applied aircraft wheel loads of 5,000, 6,000, 7,000 and 8,000 pounds. Results for each load shown in Figure 26 were obtained with a constant tire deflection by changing the tire pressure. Figure 26 shows that the increase in vertical load from 5,000 to 8,000 pounds decreased the friction coefficient slightly in the velocity range of 60 to 140 mph. However, Luthman (1955) indicated that the relationship of load with friction coefficient was not conclusive, since a constant tire deflection was maintained for all the loads.

Hample (1955) conducted some laboratory tests on the frictional resistance of small sections of aircraft tires on concrete surfaces with three different finishes. The results shown in Figure 27 indicate that the apparent friction coefficient decreased with an increase in normal pressure up to approximately 1,100 psi. There was no suitable explanation for the smooth-surface curve appearing between semismooth- and rough-surface curves in Figure 27. Hample (1955) indicated that the results were obtained under laboratory conditions which were considerably different from those encountered during the landing of aircraft, but they were of interest because of the pressures covered.

5. **Temperature.** Reinhart (1959) indicated that tread-surface temperatures in excess of 400° F and perhaps as high as 1,000° F were developed during skids on dry pavement surfaces. An evaluation of the effect on friction coefficient caused by heating of a tire during the skidding process was made by Milwitzky, Lindquist, and Potter (1955). In this evaluation, it was assumed that a tire was a good insulator so that the heat produced by the skidding remained on the surface of the tire. The temperature rise at the surface was then directly proportional to the concentration of skidding energy per unit of tire contact surface area. An equation was derived to show how the energy concentration varied on the tire surface. It was evident that the greatest energy concentration occurred at a slip ratio equal to 1 (locked wheel) for a given ratio of vertical load to tire width. An increase in energy concentration on the tire surface occurred with an increase in the ratio of the vertical load to the tire width. Since the temperature rise of the surface was directly proportional to the concentration of skidding energy, it followed that the

temperature was the highest at a slip ratio equal to 1 and that the temperature increased with an increase in the ratio of the vertical load to the tire width. The increase in temperature increased the melting of rubber which lowered the friction coefficient. Thus, the friction coefficient reached its minimum value at a slip ratio equal to 1, and it decreased with an increase in the ratio of vertical load to tire width.

Hample (1955) conducted some laboratory experiments to determine the effect of temperature on friction coefficient. Tests were conducted at room temperature, 300, 400, 500, 600, and 700°F. The results shown in Figure 28 indicate that the apparent friction coefficient decreased with an increase in temperature.

Pavement Factors. A considerable amount of work has been conducted and published on the effects of pavement factors on the friction coefficient. Numerous factors related to pavements were found through investigations conducted in laboratories and in the field. However, the true indication of the effect of each individual factor was not provided in many studies since many of the factors operated in combination with other factors.

1. Types of Pavement. Many skid tests have been conducted on rigid and flexible pavement surfaces to determine the effect of the types of pavement on friction coefficient. Finney and Brown (1959) conducted many skid tests in Michigan on highway surfaces made of portland-cement concrete, bituminous concrete, sheet asphalt, and bituminous surface treatments. The tests were conducted with a trailer similar to the one used by the General Motors Proving Grounds. The friction coefficients on 162 projects using portland-cement-concrete pavements ranged from 0.35 to 0.67; 54 percent of the projects had friction coefficients between 0.45 and 0.55. An attempt made to compare the friction coefficients of surfaces with gravel or limestone coarse aggregate detected no significant trend. No notable difference was expected until wear had progressed sufficiently to expose the coarse aggregate beneath the surface mortar layer. For asphaltic-concrete pavements, the study was separated into projects by the type of coarse aggregate used such as crushed limestone and crushed gravel.

The average friction coefficient, in relation to the wear factor, for the portland-cement-concrete pavements and the asphaltic-concrete pavements with crushed limestone and crushed gravel is shown in Figure 29. The wear factor was computed as the product of average daily traffic volume per traffic lane since construction, weighted for percent of commercial traffic, divided by 1,000, and multiplied by the age of the project in years. The percent of commercial traffic for each project was converted into an equivalent number of automobiles so that the total traffic was considered as entirely composed of passenger vehicles. The curves in Figure 29, established statistically, indicate that a linear relationship existed between the friction coefficient and the wear factor for the three pavement surfaces. The portland-cement concrete had the highest friction coefficients; the crushed-gravel bituminous concrete had the next highest; and the crushed-limestone bituminous concrete had the lowest. Since the linear lines have nearly the same slope, the differences in the friction coefficients between the three pavement surfaces were approximately the same at any wear factor from zero to 100.

The ages of the 13 sheet-asphalt surface projects in Michigan ranged from zero to 38 years. With the exception of one project, which had an unusually low friction coefficient of 0.23, the sheet-asphalt surfaces had values ranging from 0.37 to 0.55. The wear factor for these projects was not determined because of the uncertainty of the traffic data.

A total of 44 bituminous surface-treatment projects in Michigan, including different combinations of aggregates and bituminous binder material tested for skid-resistance, showed a wide range of friction coefficients. The wet friction values ranged from 0.15 to 0.65 with 65 percent of the results less than 0.40 and 33 percent below 0.30.

White and Thompson (1958) measured the dry and wet friction coefficients of all major types of highway surfaces in Mississippi with the stopping-distance method. This study included portland-cement-concrete pavements as well as hot- and cold-mix bituminous surfaces.

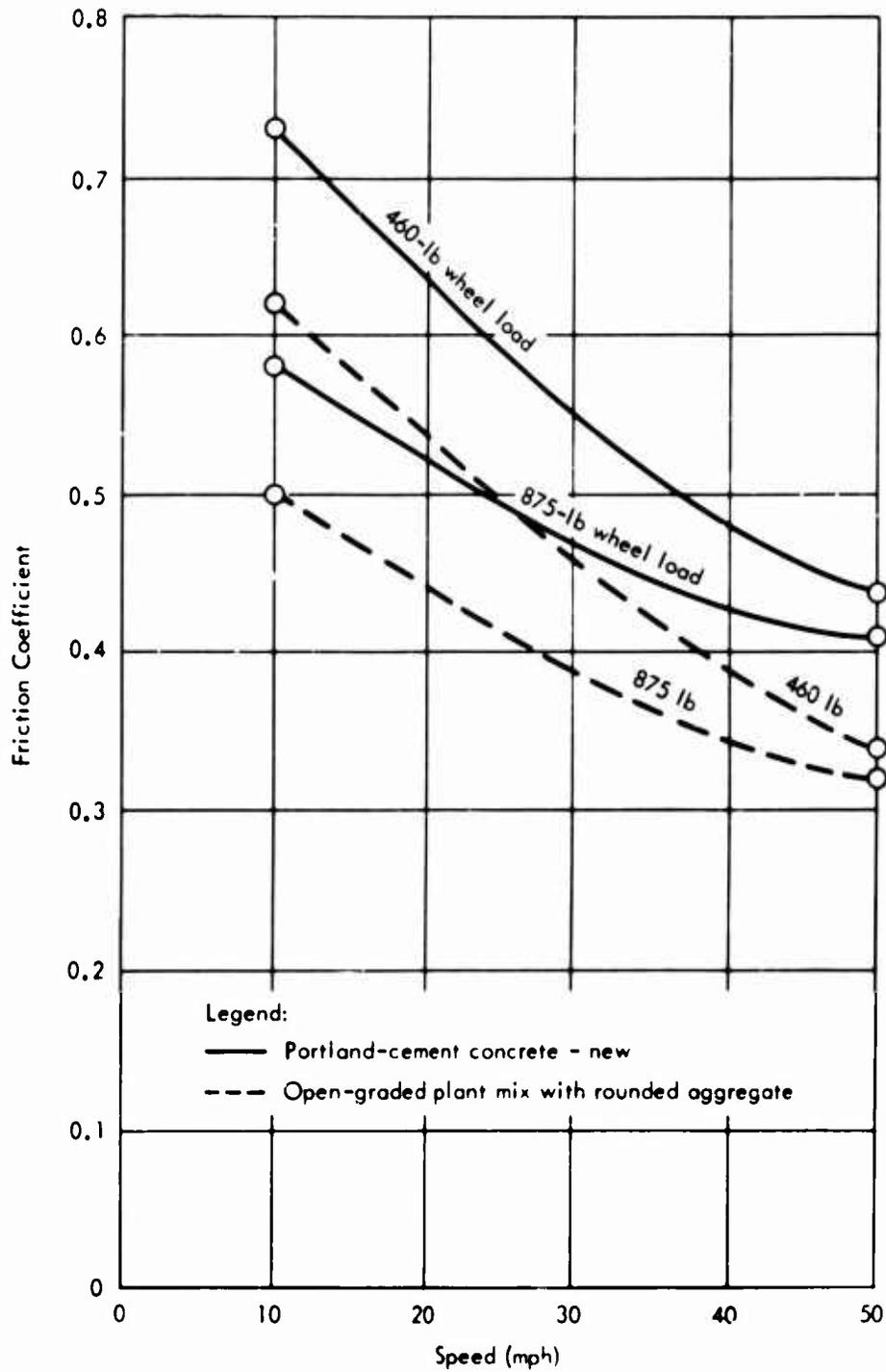


Figure 25. The effect of wheel load on the skid resistance of wet, portland-cement-concrete and plant-mix-asphalt surfaces. *Source: Highway Noise Abatement Handbook, National Highway Traffic Safety Administration, 1971*

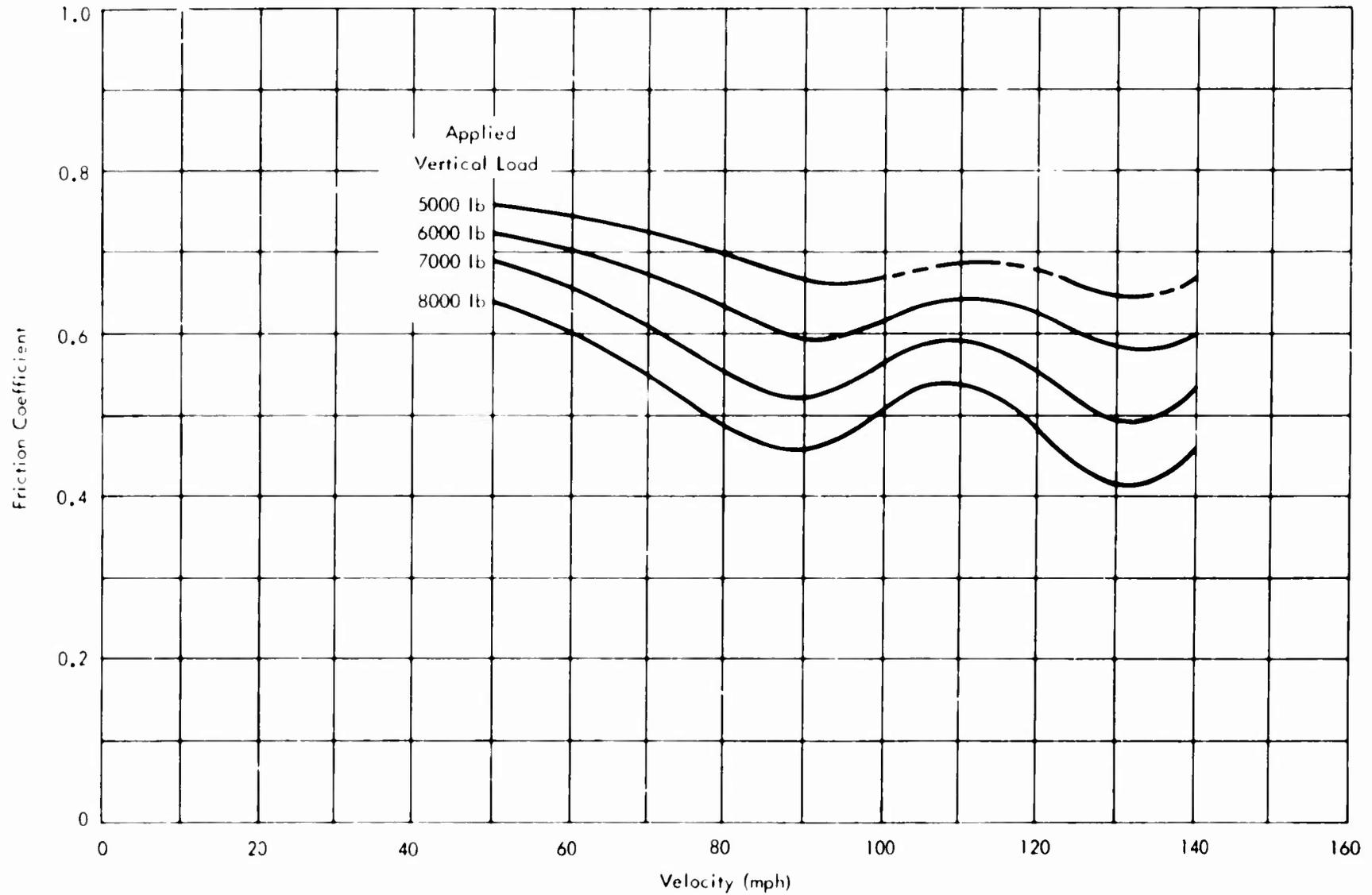


Figure 26. Friction coefficient versus velocity curves for various applied vertical loads maintaining 32 percent tire deflection. (Luthman, 1955.)

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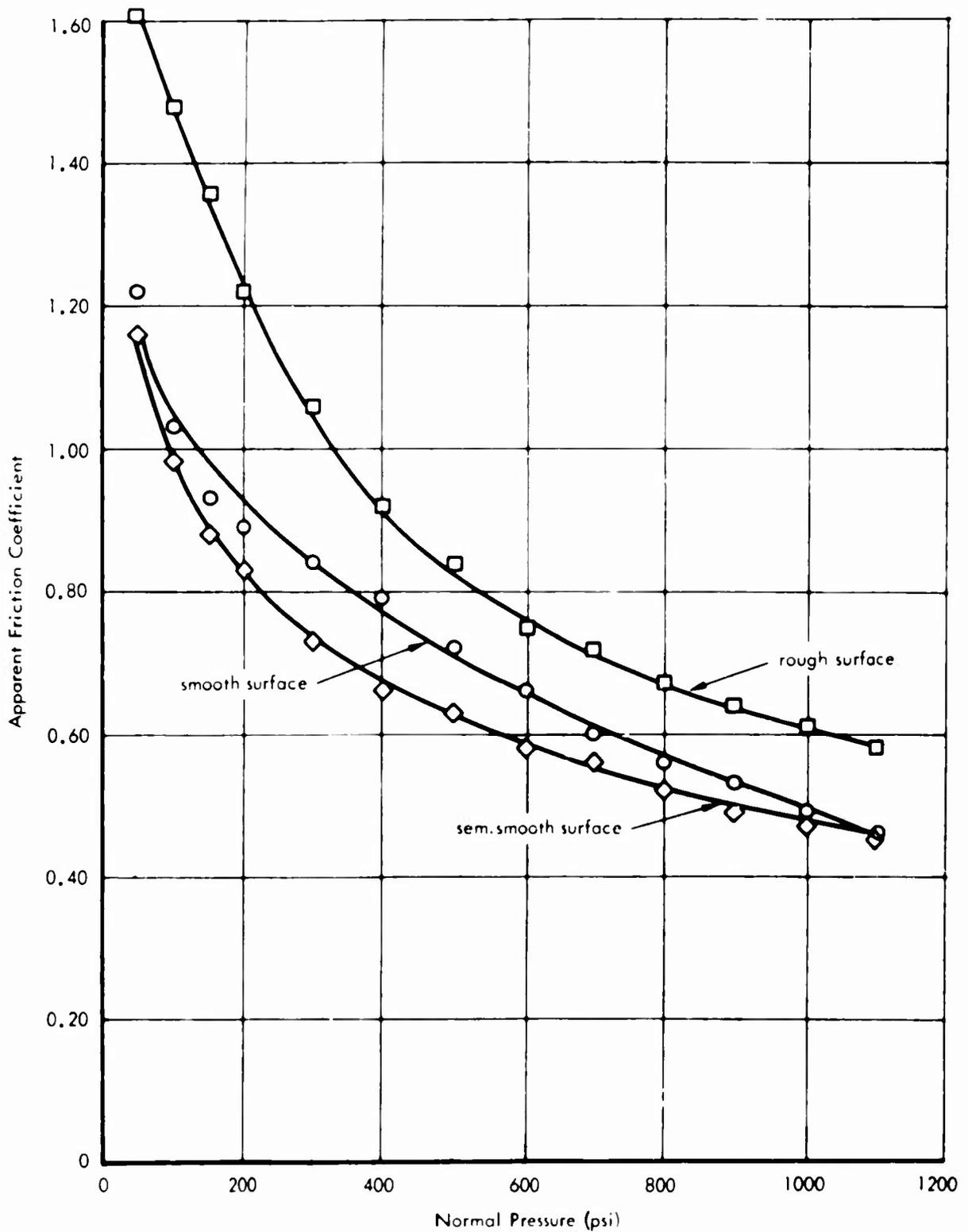


Figure 27. Apparent friction coefficient versus normal pressure for high-normal-load tests at room temperature. Averaged results for all surfaces. (Hample, 1955.)

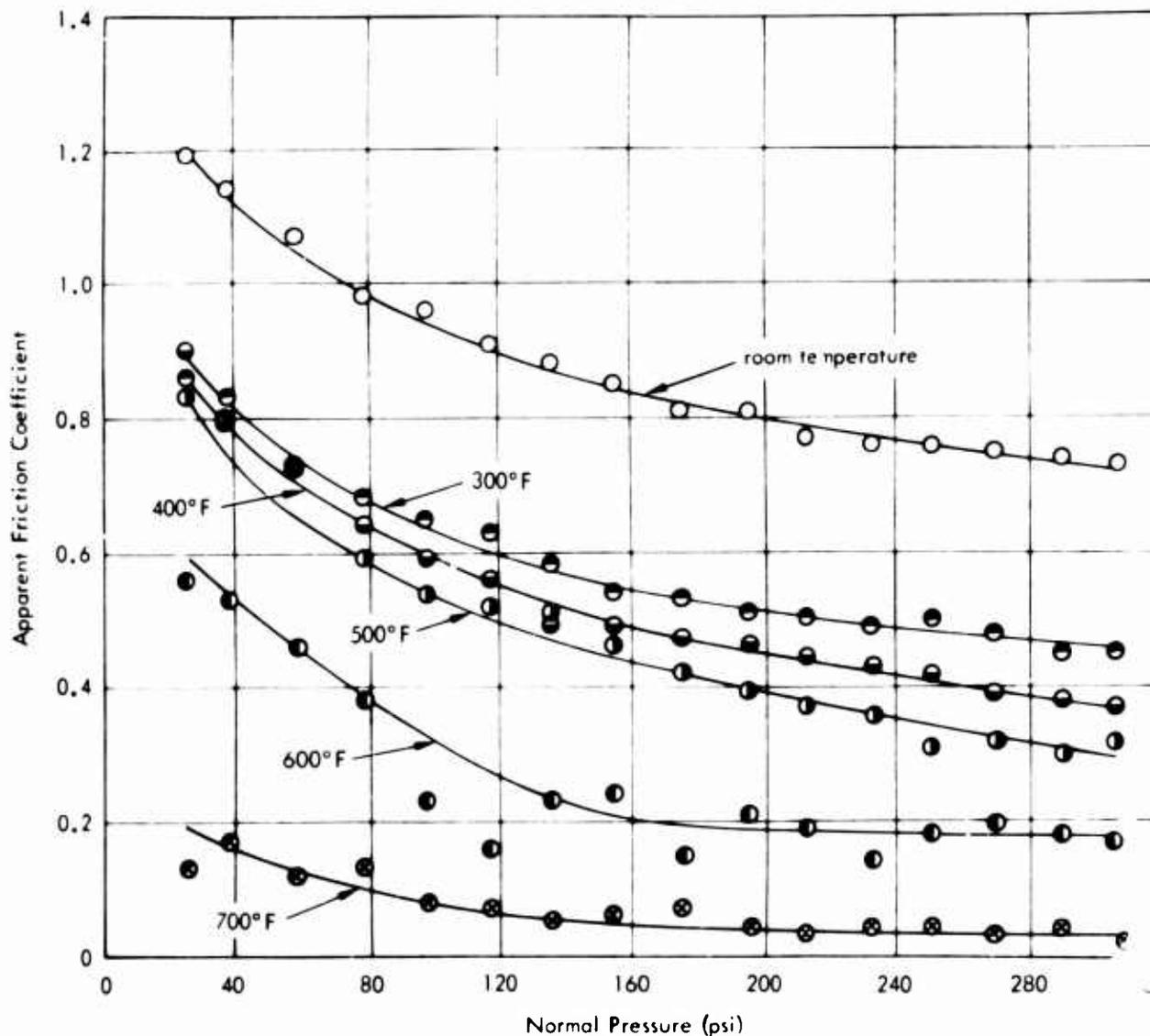


Figure 28. Apparent friction coefficient versus normal pressure for low-normal-load tests. Averaged results for all surfaces. All values are arithmetical averages. (Hample, 1955.)

Hot-mixed pavements tested were sand asphalts, modified sand asphalts, and asphaltic concrete. Cold-mixed pavements tested were slag mixtures, asphaltic-limestone mixtures with and without quartz sand, and crushed reef-shell with quartz sand.

Tests were made on approximately 200 projects and results from about 2,000 skid measurements were reported. Twenty-eight of the 200 projects were found to have friction coefficients below 0.40. Most of the pavement sections with friction coefficients below 0.40 had excess bitumen or polished aggregates.

Figure 30 shows the types of pavement which had wet friction coefficients above 0.40 at a test speed of 40 mph. The average friction coefficient and the corresponding average stopping distance for these pavements when wet, was 0.51 and 104.7 feet, respectively. With dry pavements, the average values were 0.74 and 72.7 feet.

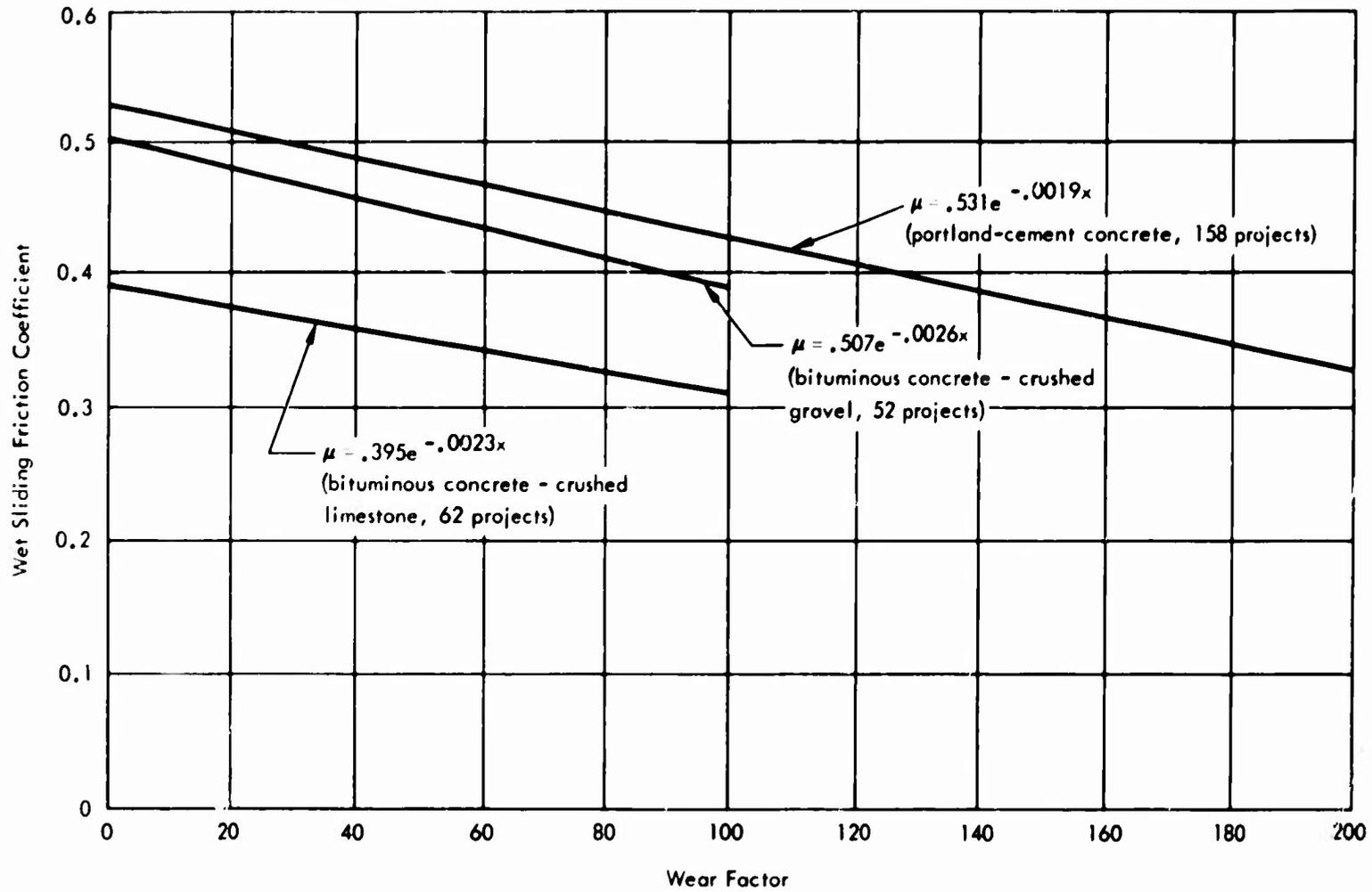


Figure 29. Comparison of friction-wear relationship: Portland-cement concrete, and asphaltic concrete with gravel and limestone aggregates. (Finney and Brown, 1959.)

Michael and Grunau (1956) measured the friction coefficients of four types of pavement in Indiana by the stopping-distance method at a test speed of 30 mph. The four types of pavement were rock asphalt, portland-cement concrete, asphaltic concrete, and bituminous surfaces. A total of 233 different roads were tested in the wet condition. Each road was tested at three locations, and two skids were taken at each location. The data was statistically analyzed, and the variations in skid resistance from skid-to-skid, location-to-location, and road-to-road were determined. The results are summarized in Table II.

For the 30 different rock-asphalt pavements in Indiana, the mean stopping distance of 180 skids was 63.3 feet, a value lower than any other type tested. The variations of the skid distances were also very low except for the location-to-location variance for the two 9-pound deslicking treatments placed over existing surfaces. One of the deslicking treatments was in good condition, but the other had a considerable portion of the resurfacing treatment worn off.

The mean stopping distance of 276 skid tests on 46 portland-cement-concrete pavements in Indiana was 81.4 feet. This mean value was significantly higher than that for rock asphalt, but significantly below the mean value for asphaltic concrete. The average skid-to-skid and location-to-location variances for these pavements were twice as high as those for rock asphalt, and the road-to-road variance was 10 times as great. These variances, however, were seldom more than half of those of the other major types of pavement surface. The comparatively low variations in skid resistance were significant, since the pavements were considerably older and had carried more traffic than the others.

The mean stopping distance for 59 asphaltic-concrete roads in Indiana was 89.2 feet, a distance higher than for portland-cement-concrete or rock-asphalt pavements. These surfaces yielded results which were quite variable. The average variances were almost twice those of portland-cement-concrete surfaces.

Skid tests on 55 bituminous surfaces in Indiana, other than rock-asphalt and asphaltic-concrete surfaces, yielded a comparatively low average stopping distance of 80.8 feet. This mean value was almost identical to that of the portland-cement-concrete pavements. The three variances, however, were of large magnitudes and exceeded those for the other pavement surfaces. The stopping distances ranged from 50 to 167 feet, displaying skid resistances ranging from excellent to poor.

In addition to the four types of pavement, Michael and Grunau (1956) conducted skid tests on some special surfaces such as a silica-sand surface and a group of six bituminous-coated aggregate surfaces. The silica-sand surface had an appearance and a texture very similar to that of rock asphalt. The mean stopping distance was 66.7 feet, which was significantly lower than any other type, except rock asphalt. The variations in results were consistently low. The six bituminous-coated aggregate surfaces had a mean stopping distance of 99.4 feet. This mean value was higher than for any of the pavement types tested. Both the location-to-location and road-to-road variances were also quite high.

Marshall and Gartner (1962) conducted skid tests on over 300 pavement surfaces in Florida using the Tapley decelerometer simultaneously with the stopping-distance method. The tests were conducted on wet surfaces with an initial speed of 40 mph. The pavement surfaces included 18 portland-cement-concrete projects, 162 asphaltic-concrete projects, 79 surface-treatment and mineral-seal projects, 32 sand-asphalt hot-mix projects, and 23 sand-bituminous road-mix projects. Ten tests were made on each project, and the average of these tests constituted the skid resistance of the specific project. The ages of the projects ranged from zero to 25 years with an average of 4 years. The traffic volume ranged from 200 to 15,000 vehicles per day with an average of approximately 2,900 vehicles per day.

The friction coefficient for each pavement type was compared on the basis of wear factor. The wear factor was computed as the product of the average daily traffic volume per lane divided by 1,000 and multiplied by the age of the project by years. This wear factor was similar to the one employed by Finney and Brown (1959) except that no attempt was made to adjust the traffic volume for the amount of commercial traffic because the percentage of commercial vehicles was fairly constant for all projects.

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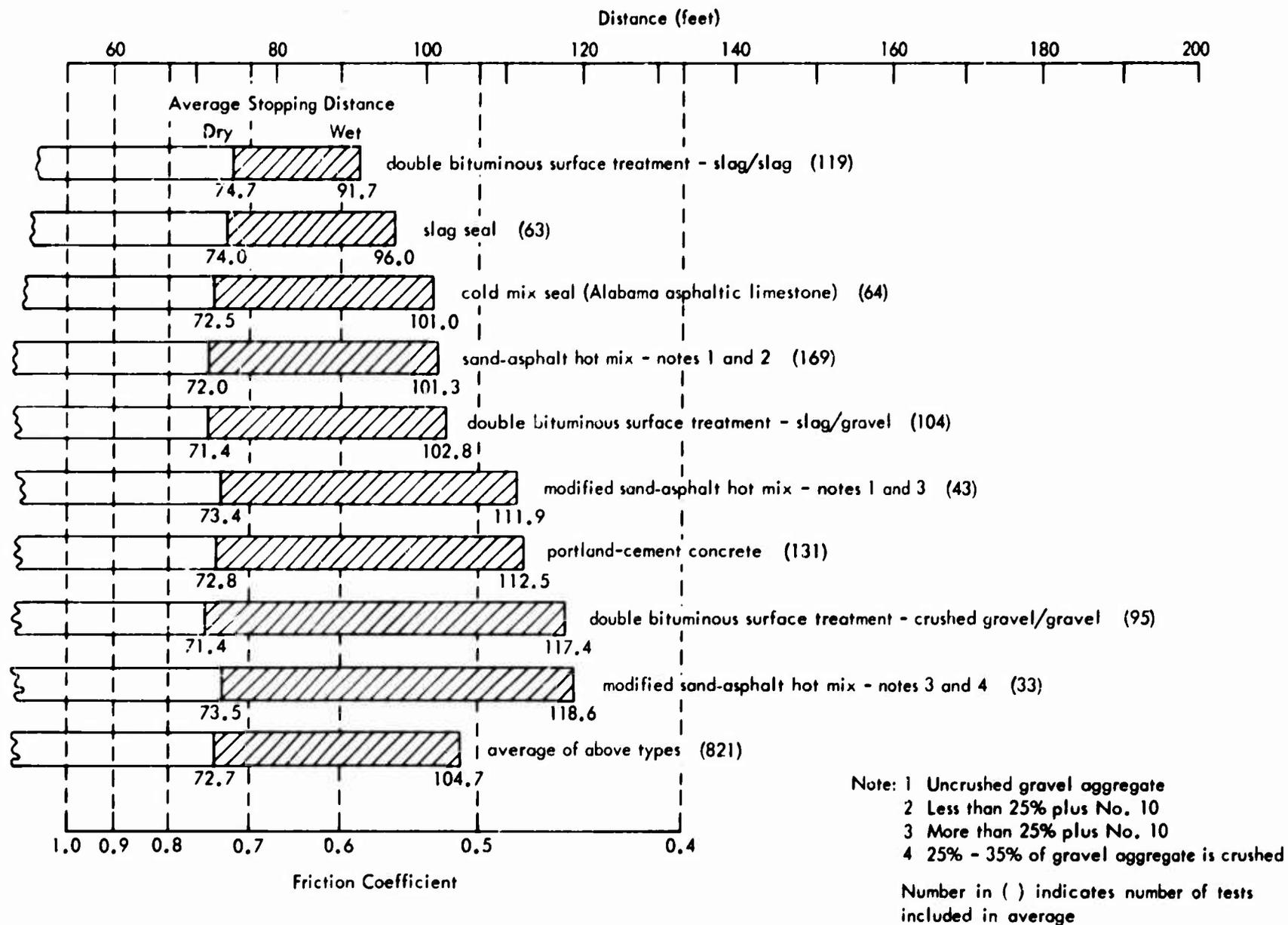


Figure 30. Average stopping distances for various types of surface having friction coefficients of 0.40 or more; testing speed, 40 mph. ©White and Thompson, National Academy of Sciences, National Research Council, 1958.

Table II. Summary of Mean Skid Distances, Average Variances, and Standard Errors

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Code No.	Surface Type	Mean Skid Distance (feet)	No. of Roads	Average Variances			Standard Error of the Mean* (feet)	Standard Error of the Mean** (feet)
				Skid-to-Skid	Location-to-Location	Road-to-Road		
1XX	Rock Asphalt	62.56	32	1.02	11.39	34.23	0.24	0.43
111	standard 30° or 60°	62.25	30	0.84	4.98	25.51	0.17	0.38
121	9° slick treatment	67.27	2	3.84	107.53	38.17	2.98	1.78
2XX	Portland-Cement Concrete	81.44	46	1.87	23.83	422.35	0.29	1.24
211	stone coarse aggregate	80.78	17	1.32	25.82	397.39	0.50	1.97
221	gravel coarse aggregate	81.83	29	2.06	22.67	446.28	0.36	1.60
3XX	Asphaltic Concrete	89.22	59	6.79	53.00	827.45	0.39	1.53
31X	stone coarse aggregate	88.78	55	6.99	55.65	830.02	0.41	1.59
311	natural sand	88.64	48	7.62	57.14	923.30	0.44	1.79
312	stone sand	89.80	7	2.64	45.43	199.99	1.04	2.18
321	gravel coarse aggregate - natural sand	95.21	4	3.99	13.12	82.43	0.74	1.65
4XX	Other Bituminous Surfaces	80.83	47	8.20	119.97	1,304.50	0.21	2.15
41X	no bleeding	74.06	30	5.11	22.34	508.30	0.35	1.68
411	all gravel	77.86	12	6.43	19.10	618.22	0.51	2.97
412	all stone	71.50	18	4.24	24.51	353.57	0.48	1.81
42X	bleeding	92.77	17	13.64	292.26	1,426.55	1.69	3.74
421	all gravel	103.44	8	23.71	355.32	1,037.55	2.72	4.65
422	all stone	83.28	9	4.69	236.41	672.01	2.09	3.53
5XX	Special Surfaces		14					
51X	bituminous coated aggregate (dense mixture)	99.38	6	8.03	200.85	918.46	2.36	5.05
511	all gravel	103.01	3	9.94	174.70	116.77	3.12	2.55
512	all stone	95.76	3	6.12	226.99	1,942.84	3.55	10.39
52X	silt & sand	66.68	1	2.82	0.83		0.37	
53X	bituminous concrete (5 1/2 % AP5)	98.35	1	1.85	13.74		1.52	
54X	bituminous concrete aggregate (U. S. Highway 40, 4 miles east of Brazil, Indiana)	150.46	1	0.24	59.30		3.14	

*Based on only those roads included in survey.

**Regarding the selected roads of each type as a random sample of Indiana roads.

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A summary of wet friction coefficients versus wear factors for various types of pavements is presented in Figure 31. All the curves were established by the method of least squares. Figure 31 permits the comparison of the various pavement types at the same wear factors. For example, at a wear factor of 5, the friction coefficient was 0.63 for portland-cement concrete, 0.61 for sand-asphalt hot-mix, 0.60 for mineral seal, 0.59 for asphaltic concrete, Type II, 0.58 for surface treatment, Type 2, and 0.52 for asphaltic concrete, Type I. The slopes of the curves on Figure 31 show the effect of wear by traffic on the six different pavement surfaces. It can be seen that wear by traffic had the least effect on portland-cement concrete and the most effect on surface treatment, Type 2.

Moyer (1959A) conducted skid tests on many portland-cement-concrete and asphalt pavements in California. Tests were conducted on both new and old pavements that were subjected to large variations in traffic volume which created varying surface conditions. The portland-cement-concrete pavements, for the most part, were finished with a Johnson Float Finisher equipped with a burlap drag. The finish varied from a dense, slick, smeary surface to a coarse sandy-surface texture. The asphalt pavements tested were many different types of seal coats, road-mix surfaces, and plant-mix surfaces. These pavements were made with a large variety of aggregates such as natural sand, uncrushed and crushed gravel, crushed rock from various types of limestone, granite, and basaltic rocks. For seal coats, the size of aggregates varied from sand size to crushed material of sizes from 1/4-inch to 1-inch. The plant-type surfaces had 1/2-inch and 1-inch maximum size aggregates.

The tests were conducted with a locked-wheel trailer towed by a truck at speeds ranging from 10 to 50 mph on both dry and wet pavements. Figures 15, 32, and 33 show friction coefficients versus speeds for different types of pavement in California, under both wet and dry surface conditions using a smooth-tread tire. In addition, results with rib-tread tires are shown in Figure 15 for the portland-cement-concrete surfaces. Comparison of Figures 32 and 33 shows, in general, that the friction coefficients for the asphalt plant-mix surfaces were slightly higher than those for the seal-coat surfaces when dry. On wet pavement surfaces, however, the friction coefficients for the seal coat with the angular aggregates were higher than for all of the plant-mix surfaces. There was only a slight difference in the friction coefficients of the wet seal-coat surfaces and the plant-mix surfaces made with rounded aggregates. The wet friction coefficients for the new portland-cement-concrete pavements, tested with a smooth-tread tire, were generally in between the wet and dry friction values for the seal-coat and plant-mix surfaces.

Nichols, Dillard, and Alwood (1956) reported on some measurements of friction coefficients by the stopping-distance method on various types of pavement in Virginia. The friction coefficients of the pavements were compared at speeds of 10, 20, 30, and 40 mph under both wet and dry conditions. The results indicated that asphalt surfaces with harsh, gritty, sandpaper-like textures gave the highest friction coefficients. These surfaces were followed by broom-finished portland-cement-concrete and the lower bituminous-type pavement surfaces.

In addition to the skid tests on various types of pavement surfaces, Mahone (1962) and Moyer (1959A) measured the friction coefficients of open-grid, steel bridge floors. Mahone (1962) used the British portable pendulum tester with a wetted rubber slider on one type of open-grid, steel floor. An average friction coefficient of approximately 0.2 was recorded indicating that the floor was extremely slippery when wet.

Moyer (1959A) used the locked-wheel trailer method and tested two types of open-grid, steel bridge floors. They were the Irving Open-Grid, Type V, and the United States Steel I-Beam-Lok. The results shown in Figure 34 indicate that the dry friction coefficients were more than twice as great as the wet friction values. It is interesting to note that the dry friction coefficients for these bridge floors were higher than the friction values, under corresponding test conditions, for the various types of pavement surfaces. The results for the wet steel floors, however, were generally lower than those for the pavement surfaces and indicated a "slippery when wet" condition for these bridge floors.

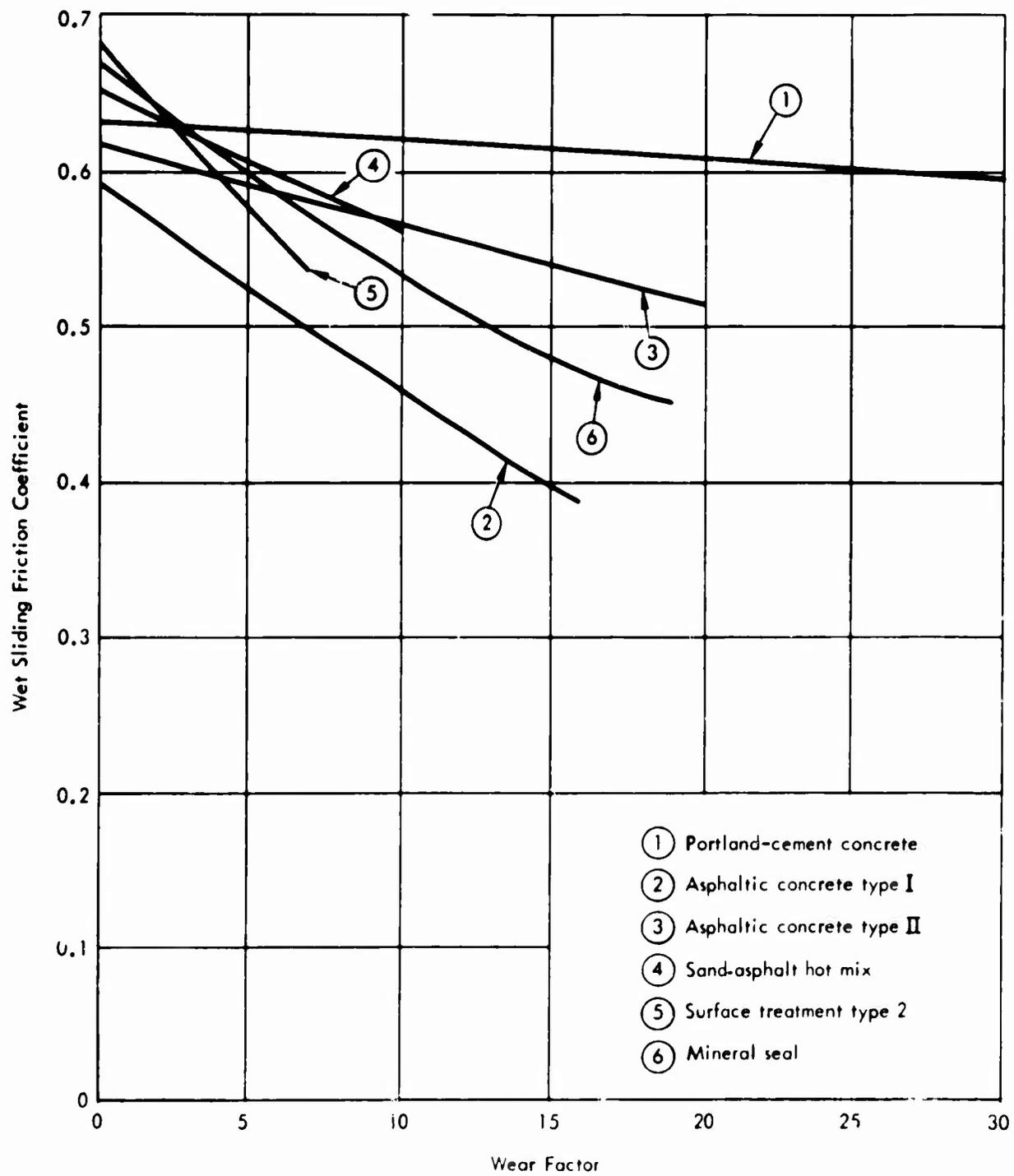


Figure 31. Friction coefficient in relation to wear for various pavement types.

Source: *Journal of Highway Engineering*, Vol. 1, No. 1, 1952, pp. 1-12.

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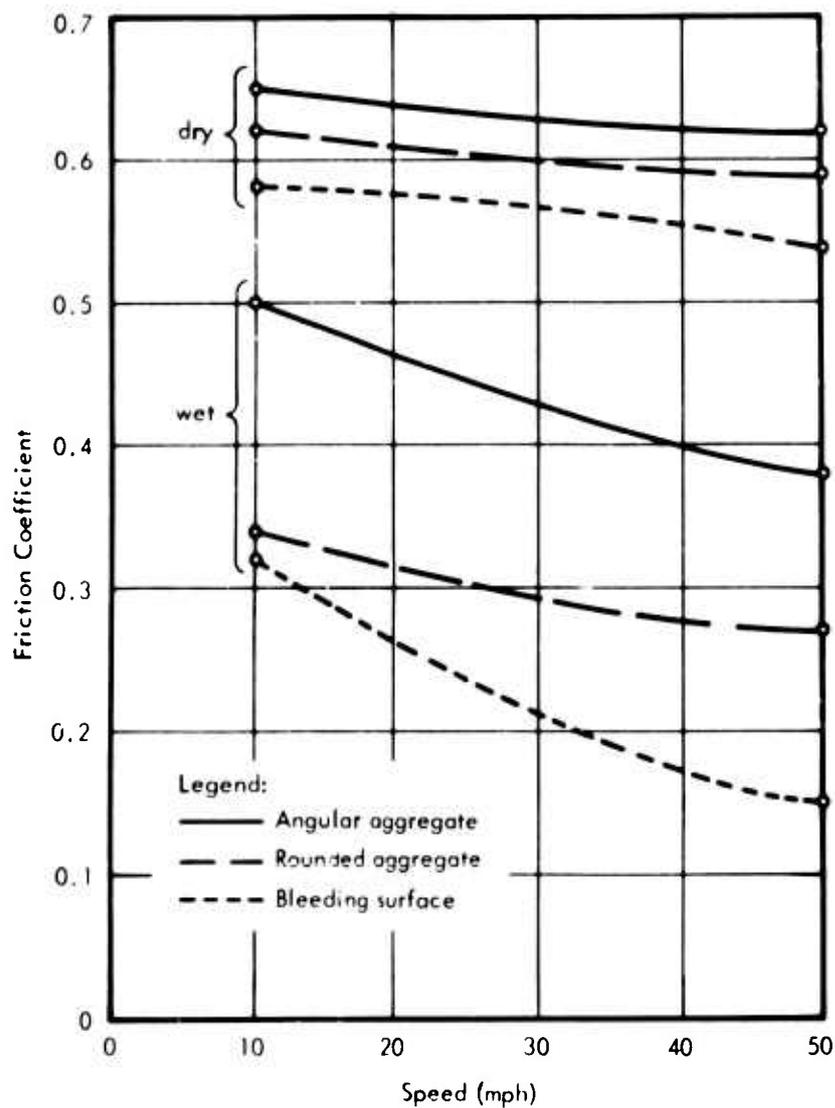


Figure 32. Skid resistance of asphalt seal coats. (Moyer, 1959A.)

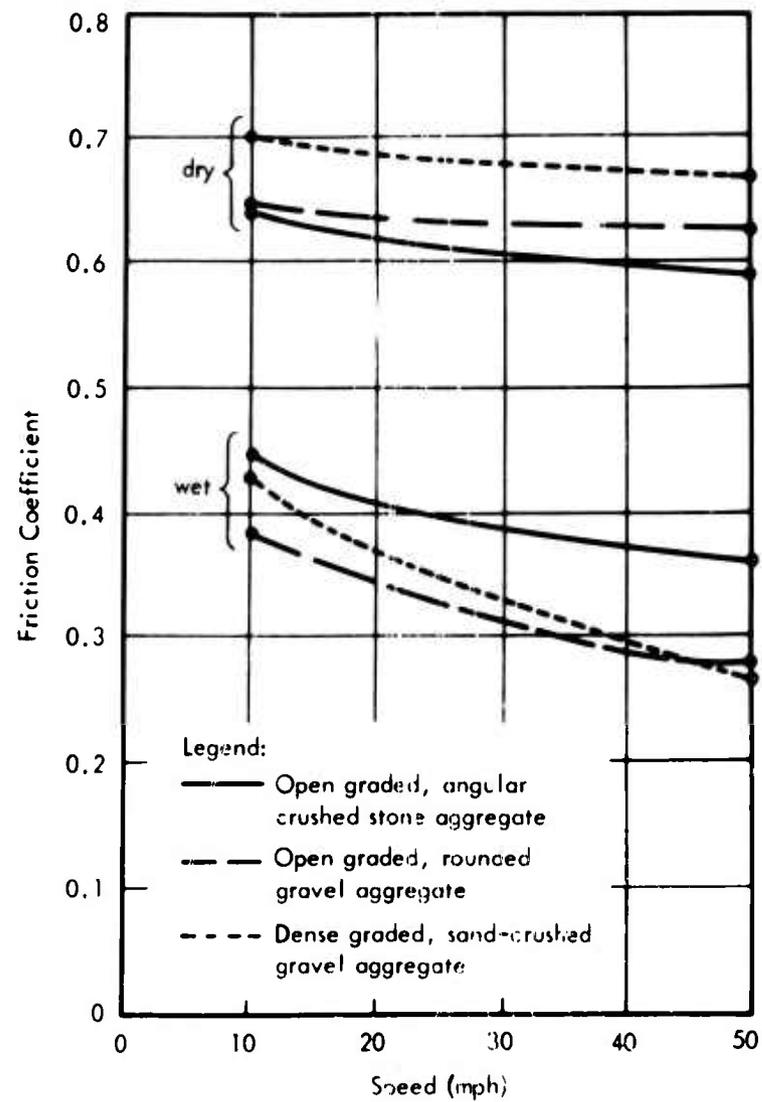


Figure 33. Skid resistance of asphalt plant-mix surfaces. Locked-wheel tests with smooth-tread tire. (Moyer, 1959A.)

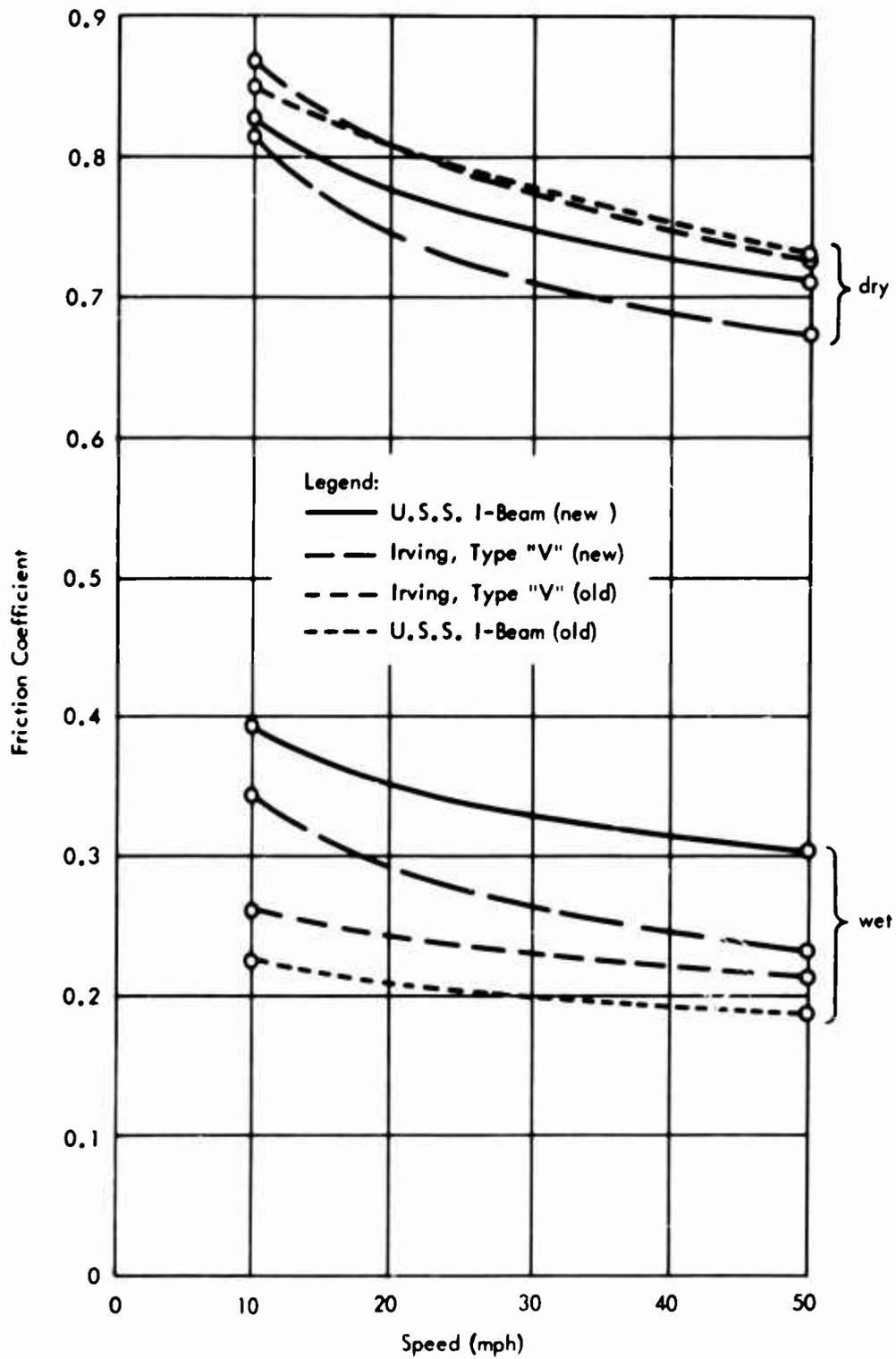


Figure 34. Skid resistance of open-grid, steel bridge floors. (Moyer, 1959A.)

The results of skid tests conducted on various pavement surfaces indicated that satisfactory friction coefficients were obtained on practically all of the different types of pavement surfaces when dry. However, a considerable decrease in friction coefficient was measured on many surfaces when wet. The initial conditions of the pavement surfaces and the changes in these conditions influenced the friction coefficients. The effect of factors which change the surface conditions will be discussed in subsequent paragraphs.

2. Aggregates and Surface Textures. Field and laboratory tests have shown that friction coefficients were influenced largely by the aggregates and the surface textures of the wearing surfaces of pavements. These two factors had properties which contributed toward high skid resistance. The size, shape, hardness (or resistance to polishing wear), and gradation of various types of aggregate were investigated. When these aggregates were combined with cements and placed to form various types of pavements by many different types of machines and techniques, the resulting pavement surfaces were certain to have many different surface textures. Surface textures for asphaltic concrete have been described as dense-graded, open-graded, sandpaper, bleeding asphalt, sharp-angular, rounded-knobby, or flat mosaic. Surface textures for portland-cement-concrete surfaces were generally provided by brooming or by dragging burlap which resulted in sandpaper-type finishes.

Although many tests have been conducted to establish the effect of each of the elements which made up the pavement, the results have not been conclusive for all of the items investigated. One example of this was the effect of the size of aggregate on the friction coefficient. Moyer (1959) reported that the wet friction coefficients for a coarse (3/8- to 1/2-inch maximum), crushed-granite aggregate surface were in the range of 0.6 to 0.5 at speeds of 10 to 50 mph. These friction coefficients were typical of the results obtained in California on asphalt seal-coat surfaces with coarse rock chips as cover material where there was no evidence of bleeding or excess asphalt. For surfaces constructed with dense-graded sand, the friction coefficients were consistently lower than those for surfaces with the coarse crushed aggregates. However, Moyer (1959) reported that tests in Virginia indicated that the fine-grained Kentucky-rock-asphalt surface consistently gave the highest friction coefficients of all types of surfaces. As reported previously, Michael and Grunau (1956) found similar results with Kentucky-rock asphalt surface in Indiana. The sand grains in the Kentucky-rock-asphalt surface were in the 1/50-inch size range and provided a sandpaper-type surface. On the basis of these results, it appeared that the size of aggregate was not necessarily a governing factor in providing a high friction coefficient.

Studies have indicated that aggregates which developed an interlocking or "gearing" of the tire gave high friction coefficients, especially on wet pavement surfaces. The results of a laboratory investigation given by Shupe and Goetz (1959) in Figure 35 show that the asphaltic-concrete specimens containing angular aggregates had appreciably higher relative-resistance values or skid resistances than corresponding rounded-aggregate specimens. However, wearing of the surfaces minimized the difference in skid resistance until there was no significant difference between the initially angular specimens and the rounded-aggregate specimens. The relative-resistance value was a measurement of wet skidding resistance expressed as a relative value with Kentucky-rock asphalt, which exhibited excellent resistance to skidding, selected as the reference material and assigned a value of 1.00.

White and Thompson (1958) studied the friction coefficients of bituminous surface treatments when the amount of crushed, angular particles was varied in seal coats. The results shown in Figure 36 indicate that the seal coat which contained more than 90-percent crushed particles had wet friction coefficients above 0.45. On the other hand, the seal coat which contained 50- to 70-percent crushed particles had a friction coefficient of 0.41, except for a short period after construction.

The results of the studies indicate that the initial shape of aggregates had a marked effect on friction coefficient, but wearing decreased the effect of the initial shape.

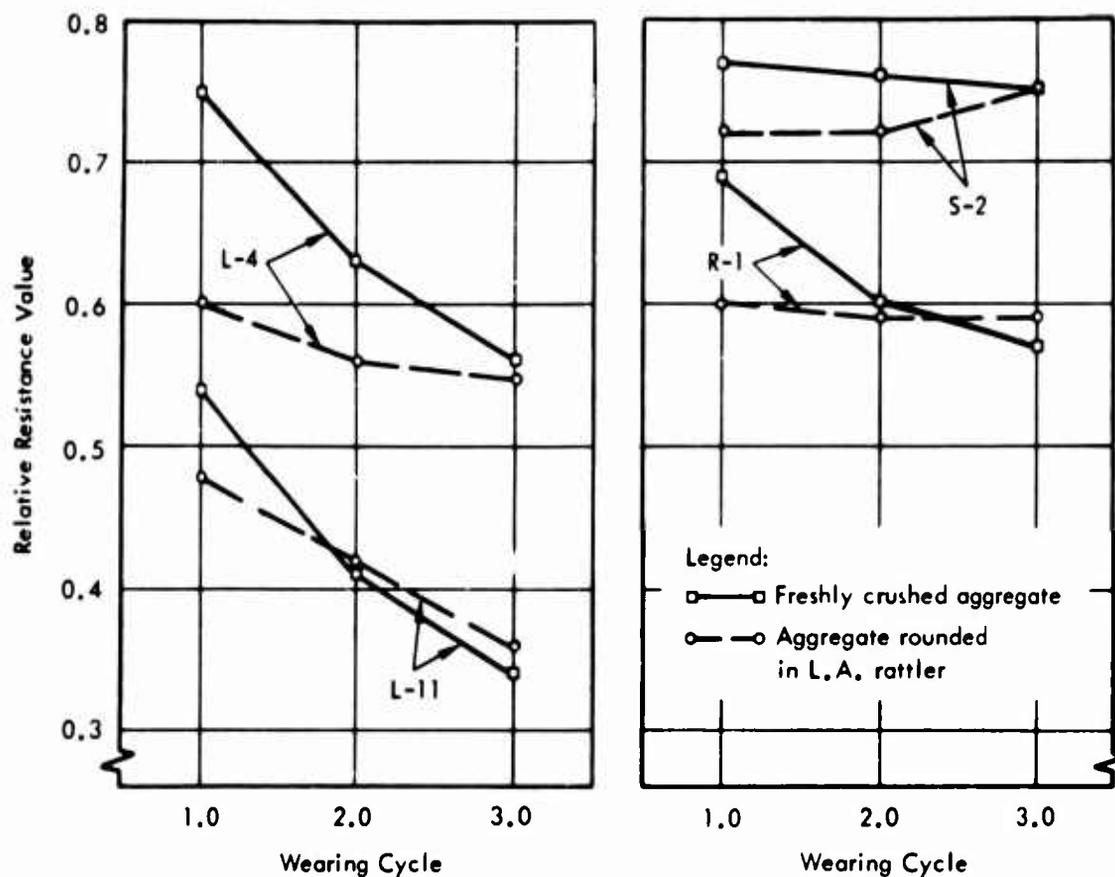


Figure 35. Effect of aggregate shape on the polishing characteristics of bituminous mixtures. © Shupe and Goetz, National Academy of Sciences, National Research Council, 1959.

To determine the effect of the hardness of aggregates on the friction coefficient, Finney and Brown (1959) conducted skid tests on portland-cement-concrete pavements made with natural sand and those made with stone sand. The results indicated that pavements made with natural sand had wet friction coefficients higher than those made from stone sand. The average friction coefficient for 23 natural-sand projects was 0.51 compared to 0.28 for the 19 projects constructed with stone sand. The quartz particles, predominating in natural sand, had a hardness of 7 in Moh's hardness scale. Limestone particles in stone sand, on the other hand, came from a sedimentary rock which had a hardness of 3. Thus, it was reasonably suspected that stone sand became smooth more rapidly than natural sand under traffic.

Stutzenberger and Havens (1958) found, in a laboratory study, that limestones never exhibited friction coefficients as high as those of sandstones. The reason was that the quartz particles in the sandstones had a hardness of 7 and could not be polished as readily as the limestones with a hardness of 3.

The results of the studies indicate that the hardness of aggregates had a marked influence on the friction coefficient and on the resistance of the aggregates to polishing. It appeared that hard aggregates were better than soft aggregates for pavement construction from the standpoint of the friction coefficient.

In an effort to increase the skid-resistance of paving mixtures containing soft, polish-susceptible aggregates, Shupe and Goetz (1959) studied the effect of blending polish-resistant aggregate with a polish-susceptible limestone. Figure 27 shows the relative-resistance

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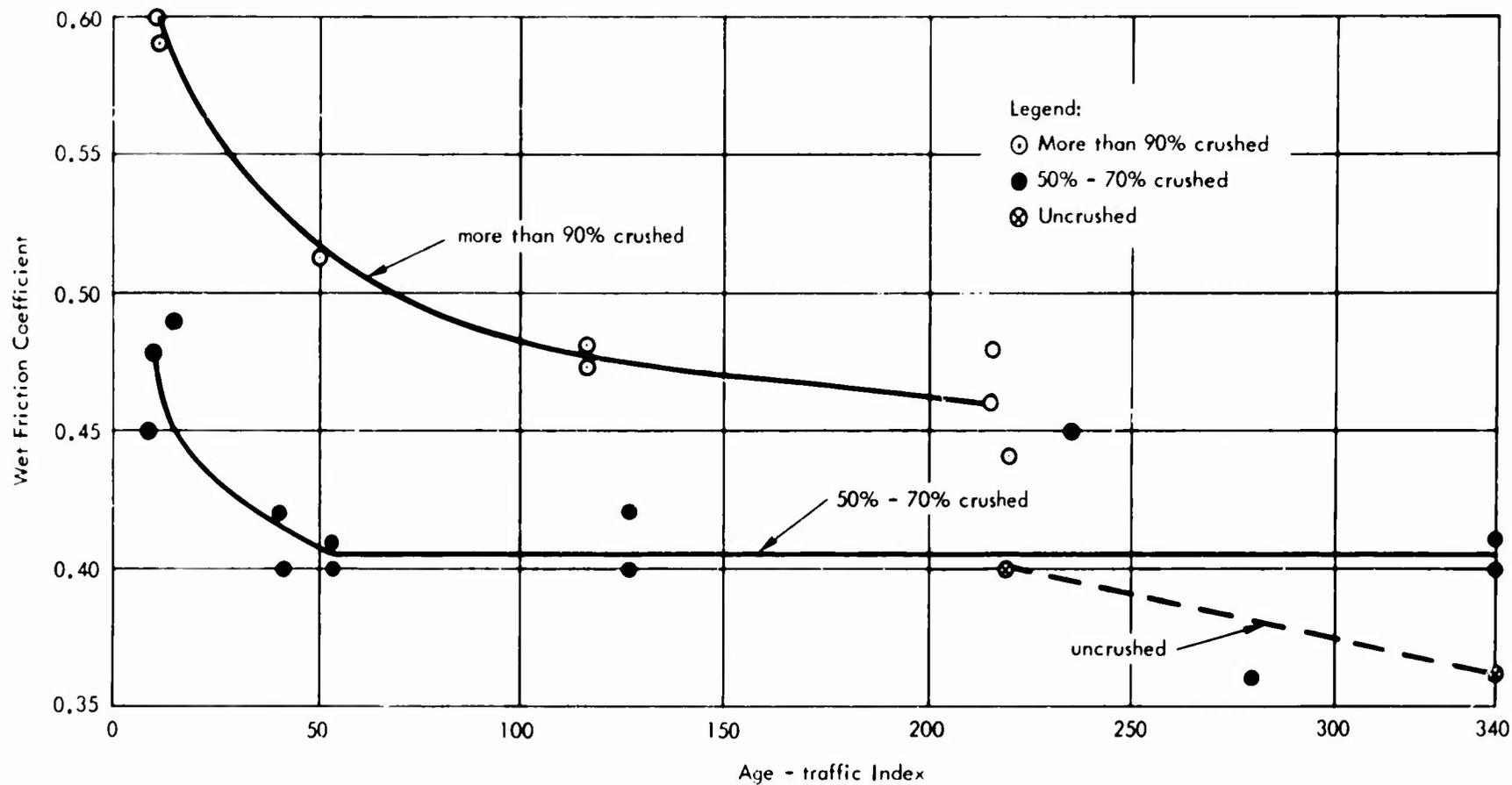


Figure 36. Wet friction coefficient versus age-traffic index to show the effect of crushed particles in gravel aggregate seal; testing speed 40 mph; double bituminous surface treatment, gravel/gravel. (Age-traffic index = age in months x average daily traffic/100. In general, wet friction coefficients below 0.40 are caused by excess bitumen and/or polished aggregate.)

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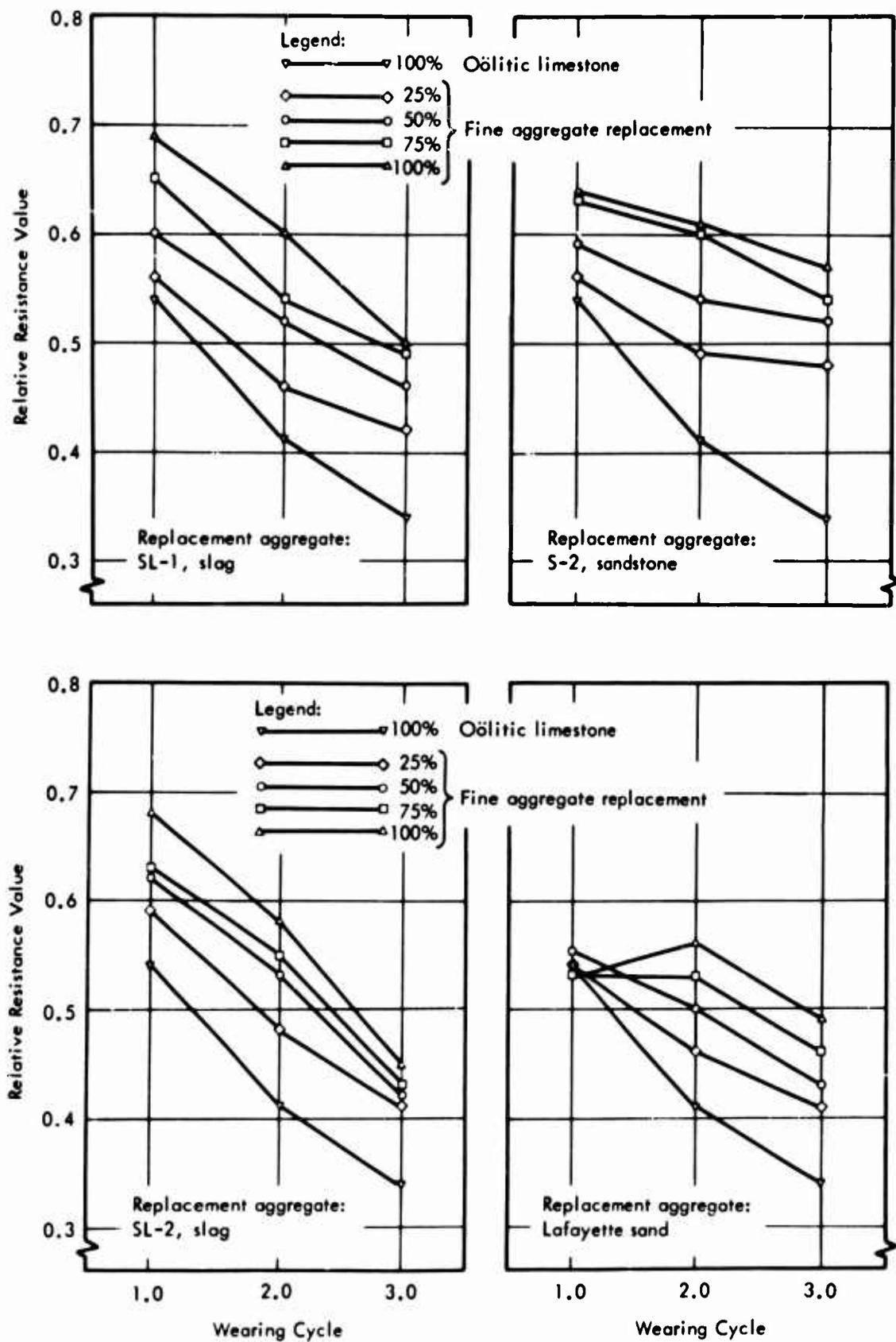


Figure 37. Effect of replacing the fine aggregate fraction with a harder material in asphaltic concrete.

Shupe and Greer, National Academy of Sciences - National Research Council, 1959

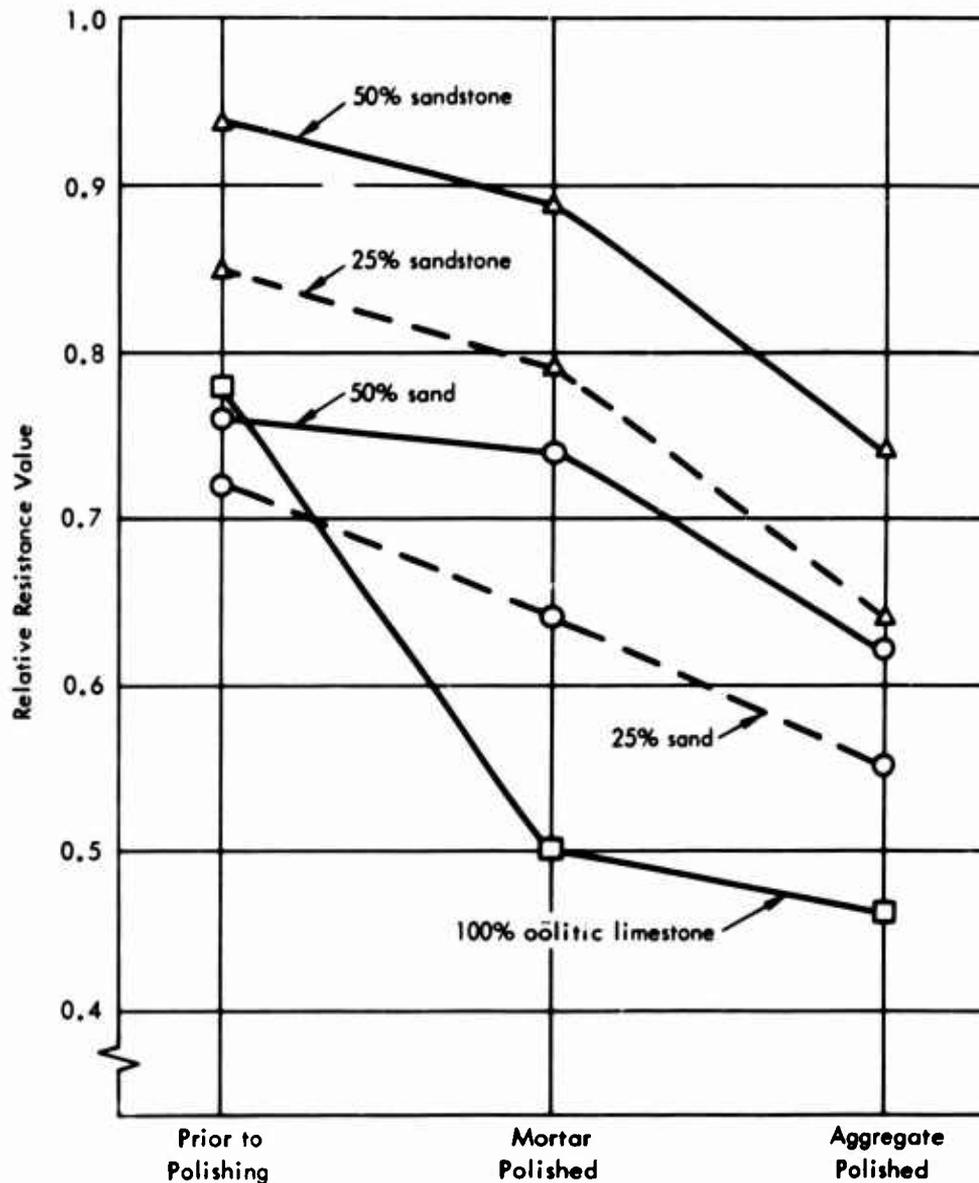


Figure 38. Fine aggregate replacement in portland-cement concrete. ©Shupe and Goetz, National Academy of Sciences - National Research Council, 1959.

values for asphaltic-concrete specimens with polish-susceptible, fine oölitic limestone replaced with various percentages of polish-resistant fine aggregates such as slags, sandstone, and Lafayette sand. Figure 38 shows the relative-resistance values for portland-cement-concrete specimens having 25 to 50 percent of the oölitic limestone replaced with natural sand or sandstone. Figures 37 and 38 show in general that the relative-resistance values or skid resistances of asphaltic and portland-cement-concrete specimens increased with an increase in the percentage of substitution of fine aggregate. However, Shupe and Goetz (1959) stated that an appreciable amount of replacement was required to substantially improve the skid resistance of the asphaltic-concrete surfaces. This appreciable quantity of polish-resistant material was more effective when used as a surface treatment over existing asphaltic-concrete surfaces. Frequently, the fine-aggregates and asphalt matrix eroded away under traffic, and the area of contact between the tires and the pavement surfaces consisted almost entirely of coarse aggregates. For such a condition, Shupe and Goetz (1959) reported that the blending of polish-resistant fine aggregates resulted in little improvement in the skid characteristics of the mixtures.

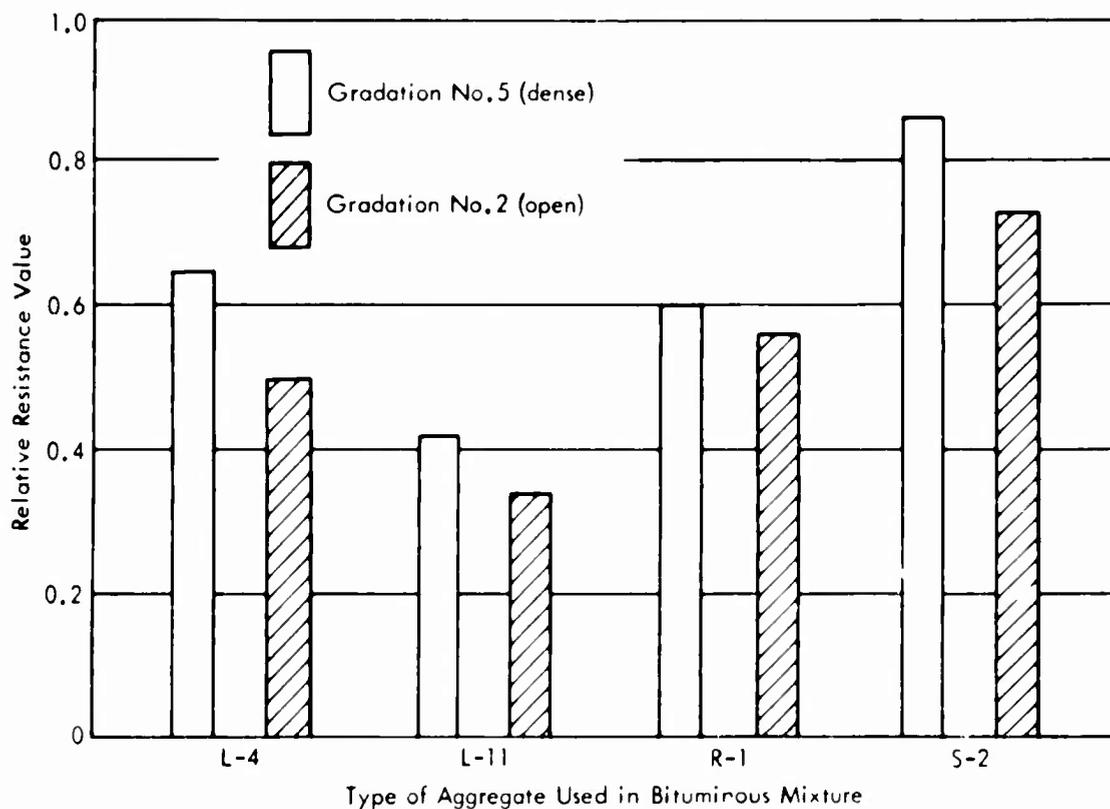


Figure 39. Comparison of the resistance to polishing of dense- and open-graded bituminous mixtures.

Copyright © National Academy of Sciences, National Research Council, 1959

The blending of a polish-resistant fine aggregate to improve the skid-resistance of a polish-susceptible limestone in portland-cement concrete was much more effective than with bituminous mixtures. Shupe and Goetz (1959) explained that the fine-aggregate mortar made an important contribution to the skid-resistance developed by portland-cement concrete even after wear progressed to a point where an appreciable amount of coarse aggregates was exposed.

Dillard and Alwood (1957) found that the substitution of polish-resistant sand for polish-susceptible aggregates in an amount equal to as much as 25 percent of the total amount of aggregates in asphaltic concrete did not consistently provide high skid resistance. The substitution of coarse, polish-resistant aggregates in an amount up to 30 percent of the total aggregates also did not provide high skid resistance.

Bituminous mixtures with five gradations ranging from very open to dense mixtures have been investigated by Shupe and Goetz (1959) to determine the effect of aggregate gradation on friction coefficient. The results for two extreme gradations are summarized in Figure 39 for highly-dolomitic limestone (L-4), dolitic limestone (L-11), rhyolite (R-1), and sandstone (S-2) aggregates. Figure 39 shows that the dense gradation gave higher relative-resistance values than the open gradation.

The effect of surface texture on friction coefficient was investigated by Moyer (1959) together with the effects of speed, types of pavement, and aggregates in paving mixes. Results of skid tests on dry pavements showed that the friction coefficients were higher on

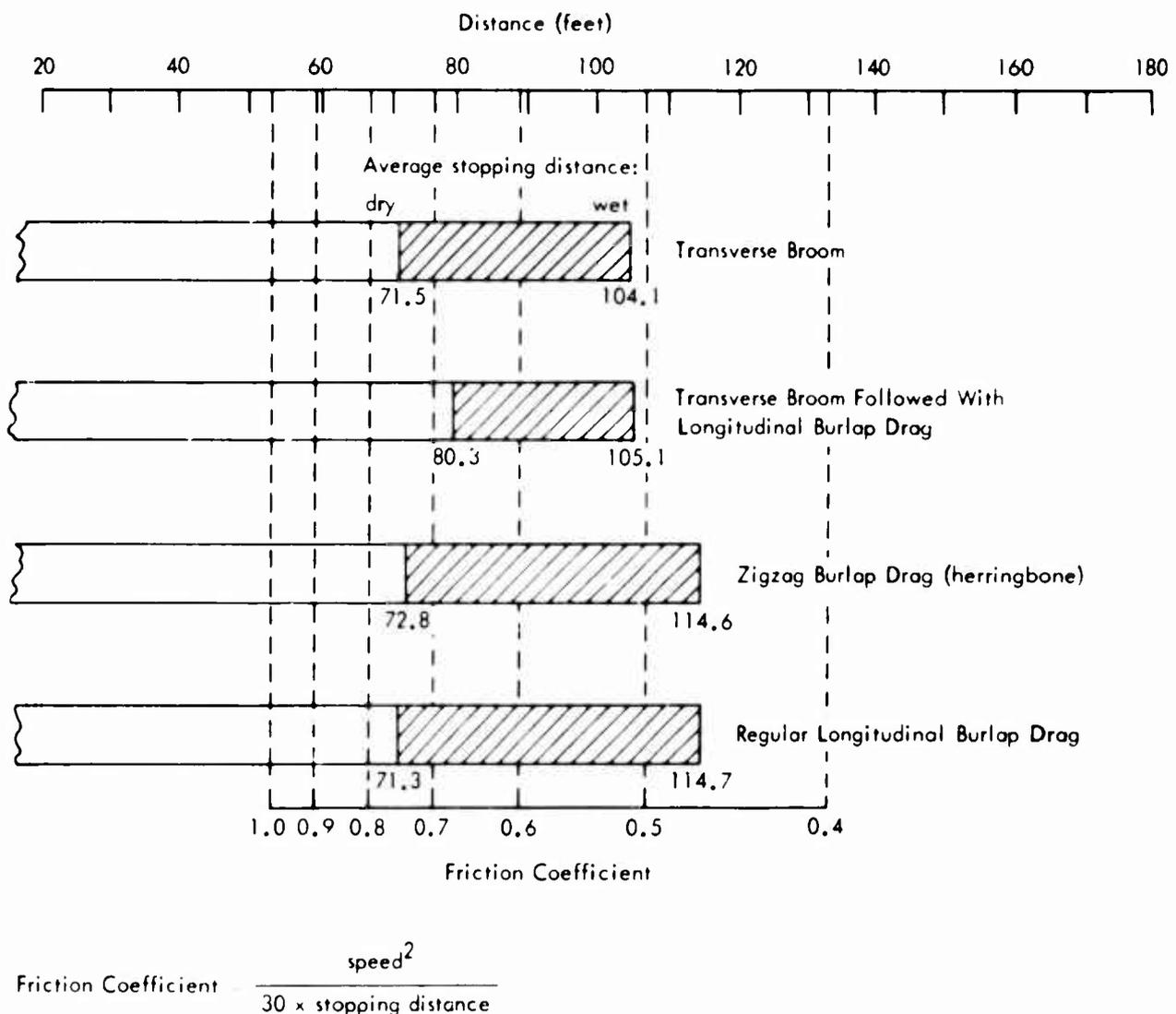


Figure 40. Relative stopping distances on cement-concrete pavement with various types of finish; age, 264 days; testing speed, 40 mph; U.S. Highway 51 south of Jackson, Mississippi.

dense-graded asphalt surfaces than on coarse, open-graded asphalt surfaces. An explanation given by Moyer (1959) was that greater contact area was provided by the dense-graded surfaces than by the coarse, open-graded surfaces. The increase in contact area presumably increased the adhesion and shearing forces developed by the tire on dry surfaces.

In the wet pavement tests, the surface textures provided by the open-graded, angular aggregates gave higher friction coefficients than the dense-graded, rounded-knobby surfaces or flat-mosaic surfaces. This result was reasonable since open-graded surfaces with asperities provided channels or voids through which water readily escaped under the wheel load.

The friction coefficients for bleeding asphalt surface, as shown in Figure 16, were low, especially at the higher speeds. Practically all of the investigators who conducted skid tests on bleeding-asphalt surfaces found low friction coefficients on this type of surface texture.

Figure 40 shows the friction coefficients for portland-cement-concrete surfaces with various types of finish. The surfaces finished by dragging burlap had lower wet friction coefficients than those finished by brooming or by a combination of brooming and dragging

burlap. When dry, the surface with the combination transverse broom-burlap drag finish gave the lowest friction coefficient, and there were only slight differences in the dry friction coefficients among the other surfaces.

Moyer (1959A) found that newly constructed surfaces with coarse-grained burlap-drag or broom finish gave higher friction coefficients when wet than the slicker or more highly polished surfaces. The friction coefficients of coarse-grained surfaces were in the range of 0.6 to 0.5.

3. Traffic, Surface Contamination, and Foreign Material. Although friction coefficients found between tires and practically all new pavement surfaces were sufficiently high, studies have shown that there were some factors which changed the friction values. These factors were traffic, surface contamination, and foreign material on the pavement surfaces. The effect of these factors will be discussed in the subsequent paragraphs. Another important factor, that of water on pavement surfaces, was previously discussed.

Reference has been made by many investigators on the effects of traffic in wearing or polishing to reduce the abrasive properties of the aggregates and in causing major changes in surface textures. In general, investigators found that wearing by traffic contributed to a reduction in the friction coefficients on wet pavement surfaces. Some of the test results are shown in Figures 29, 31, and 36.

Moyer (1959) reported that the changes in surface textures of pavements depended on the type of aggregates used and on the type of construction. On rigid pavement surfaces of portland-cement concrete, the wearing was generally confined to the removing of the sand-cement mortar and to the rounding of the peaks and edges of the aggregate particles on the surface. The flexible bituminous surfaces were subjected to not only the polishing-wear effect, but to plastic deformation as well. The traffic compacted and increased the density of asphalt material. This developed to a finer-grained texture which was reported by Moyer (1959) to lower the skid resistance under wet pavement conditions. On certain types of asphalt pavements, traffic had a tendency to reorient the aggregate particles and change the coarse-textured angular-aggregate surface to a flat-mosaic-pattern.

Figure 41 shows the friction coefficient versus speed for passing and traffic lanes of asphalt seal-coat and portland-cement-concrete pavements. Moyer (1959) estimated that traffic on the traffic lane averaged 12,000 vehicles per day, and traffic on the passing lane averaged 3,000 vehicles per day for both types of pavement. Figure 41 shows that the traffic lanes had lower friction coefficients than the passing lanes. The difference between the two lanes was about the same for the asphalt seal-coat and portland-cement-concrete pavements.

Finney and Brown (1959) made skid-resistance tests on the adjacent passing and traffic lanes of portland-cement-concrete and two asphaltic-concrete pavements. Comparative results for 8 projects showed that the traffic lanes, which carried more traffic than passing lanes, had wet friction coefficients lower than those of the passing lanes. The difference was as much as 36 percent.

Traffic not only caused wearing or polishing but brought an accumulation of surface contamination such as oil drippings, grease, and rubber on pavement surfaces. Moyer (1959) reported that oil drippings on traffic lanes of California highways carrying 5,000 vehicles per day was estimated at 2 quarts per 1,000 miles for each vehicle. This estimate was probably high, but the discoloration by oil films of newly constructed concrete pavements was clearly evident on highways carrying high traffic volumes within a month after the pavements were opened to traffic.

The presence of rubber on highway pavement surfaces has been evident by tire skid marks. Moyer (1959) indicated that rubber particles were continually being removed from tires in normal driving operations, but only the skid marks were visible. Evidence of very heavy rubber deposits was also visible in the touchdown areas of airfield runway surfaces.

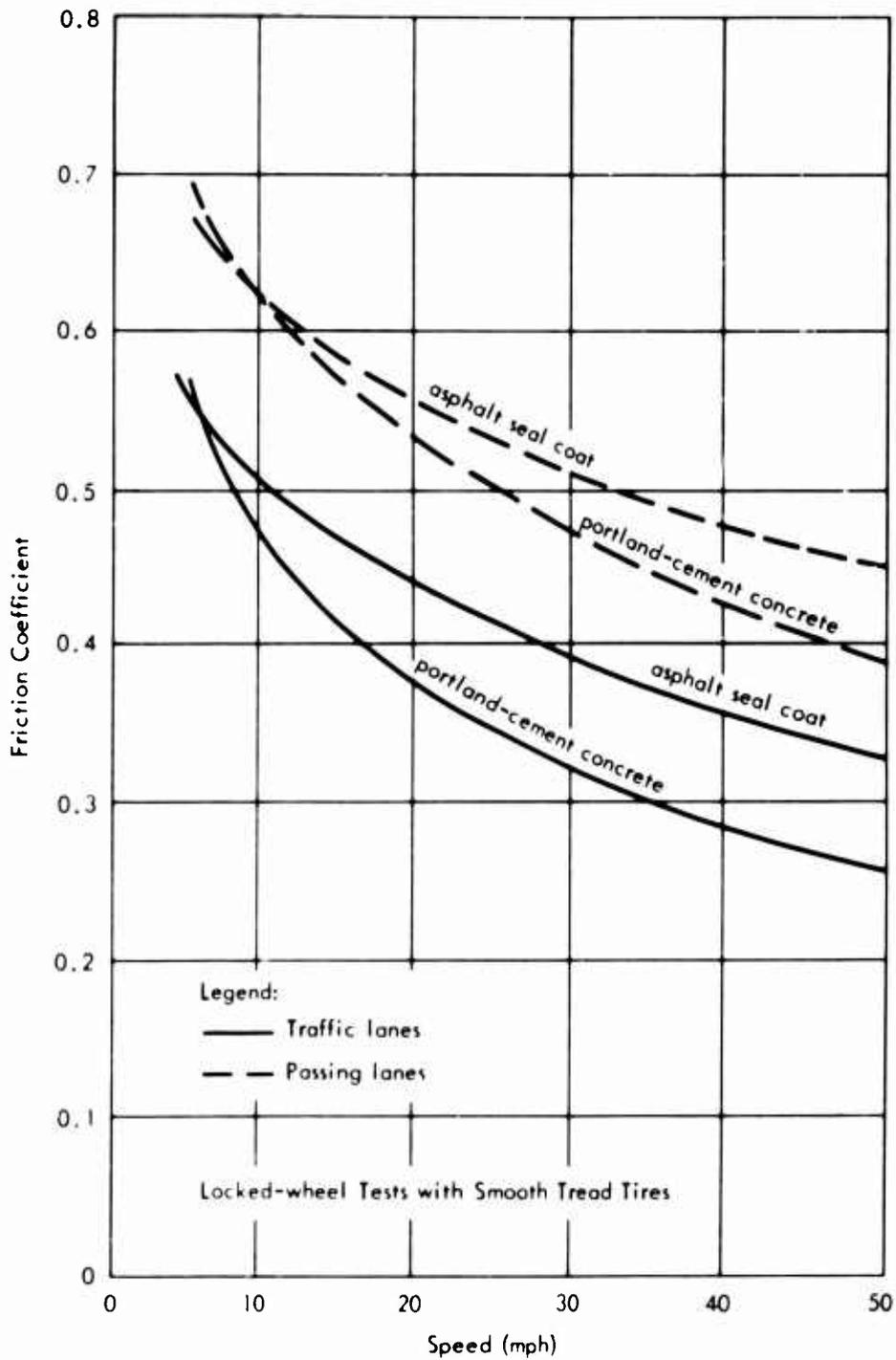


Figure 41. Friction coefficients on asphalt and portland-cement-concrete surfaces in wet condition in traffic lanes and passing lanes of divided highways. (Moyer, 1959.)

Some tests have been made by various investigators to determine the effect of these contaminants on the friction coefficient. Since the effects of contaminants generally combined with those of other variables, no accurate determinations of the effect of the individual contaminants were possible.

A series of skid tests has been conducted by Moyer (1959) on various portions of a runway at Moffett Field, California. The purpose was to determine the friction coefficients of portland-cement-concrete surfaces with, and without, visible rubber deposits. The friction coefficients of the two surfaces are shown in Figures 42 and 43. On the dry surface, the rubber deposits had no significant effect. However, on the wet pavement, the friction coefficients for sections without rubber deposits were 25 to 30 percent higher than those for the sections with heavy rubber deposits.

Mud, wet leaves, and other foreign material on pavement surfaces were reported by Moyer (1959) to cause skidding hazards. Friction values on a pavement with one type of mud were of the same magnitude as those measured on wet, packed snow. Paved shoulders adjacent to many of the major highways have decreased the amount of foreign material on pavements and, consequently, the skidding hazards caused by them. The vigorous effort to remove foreign objects which cause damage when drawn into jet engines has also decreased the skidding hazards on airfield pavements.

Moyer (1959) reported that the most effective way of removing contaminants accumulated on pavement surfaces was brought about by the cleansing effect of heavy rains and by the scrubbing effect of tires of vehicles operating on the wet pavement. The improvement in the friction values on concrete and asphalt pavements in California, believed to be brought about by removal of contaminants after heavy rains, is shown in Figure 44. The improvement was from 20 percent to as much as 60 percent.

4. Temperature, Weather, and Climate. Three different temperature measurements found to introduce a variable effect on the friction coefficient were ambient temperature, road-surface temperature, and tire temperature. The effect of tire temperature was previously discussed. Moyer (1959) reported that locked-wheel trailer tests on dry portland-cement-concrete and asphaltic-concrete pavements in California showed a decrease in friction coefficient with a rise in ambient temperature. At an average ambient temperature of 70° F, the friction coefficient averaged 0.65, and this average value decreased to 0.60 when the ambient temperature increased to about 95° F. This reduction reflected changes in the tire temperature and the shear strength as well as in the elastic and plastic properties of the tread rubber.

Repeated tests on the same portland-cement-concrete and asphaltic-concrete pavement surfaces when wet also showed a decrease in the friction coefficient with a rise in the ambient temperature, but the decrease was not as much as on the dry surfaces. Moyer (1959) reported that two factors contributed to the decrease on wet asphaltic-pavement surfaces. These were the changes in viscosity of the water and of the asphalt, caused by changes in ambient temperature.

Finney and Brown (1959) conducted skid tests during a 24-hour period at the same location on two adjacent types of newly constructed portland-cement and bituminous-concrete surfaces. The purpose was to determine the effect of pavement temperature on friction coefficient. The results shown in Figures 45 and 46 indicate that there was a difference in friction coefficient of approximately 15 percent during a 24-hour change in pavement temperature of about 30° F.

Moyer (1959) reported that surface textures of asphalt pavements in some locations were subjected to wide variations of weather and climate. These variations in turn changed the skid-resistance characteristics of the pavements. Weathering usually counteracted the effect of polishing caused by traffic wear. Oxidation of the thin film of asphalt on exposed aggregate particles by the sunlight, and other weathering effects such as temperature changes, freezing and thawing, and wetting, improved the surface texture and consequently the skid resistance.

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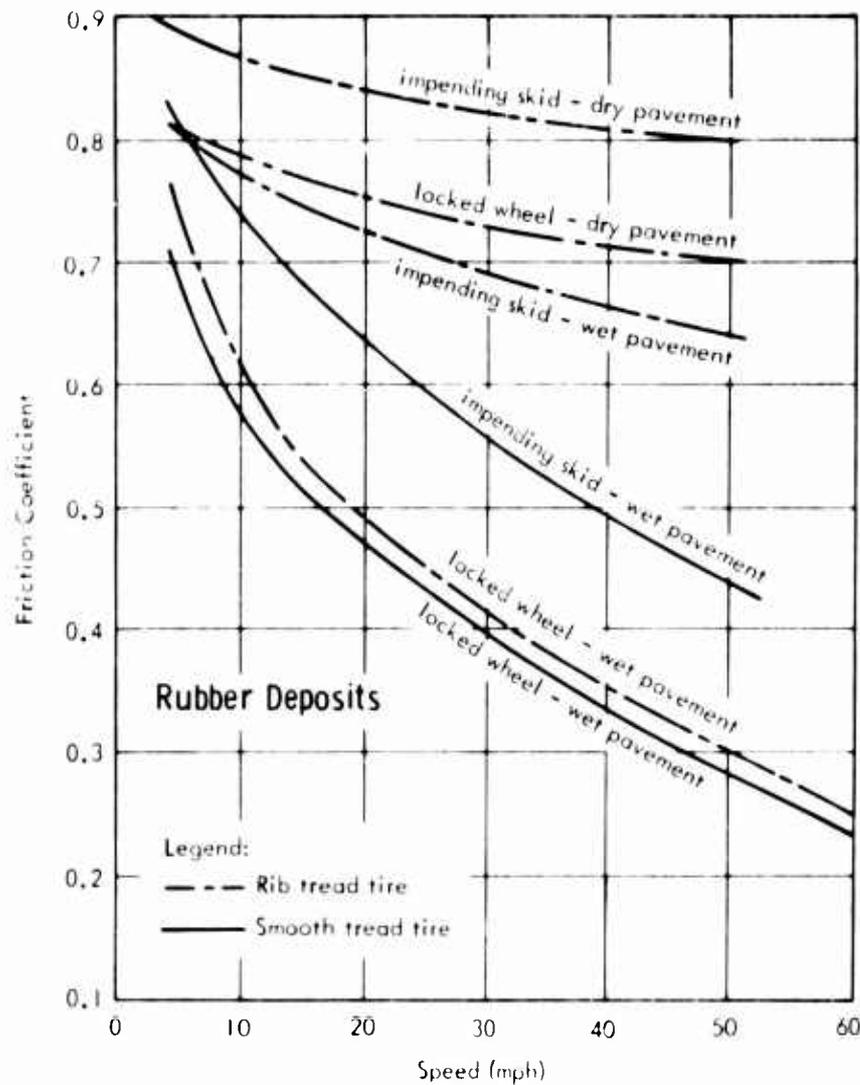


Figure 42. Friction coefficients measured in impending-skid and locked-wheel braking tests for dry and wet pavement conditions on sections of portland-cement-concrete runways with heavy rubber deposits, Moffett Field, California. (Moyer, 1959.)

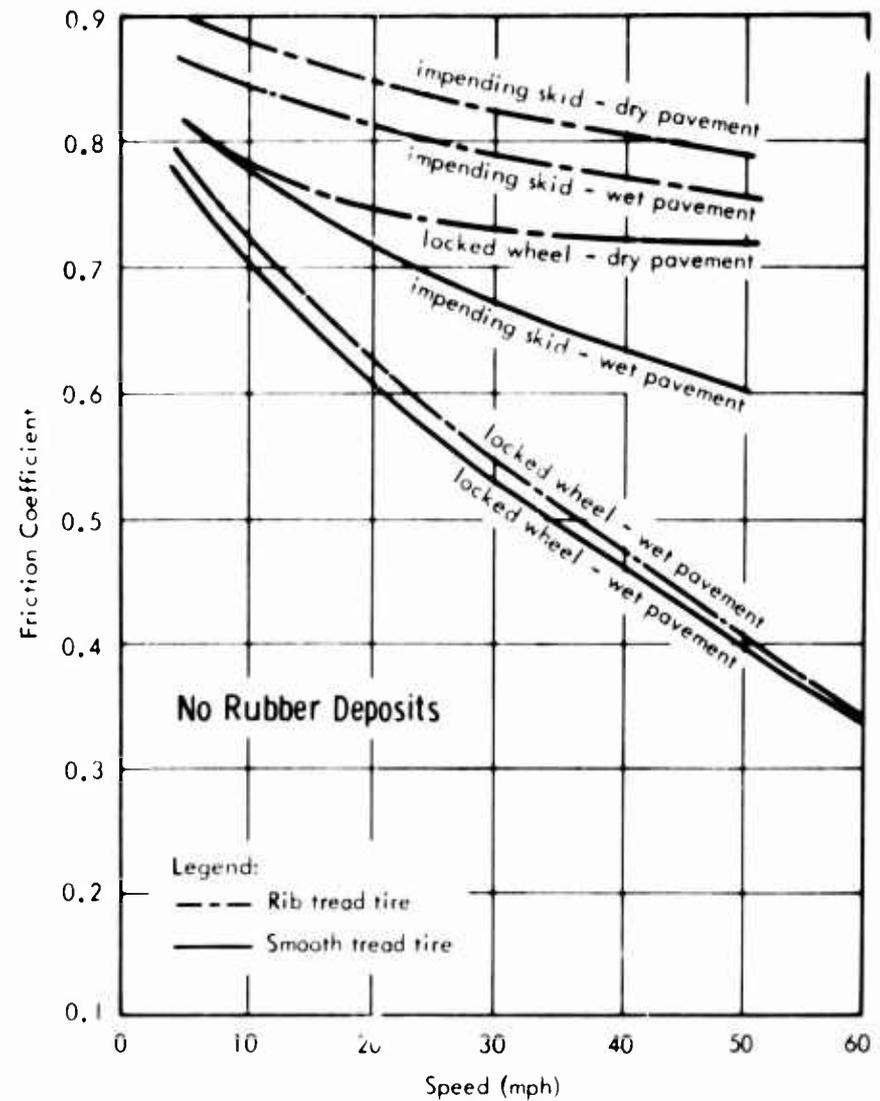


Figure 43. Friction coefficients measured in impending-skid and locked-wheel braking tests for dry and wet pavement conditions on sections of portland-cement-concrete runways with no rubber deposits, Moffett Field, California. (Moyer, 1959.)

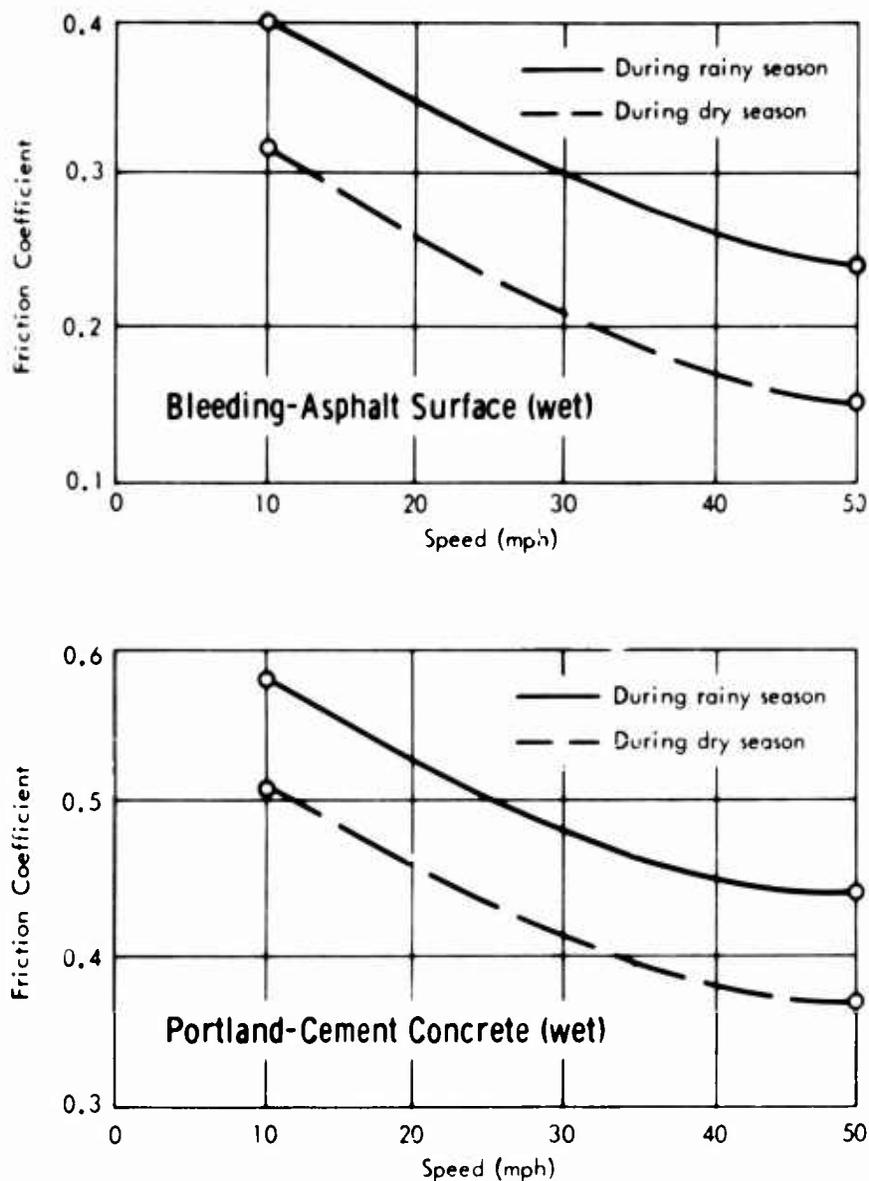


Figure 44. The effect of seasonal differences on the skid resistance of a portland-cement-concrete pavement and a bleeding-asphalt surface. (Moyer, 1959.)

Repeated skid tests on the same pavements in California on a seasonal and annual basis indicated that the friction coefficient varied in a cyclic pattern. During the summer or dry season, the wearing effect of traffic and the accumulation of oil and other contaminants steadily decreased the friction coefficient. During the winter, the trend was reversed mainly by the cleansing effect of winter rains.

Giles and Sabey (1959) made systematic skid measurements on 12 typical examples of different pavement surfaces using the British portable skid-testing device. The results of these skid measurements are shown in Figure 47. The extreme difference in friction coefficients between the summer and winter months ranged from 0.14 to 0.30. The winter months had higher friction values. The mean difference was 0.18.

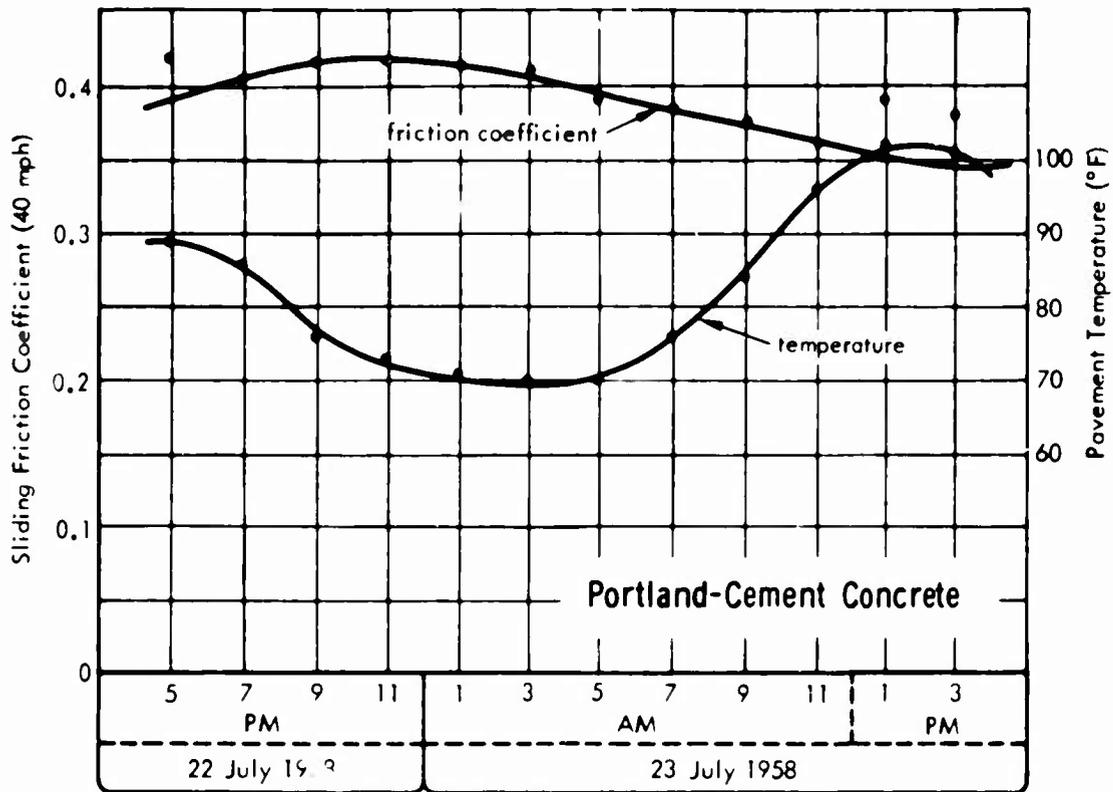


Figure 45. Hourly temperature-friction relationships: Portland-cement concrete. (Finney and Brown, 1959.)

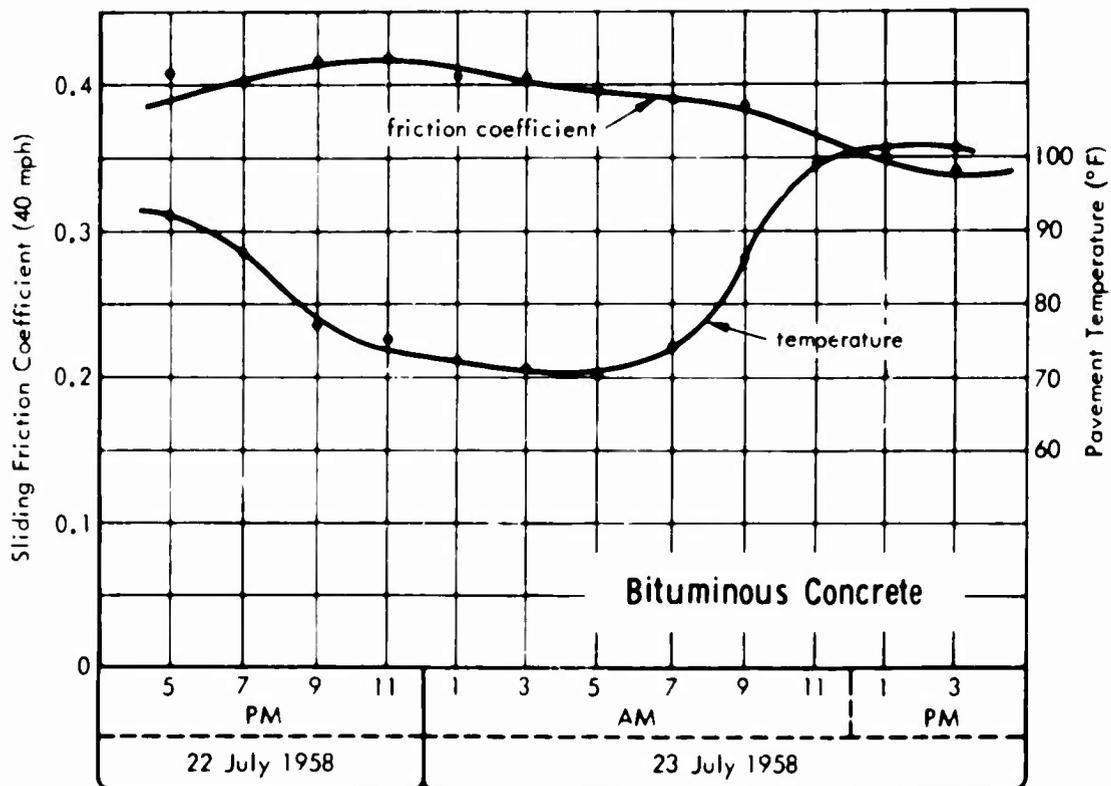


Figure 46. Hourly temperature-friction relationships: Bituminous concrete. (Finney and Brown, 1959.)

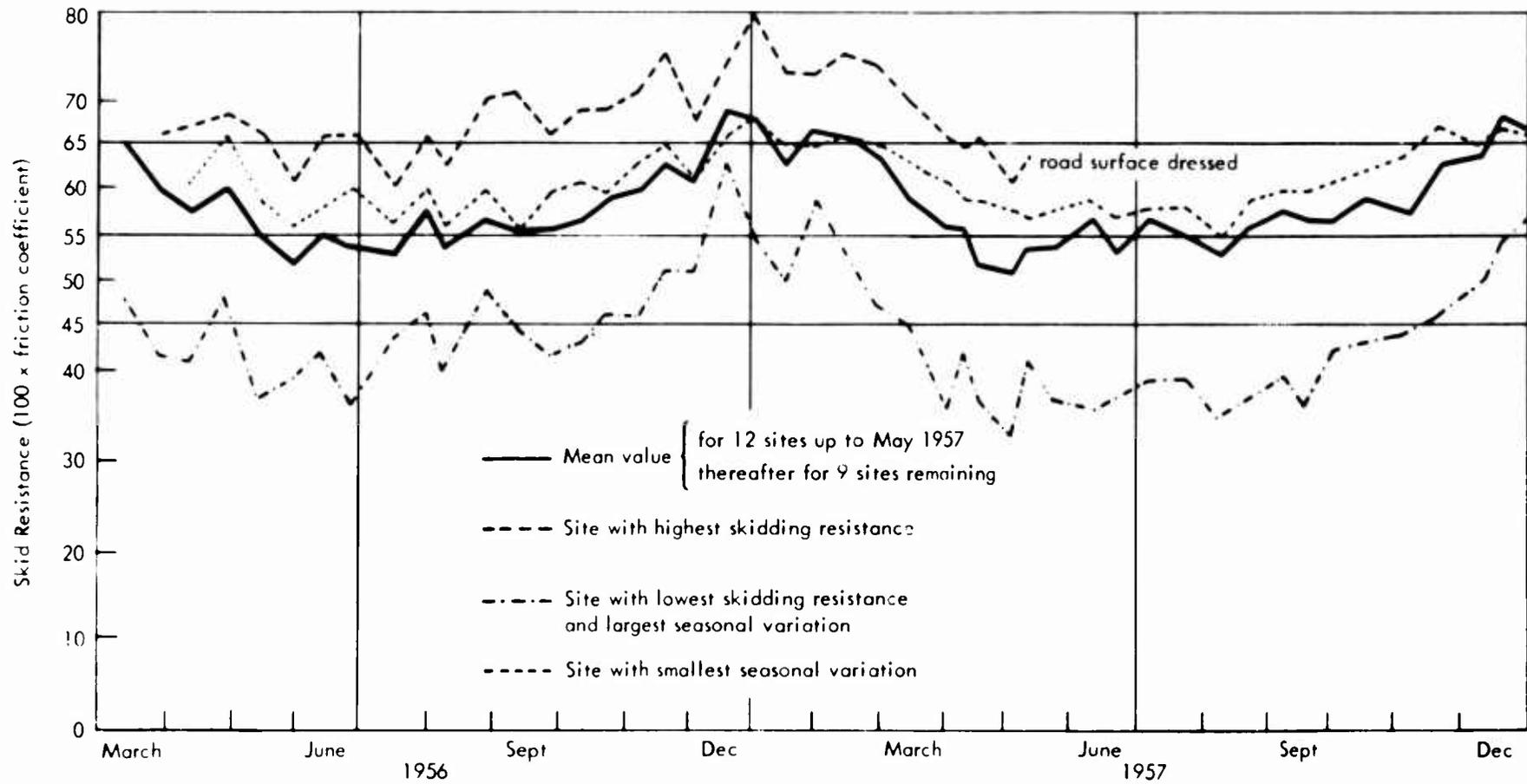


Figure 47. Seasonal variation in skidding resistance: Tests made at fortnightly intervals. (Giles and Sabey, 1959.)

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In locations with extreme climate, freezing and thawing, chemical treatments, and abrasives applied on pavement surfaces contributed to an increase in skid resistance during the winter. However, pavements with snow or ice, especially when covered with a thin film of water, gave extremely low friction coefficients. In these adverse winter conditions, the friction coefficients measured were not those between pavement surface and tires but those between wet snow or ice and tires.

Skid-Resistance Standard

Little information was found on a skid-resistance standard or an acceptable minimum friction coefficient for highway pavements. No such information was found for airfield pavements. Many investigators, realizing that numerous variables affected the friction coefficient, probably never attempted to draw a line between safe and unsafe friction values. Obviously, if such lines were drawn, pavement surfaces considered safe may become unsafe or vice versa, depending on the method of test or device used and on the conditions of the test.

Nicholas, Dillard, and Alwood (1956) reported that the state of Virginia used a rather broad band of the boundary between safe and unsafe friction coefficients. The limits of the band were governed to a certain extent by the cost of improving the pavement surfaces to a safe condition. A safe stopping distance of 133 feet from 40 mph, corresponding to a friction coefficient of 0.40, was selected as a starting point. Pavement surfaces which had stopping distances higher than 133 feet were regarded with suspicion. When the stopping distance increased to 143 feet or more, the pavements were resurfaced to improve the friction coefficient.

From investigations of accident sites and results of skid tests, Giles (1959) suggested different values of sideways-force coefficients for three categories of road sites. Using the stopping-distance method at an initial speed of 30 mph on a wet surface, a minimum of 0.60 was suggested for the most difficult sites such as steep curves and grades. Above 0.50 was suggested for general requirements and above 0.40 for easy sites or mainly straight roads which were unlikely to create conditions of emergency.

Methods of Improving Friction Coefficient

Various methods have been tried to improve the friction coefficient between pavement surfaces and tires. The improvements in brakes, tire composition, and tread design, and the development of anti-skid devices all have contributed materially to increase the friction coefficient for vehicles and aircraft. These factors were previously discussed. Improvements have also been made in pavement surfaces. These improvements included resurfacing with special paving mixtures and treatment of existing surfaces by mechanical or chemical means.

The term deslicking used by highway engineers meant the application of surface treatments to increase the friction coefficient between pavement surfaces and tires. Obviously, surface treatments were desired which not only improved the skid resistance substantially, but also retained a high friction coefficient with age, traffic wear, and weathering. Experiments with deslicking mixes were conducted by many investigators such as Dillard and Alwood (1957), Marshall and Gartner (1962), Goodwin, Maney, and Womack (1962), Nagin, Nock, and Wittenwyler (1957), and Creamer and Brown (1957).

Fine-grained (sandy) type asphalt plant mixes using 3 types of crushed sandstones and an unwashed bank sand with 6- to 8-percent asphalt content, applied at the rate of 8 to 15 pounds per square yard, were experimented with by Dillard and Alwood (1957). The results of the tests on these deslicking mixes together with those of rock asphalt are shown in Table III, and indicate that all of the asphaltic treatments showed excellent skid resistance. There was relatively little change in the skid resistance in one year.

Table III. Skid Test Results on Deslicking Treatments at Age 1-3 Months and of One Year

Reprinted by permission of the Association of Asphalt Paving Technicians from Providing Skid-Resistant Roads in Virginia by J. H. Dillard and R. L. Akland, Proceedings of the Association, Volume 26, 1957.

Sand	Stopping Distance, (feet); at 40 mph; Pavement Wet	
	1-3 Months	1 Year
Rock Asphalt	90	94
A	85	91
B	91	87
C	89	92
D	96	95

Marshall and Gartner (1962) reported that Florida treated pavements with mineral seal and slurry seal. A durable mineral seal was obtained by using 0.12 to 0.18 gallon per square yard of cutback asphalt (Grade RC5) or asphalt cement (Penetration Grade 150-200), and 0.13 to 0.18 cubic feet per square yard of slag cover material having a uniform gradation from 1/2-inch to No. 16 sieve. Florida expected a friction coefficient in excess of 0.60 for several years on this surface even when subjected to moderately high traffic volumes.

Slurry seal mix was used in Florida on eight experimental sections having various surface and traffic conditions. The basic mix consisted of local sand, limestone or slag screenings, emulsified asphalt (SS-1), and portland cement mixed in a transit mixer with a sufficient amount of water to obtain a creamy consistency. This mixture was spread approximately 1/8-inch thick on the pavement surface by means of a spreader box. Slurry sealing with this mix design increased the friction coefficient from below 0.40 to over 0.60. After a year of service, little change in the results was reported. The mix containing slag screenings was reported to be showing the best performance.

Experiments with surface treatment made from thermosetting epoxy resins which were relatively new in the field of paving material were conducted by Goodwin, Maney, and Womack (1962), Nagin, Nock, and Wittenwyler (1957), Creamer and Brown (1957), and others. In applying this type of surface treatment, the following method was generally used: The basic epoxy binder was mixed with the catalyst. This mixture was applied to the cleaned pavement surface by squeegee, by broom, or by spraying equipment. Immediately afterward, aggregate was spread and rolled over the liquid mixture. After the coating hardened, the excess aggregate was removed by means of a mechanical sweeper.

The results of skid tests on an epoxy-resin coating given by Goodwin, Maney, and Womack (1962) are shown in Figure 48. It can be seen from Figure 48 that the coating lost some of its initial skid resistance after one year. However, the permanence of the deslicking operation was not determined since the pavement surface had not been subjected to sufficient aging and traffic.

Finney and Brown (1959) reported that Michigan installed a non-skid surface treatment using two types of binder materials with aluminum oxide grits. One binder was of the epoxy-resin type and the other was a compound of asphalt and latex. No results of this surface treatment were given, but Finney and Brown (1959) indicated that Michigan anticipated the future installation of more of these treatments.

Brickler (1959) reported on an experiment with a thin mortar topping made with portland cement and natural silica sand placed over a cleaned section of portland-cement-concrete pavement. The project was exploratory in nature and was conducted to determine the best conditions of construction and curing practices. No results of skid tests were given, but it was observed that portions of the treatment came off under traffic. A thin treatment of 1/8-inch thickness was observed to have adhered to the old pavement surface better than thicker layers.

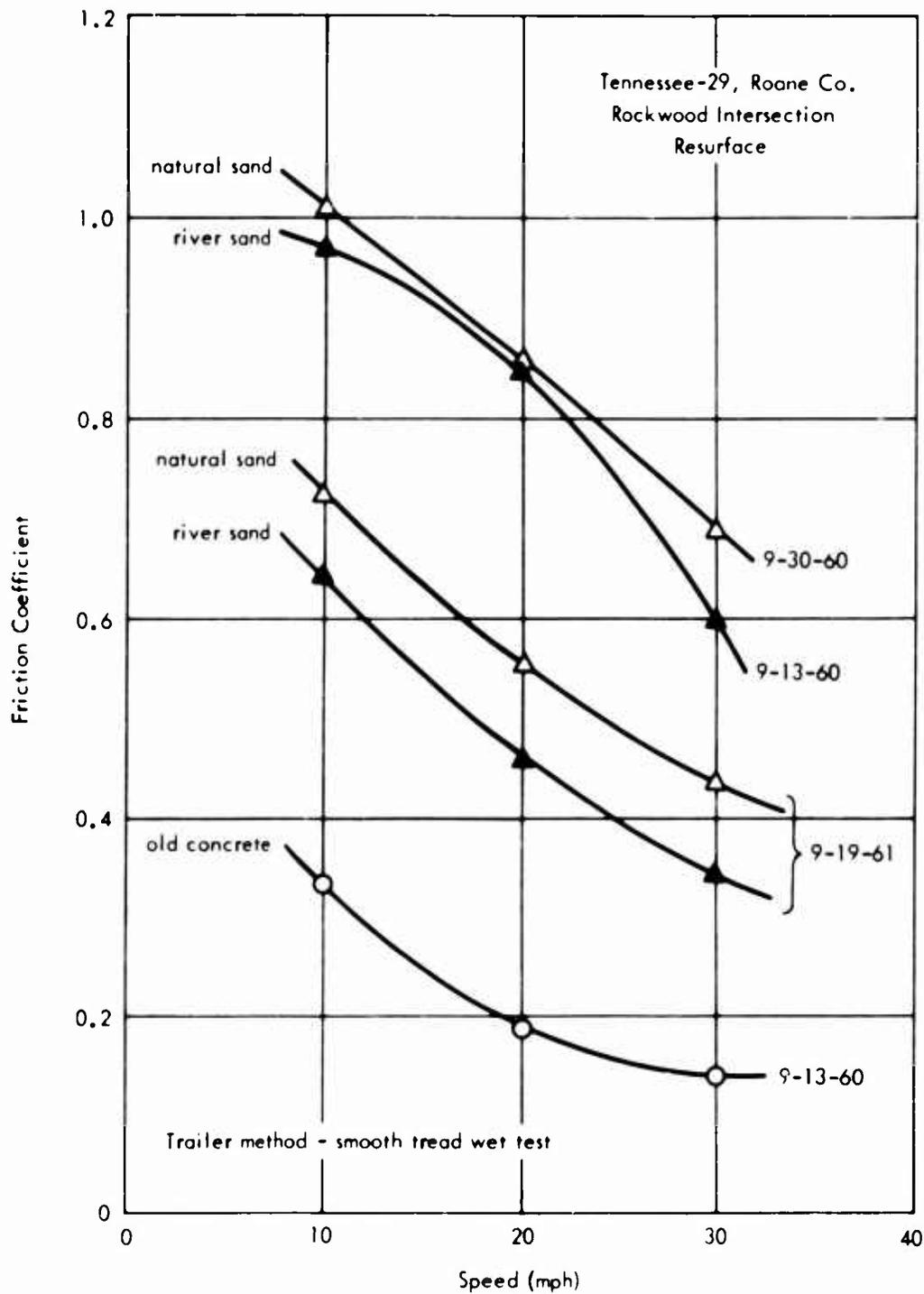


Figure 48. Skid-test results on the experimental surfaces compared with the original concrete surface.

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The Ministry of Aviation (1961) measured the friction coefficient between aircraft tires and brushed portland-cement-concrete pavement surfaces treated in the following manner:

1. Hydrochloric acid was spread over a section of the runway pavement at Coltishall, England, producing a uniform surface texture like that of fine sandpaper.
2. A bank of gas jets mounted on a trolley was moved slowly over a section of the runway surface in a direction normal to the runway axis. The resulting surface showed rusty-colored burn lines approximately 1/4-inch wide at 1/2-inch pitch. The burnt surface had a slightly rougher texture than the untreated surface.
3. A series of cutters mounted on a self-propelled trolley produced grooves normal to the runway axis about 1/4-inch wide and 1/8-inch deep at about 1-inch pitch.

It was concluded from the test results that the burning treatment gave no appreciable increase in friction coefficient. However, the acid-etching and mechanical grooving process gave an increase in friction coefficient of 10 to 15 percent over a speed range of 30 to 75 knots.

SUMMARY

A review of the problem of aircraft skidding on Naval airfields during landing and a comprehensive literature search of the work conducted on friction coefficient were made.

The review of the skidding problem at Navy airfields indicated that low braking force or low friction coefficient was not the sole cause of aircraft accidents during landings. Other factors such as pilot error, equipment malfunction, and adverse wind and weather conditions played important roles in causing accidents.

The literature search revealed that a great amount of work has been conducted on different phases of the subject of friction coefficient between rubber tires and pavement surfaces. The work included basic theoretical studies, development of friction measuring devices, and investigations to determine the factors which affected friction coefficient. In addition, work has been conducted to find means of restoring slick pavement surfaces to high friction levels.

Basic studies indicated that the total frictional force between rubber tires and pavement surfaces did not necessarily follow the basic laws of solid friction. The total frictional force involved, in addition to the basic frictional force, a mechanical force which results from interlocking of the tire tread with aggregate particles protruding from the pavement surface. The friction coefficients measured on dry pavements were generally high when a sufficient amount of protruding aggregates were present. Water on pavement surfaces acting as a lubricant, however, reduced the friction coefficient. At high speeds, when a sufficient amount of water was present to cover the protruding aggregates, tires were known to stop rotating and "plane" on the wet surface. In such instances, the friction coefficient was almost entirely lost.

It was found that the friction coefficient varied with the slip ratio. The maximum friction coefficient was obtained at the point of incipient skid, which occurred at relatively low slip ratios. Obviously, if brakes were applied and maintained at the incipient skid point, the vehicle had the highest deceleration and shortest stopping distance possible by braking. Sudden hard braking, however, caused vehicles to skid in irregular paths and, in some instances, to spin. Thus, reduction of skids by proper application of brakes helped in avoiding dangerous accidents.

Various field methods or devices have been developed and used to measure the friction coefficient between tires and pavement surfaces. Among the most popular were the stopping-distance and trailer methods. Other testing devices such as the Tapley decelerometer, the British portable tester, and the bicycle-wheel apparatus have been used by some investigators.

Except for one or two, the devices were primarily developed to measure the friction coefficient under simulated conditions of vehicle deceleration during braking. Only the FAA device, which is still in the development stage, showed any promise of simulating conditions of high velocities, high tire pressures, and heavy loads of landing aircraft.

Comparative tests made with the various devices showed, in general, that the measured friction coefficients differed substantially from each other. The qualitative differences in the results made it impossible to make measurements by the different devices which could be directly compared. However, satisfactory correlation of results between some devices were found by some investigators. No particular device was found to be the best for measuring friction coefficient. Each had its advantages and disadvantages.

Numerous factors affecting friction coefficients were found through investigations. From the standpoint of vehicle and aircraft operation, speed and braking techniques affected the friction coefficients. Average speeds on highways have increased in the past and are expected to increase to as high as 80 mph. Touchdown speeds of some landing aircraft were found to be as high as 185 mph. An increase in speed, in general, had little effect on the friction coefficients of dry pavement surfaces, but decreased the friction coefficients of wet surfaces. Results of tests made with an instrumented aircraft, however, revealed that the friction coefficients increased on wet surfaces with an increase in speed from 80 to 100 knots to higher speeds.

The brakes on vehicles have been designed to permit locking of the wheels. Unfortunately, the locked-wheel friction coefficient was found to be lower than the incipient-skid coefficient. Thus, judicious use rather than hard application of brakes was sometimes necessary to stop the vehicle within the required short distances. The locked-wheel condition was found to be more critical for landing aircraft than for vehicles on highways. Blowouts and quick disintegration of aircraft tires have been experienced after locked-wheel skids of very short duration. To aid pilots in avoiding the locked-wheel condition, skid-control systems have been developed. These systems permitted pilots to avoid the locked-wheel condition, and increased the friction coefficient between tires and pavement surfaces. Some experiments have been made with skid-control systems on highway vehicles with promising results.

The effects of tread design, tread composition, inflation, vertical load, and tire temperature on the friction coefficient have been investigated. Ribs or grooves and lateral edges made with molded slots and cut slits in tire treads were found to improve friction coefficients on wet pavement surfaces, but not on dry surfaces. Ribs, lug type elements, "tractionizing", lateral cuts, and incorporation of non-adhering material such as corn grits, nut shells, salt, and other materials in the treads of mud and snow tires also improved friction coefficients on winter surfaces. The improvement in the friction coefficient through tread design, however, was generally limited by the shear strength or tearing resistance of the rubber compound. Thus, for aircraft tires subjected to high speeds and loads, a minimum number of ribs and no slots, slits, or lateral edges were generally used. Tear-resistant tires during aircraft landings were of prime importance because of the quick disintegration of damaged tires.

Studies indicated that some tread compositions or rubber compounds gave higher friction coefficients than others, but the selection of tread composition was not merely based on friction coefficient. It was necessary to consider other essential service characteristics such as abrasion, weather and ozone resistance, hysteresis, heat buildup, cornering noise, steering ability, and resistance to groove cracking. Alterations in tread composition to improve one or more of the service characteristics adversely affected some of the others. Thus, the final selection of tread composition was a compromise to suit all of the essential service characteristics.

Some investigations showed that the inflation pressure, which was as high as 400 psi in some aircraft tires, had very little effect on the friction coefficient. In general, only a slight decrease in the friction coefficient was found with an increase in inflation pressure. On dry pavement, this trend was explained by the differences in temperature of the tire contact region.

Studies indicated that vertical load or wheel load, which was as high as 25,000 pounds per main wheel for some Naval aircraft, affected the friction coefficient. An increase in vertical load generally decreased the friction coefficient. It was explained that the decrease in friction coefficient was caused by the decrease in the tire contact area per unit load with an increase in load. This provided less opportunity for the tire to grip the road surface and decreased the friction coefficient.

The effect of tire-tread surface temperature on friction coefficient has been studied from the analytical as well as from the experimental approach. An analytical study indicated that the temperature was highest at a slip ratio of 1 for a given ratio of vertical load to tire width and increased with an increasing ratio of vertical load to tire width. Since an increase in temperature increased the melting of rubber which acted as a lubricant, it was reasonable that the friction coefficient was lowest at a slip ratio of 1 and increased with an increasing ratio of vertical load to tire width. Results of laboratory experiments showed that an increase in temperature decreased the friction coefficient.

Numerous factors related to pavements, especially to the surface of pavements, have been found to influence the friction coefficient. These factors were types of pavement, aggregates, surface textures, traffic, surface contamination, foreign material, temperature, weather, and climate. Most of these factors decreased the friction coefficient of pavement surfaces while some had beneficial effects.

The results of numerous skid tests on various pavement surfaces indicated that satisfactory friction coefficients were obtained on practically all of the different types of paved surfaces when dry. An exception was bleeding-asphalt surfaces. However, a considerable decrease in friction coefficients was measured on many paved surfaces when wet. On some surfaces the decrease was enough to consider the surfaces "slippery when wet". Since many factors affected the friction coefficient, no particular types of pavement, except for open-grid, steel bridge floors, were determined to be consistently in the "slippery when wet" category.

Field and laboratory studies have shown that many aspects of aggregates and surface textures influenced the friction coefficient. The size of aggregates was not necessarily a governing factor in providing a high friction coefficient. However, it was found that hard, angular aggregates used in paving mixes, provided higher friction coefficients than soft, rounded aggregates. A laboratory investigation indicated that an extremely dense gradation gave higher skid resistance than a very open gradation. The blending of hard or polish-resistant aggregates with soft polish-susceptible aggregates in asphalt paving mixes did not consistently provide a high friction coefficient. The polish-resistant aggregates were more effective in many instances when used in surface-treatment mixes over existing asphaltic-concrete surfaces. The blending technique tried with portland-cement concrete was more successful than with bituminous mixtures.

Results of skid tests on dry asphalt pavements showed that the friction coefficients were higher on dense-graded surface textures than on coarse open-graded surface textures. On wet asphalt surfaces, however, the reverse was generally true. These results were explained by the fact that, on dry pavement, the dense-graded surfaces provided more contact area than the coarse open-graded surfaces. The tires developed better adhesion and greater shearing forces on a high contact area than on a low contact area. On wet pavements, the open-graded surfaces provided channels or voids through which the water was able to escape. Thus, the friction coefficients on wet open-graded surfaces were higher than those on wet dense-graded surfaces. No such definite relationship was found on portland-cement-concrete surfaces, but coarse-grained burlap drag or broom finish gave higher wet friction coefficients than the slicker, more highly polished surfaces.

Although high friction coefficients were measured on practically all new pavement surfaces, traffic, surface contamination, and foreign material changed the friction values. Traffic caused wearing of the surfaces which contributed to a reduction in the friction coefficient. Traffic also caused an accumulation of oil drippings, grease, and rubber on

pavement surface, all of which lowered the friction coefficient. Mud, wet leaves, and other foreign material caused skidding hazards. However, paved shoulders adjacent to many of the highways have decreased the amount of foreign material. Rigorous cleaning efforts to eliminate damage to jet engines caused by foreign objects have also decreased the amount of foreign material on many airfield pavement surfaces.

In addition to tire temperature, ambient temperature and pavement temperature affected the friction coefficient. On dry as well as on wet surfaces, a decrease in the friction coefficient was found with an increase in the ambient temperature. The decrease was greater on dry surfaces than on wet surfaces. Changes in friction coefficients were found with changes in pavement temperature, but the relationship was not definite.

Surface textures of asphalt pavements in some locations were improved by the weathering effects which counteracted the wearing by traffic and improved the friction coefficient. The beneficial weathering effects were sunlight, rain, temperature changes, and freezing and thawing, all of which helped oxidation of the thin films of asphalt or tar on exposed aggregates.

In some locations, repeated tests on pavement surfaces on a seasonal and annual basis, indicated that the friction coefficient varied in a cyclic pattern. During the summer, the wearing by traffic and the accumulation of oil drippings and other contaminants decreased the friction coefficient. During winter, the trend was reversed because of the cleaning effect of winter rains. In locations with extreme climate, freezing and thawing, chemical treatments, and abrasives applied on pavement surfaces contributed to an increase in the friction coefficient during the winter. However, pavements with snow or ice, especially when covered with a thin film of water, had extremely low friction coefficients.

Little information was found in literature on a skid-resistance standard or an acceptable minimum friction coefficient for highway pavements. No such information was found for airfield pavements. The standards that have been established usually used a broad band of the boundary rather than a definite line between safe and unsafe friction coefficients.

Various methods of treating old pavement surfaces have been tried to improve the friction coefficient. These methods included resurfacing with a thin layer of deslicking mixes, and treatment of existing surfaces by mechanical or chemical means. Some of the resurfacing materials were reported to retain high friction coefficients up to a year after installation. However, the permanence of the treatments was not determined since the surfaces have not been subjected to sufficient aging and traffic.

The mechanical and chemical means investigated consisted of spreading hydrochloric acid, burning with a series of gas jets, or cutting a series of grooves in the portland-cement-concrete surfaces. The burning process gave no appreciable increase in friction coefficient. However, the acid-etching and grooving process improved the friction coefficient by 10 to 15 percent over the speed range of 30 to 75 knots.

RECOMMENDED FIELD-TESTING DEVICE

It appears from this study that a field-testing device which incorporates the following requirements, features, and simulated conditions of landing Naval aircraft during braking will give realistic readings of friction coefficient:

1. Measure the friction coefficient continuously or at short intervals between the pavement surface and single aircraft tire from a slip ratio of 0 to nearly 1, at speeds up to 115 mph, with vertical or wheel loads up to 25,000 pounds and tire pressures up to 400 psi.

2. Incorporate automatic features for pre-wetting the pavement surface, varying the vertical load, and varying the slip ratio.
3. Produce permanent and direct reading records of the friction coefficient, vertical load, slip ratio, and speed.
4. Be safe for any operators of the device when operating on dry as well as on wet pavement surfaces.

The brief specification of the above device is nearly the same as the one for the FAA device which is currently being developed. The differences are not very significant. Therefore, it is recommended that no effort be made at this time to develop another device which will be similar to the FAA device.

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