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Literature Survey of Tire-Road Experiments

by

James F. Sinnamon

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University of Michigan
Huron Parkway and Baxter Road
Ann Arbor, Michigan 48105

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16. Abstracts The literature survey is restricted to publications which report the results of tests performed with real tires on actual road surfaces. The objective of the survey was to identify and summarize a compact source of reference material believed to contain most of the current knowledge derived from on-the-road testing of automobile and aircraft tires. To this end, 38 references are individually summarized in a standard format outlining goal of tests, equipment used, road surfaces, tires tested, test procedure, techniques for analyzing and presenting data, and conclusions. A summary of the survey is presented.

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LITERATURE SURVEY
OF
TIRE-ROAD EXPERIMENTS

James F. Sinnamon

Project 329180

Tire Traction Characteristics
Affecting Vehicle Performance

Interim Document 1 (revised)

February 1974

Sponsored by
The Motor Vehicle Manufacturers Association

INTRODUCTION

A survey of the literature on tire-road experiments was undertaken as part of the HSRI research project, "Tire Traction Characteristics Affecting Vehicle Performance", sponsored by the Motor Vehicle Manufacturers Association. The tire properties which are of primary importance in determining vehicle performance are (1) those mechanical properties which affect the handling response of the tire-vehicle system, and (2) the maximum friction capability of the tire, especially on wet surfaces, usually called skid resistance. An exhaustive survey of the literature on these two areas of tire performance would be a monumental task. Therefore, it was decided to restrict the survey to those literature references which report the results of tests performed with real tires on actual road surfaces. In spite of this constraint, the significant literature within this subset of the total has not been exhausted. Herein, 38 references are summarized. It is believed that these references contain most of the current knowledge on the subject.

Each reference has been summarized using a standard format for quick and easy reference. This format divides each summary into the following categories:

GOAL OF TESTS

A brief description of the purpose and objectives of the experiments is given. A statement telling which tire performance parameters are investigated and which tire and surface variables (surface texture, water depth, tread depth, etc.) are dealt with is also made.

EQUIPMENT USED

A description of the test equipment and its capabilities is given.

ROAD SURFACES

The type of surfaces (concrete, asphalt, ice, etc.) upon which the tests are conducted is indicated, and when possible a description of the surface texture is given and water depth specified.

TIRES TESTED

A description of the tires tested, giving type of construction, size, tread pattern, rubber resilience and hardness, etc. is given.

TEST PROCEDURE

The important features of the test method are described and the range of test variables dealt with (such as speed, tire load, slip angle, etc.) is indicated.

TECHNIQUE FOR ANALYZING AND PRESENTING DATA

The methods used to process and present the experimental data are briefly described.

CONCLUSIONS

The conclusions drawn from the experimental data by the author of the reference are listed.

Thus the purpose and scope of the experiments and the main conclusions derived from them are contained in a concise summary only a few pages in length, so that, by reading this survey, one can obtain a fairly good understanding of what has been accomplished in the field of tire-road testing.

The references are ordered by last name of the author.

SUMMARY OF THE LITERATURE SURVEY

I TECHNIQUES OF MEASURING TIRE TRACTION PERFORMANCE

Several methods have been used to measure tire traction performance. One of the earliest and simplest of these is the locked wheel skid trailer, usually towed by a light truck. This method is most often used to monitor the skid resistance of public highways using a standard tire [4]*. However, more sophisticated trailers capable of measuring braking force over the entire range of wheel slip from free rolling to lockup have been used to study the effects of tire and road surface variables [14].

Only brief attention has been given to the literature reporting on the use of the locked wheel stopping distance method [28]. Traction data obtained by this method is of limited value because vehicle speed, which is one of the most important variables, is not held constant.

At the NASA Langley Research Center there is a facility called the Langley Landing Loads Track, consisting of a fixture, guided by rails, upon which a test tire is mounted. This fixture is catapulted at high speed over a section of specially constructed pavement on which water depth can be precisely controlled. A portion of this surface consists of a glass plate through which the tire contact patch can be photographed. This facility has been used primarily to study hydroplaning phenomena and wet traction performance of aircraft tires [17, 22, 23], although some experiments using automobile tires have been done [21].

A few experiments performed on the wetted internal drum tire testing machine at the University of Karlsruhe, Germany [1, 10] have been included in this survey. The internal drum has an advantage in that water depth can be closely controlled and

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* Numbers in square brackets refer to the list of literature references given at the end of this survey.

accurately measured. However, it is not feasible to simulate real road surface texture. Gengenbach [10] has done some interesting work on the effects of water depth and tread pattern variations using this machine.

Researchers at the Road Research Laboratory in England have gathered a large quantity of tire traction data using a front wheel braked automobile. In this method, the front brakes are gradually applied while vehicle speed and deceleration, and test wheel angular velocity are recorded. From this data, curves of braking force coefficient versus wheel slip can be derived.

Mobile tire testers of the type used by the Highway Safety Research Institute [6, 7, 32], the Road Research Laboratory [16], the Cornell Aeronautical Laboratory [8], and NASA [3] have been used primarily to investigate tire characteristics for application to vehicle dynamic simulation. Of particular importance is the capability of these machines to measure tire shear force generation characteristics under conditions of simultaneous braking and cornering. The use of these testers to measure the effects of longitudinal (brake) slip upon the cornering characteristics of tires has permitted significant advances in the art of vehicle dynamic simulation.

Three methods are commonly used to wet the road surface. Skid trailers are often towed by a truck carrying a water tank from which water is sprayed in front of the test wheel. This method has also been used with the mobile tire test machines. Water flow rate can be adjusted according to vehicle speed to provide a water film of consistent depth, and water depth is sometimes estimated by calculating the volume of water applied per unit area of road surface from known values of vehicle speed and water flow rate. Watering trucks are sometimes used to wet large areas of a test surface prior to testing, and replenishing the water film periodically as it evaporates. This method has the disadvantage that water depth varies with time.

At the Langley Landing Loads Track, water depth is maintained by dams along the edges of the test surface. This method is well suited to provide deep water covers for the study of hydroplaning phenomena.

Sprinkler systems, such as the one used at the Road Research Laboratory, have the advantage that water depth can be maintained at a fairly constant value for extended periods of time, although the effects of large variations in wind velocity must be accounted for. In locations where wind is a major problem, the test surface can be protected by wind screens. By regulating flow rate, average water depth can be varied and the values can be correlated with values measured during natural rainfall. In this manner, highly realistic test surface conditions can be provided.

Water depth has been measured by two basic methods. One method, already mentioned in connection with the watering truck, is to evaluate the quantity of water applied to a known area of surface to derive an average water film thickness. A closely related method is to measure the quantity of water drawn from a known area of surface by suction [14]. The other method is to measure the thickness of the water film above the surface asperities using either a stepped template, as is done by NASA, or an electrical probe attached to a micrometer dial, which is done at the Road Research Laboratory. This method tends to be useful only on relatively smooth textured surfaces because on coarse textured surfaces even high rates of water application may produce no standing water above the asperities.

With either method, there is difficulty in making a meaningful measurement because of the fact that test surfaces usually have irregularities which cause water depth to vary from point to point. There is still a need to agree upon a standard and meaningful method of quantifying surface contamination.

The references in this survey report on three methods of quantifying surface texture. One method gives the average texture depth which is determined by measuring the area of surface required to absorb a known quantity of sand or grease [23, 30]. Another method gives the mean void width determined from stereo photographs of the surface [31]. A third method uses stereo photographs to determine a profile ratio, defined as the ratio of the length of surface profile to the length of a baseline [30]. All three of these methods yield a statistically significant correlation between the surface texture measurement and the rate at which braking force coefficient decreases with increasing speed. The profile ratio numeric yields the best correlation probably because it is somewhat sensitive to the sharpness of the asperities as well as to texture depth. All of these correlations show a large amount of scatter; indicating that these methods do not account for all features of surface texture that affect wet friction. Furthermore, these measures of texture deal only with macrotexture while microtexture is known to have a strong influence upon the level of friction provided by a surface. There is a great deal of work yet to be done on the problem of defining and quantifying road surface texture so that tire/road frictional performance can be predicted.

II SUMMARY OF CONCLUSIONS CONCERNING TIRE/ROAD FRICTIONAL PHENOMENA (from references in this survey)

TREAD PATTERN. A tread pattern improves wet traction on surfaces having a smooth macrotexture, but has little or no effect on rough surfaces on which the asperities provide sufficient drainage [11, 20]. In fact, on very rough surfaces, a smooth tread tire is often somewhat superior [20]. However, at high speeds (80 mph or higher), coarse surface texture as well as tread pattern is essential [34].

The ratio (perimeter of contact area)/$\sqrt{\text{contact area}}$ has been shown to correlate with tread pattern effectiveness [12].

Transverse or lateral grooves in the shoulder region appear to be highly effective [18, 2].

For a given speed, groove depth, and water depth, there is a value for the ratio of groove area to total contact area above which no further improvement in wet traction is obtained. This value increases with increasing water depth [10].

Increasing the number of ribs while keeping the ratio of rib width to groove width and the product, number of ribs × rib width, constant improves wet traction up to certain point above which no further improvement is obtained [25].

For a given rib width, groove depth, water depth, and number of ribs, there is a groove width above which no further improvement in wet braking friction is obtained [25].

The effectiveness of sipes or knife-cuts has been a matter of some dispute [29]. However, most investigators have found that sipes improve wet traction on smooth, polished surfaces [33, 21, 24].

On dry surfaces, smooth tread tires provide somewhat better longitudinal traction than patterned tire treads [9]. Also on dry surfaces, maximum cornering force is very sensitive to small amounts of wear in the shoulder region for tires that are produced with a sharp corner at the shoulder. Maximum cornering force increases as the shoulder becomes rounded [32].

Cornering stiffness increases as the tread wears [19]. Braking stiffness (the initial slope of the braking force vs. wheel slip curve) is very sensitive to tread wear, and increases with decreasing tread depth [15].

Studded Tires give a large improvement in traction on smooth ice [2, 38]. The amount of improvement depends strongly upon the number of studs and the number of rows of studs.

TREAD COMPOUND. Rubbers having high hysteresis (low resilience) provide superior wet traction. However, there is confusion as to the interaction between rubber resilience and surface texture. Some investigators report improvement on surfaces of all textures [24], others find improvement only on surfaces having rough macrotexture, and still others find improvement only on surfaces having a harsh microtexture [33].

Increasing rubber hardness improves wet traction up to a point; above which no further improvement is obtained [12]. In the range of hardnesses practical in production tires there is little effect.

TIRE CONSTRUCTION. When compared to a bias ply tire of the same size, rubber compound, and tread pattern, the radial ply tire gives somewhat higher values of peak braking force coefficient, but no difference in locked wheel coefficient [27] (the differences are small). However, compared to a typical production bias ply tire, much larger differences are observed [26] because radial construction allows greater freedom in tread pattern design and tread rubber compounding.

Radial ply tires have higher cornering stiffness than do bias ply tires [19].

TIRE LOAD AND INFLATION PRESSURE. An increase in load usually causes a decrease in both braking and cornering traction on both wet and dry surfaces [7, 28].

An increase in inflation pressure causes a decrease in dry friction and a decrease in wet braking friction at speeds below the hydroplaning speed [4, 36]. But in deep water at high speeds, traction is improved when inflation pressure is increased because the hydroplaning speed is raised.

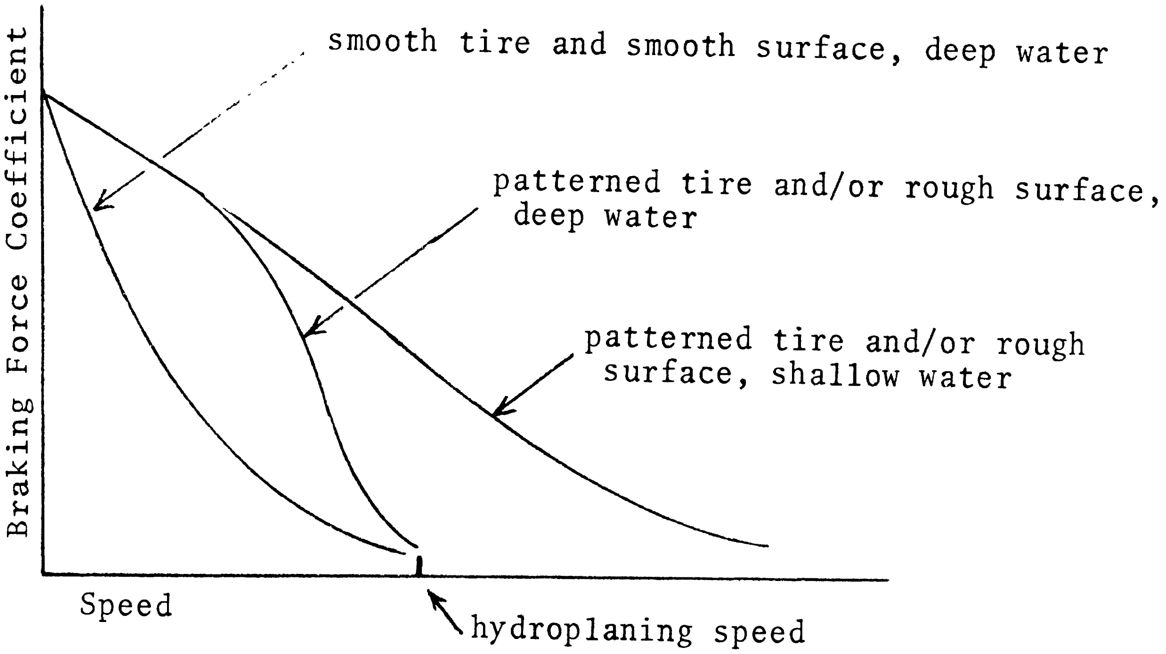
With respect to tire/road friction, changes in load and inflation pressure in the range that can be used in automobile tires have a relatively small effect, but these variables are very important for aircraft tires which may be operated over a greater range of loads and inflation pressures.

An increase of inflation pressure causes an increase in cornering stiffness.

WATER DEPTH AND TIRE SPEED. Even a very small amount of water, enough to make the surface "just damp", can cause a large decrease in friction coefficient, especially on surfaces having a polished microtexture [23].

An increase in water depth causes a decrease of wet friction. The effect is greatest at high speed on smooth surfaces. Most of the decrease occurs in the first 3-4 mm of water depth. At greater depths, for most tires, the tread grooves become flooded and no further effect of increasing depth is seen [35].

In deep water (more than 3-4 mm), tread pattern and surface texture have a large effect only at speeds below the hydroplaning speed; but in shallow water tread pattern and surface texture continue to have an effect at higher speeds [35].



Both peak and locked wheel braking force coefficients decrease with increasing speed on wet surfaces. However, the locked wheel value usually decreases more rapidly than does the peak value. This effect is most marked on smooth textured surfaces, so that smooth surfaces tend to show a greater difference between peak and locked wheel values [13].

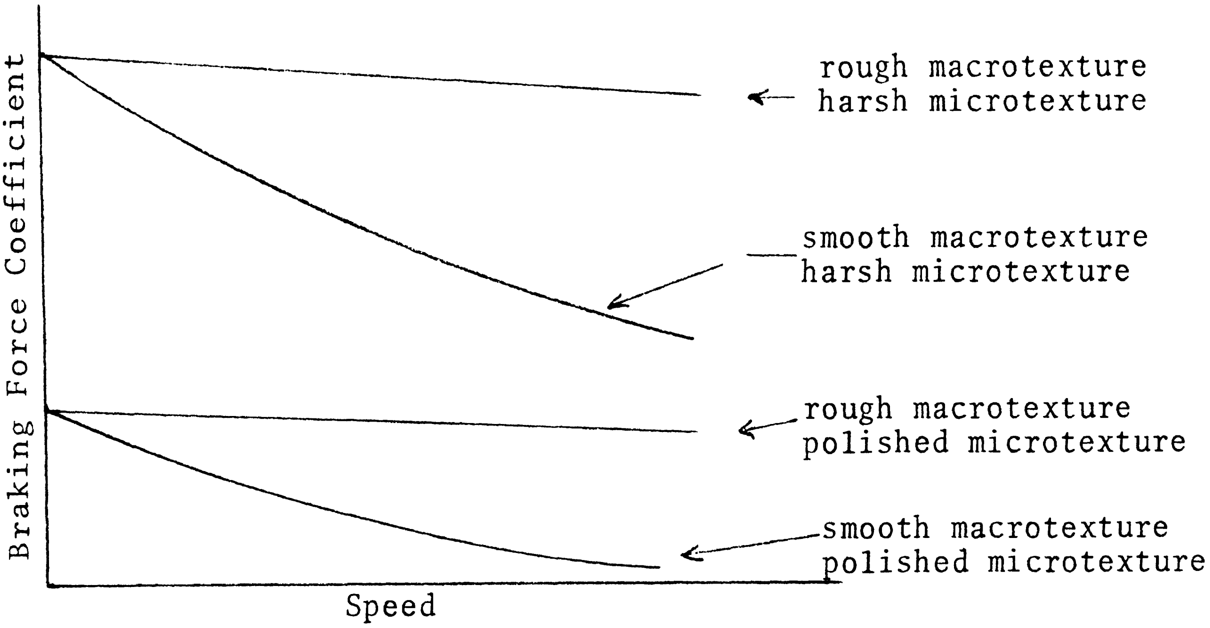
On dry surfaces, locked wheel braking force decreases with speed for low speeds, reaches a minimum, then increases with increasing speed [6, 11, 28].

ROAD SURFACE TEXTURE. Many of the effects of surface texture, as they interact with tread pattern, rubber compound, and water depth have already been indicated in this summary, but a few more points should be made.

Macrotexture (large scale roughness of the type that can be detected visually) has the primary function of providing drainage channels for water trapped between the tire and road. Surfaces having rough macrotexture show a less rapid decrease of friction with increasing speed than do surfaces having smooth macrotexture [30].

Microtexture (small scale surface roughness on the order of .05 mm) has the function of preventing the formation of a thin, viscous, lubricating film of water between the tire and road. A harsh microtexture provides a high level of friction, but a surface having a smooth, polished microtexture will give poor friction even at low speeds [23].

Studies on the variation of wet friction with texture depth indicate that for a given tire tread and water depth there is a value of average texture depth above which no further improvement friction is obtained [23].



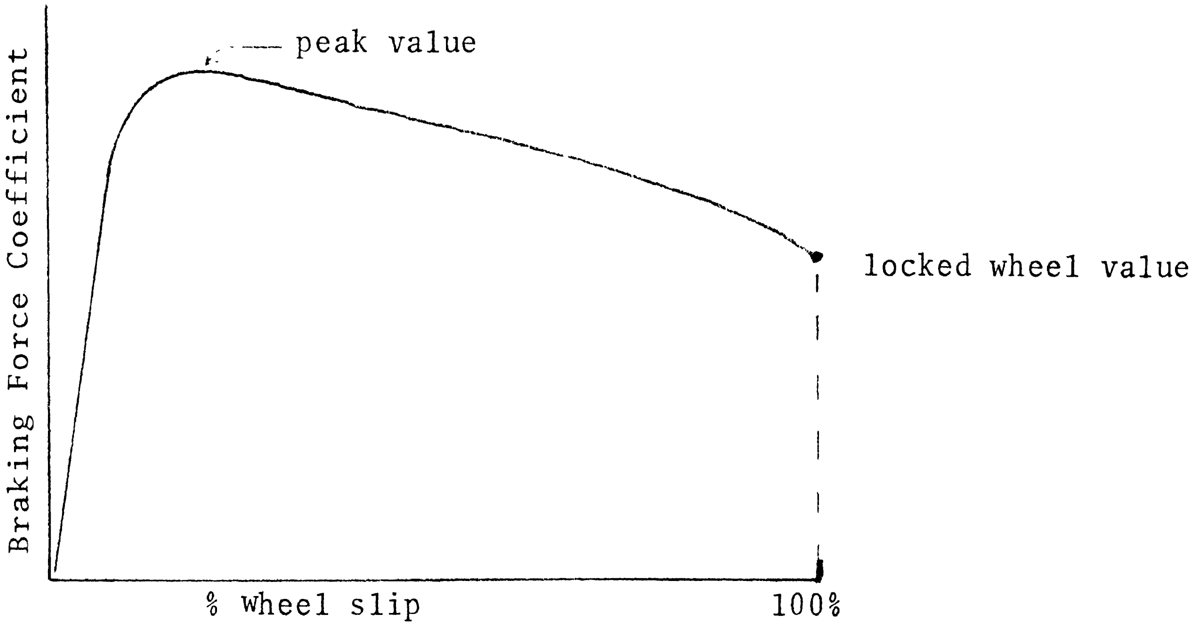
HYDROPLANING. If water depth is sufficiently large, hydroplaning will occur at the speed given by the following equation derived by Horne

$$V_p = K\sqrt{P}$$

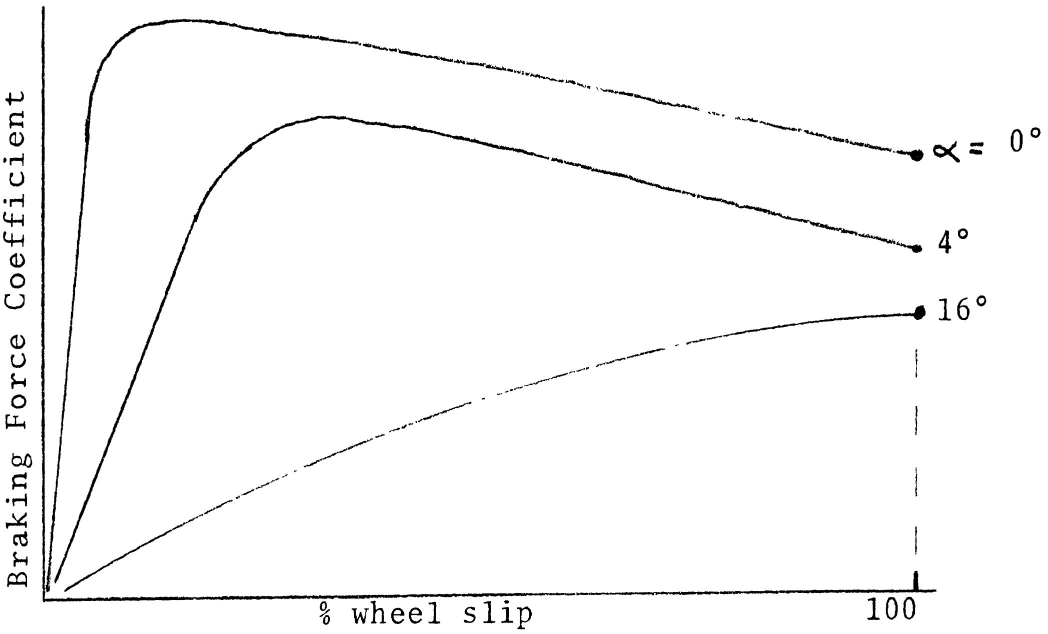
where the value of the constant, K, depends upon the units of the hydroplaning velocity, V_p, and the tire inflation pressure, P [21].

At lower water depths, tread pattern and surface texture become important variables. The water depth at which the above equation becomes valid depends upon tread pattern and surface texture [36].

COMBINED BRAKING AND CORNERING. In pure braking, a curve of braking force coefficient versus wheel slip shows a rapid initial rise to a peak between 7% and 25% slip, followed by a gradual decrease as wheel slip increases toward lockup [15].



The effect of a slip angle upon the BFC versus wheel slip curve is to decrease the initial slope, shift the peak to a higher value of slip, and to decrease the maximum available braking force. At large slip angles, maximum braking force is obtained at lockup. Also cornering force obtained at a given slip angle is reduced when a braking force is applied [6, 16].



Considerable progress has been made in the field of tire traction research which has led to significant improvements in tire and road performance. However, it is still not possible to predict the traction performance of a tire-road system based on the many tire and surface variables. Indeed, there is, as yet, no agreement as to how to quantify many of these variables in a meaningful way. It is clear that there is a great deal of definitive work yet to be done in this field.

LITERATURE REFERENCES

Reference #1

W. Bergman, H.R. Clemett, and N.J. Sheth

"Tire Traction Measurement on the Road and in the Laboratory"

SAE Paper No. 710630

Goal of Tests

To measure wet coefficient of friction for cornering, braking, driving, and combinations of these for several tires on both test drum and road surfaces; and to correlate the test drum and road surface results to show that traction performance on the road can be predicted from lab measurements.

Equipment

The lab measurements were done on the 12.5-foot diameter internal drum machine at the University of Karlsruhe, Germany.

The road tests were done with an automobile instrumented to measure speed, lateral and longitudinal acceleration, and drive-shaft torque.

Road Surfaces

The test drum had a 3M 80 grit abrasive surface. A water depth of .2 mm above the asperities was used.

Two road surfaces were used:

(1) Asphalt with smooth macrotexture but harsh microtexture - similar to the drum surface. This surface was wetted by a watering truck.

(2) Troweled concrete similar in texture to (1); watered by a sprinkler system. It had an ASTM skid number of 30.

Tires Tested

205 HR-15	radial ply
H78-15	bias belted
8.55-15	bias ply
215 R-15	radial ply
8.45-15	SAE traction tire
H78-15	bias belted

All were regular production, commercially available tires.

Test Procedure

(a) Laboratory tests:

Tests were conducted in the following operating modes:

1. Cornering at zero camber without power application.
2. Cornering at 4° camber with power application.
3. Cornering at zero camber with power application.
4. Straight-ahead braking.
5. Power application at zero slip angle.

All tests were done at 30 mph, except braking at 30 and 60, and at a load of 1000 lbs.

Lateral and longitudinal forces were recorded while slip angle or torque was increased gradually until peak force was reached.

(b) Road tests:

Road tests were conducted in the following operating modes:

1. Cornering without power application - with test tires mounted on the front wheels of an instrumented test car, steer angle was gradually increased until front end breakaway was detected. These tests were done at 30 mph.
2. Cornering with power application - with test tires mounted on the rear wheels, lateral acceleration and driveshaft torque were measured while steer angle was gradually increased until rear wheel breakaway was obtained for full throttle acceleration at 30 mph.
3. Straight-ahead braking - peak deceleration of a front wheel braked car was measured at 30 and 60 mph.
4. Straight-ahead driving - driveshaft torque and drawbar force was measured while pulling a dynamometer at 2.5 mph. Engine throttle was increased until 150% slip was obtained.

Two samples of each tire type were given 4-6 test runs in each mode on each surface and on the test drum.

Technique for Analyzing and Presenting Data

Regression analysis was used to fit ellipse equations to the data for peak coefficient of friction in cornering, braking, driving, and combinations of cornering and braking. Statistical methods and normalization techniques were then used to evaluate the degree of correlation between laboratory and road test data. The data is presented mostly in tabular form; correlation plots of lab traction coefficients versus road traction coefficients are also presented.

Conclusions

(1) A good fit to measured values of peak coefficient of friction in cornering, braking, driving, and combinations of these can be obtained using the ellipse equation.

(2) Correlation between laboratory and road test data was sufficiently high to permit road performance on these two surfaces to be predicted from test drum data. (An overall coefficient of correlation of .96 was obtained.)

Reference #2

K. D. Bird and F. R. Haselton

"Evaluation of Studded Tire Performance"

C.A.L. Report No. 159, 1967

Goal

The literature on studded tire performance is analyzed and correlated. The data in the existing literature is presented and discussed and conclusions about stud performance are drawn.

Equipment

Three locked wheel skid trailers supplied by General Motors, Portland Cement Association, and the Tennessee Highway Research Group.

Automobiles were used for locked wheel stopping distance tests. Driving traction tests used a traction dynamometer.

Tires Tested

7.50 x 14 bias ply tires with snow tread. Both studded and non-studded tires of the same tread compound and pattern were tested. The studded tires had from 48 - 260 studs.

Road Surface

Clear, smooth ice having various surface temperatures.

Test Procedure

Stopping distance tests were conducted by locking all four wheels at 20 mph. The skid trailers were used to measure locked wheel friction coefficient at 20 mph. Driving traction was evaluated by two methods: (1) pull force developed by an automobile towing a traction dynamometer was measured, and (2) acceleration from a rolling start at 10 mph was measured. Ice temperature varied between -5 and +32°F.

To evaluate the effect of studs on bare pavement performance, both skid trailer and stopping distance tests were performed on two bituminous surfaces under both wet and dry conditions.

Technique for Analyzing and Presenting Data

The effectiveness of studs was determined by subtracting the friction coefficient for the unstudded tire from that for the studded tire under the same test conditions. The result, called the "stud resistance coefficient," is plotted against such variables as ice temperature, number of studs, etc.

Conclusions

(1) Ice temperature is an important variable and must be accurately monitored in tire on ice friction tests.

(2) Locked wheel friction coefficient increases with decreasing ice temperature for both studded and non-studded tires.

(3) The "stud resistance coefficient" is a maximum (typically about .08-.10) at 32°F ice temperature and drops to a small value (usually less than .02) at temperatures below 0°F.

(4) When compared to a vehicle equipped with ordinary non-studded, non-snow tread tires, a vehicle equipped with four studded snow-tread tires will stop from 20 mph on 30°F ice in about a 30% shorter distance.

(5) The number of studs does not appear to be a significant variable, but stud resistance coefficient increases as the number of lines of studs increases.

(6) Due to experimental problems, the effectiveness of studs on packed snow has not been established.

(7) Studs have only a small detrimental effect on bare pavement friction. With 144 studs, stopping distances are increased by less than 5%.

(8) Studs are about as effective in traction as in braking.

(9) As of 1967 there was insufficient data to assess the effects of studs upon cornering traction. However, it is evident that little or no improvement will be obtained unless all four tires are studded.

Reference #3

T. A. Byrdsong

"Investigation of the Effect of Wheel Braking on Side-Force Capability of a Pneumatic Tire"

N.A.S.A. Technical Note, NASA TN D-4602, 1968.

Goal of Tests

To determine the effect of braking force on the cornering force generated by a tire at a constant slip angle. The effect of speed up to 30 mph was also investigated.

Equipment

A mobile tire tester. Vertical tire load and the horizontal forces parallel and perpendicular to the wheel plane were measured by a three-component strain gage load cell. Angular velocity of the tire was measured with a D.C. tachometer generator while a fifth wheel was used to measure speed.

Road Surfaces

All tests were performed on one concrete surface, both wet and dry. For the wet surface tests, a water depth of 1/2 inch was used.

Tires Tested

A smooth tread, bias ply automobile tire, size 7.75 x 14.

Test Procedure

Brake force, side force, wheel angular velocity and vehicle speed were recorded while brake force was slowly increased until lockup occurred.

All tests were done with inflation pressure at 30 psi and tire load at 1000 pounds.

Tests were done at 10, 20, and 30 mph. on wet and dry pavement for two values of slip angle , 4° and 8°.

Technique for Analyzing and Presenting Data

The measured values of brake force and side force were transformed to components parallel and perpendicular to the direction of travel, then plotted.

Results are presented as plots of brake force coefficient and cornering force coefficient versus longitudinal (brake) slip at constant slip angle. Also, plots of peak brake force coefficient and free rolling cornering force coefficient versus speed are presented.

Conclusions

(1) On the dry surface, more than 75% of the free-rolling value of cornering force is available when longitudinal (brake) slip is such that brake force is at its maximum (usually about 10-20%). On the wet surface, more than 50% of the free-rolling cornering force is available.

(2) For values of longitudinal slip greater than that at which peak brake force occurs, cornering force decreases rapidly to zero at lockup.

(3) For speeds in the range of 0-30 mph, speed has no significant effect on dry road friction; but on the wet surface, friction values were greatly decreased by increasing speed.

(4) For maximum control in maneuvers involving simultaneous braking and cornering, longitudinal slip should be controlled such that brake force is held at or near its peak value.

Reference #4

W. Close

"Locked-Wheel Friction Tests on Wet Pavements"

Highway Research Board, Bulletin 302, Skid Testing,
1961, p. 18.

Goal of Tests

To make extensive skid resistance measurements on U.S. public highways and to correlate the results with data on pavement composition, surface finish, age, and traffic density.

Equipment

A two-wheel skid trailer pulled by a watering truck.

Road Surfaces

More than 400 concrete and asphalt surfaces along 6500 miles of public highways were tested.

Tires Tested

The standard skid test tire used in the First International Skid Conference Correlation Study tests conducted in Virginia, 1958, was used for all the tests.

Test Procedure

Locked wheel brake force coefficient at 40 mph was measured at five-mile intervals along 6500 miles of public highways through 20 states. The surface was wetted by a watering truck.

Technique for Analyzing and Presenting Data

Wherever possible, data concerning surface composition, surface finish treatment, age, and traffic density was obtained for the tested surfaces. The data was grouped according to composition and finish, and for each group, friction coefficient is plotted versus a wear index defined as

$$\text{wear index} = \frac{A \times T \times L}{1000}$$

where

A = age in years

T = average daily traffic count

L = correction factor for lane distribution of traffic

Conclusions

(1) Locked wheel BFC drops rapidly due to road surface wear at first but levels off to a constant value.

(2) Of all the concrete surfaces tested, the belt finished surface with course grained large igneous aggregate and small natural sand aggregate had the highest friction in the fully worn state.

(3) On the average, the concrete surfaces tested in this study gave slightly higher initial values of friction coefficient and are less affected by wear than the asphalt surfaces.

Reference #5

H. C. A. van Eldik Thieme and H. B. Pacejka

"The Tire as a Vehicle Component"

Section 7.3.2 of Mechanics of Pneumatic Tires, edited by S. K. Clark, National Bureau of Standards, Washington, D.C., 1972.

Goal of Tests

The cornering force-slip angle characteristics of tires on a wet surface were investigated.

Equipment

An air spring tire test trailer equipped with two symmetrically inclined (yaw and camber) wheels, one of which is the test tire, was used. Slip angle can be varied continuously as the trailer is being towed while cornering force and aligning moments are measured. A sprinkler system was used to wet the surface.

Road Surfaces

The tests were done on a smooth, polished, wet asphalt surface. The drainage meter of Moore showed no drainage capacity, and the British Portable Skid Resistance Meter gave a value of 25.

Tires Tested

Two tires of size 5.60-13 were tested. Tire (a) - four circumferential grooves and no sipes on the center rib. Tire (b) - four circumferential grooves but the grooves were wider than on tire (a) and all ribs were siped. This tire had lower rubber resilience and higher rubber hardness than tire (a).

Test Procedure

Cornering force, aligning moment , and slip angle were recorded while slip angle was slowly varied from zero to 15°, then to -15°, then back to zero as the trailer was towed over the test surface at speeds up to 40 km/hr. The slip angle cycle time was about five seconds.

Tire load was 270-330 kg and inflation pressure was 1.7 kg/cm^2.

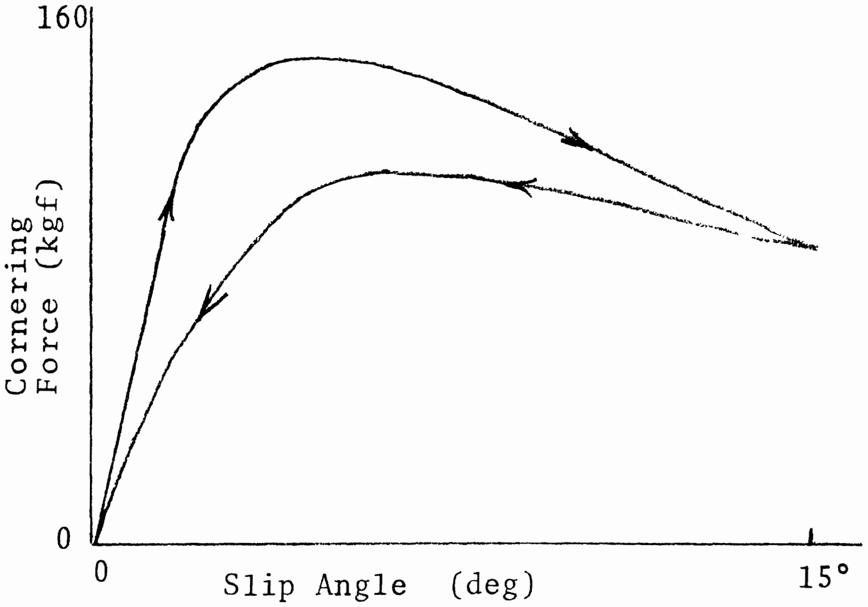
Technique for Analyzing and Presenting Data

The data was recorded on a U-V Brush recorder after being passed through a low pass filter. This data was hand plotted.

Plots of cornering force and aligning moment versus slip angle are presented.

Conclusions

On this slippery surface at 40 km/hr, it was observed that lateral force, F_y, after passing through its peak and dropping to its minimum value as slip angle increases, does not recover its peak value when slip angle is then decreased back to zero. This is illustrated below.



A similar loop is observed for aligning moment. This behavior was not observed at the lower speed of 30 km/hr.

Tire (b) was able to generate higher cornering forces than tire (a). This difference is attributed to the differences in tread pattern and rubber compound.

Reference #6

P. S. Fancher, Jr., H. Dugoff, K. C. Ludema, and L. Segel

"Experimental Studies of Tire Shear Force Mechanics"

Summary Final Report prepared by the Highway Safety Research Institute for the National Bureau of Standards under contract CST-928-5, 1970.

Goal of Tests

Tire shear force generation under conditions of combined braking and cornering was investigated on both wet and dry surfaces.

Equipment

The mobile tire tester of the Highway Safety Research Institute was used for these tests. This tester consists of a truck which carries a fixture upon which the test tire is mounted. This fixture contains a load cell and a tachometer to measure tire load, braking force, cornering force, aligning moment, and test wheel angular velocity. By means of a hydraulic transmission, the test wheel angular velocity can be continuously varied from free rolling to lockup.

The road surfaces were wetted from a water tank carried by the truck.

Road Surfaces

(1) Dry concrete

(2) Wet concrete

(3) Wet traffic paint - an asphalt surface painted to eliminate the microtexture, giving a low coefficient.

Tires Tested

(1) Firestone bias ply

(2) Goodyear Polyglass belted-bias

(3) Michelin steel belted radial

Test Procedure

The data was obtained by lowering the tire onto the road at a fixed slip angle and varying wheel rotational speed from free rolling to lockup while braking force, cornering force, test wheel angular velocity, and vehicle speed were recorded.

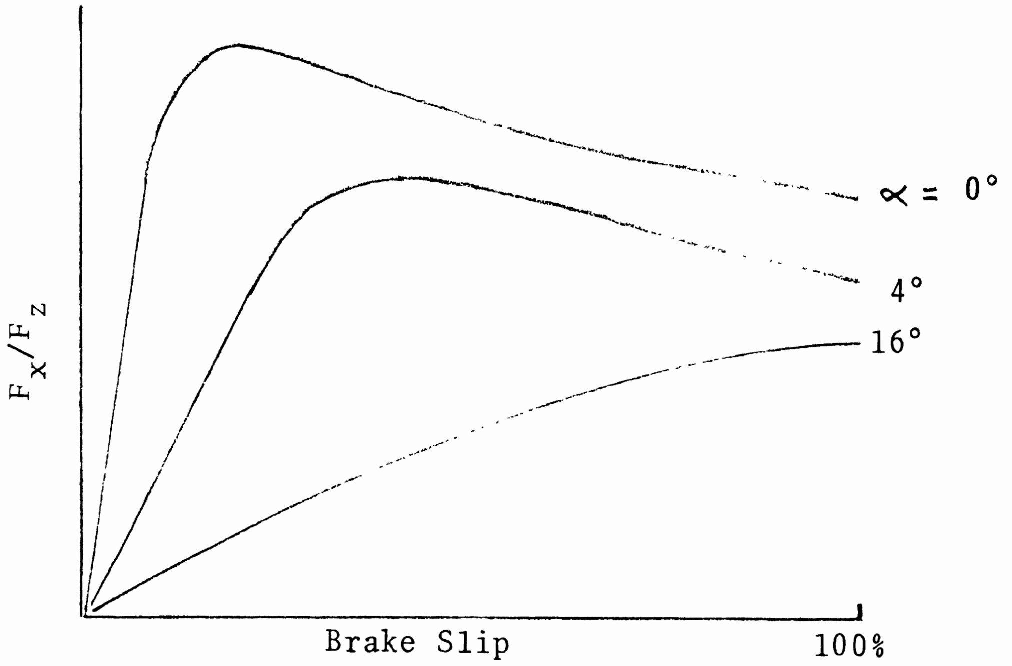
Data was taken at speeds of 20, 30, 40, and 50 mph. and at slip angles of 0, 1, 2, 4, 8, and 16 degrees. Tire load was 1000 pounds and inflation pressure was 24 psi for all tests.

Technique for Analyzing and Presenting Data

Force and slip values were obtained from traces of a recording galvanometer and the averages of five replications were plotted to obtain the force vs slip curves. The results are presented as plots of brake force coefficient and lateral force coefficient versus brake slip at constant slip angle with slip angle as a parameter.

Conclusions

(1) The effect of a slip angle upon the braking force coefficient versus longitudinal (brake) slip curve is to decrease the initial slope, shift the peak to a higher value of slip, and to decrease the maximum available braking force. At high slip angle, maximum braking force is obtained at lockup.



(2) At a constant slip angle, lateral force decreases as longitudinal slip is increased.

(3) The above conclusions hold for both wet and dry surfaces. However on wet surfaces the fall-off of braking force with increasing brake slip beyond the peak is more pronounced.

(4) For the radial and belted bias tires the effect of increasing speed was to reduce the level of forces without changing the shape of the force versus slip curves. But for the bias ply tire a higher locked wheel braking force was obtained at 50 mph than at 20 mph.

(5) The frictional characteristics of all three types of tires on wet surfaces are non-isotropic. Longitudinal and lateral coefficients of friction are different, and for a locked wheel the resultant shear force is not colinear with the direction of sliding.

(6) Cornering stiffness and braking stiffness are sufficient parameters to describe the shear force characteristics of a tire at low values of slip angle and brake slip, but at high values of slip, parameters describing the distribution of contact pressure in the contact patch are needed.

Reference #7

P. S. Fancher,Jr., and L. Segel

"Tire Traction Assessed by Shear Force and Vehicle Performance"

Tire Science and Technology, Vol. 1, No. 4, November 1973.

Goal of Tests

Maximum lateral force, peak and locked wheel braking force, and maximum resultant force (resultant of combined braking and cornering force) were measured for tires on wet surfaces. Tire traction ratings based on these quantities are compared with ratings derived from J-turn and diagonal braking performance of a vehicle equipped with the same tires. Also, the influence of surface, speed, and load was investigated.

Equipment

The mobile tire tester of the Highway Safety Research Institute was used to obtain the traction data.

Road Surfaces

Three surfaces at the Texas Transportation Institute were used: wet concrete, wet asphalt, and wet Jennite.

Tires Tested

A sample of ten commercially available tires; three bias ply size 8.25-14, three bias-belted size G78-14, three radial ply size 205R-14, and the SAE standard tire.

Test Procedure

Traction fields for the ten tires on each surface were obtained by recording braking force, lateral force, speed and test wheel angular velocity while longitudinal (brake) slip, was gradually increased from free rolling to lockup with slip angle constant. Slip angles of 0, 2, 4, 8, and 16 degrees, tire loads of 600, 1000, and 1400 pounds and speeds of 10, 30, and 50 mph were used.

Technique for Analyzing and Presentinting Data

From the data records, carpet plots of (1) braking force versus longitudinal slip and load, and (2) lateral force versus slip angle and load for each tire-surface combination were constructed. From these plots, three performance variables were derived (1) maximum lateral force, (2) maximum braking force, and (3) locked wheel braking force. A fourth performance variable, maximum resultant force, was obtained by evaluating the maximum resultant obtained when longitudinal slip was gradually increased while running at 8 degree slip angle. The ranking of these tires are tabulated. Rank correlations between the performance variables, and between the performance variables and the vehicle J-turn and stopping distance test results are presented.

Conclusions

(1) Maximum lateral force ranking and vehicle J-turn performance ranking correlate well enough to show that vehicle speed at breakaway in a J-turn maneuver can be predicted from maximum lateral force measurements.

(2) Rankings based on locked wheel braking force did not correlate well with vehicle stopping distance results because stopping distance is very sensitive to small changes in test conditions.

(3) The radial tires produced larger shear forces, on the average, than did the belted-bias tires, and the belted bias tires produced larger shear forces than did the bias ply tires.

(4) The traction performance of radial tires is less sensitive to tread wear than is the bias ply tire.

(5) An increase in speed from 10 to 50 mph causes a very large decrease in wet shear force capability on smooth surfaces.

(6) An increase in vertical load causes a decrease in shear force performance in most cases. However, changes in tire load normally encountered in practice have a smaller effect than a 20 mph change in speed.

Reference #8

A. G. Fonda

"Tire Tests and Interpretation of Experimental Data"

Proceedings of the Automobile Division of the Institute
of Mechanical Engineers, 1956-57.

Goal of Tests

Cornering force and aligning moment characteristics of a tire as related to slip angle, camber angle, inflation pressure, and tire size were investigated.

Equipment

The Airforce-Cornell mobile tire tester was used for these tests.

Tires Tested

Three smooth, round, treadless bias ply tires; sizes 5.00 x 16, 6.00 x 16, and 7.00 x 16.

Road Surface

The tests were performed on one dry road surface.

Test Procedure

Lateral force and aligning moment were measured for slip angles of -30 to +30 degrees, camber angles of -30 to +30 degrees, and for inflation pressures from 18 to 45 psi.

All tests were performed at a load of 925 pounds.

Technique for Analyzing and Presenting Data

Values of forces and moments were read from recording oscillograph records through an optical enlarger, sorted and listed by a computer, then plotted. The data is presented in the form of plots of:

(1) Cornering stiffness versus inflation pressure for each tire size.

(2) Lateral force versus camber angle at zero slip angle.

(3) Maximum available cornering force versus inflation pressure at zero camber.

(4) Maximum available cornering force versus camber angle.

(5) Pneumatic trail versus lateral force.

Conclusions

(1) Tire size had no effect upon cornering stiffness and its variation with inflation pressure.

(2) No definite trend was observed for cornering stiffness as affected by camber.

(3) Maximum available cornering force increases with increasing inflation pressure.

(4) Maximum available cornering force increases with positive camber and decreases with negative camber.

(5) Pneumatic trail decreases linearly with increasing lateral force for slip angles up to 10 degrees.

(6) Cornering stiffness increases with increasing inflation pressure.

Reference #9

B. Forster

"Tests to Determine the Adhesive Power of Passenger-Car Tires"

NACA Technical Memorandum 1416, 1956.

Goal of Tests

To determine cornering force-slip angle and braking force-longitudinal slip relationships for several tires on several road surfaces, both wet and dry, as affected by speed, load, inflation pressure, and tire size.

Equipment

A single wheel trailer was towed by a truck. The trailer was instrumented to measure brake force, cornering force, and test wheel rotational speed.

Tires Tested

A sample of 15 commercially available tires of various sizes and tread patterns were tested.

Road Surfaces

Eight different public road surfaces, some asphalt and some concrete, in the vicinity of Berlin, Germany were tested.

Test Procedure

Brake force-longitudinal slip data was taken for slip values from 0 - 100% (free rolling to lockup) and cornering force-slip angle data was taken at slip angles up to 30 degrees.

Speed:	6-73 km/hr
Load:	160-390 kg.
Inflation Pressure:	1.0, 1.5, 2.0, 2.5 atm.

Measurements were made on both dry and wet roads. The roads were not artificially wetted, but wet road data was taken on rainy days.

Some data on simultaneous braking and cornering was obtained by measuring cornering force at various slip angles with the brake applied such that the brake force coefficient was .37.

Conclusions

A. Braking Tests

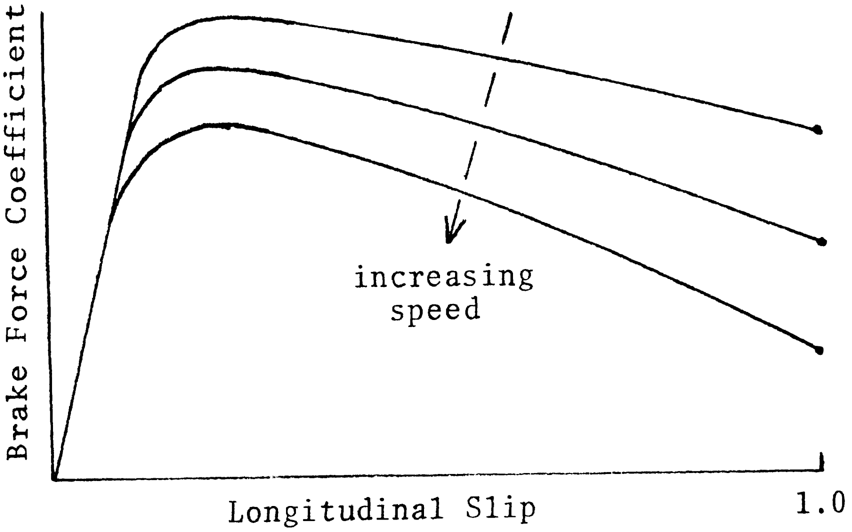
(1) The brake force versus longitudinal slip curve has a steep initial slope, a peak between 10 and 20% slip, followed by a gradual decrease as slip increases toward lockup.

(2) The initial slope of the brake force versus longitudinal slip curve is independent of speed. However, both peak and locked wheel brake force decrease with increasing speed, with locked wheel values more strongly affected than peak values.

(3) At very low speeds the peak and locked wheel brake force approach the same value.

(4) An increase in inflation pressure causes a decrease in both peak and locked wheel brake force.

(5) The conclusions stated above apply for both wet and dry surfaces, but peak and locked wheel friction values are lower on wet surfaces. Also, peak and locked wheel brake force decrease more rapidly with increasing speed on wet roads.



B. Cornering Tests

(1) The cornering force versus slip angle curve shows a steep initial slope, a peak value (usually at 10-20 degrees slip angle) usually followed by a gradual decrease at higher slip angles.

(2) Cornering stiffness (the initial slope of the cornering force versus slip angle curve) is independent of speed, load, and road surface; but increases with increasing inflation pressure and with increasing tire section width.

(3) Peak cornering force coefficient is nearly independent of load over the range considered.

(4) Peak cornering force decreases with increasing inflation pressure on both wet and dry surfaces.

(5) Peak cornering force decreases with increasing speed, and wet surfaces show a greater decrease than dry surfaces.

(6) The application of a brake force while cornering causes a decrease in the peak cornering force coefficient.

C. Effects of Tread Pattern and Road Surface

(1) On dry roads; tread pattern has only a small effect; with the smooth tread tire showing a slight superiority in both cornering and braking.

(2) On dry roads the surface texture has a significant effect. New surfaces have coefficients of .8-1.1, but a worn and polished surface may have only .6.

(3) On wet surfaces, tread pattern and surface texture are both significant, and these interact in a complex manner. On coarse textured surfaces, high friction is obtained even with smooth tread tires, but on smooth textured surfaces tread grooves are essential.

(4) On smooth, polished, surfaces, tires with transverse tread grooves show the best frictional performance.

Reference #10

W. Gengenbach

"Experimentelle Untersuchung von Reifen auf nasser Fahrbahn"
(Experimental investigation of Tires on Wet Tracks)

Automobiltechnische Zeitschrift, Vol. 70, 1968, pp. 310-316.

Goal of Tests

To investigate the influence of tread pattern design, tread groove depth, water depth, speed, inflation pressure, and camber angle upon the cornering and braking force capability of tires on wet surfaces.

Equipment

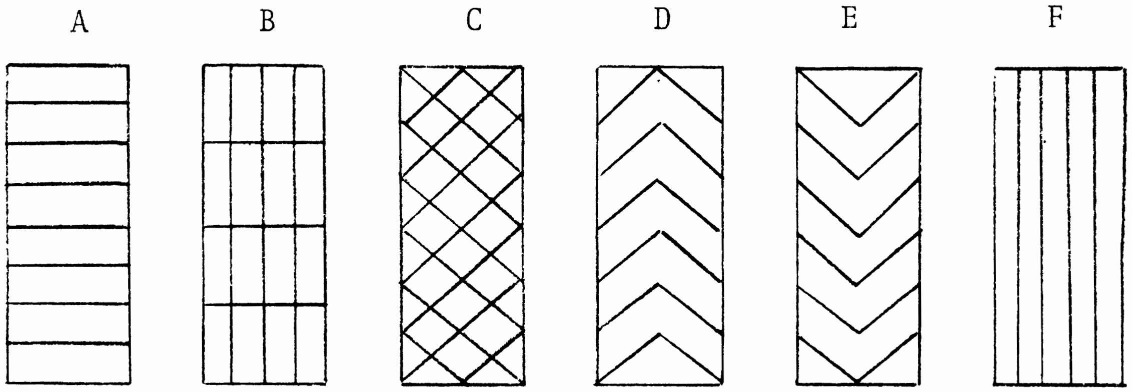
The tests were done on the internal drum tire test machine at Karlsruhe University, Germany. The drum is 12.5 feet in diameter. Water depth can be controlled to close tolerances.

Road Surface

An artificial abrasive surface was applied to the drum.

Tires Tested

Six different tread patterns were cut on 5.60 x 15 bias ply tires and on 155 x 15 radial ply tires. Groove width was 3 mm., groove depth was 7 mm. and the ratio of groove area to total contact patch area was .2 for all patterns. The tread patterns are shown below.



Two production tires, a 5.60 x 15 bias ply, and a 155 x 15 radial ply were also tested.

Test Procedure

The six tires with specially cut tread patterns were tested to determine maximum cornering friction for water depths of .2, 1.0, and 2.0 mm and speeds from 30 to 120 km/hr.

A study of the effects of varying the ratio of groove area to total contact patch area was done by varying groove width on the circumferentially grooved tire (F).

The 5.60 x 15 production bias ply tire was used to study the effects of camber angle and tread groove depth.

Tire load was 300 kg. for all tests and inflation pressure was 1.5 atm. for all tests except the inflation pressure variation study.

Method for Analyzing and Presenting Data

Graphs of maximum cornering force versus speed at various water depths are presented for each of the special tread patterns.

Graphs of maximum cornering and braking force versus inflation pressure, camber angle, tread depth, and the ratio of groove area to contact area at various speeds and water depths are presented for the two production tires.

Conclusions

(1) For a given speed, groove depth and water depth, there is a value for the ratio of groove area to total contact patch area above which no improvement in traction is obtained. This value increases with increasing water depth.

(2) Increasing inflation pressure at constant tire load improves braking and cornering traction.

(3) Camber angle has only a small effect upon wet surface friction.

(4) The six specially cut patterns vary greatly in maximum cornering force at high speeds. The transversely grooved pattern (A) appears to give superior results.

Reference #11

C. G. Giles and F. T. W. Lander

"The Skid-Resisting Properties of Wet Surfaces at High Speeds: Exploratory Measurements with a Small Braking Force Trailer"

Journal, Royal Aeronautical Society, Vol. 60, 1956, p. 83-94

Goal of Tests

The variation of locked wheel brake force coefficient with speed up to 100 mph. on several different runway surfaces was investigated.

Equipment

A single wheel skid trailer towed by a Jaguar sports car was used.

A watering truck was used to wet the surfaces.

Road Surfaces

Seven runway surfaces representing a wide variety of surface textures were tested: two bitumen macadam, one bitumen macadam with gravel aggregate, and four concrete. Photographs showing the surface textures are presented, but quantitative measures of texture were not performed.

Water depth was maintained at approximately .06 inch.

Tires Tested

Two 4.00 x 16, 6 ply aircraft tires made especially for this test; one smooth tread, and one having both circumferential and lateral grooves.

Test Procedure

For each tire-surface combination, three measurements of locked wheel BFC at 10 mph speed increments between 20 and 100mph (i.e. 10, 20, 30,---90, 100 mph) were made. Test wheel rotational speed and friction force were recorded while the test wheel was locked for 2-3 seconds. Also, one surface was tested in a dry condition at speeds between 55 and 100 mph.

For all tests, tire load was 317 pounds and inflation pressure was 20 psi.

Technique for Analyzing and Presenting Data

For each surface, a graph of locked wheel BFC versus speed for the smooth and grooved tires is presented.

Conclusions

(1) Locked wheel BFC decreases with increasing speed for all the wet surfaces tested, but those surfaces having a rough texture show the least decrease. On the roughest surface a coefficient of .4 was obtained at 100 mph even with the smooth tire.

(2) On smooth textured, wet surfaces a tread pattern improves friction significantly especially at high speeds, but has little affect on rough surfaces.

(3) On dry surfaces, locked wheel BFC decreases only slightly with increasing speed, but above 80 mph BFC increases with increasing speed.

Reference # 12

G. Grime and C.G. Giles

"The Skid Resisting Properties of Roads and Tires"

Proceeding of the Automobile Division, Institution of Mechanical Engineers, 1954-55, No. 1, p. 19.

Goal of Tests

To investigate the effects of road surface texture, tread pattern, and tread rubber hardness upon skid resistance on wet roads.

Equipment Used

An automobile, with a fifth wheel mounted within the wheelbase to run at a high slip angle (20°) while wheel load and cornering force are recorded, was used to measure side force coefficient.

An automobile instrumented to record deceleration was used to measure locked wheel brake force coefficient (BFC).

Road Surfaces

For the surface texture study, a large sample of public road surfaces in England having a wide variety of composition and texture were tested.

The tread pattern and rubber hardness tests were done on the specially constructed test surfaces at the Road Research Laboratory.

No quantitative measures of surface texture were made.

Tires Tested

The surface texture study was done using a smooth tread tire.

For the tread pattern study, one smooth tread tire, and ten tires having a variety of straight circumferential grooved, zig-zag circumferential grooved, and block-type tread patterns were tested.

For the rubber hardness tests a smooth tread tire and a zig-zag circumferential grooved tire, each with three values of rubber hardness (25, 60, and 75 on the Dunlop scale) were used.

Test Procedure

Data for the surface texture study was obtained by measuring side force coefficient at 30 mph.

Data for the tread pattern and rubber hardness studies was obtained by measuring locked wheel deceleration of an instrumented vehicle at 30 mph.

Technique for Analyzing and Presenting Data

Results of the tread pattern study were presented by plotting locked wheel BFC versus the parameter

$$(\text{perimeter of contact area})/(\sqrt{\text{contact area}}).$$

Conclusions

(1) Both rough macrotexture and harsh microtexture are necessary to insure high skid resistance.

(2) Two road surfaces, similar in macrotexture and made of the same aggregate and binder, can differ in friction by a factor of 9 due to wear, polishing, or contamination with oil.

(3) A tread pattern gives a significant increase in BFC on surfaces having a smooth macrotexture but makes little or no difference on rough surfaces.

(4) The effectiveness of a tread pattern tends to increase with an increase of the parameter

$$(\text{perimeter of contact area})/(\sqrt{\text{contact area}}).$$

(5) Locked wheel BFC tends to increase with increasing tread rubber hardness up to a certain point above which no further improvement is obtained.

(6) Neither tread pattern nor an increase in rubber hardness has any effect on polished surfaces which lack microtexture.

Reference #13

K. A. Grosch and G. Maycock

"Influence of Test Conditions on Wet Skid Resistance of Tire Tread Compounds"

Rubber Chemistry and Technology, Vol. 41, No. 2, March 1968, pp. 477-493.

Goal of Tests

The influence of rubber compound, surface texture, and speed upon peak and locked wheel braking force coefficient on wet surfaces was evaluated.

Equipment

A front wheel braked car was used for these tests. This vehicle was modified so that brake torque could be applied at a controlled rate only to the front wheels, on which the test tires are mounted. This vehicle was instrumented to measure vehicle speed and deceleration.

A sprinkler system was used to provide a consistent wet surface.

Road Surfaces

Four surfaces at the Road Research Laboratory test track were tested.

(1) Fine cold asphalt
(2) Polished concrete
(3) Rounded gravel macadam
(4) Quartzite macadam

For a description of the textures of these surfaces see reference #27.

Water depth was about .02 inches.

Tires Tested

Six tires all of the same size (6.40 x 15) and tread pattern (6 circumferential grooves and siped) were tested. Five were made with rubber compounds specially formulated to give a wide range of resilience but about the same hardness. The sixth tire was made with a compound commonly used for commercially available tires. Values of rubber hardness at 20° C. and resilience between 20°C and 100°C are tabulated for each compound.

Test Procedure

Vehicle speed and deceleration were recorded as the front brakes were gradually applied until lockup occurred. Tests were performed at speeds between 20 and 80 mph. Tire load was 800 pounds and inflation pressure was 24 psi for all tests.

Technique for Analyzing and Presenting Data

Values of peak and locked wheel BFC were computed from the vehicle deceleration records.

Graphs of peak and locked wheel BFC versus speed with rubber compound as a parameter are presented for each surface. Using the method of least squares, equations of the form $\mu - \bar{\mu} = b(V - \bar{V})$, where $\bar{\mu}$ and $\bar{V}$ are the mean BFC and speed, were fitted to the data. The values of $\bar{\mu}$, $\bar{V}$, and b are tabulated.

Conclusions

(1) Values for locked wheel BFC decrease more rapidly with speed than do peak values.

(2) Both peak and sliding BFC are most speed dependent on smooth surfaces.

(3) Smooth textured surfaces show a larger difference between peak and sliding BFC than do coarse textured surfaces.

(4) Increasing rubber hysteresis increases both peak and locked wheel BFC, but the effect is greater for peak BFC. This can be attributed to temperature rise, due to sliding friction, causing a decrease in rubber hysteresis.

Reference #14

J. L. Harned, L. E. Johnston, and G. Scharpf

"Measurement of Tire Brake Force Characteristics as Related to Wheel Slip (Antilock) Control System Design"

S.A.E. Paper No. 690214, 1969

Goal of Tests

The influence of (1) road surface, (2) speed, (3) water depth, (4) tread wear, (5) tread pattern, and (6) tire aspect ratio upon the braking force versus slip characteristics of tires is investigated. The results are discussed with reference to antilock brake systems.

Equipment

A single wheel friction trailer was used for these tests. Wheel slip was controlled by an anti-lock brake system modified to permit slip amplitudes of 100%.

The test surfaces were wetted with a sprinkler system.

Road Surfaces

Nine different asphalt and concrete surfaces representing a wide variety of textures were tested. Tests were also performed on smooth ice at the National Safety Council ice test facility at Stevens Point, Wisconsin.

Tires Tested

Identification	Construction	Tread Pattern	Size	Load Rating at 24 psi	Hardness, Durometer	Polymer Analysis* SBR, %	Polymer Analysis* PBD, %
1. 80 series bias American OEM	Diagonal crossed-ply	Highway type pattern with 5 ribs and multiple sipes	7.75-14	1270	57	55	45
2. 80 series snow American commercial	Diagonal crossed-ply	Open pattern with sipes	7.75-14	1270	57	55	45
3. 80 series radial American commercial	Belted and radial ply	Highway type pattern with 5 ribs and multiple sipes	195R-14	1270	60	50	50
4. 80 series 108 stud snow American commercial	Diagonal crossed-ply	Open pattern with sipes and 108 tungsten carbide studs	7.75-14	1270	57	55	45
5. 80 series fiberglas American experimental	Belted and diagonal crossed-ply	Highway type pattern with 7 ribs and multiple sipes	7.75-14	1270	61	100	0
6. 70 series fiberglas American experimental	Belted and diagonal crossed-ply	Highway type pattern with 7 ribs and multiple sipes	D70-14	1120	61	100	0
7. 80 series radial European commercial	Belted and radial ply	Highway type pattern with 7 ribs and maximum sipes	205R-14	1380	61	65	35
8. 80 series radial European commercial	Belted and radial ply	Open pattern with 4 ribs, multiple transverse grooves and sipes	7.50-14	1270	60	100	0
9. 80 series 200 stud snow European experimental	Belted and radial ply	Open pattern with sipes and 200 tungsten carbide studs	205R-14	1380	61	65	35
10. 80 series snow European commercial	Belted and radial ply	Open pattern with sipes	205R-14	1380	61	65	35

*SBR - Styrene Butadiene; PBD - Polybutadiene

Test Procedure

Braking force, wheel rotational speed, vehicle speed and acceleration were recorded on magnetic tape while several wheel slip cycles were executed as the trailer was towed over the test surface.

Speeds of 20, 40, and 60 mph were used, and each tire was run at its rated load at 24 psi. Every tire was broken in by 100 miles of normal driving before being tested.

Water depth was controlled by varying the flow rate from the sprinkler system, and measured by measuring the amount of water drawn off by suction from a known area of road surface.

Technique for Analyzing and Presenting Data

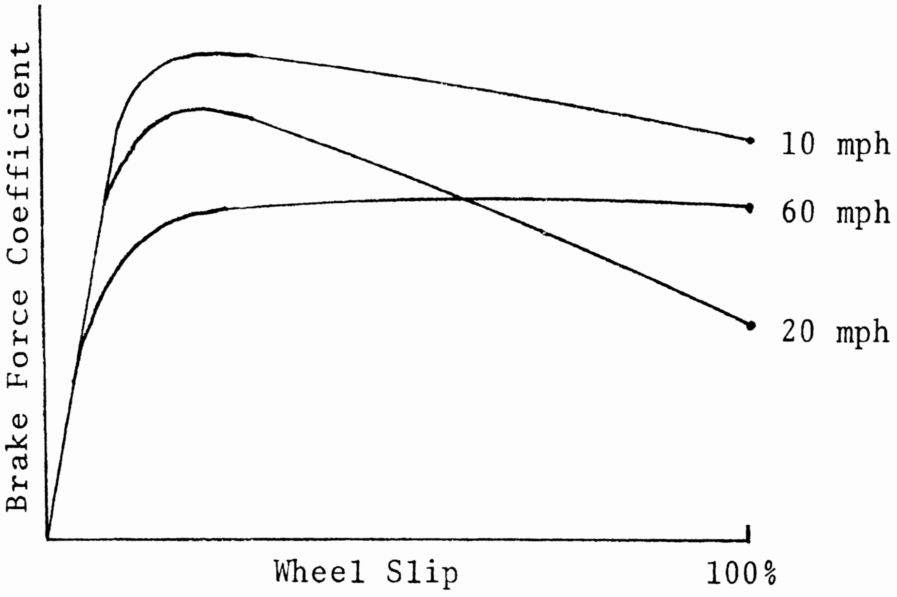
The data on magnetic tape was fed to an analog computer which filtered out noise due to road surface irregularities, computed values of brake force coefficient and wheel slip, and plotted the results on an X-Y plotter.

By superimposing the μ-slip curves obtained from several slip cycles on a given surface, the variability of surface friction was studied.

Results are presented in the form of plots of braking force coefficient versus wheel slip obtained by averaging the results of at least five slip cycles.

Conclusions

(1) On the dry asphalt and concrete surfaces locked wheel braking force coefficient first decreases with increasing speed, reaches a minimum at about 20 mph, then increases with increasing speed above 20 mph. However, the peak value continues to decrease for all speeds so that, at high speeds, maximum braking force may occur at lockup.



(2) On wet surfaces both peak and locked wheel brake force coefficients decrease with increasing speed at all speeds, and the rate of decrease is greater on wet surfaces than on dry surfaces.

(3) Variability of friction coefficient between different points on a dry surface is usually about .05. On wet surfaces, this variability is much larger (.1-.2) because of non-uniform water depth and it increases with increasing speed.

(4) On loose gravel roads, maximum braking force is obtained at lockup.

(5) An increase of water depth causes a decrease of both peak and locked wheel braking force, and the effect is greatest at high speeds. However at low water depths (.02 in or less) the peak value remains high even at high speeds.

(6) On smooth ice, studded tires give significantly higher coefficients than unstudded tires, and the unstudded snow tread tire is somewhat superior to the highway tread tire. Peak and locked wheel coefficients have approximately the same value and are independent of

speed; except the tire with a very large number of studs (tire No. 9) which gave higher peak than locked wheel values and gave higher coefficients at higher speeds.

(7) Wet traction decreases with increasing tread wear and the ratio of peak to locked wheel coefficients increases.

(8) Tire aspect ratio has no effect on locked wheel braking force on wet surface but does affect the peak value. At low speeds, the low aspect ratio tire gave higher peak values, but at high speeds the high aspect ratio tire was superior.

Reference #15

K. E. Holmes

"Braking Force/Braking Slip Measurements Over a Range of Conditions Between 0 and 100 per cent Slip"

Road Research Laboratory Report LR 292, 1970.

Goal of Tests

The braking force-braking slip relationship of tires on wet roads as affected by road surface texture, speed, tread rubber compound, tread pattern, and tire construction was investigated.

Some measurements for combined braking and cornering were also performed.

Equipment

The Road Research Laboratory mobile tire tester was used for these tests. This tester consists of a truck with the test tire mounted within its wheelbase. The test wheel fixture is instrumented to measure braking force, cornering force, aligning moment, tire load, and wheel rotational speed. By means of a hydrostatic transmission, test wheel angular velocity can be varied from free rolling to lockup while running at a constant slip angle.

A sprinkler system was used to provide a consistently wet surface.

Road Surfaces

The tests were done on five surfaces at the Road Research Laboratory test track. These surfaces provide a wide variety of textures.

	Macrotexture	Microtexture
(1) mastic asphalt	smooth	polished
(2) fine cold asphalt	smooth	harsh
(3) quartzite macadam	rough	harsh
(4) bridport macadam	rough	polished
(5) mixed aggregate macadam	rough	harsh

An equal volume of water was applied to all surfaces. Water depth was .5-.75 mm above the asperities on the smooth surfaces (1) and (2).

Tires Tested

Make	Tread Pattern	Construction	Size	Resilience*	Hardness≠
Dunlop	Smooth ≠	Crossed ply	5.00x16	55	63
Dunlop Gold Seal	Patterned	Crossed ply	5.25x16	51	58
Dunlop	Smooth ≠	Crossed ply	5.00x16	38	63
Dunlop Gold Seal	Patterned	Crossed ply	5.25x16	31	62
Dunlop C41	Patterned	Crossed ply	5.90x15	31	63
Pirelli Cinturato	Patterned	Textile banded radial ply	165x15	36	65
Dunlop SP41	Patterned	Textile banded radial ply	165x15	35	60
Michelin 'X Stop'	Patterned	Metal banded radial ply	165x15	39	60
Michelin 'X Rib'	Patterned	Metal banded radial ply	5.50x16	-	-
Michelin 'X Rib'	Worn ≠	Metal banded radial ply	5.50x16	-	-

Test Procedure

Braking force, tire load, test wheel angular velocity and vehicle speed were recorded while the test vehicle traversed a 30 foot section of each test surface at constant speed.

Speeds of 10, 20, and 30 mph were used. Tire load was 500 pounds and inflation pressure was 16 psi.

A series of braking tests were done at loads from 400 to 800 pounds to investigate the effect of tire load.

Technique for Analyzing and Presenting Data

The experimental data records and the calibration data were used as input to a computer which processed this data to compute values for braking force coefficients (BFC) and corresponding values of slip, and plotted BFC versus slip using a plotter.

Conclusions

(1) BFC rises rapidly with increasing slip to a peak between 7% and 25% slip, followed by a gradual decrease, then falls off rapidly between 80% and 100% slip to the locked wheel value.

(2) Smooth tires gave lower BFC values only on those surfaces having a smooth macrotexture.

(3) Lower resilience rubber gives higher peak and locked wheel BFC.

(4) BFC decreases with increasing speed, especially on smooth surfaces.

(5) In the speed range considered (10-30 mph) microtexture is more important than macrotexture.

(6) The worn tire, which has a very thin layer of rubber over the cords, shows a very high value of braking stiffness; 90% of its peak value of BFC is obtained at only 1% slip.

(7) The effect of a constant slip angle upon the BFC versus braking slip curve is to (1) decrease the initial slope, (2) reduce the peak value, and (3) to shift the peak to a higher value of brake slip.

(8) Tire load had no effect on braking force coefficient over the range covered.

Reference #16

K. E. Holmes and R. D. Stone

"Tire Forces as Functions of Cornering and Braking Slip on Wet Road Surfaces"

Road Research Laboratory Report LR 254, 1969.

Goal of Tests

To investigate:

(1) braking force as a function of longitudinal (braking) slip

(2) cornering force and aligning moment as a function of slip angle

(3) resultant shear force as a function of resultant slip for combined braking and cornering

as affected by speed, road surface, tire construction, tread, and rubber resilience on wet surfaces.

Equipment

The tests were done using a mobile tire tester consisting of a vehicle to which a fifth test wheel is mounted. The test wheel fixture is instrumented to measure braking force, cornering force, aligning moment, tire load, and test wheel rotational speed. By means of a hydrostatic transmission, test wheel angular velocity can be varied from free-rolling to lockup while running at a constant slip angle.

A sprinkler system was used to wet the road surfaces.

Road Surfaces

Tests were run on five surfaces at the Road Research Laboratory test track. These surfaces represent a wide variety of textures.

(1) mastic asphalt - smooth macrotexture, polished microtexture

(2) fine cold asphalt - smooth macrotexture, harsh microtexture

(3) quartzite macadam - rough macrotexture, harsh microtexture

(4) bridport macadam - rough macrotexture, polished microtexture

(5) mixed aggregate macadam - rough macrotexture, harsh microtexture.

Water depth was .02 - .03 inches.

Tires Tested

Make	Tread Pattern	Construction	Size	Resilience*	Hardness∠
Dunlop	Smooth ≠	Crossed ply	5.00x16	55	63
Dunlop Gold Seal	Patterned	Crossed ply	5.25x16	51	58
Dunlop	Smooth ≠	Crossed ply	5.00x16	38	63
Dunlop Gold Seal	Patterned	Crossed ply	5.25x16	31	62
Dunlop C41	Patterned	Crossed ply	5.90x15	31	63
Pirelli Cinturato	Patterned	Textile banded radial ply	165x15	36	65
Dunlop SP41	Patterned	Textile banded radial ply	165x15	35	60
Michelin 'X Stop'	Patterned	Metal banded radial ply	165x15	39	60
Michelin 'X Rib'	Patterned	Metal banded radial ply	5.50x16	–	–
Michelin 'X Rib'	Worn ≠	Metal banded radial ply	5.50x16	–	–

Test Procedure

Braking force, cornering force, aligning moment, test wheel angular velocity, and vehicle speed were recorded while the test vehicle traversed a 30 ft. section of each test surface at constant speed.

Speeds of 10 to 60 mph were used. Tire load was 500 pounds, and inflation pressure was 16 psi.

Technique for Analyzing and Presenting Data

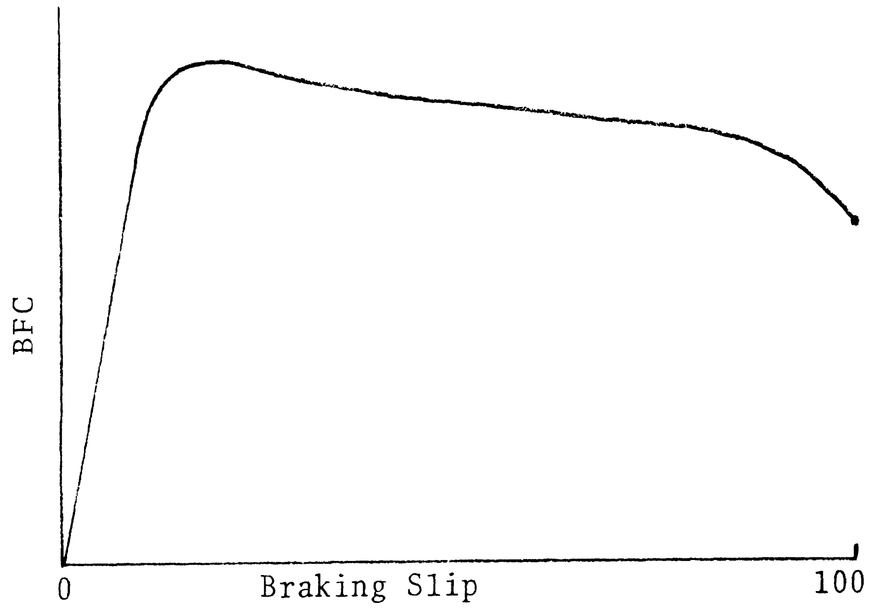
The experimental data records and the calibration data were used as input to a computer which processed this data to produce output in both tabular and graphical form in appropriate units. The computer was also used to perform a multiple regression analysis to evaluate the relative importance of test variables such as speed, rubber resilience, tread pattern, brake slip, and slip angle.

The data is presented in graphical form.

Conclusions

A. Pure braking

(1) A plot of braking force versus braking slip shows a rapid initial rise to a peak at 7-25% slip, followed by a gradual decrease, then a more rapid decrease between 80 and 100% slip. The initial slope seems to be independent of speed and surface.



(2) An increase in speed lowers the braking force versus slip curve generally, and locked wheel values drop more than peak values.

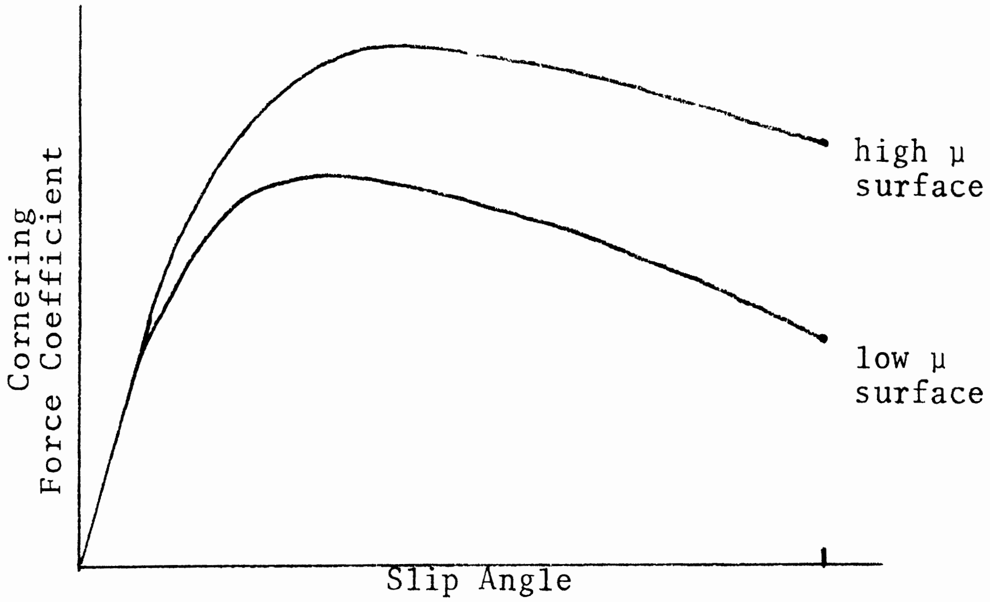
(3) The decrease of BFC with increasing speed is greatest on surfaces having a smooth macrotexture.

(4) Tread pattern improves BFC at high speeds especially on smooth surfaces

(5) Tires made of lower resilience rubber gave higher BFC at all speeds and on all surfaces, both harsh and polished.

B. Pure Cornering

(1) A plot of cornering force versus slip angle shows a linear initial rise followed by a peak at a value of slip angle that depends on the level reached, followed by a gradual decrease for higher values of slip angle. The initial slope is independent of speed and surface.



(2) The effects of speed, surface texture, rubber resilience, and tread pattern are similar to those stated for pure braking.

(3) A plot of aligning moment versus slip angle shows a rapid rise to a peak value followed by a rapid decrease to zero when cornering force reaches its peak value.

C. Combined Braking and Cornering

(1) A plot of cornering force versus slip angle at constant braking force has the same initial slope but a lower peak value when compared to the pure cornering case.

(2) A plot of cornering force versus slip angle at constant brake slip has a much lower initial slope and the peak occurs at a higher slip angle than in the pure cornering case.

(3) Curves of braking force versus brake slip at constant slip angle have a lower initial slope and a reduced peak value which occurs at higher slip compared to the pure braking case.

(4) The experimental data does not support the friction circle concept.

(5) Plots of resultant shear force versus resultant slip have a shape very similar to those of brake force versus brake slip.

Reference #17

W.B. Horne and T.J.W. Leland

"Influence of Tire Tread Patterns and Runway Surface Conditions on Braking Friction and Rolling Resistance of a Modern Aircraft Tire"

NASA Technical Note D-1376, 1962

Goal of Tests

Tests were performed to investigate braking friction and rolling resistance of aircraft tires as affected by the following factors:

(1) Tread pattern design and wear

(2) Surface texture

(3) Surface contamination (water, slush, jet fuel, and fire extinguishing foam)

(4) Tire load

(5) Inflation pressure

(6) Speed

Equipment

The experiments were done at the Langley Landing Loads Track. This test facility consists of a water jet catapult which accelerates a test carriage, upon which the test tire is mounted, over a test surface. The test carriage is instrumented to measure speed, brake force, tire load, and test wheel angular velocity.

Road Surfaces

Three surfaces considered representative of actual runway surfaces were used.

(1) Portland cement concrete
(2) Smooth asphalt with a sand finish
(3) Rough asphalt with a gravel aggregate
    (highway specification)

The surface contaminants used were water, slush, JP-4 jet fuel and fire extinguishing foam.

Water depth ranged from just damp at the high spots of the surface to .5 inches for the deepest puddles. This is considered representative of actual runway conditions in heavy rain. For the rolling resistance measurements, a water depth of .25-1.75 inches was used.

Slush depth was .5-2.0 inches.

One braking test was performed on asphalt contaminated with jet fuel. The surface was coated with fuel, then allowed to soak in and dry for one hour. The surface was then lightly sprayed with water just before the test run.

Braking tests were also performed on foam 2-5 inches deep.

Tires Tested

A sample of twenty-five 32 x 8.8, 22 ply rating, type VII aircraft tires was tested. These tires differed primarily in their tread patterns, representing a variety of dimpled, laterally grooved, and circumferentially grooved patterns.

Test Procedures

As the test wheel moved over the surface, wheel slip was varied from free-rolling to lockup while speed, tire load, braking force, and test wheel angular velocity were recorded on an oscillograph.

Tire load was varied from 9,000 to 22,000 lbs., inflation pressure from 85 to 350 psi and speed from 13 to 104 knots.

Technique for Analyzing and Presenting Data

Braking performance is expressed as an average coefficient of friction, μ_{ave}, derived from the brake force versus slip curve by averaging the BFC obtained for values of slip between 10 and 50%.

The data was presented in the form of plots of BFC versus slip for each test. Also graphs of μ_{ave} or rolling resistance versus speed for the various test conditions are presented.

Conclusions

(1) Rolling resistance increases with increasing speed.

(2) Fluid displacement drag increases as the square of speed and linearly with fluid depth and density.

(3) For a free-rolling tire on a wet surface, the center of vertical contact pressure moves progressively forward as speed increases so that when hydroplaning occurs the tire spins down.

(4) On dry surfaces peak BFC is practically independent of speed but decreases with increasing ground bearing pressure.

(5) On wet surfaces peak BFC decreases with increasing speed.

(6) Locked wheel BFC decreases with increasing speed on both wet and dry surfaces and is usually lower than the peak BFC. At low speeds locked wheel BFC approached the peak value.

(7) Tread pattern has a very important influence on wet surfaces. Dimple treads are not significantly better than smooth treads. Of the treads tested, the circumferential grooves were the most effective, the greater the number, width, and depth of grooves the better.

(8) Reducing inflation pressure increases wet friction at low speed but reduces friction at high speeds.

(9) Increasing tire load while keeping inflation pressure constant reduces average friction coefficient.

Reference # 18

J.D. Kelly, Jr.

"Factors Affecting Passenger Tire Traction on
the Wet Road"

SAE Paper 680138, 1968

Goal of Tests

To evaluate the effects of tread pattern design, tire construction variables, tread rubber compound, speed, tire load and inflation pressure, ambient temperature, and surface texture upon locked wheel brake force coefficient (BFC) and maximum cornering force coefficient on wet road surfaces.

Test Equipment

Locked wheel BFC was evaluated using a two-wheel skid trailer.

Cornering traction was evaluated by measuring maximum speed attained on a 250 ft. diameter skid pad.

Road Surfaces

For BFC measurement, two surfaces were used:

(1) Course textured asphalt, $\mu = .7$

(2) Smooth textured, painted asphalt, $\mu = .1$

For cornering tests an asphalt surface of $\mu = .5$ was used.

These surface coefficients were measured at 20 mph with the ASTM standard tire.

Average texture depth not specified.

Water depth was approximately .04 inch for all tests.

Tires Tested

The tread pattern study used bias ply tires all having the same size (not specified) and rubber compound (not specified) but with a wide variety of tread patterns.

The effects of crown angle and the addition of a belt upon the performance of bias ply tires were evaluated using a grooved and siped tire similar to a typical production tire.

The effects of radial construction were evaluated using five tires each having one of the tread patterns used in the tread pattern study.

Effects of surface, rubber compound, load, inflation pressure and ambient temperature were investigated using a grooved and siped bias ply tire similar to a typical production tire.

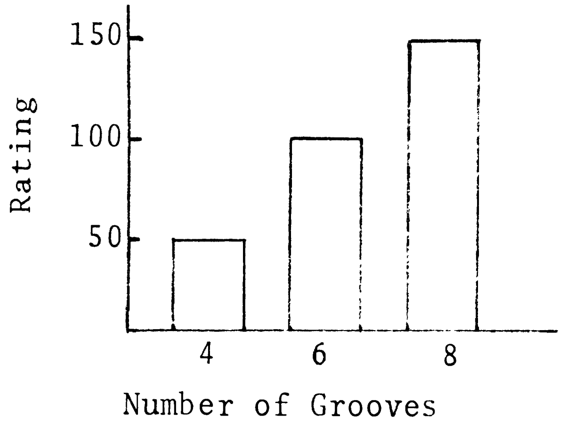
Test Procedure

Few details about the test procedure are given. Variables such as speed, tire load, and inflation pressure were not specified for most of the tests, but were held constant. No tire run-in procedure was discussed.

A standard circumferentially grooved tire was used as a control tire.

Technique for Analyzing and Presenting Data

The traction performance of each tire is rated relative to the performance of the straight grooved control tire, which is arbitrarily given a rating of 100. Results are presented in the form of bar graphs showing relative traction ratings (example).



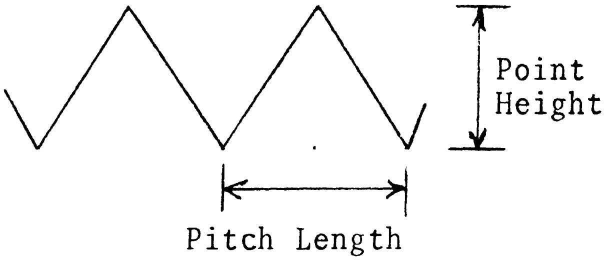
Conclusions

Tread Design

(a) Tread pattern design makes no significant difference on course textured surfaces, but on smooth surfaces, where no other means of water drainage exists, it is the most important tire variable.

(b) Sipes increase BFC on smooth surfaces, but decrease cornering traction.

(c) Jagged or zigzag grooves offer little if any advantage over straight grooves, but if jagged grooves are used, higher point height improves BFC slightly but pitch length seems to have no effect.



(d) For a given tread width, increasing the number of grooves improves BFC but has a small detrimental effect upon cornering traction.

(e) For a given number of grooves there is an optimum tread width for which maximum braking and cornering traction is obtained.

(f) Tread radius has no affect on braking traction but a lower radius improves cornering traction.

(g) Grooves in the shoulder region are more important than those in the center of the tread. Transverse grooves or sipes in the shoulder region give dramatic improvements in BFC. On the low coefficient surface a four groove tire with transverse grooves in the shoulder region and no sipes gave performance superior to that of the same tire with sipes added. Apparently the role of sipes is to provide drainage and/or wiping action in the shoulder region.

Tire Construction

(a) For bias ply tires, cord angle has no affect on BFC, but low angles improve cornering traction slightly.

(b) The addition of a belt to a bias ply tire has no effect provided the grooves are wide enough that they do not completely close in the contact patch of the non-belted tire.

(c) Radial construction does not provide superior locked wheel BFC, but does seem to offer a slight improvement in cornering traction.

Tread rubber compounds having high hysteresis improve traction on course textured surfaces.

BFC is independent of speed on course textured surfaces for speeds up to 40 mph, but on smooth textured surfaces BFC decreases with increasing speed. Speed and surface texture are the two most important variables in the wet traction problem.

Increasing tire load at constant inflation pressure increases BFC.

Experiments in which inflation pressure was varied at constant load indicate that there is an optimum pressure for maximum traction.

The effect of ambient temperature is small and both increases and decreases in BFC with changing temperature have been noted.

Reference #19

P. Koessler and G. Senger

"Comparative Investigations Into the Cornering Characteristics of Car Tires"

MIRA Translation No. 26/65 - Motor Industry Research Association, Lindley, England. Originally published in German in Deut. Kaft., No. 172, 1964.

Goal of Tests

To determine the following relationships:

(a) Slip angle - lateral force - load

(b) Slip angle - aligning moment - load

(c) Camber angle - lateral force - load

as affected by the following variables:

(a) tire size
(b) inflation pressure
(c) tread depth
(d) construction (bias ply, radial)
(e) manufacturer (brand)

Test Equipment

Flat bed tire tester with a concrete surface 5 meters in length. Its speed was .2 m/sec. Strain gage load cells were used to measure lateral force, load, and aligning moment.

Road Surface

All tests were done on the dry concrete bed surface.

Tires Tested

This table specifies tire size, rim size and the inflation pressure at which the tests were performed. Column 4 gives the pressures at which the lateral force-slip angle-load test were done. Column 5 gives pressures for aligning moment-slip angle-load tests. Column 6 gives pressures for lateral force-camber angle-load tests. Pressures are in kg/cm^2.

TABLE 1

TABULATION OF TYRES TESTED, INFLATION PRESSURES USED AND THE APPROPRIATE DIAGRAMS

Tyre Size	Make	Rim	S′ at Inflation Pressure P ($\frac{kg}{cm^2}$)	M at Inflation Pressure P	S″ at Inflation Pressure P	Remarks
5.90 - 13	1	4 J x 13	1,2 1,4 1,7 2,0 2,25	1,4 2,0	2,0	
6.40 - 13	1	5 JK x 13	1,4 2,0 2,5	1,4 2,0	2,0	
6.40 - 13	2	5 JK x 13	1,4 2,0 2,5	2,0	2,0	
6.40 - 13	3	5 JK x 13	1,4 2,0 2,5	2,0	2,0	
6.40 R - 13	4	5 JK x 13	1,4 2,0 2,5	2,0	2,0	
6.40 S - 13	1	5 JK x 13	1,4 2,0	2,0		
6.40 - 13 M+S	1	5 JK x 13	1,4 2,0	2,0		
7.00 - 13	1	5 JK x 13	1,4 2,0	1,4 2,0	2,0	
7.25 - 13	1	5 JK x 13	1,2 1,4 1,7 2,0 2,25	1,4 2,0	2,0	
7.00 S - 14	1	5 JK x 14	1,4 2,0	2,0		
5.60 - 15	1	4 J x 15	1,4 2,0	1,4 2,0		
5.60 - 15	1	4 J x 15	1,4			8mm Tread
5.60 - 15	1	4 J x 15	1,4			3mm Tread
5.60 - 15	1	4 J x 15	1,4			3mm Tread
6.40 - 15	1	4 1/2 K x 15	1,2 1,4 1,7 2,0 2,25	1,4 2,0	2,0	

Test Procedures

Slip angles were measured relative to the position of zero lateral force.

The tires were new but run at a slip angle until noticeable wear had occurred before beginning test runs.

To evaluate reproducibility of the data, many test runs were made with a single tire. Results:

Scatter in cornering force data = ± 1.5%
Scatter in aligning moment data = ± 5%

Technique for Analyzing and Presenting Data

The results are presented in the form of plots of:

(1) Lateral force vs. wheel load with slip angle as a parameter.

(2) Aligning moment vs. slip angle with load as a parameter.

(3) Lateral force vs. wheel load with camber angle as a parameter.

(4) Lateral force vs. aligning moment with slip angle and load as parameters (Gough diagrams).

Conclusions

1. Two tires from the same production run, after being worn to a tread depth of 3 mm. by normal driving, show no difference in cornering stiffness, but at high cornering forces the slip angle required to produce a given lateral force differed by as much as 3 degrees.
2. The cornering stiffness of otherwise identical tires increases as tread depth decreases. The effect of tread wear is most noticeable at high slip angles.

3. Comparison between a tire before and after 1,250 km of road service shows the difference to be negligible, but a significant increase in aligning moment was observed.

4. Comparison between tires of different size:

   (a) For two tires of different size but having the same rim diameter (7.25 x 13, 6.40 x 13) at the same inflation pressure, the larger tire has a higher cornering stiffness.

   (b) For constant tire width and section height but different rim diameter (6.40 x 13, 6.40 x 15), the larger size shows only a very slight increase in cornering stiffness.

   (c) If the above two comparisons are repeated with inflation pressure adjusted to obtain equal rated load capacity, the wider tread tire has greater stiffness, and smaller rim diameter causes greater cornering stiffness.

   (d) The effect of tire size was observed to be smaller than the effect of changing pressure.

   (e) No trend in aligning moment or camber thrust with tire size was observed.

5. Effect of inflation pressure:

   (a) Higher pressures produce higher cornering stiffness. The increase is greater at high loads than at low loads.

   (b) Aligning moment decreases with increasing pressure.

6. Effect of tire construction:

   (a) When radial and bias ply tires of the same size and brand were compared, the radial gave higher cornering stiffness. However, the difference is greatest at high slip angles where the radial produced significantly higher cornering forces at a given slip angle.

    - (b) The tire with a snow tread has a lower cornering stiffness than the same tire with normal tread.
    - (c) Camber thrust is much smaller for radial tires.

7. Tires of the same size and construction but of different brand (manufacture) vary significantly in all traction characteristics (slip angle at a given lateral force can differ by as much as 25%).

Reference #20

F. T. W. Lander and T. Williams

"The Skidding Resistance of Wet Runway Surfaces With Reference to Surface Texture and Tire Conditions"

Road Research Laboratory Report LR 184, 1968.

Goal of Tests

The wet surface braking performance of an aircraft tire as affected by inflation pressure, load, surface texture, and tread wear was investigated.

Equipment

The Road Research Laboratory heavy load test vehicle was used for these tests. This vehicle consists of a truck with a fixture, upon which the aircraft tire to be tested is mounted, attached between the wheelbase on the vehicle centerline. The test wheel fixture is instrumented to measure braking force, brake torque, test wheel angular velocity, and tire load. The test wheel is fitted with an anti-lock brake system.

A sprinkler system is used to provide a consistently wet surface.

Road Surfaces

Four surfaces at the Road Research Laboratory test track and three runway surfaces, providing a wide range of surface textures, were tested.

Surface	Texture depth	
	mm	ins
Smooth polished concrete	0.13	(0.005)
Fine cold asphalt	0.33	(0.013)
Polished gravel macadam	1.19	(0.047)
Quartzite macadam	1.55	(0.061)
Slurry sealed asphalt	0.31	(0.012)
Brushed concrete	0.41	(0.016)
Farnborough experimental surface coarse textured macadam	2.24	(0.088)

Texture depth was measured using the "sand patch" method.

Water depth was .04 inches.

Tires Tested

Two aircraft tires, one smooth and one having a circumferential groove tread pattern, were tested.

Tyre size	35 x 10 x 17 in (89 x 25 x 43 cm)
Tread Pattern	5 ribs 29 mm ($1\frac{1}{8}$ in) wide. 0.475 mm (3/16th in) grooves between ribs depth 0.635 mm (0.25 in)
Tread Rubber hardness (Dunlop scale)	64 – 66
Resilience* (% at 20°C)	45 – 52

Test Procedure

Locked wheel braking force was measured by locking the brakes for a period of one second several times while passing over the test surface.

Traction performance with anti-lock braking was measured by allowing the anti-lock system to cycle several times while passing over the test surface.

The test program consisted of studying the effects of:

(1) varying load and inflation pressure while maintaining constant tire contact area.

(2) varying inflation pressure while keeping load constant

(3) changes in surface texture

(4) diminishing groove depth from new to worn smooth

(5) increasing speed

Tire loads from 1-5 tons, inflation pressures from 25-260 psi, and speeds up to 60 mph were used.

Technique for Analyzing and Presenting Data

Locked wheel BFC was obtained by averaging the values from the several brake applications on each surface. For the anti-lock data, the BFC is the average value obtained over several cycles.

The results are presented as plots of braking force coefficient versus speed.

Conclusions

(1) Surface texture is one of the most important variables influencing tire traction on wet surfaces.

(2) Braking force coefficients on these wet surfaces with anti-lock braking were always higher than the locked wheel values, the average improvement being .13.

(3) Increasing tire load, while adjusting inflation pressure to maintain constant contact area caused a decrease in BFC on smooth textured surfaces but no effect was seen on rough surfaces.

The same results were obtained when inflation pressure was increased at constant load.

(4) Tread grooves increase braking force only on smooth surfaces. On rough surfaces, the smooth tire gave coefficients equal to and sometimes greater than the grooved tire. On smooth surfaces, braking force falls off rapidly with decreasing groove depth for groove depths below 3 mm.

Reference #21

T. J. W. Leland

"An Evaluation of Some Unbraked Tire Cornering Force Characteristics"

NASA Technical Note D-6964, 1972.

Goal of Tests

Tests were performed to investigate the influence of tire tread pattern, water depth, and surface texture upon wet cornering friction and hydroplaning speed of automobile tires.

Equipment

These tests were performed at the Langley Landing Loads Track. For a description of this facility see Reference 17.

Road Surfaces

Tests were performed on two surfaces:

(1) Concrete trowelled to a very smooth finish

(2) Concrete roughened by sandblasting.

A portion of the test surface consisted of a glass plate through which the tire contact patch was photographed.

The surfaces were tested dry and at water depths of .04 and .4 inches.

Tires Tested

Six automobile tires, size 6.50 x 13, were tested:

(1) A smooth tread bias ply tire, having normal tread rubber thickness, but no grooves.

(2) A bias ply tire with 4 evenly spaced straight circumferential grooves .18 inch wide and .25 inch deep.

(3) Same as (2) but with lateral grooves spaced at 1/2 inch intervals on the shoulder ribs.

(4) Same as (2) but with dimples in the shoulder ribs.

(5) A regular production tire with four zig-zag grooves and sipes.

(6) A radial ply tire with a tread pattern similar to (5) (grooved and sipes) but with lateral groove on the shoulder ribs.

Test Procedure

Cornering force at slip angles of 3, 4.5, and 6 degrees was measured for each tire on each concrete surface. Test wheel angular velocity was recorded to detect spin-down which indicates the onset of hydroplaning. Photographs of the water drainage pattern in the contact patch were taken as the tire passed over the glass plate.

Speeds of 20-90 mph were used. Tire load was 835 pounds and inflation pressure was 27 psi for all tests.

Technique for Analyzing and Presenting Data

A plot of cornering force versus speed with slip angle as a parameter is presented for each tire-surface combination. The results are compared to the hydroplaning speed as predicted by the equation of Horne.*

$$V_P = 10.3 \sqrt{P}$$

Conclusions

(1) On the dry surfaces, cornering force at given slip angle increases somewhat with increasing speed.

(2) A smooth tread tire will hydroplane at the speed given by the Horne equation even at small water depths.

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*"Phenomena of Pneumatic Tire Hydroplaning," W.B. Horne, et al., NASA Technical Note D-2056, November 1963.

(3) In shallow water (.04 inch) tread grooves are highly effective in delaying the onset of hydroplaning. A grooved tire will not hydroplane at the speeds and water depths normally encountered by automobiles.

(4) Dimples in the tread do not improve wet traction.

(5) Lateral grooves in the shoulder region provide a large improvement over the simple circumferential groove pattern.

(6) The zig-zag grooves of the production tire appear to provide less efficient drainage than straight grooves. However, the good traction performance of this tire indicates that sipes are highly effective on this smooth surface.

(7) The micro-texture provided by sandblasting the smooth concrete surface improves the overall level of friction but did not affect its rate of decrease with increasing speed.

(8) In deep water (.4 inches), the patterned tires hydroplane at the same speed as the smooth tire— at the speed predicted by Horne's equation. However, at speeds below the hydroplaning speed the grooves provide a large increase in friction.

Reference #22

T.J.W. Leland and G.R. Taylor

"An Investigation of the Influence of Aircraft Tire
Tread Wear on Wet Runway Braking"

NASA Technical Note, NASA TN D-2770, 1965

Goal of Tests

To determine the effect of diminishing tread groove depth upon the wet runway braking performance of aircraft tires.

Equipment

The experiments were done at the Langley landing loads track. This test facility consists of a water-jet catapult which accelerates a test carriage, upon which the test tire is mounted, over a test surface.

A sprinkler system was used to maintain the surface in a consistent wet condition.

Road Surface

Concrete - texture not described.

Tests were done with the surface dry, just damp (no standing water above surface asperities), and wet with water depths of .1 - .3 and 1.0 inch.

Tires Tested

32 x 8.8, type VII, 22-ply-rating aircraft tires.

Three tires were tested.

Tire I - specially molded with a smooth tread

Tire II - a standard dimple-tread tire

Tire III - a standard three-groove tire

Tire tread wear was simulated by using the smooth and dimple tread tires to represent completely worn tires, then cutting progressively deeper grooves to simulate various wear conditions. On tire I, five grooves of equal depths were cut to simulate uniform wear. On tire II, five grooves were cut with the center groove having a smaller depth than the others to simulate non-uniform wear. Tire III was modified by cutting two additional grooves to simulate a new five-groove tire.

Groove widths: Tire I - .29 inch
Tire II - .22 inch
Tire III - .375 inch

Test Procedure

As the tire moved over the test surface, brake torque was gradually applied while brake force, speed and test wheel rotational speed were recorded. The brake cycle was initiated by magnetic pickups so that the same portion of surface was used for every test.

Tire load was 10,500 lbs for all tests.

A tire pressure of 150 psi was used for most tests, but some were run at 90 psi.

Speeds ranged from 20 to 100 knots.

Technique for Analyzing and Presenting Data

Braking performance was expressed in the form of an average coefficient of friction, μ_{ave}, derived from the BFC versus slip curve by averaging the BFC obtained for slip values between 10 and 50%.

The data was presented in the form of graphs of μ_{ave} versus speed or tread wear.

Conclusions

(1) Smooth and dimple-tread tires show the same braking performance.

(2) Tread wear has only a small affect on μ_{ave} until the tread is about 80% worn, after which μ_{ave} drops rapidly.

(3) In the non-uniform wear case, even when the center groove is completely worn, braking performance is still significantly better than for a smooth tire.

(4) Tire III with the widest grooves produced the highest friction coefficients.

(5) Lower tire pressure (90 psi) gave a noticeably higher μ_{ave} than the high inflation pressure (150 psi) on the dry surface, but very little difference was obtained on wet surfaces.

(6) Significant reduction in μ_{ave} occurs when the surface is "just damp" (no standing water).

(7) The experiments at a water depth of 1.0 inch substantiate the hydroplane velocity equation of Horne; and also show that in deep water, rapid loss of friction occurs at speeds below the hydroplaning speed when the tread is more than 60% worn.

Reference #23

T.J.W. Leland, T.J. Yager, and U.T. Joyner

"Effects of Pavement Texture on Wet Runway Braking Performance"

NASA Technical Note D-4323, 1968.

Goal of Tests

The influence of load, inflation pressure, and surface texture upon both wet and dry surface braking performance of aircraft tires was investigated.

Equipment

The tests were done at the Langley Landing Loads Track. For a description of this facility see Reference 17.

Road Surfaces

Tests were performed on five different surfaces:

(1) Concrete trowelled to a very smooth finish - average texture depth = .4 mm.

(2) Textured concrete - average texture depth = 2.0 mm.

(3) Small aggregate asphalt - average texture depth = 3.4 mm.

(4) Large aggregate asphalt - average texture depth = 5.6 mm.

(5) Wet smooth ice.

Surface texture depth was measured using the "grease patch" method.

The surfaces were tested dry, just damp, and at a water depth of .1-.2 inches.

Tires Tested

Three 32 x 8.8 type VII, 22 ply rating aircraft tires with treads made of natural rubber were tested:

(1) smooth tread - tread rubber thickness equal to a new tire but no grooves

(2) three equally-spaced circumferential grooves .5 inch wide

(3) four equally-spaced circumferential grooves .5 inch wide.

Test Procedure

Tire load, braking force, speed, and test wheel angular velocity were recorded while the brake was gradually applied from free-rolling to lockup as the test tire traversed each test surface.

Tests were performed at speeds of 25, 50, 75, and 100 knots.

The smooth tire was tested at intervals throughout the test program to detect changes in test environment and to measure the effects of surface wear.

Technique for Analyzing and Presenting Data

Curves of braking force coefficient versus braking slip were derived from the recorded data. From these, an average braking force coefficient, μ_{ave}, defined as the average value of friction coefficient obtained between 10 and 50% slip was derived.

Plots of μ_{ave} versus speed for the various tire, surface, and test conditions are presented.

Conclusions

A. Dry Surfaces

(1) No significant differences in friction between the four surfaces was observed.

(2) μ_{ave} decreases with increasing speed.

(3) An increase in tire-surface contact pressure, caused by an increase of tire inflation pressure and/or an increase in load, reduces friction significantly.

B. "Just Damp" Surface

(1) Even a very thin film of water can cause a large decrease in friction.

(2) There were large differences in friction between these surfaces even in the "just damp" condition. The smooth concrete showed very low friction even at low speed. Surface texture is important even at low speeds and thin water films.

C. Flooded Surface (.1-.2 inch water depth)

(1) On very rough textured surfaces there is little decrease in μ_{ave} relative to the damp surface value, except at speeds close to the hydroplaning speed where μ_{ave} drops rapidly.

(2) Increasing tire-surface contact pressure decreases friction at lower speeds, but improves friction at high speeds because the hydroplaning speed is raised.

D. Surface Texture Effects

(1) A plot of μ_{ave} versus average texture depth for constant speed shows μ_{ave} increasing with increasing texture depth but leveling off to a constant value

at high texture depth. At high speeds the curve levels off at higher texture depths. At texture depths greater than 4.0 mm no significant improvement is obtained.

(2) The effect of surface wear is to decrease μ_{ave}. However, the effect of wear may not be predictable from changes in average texture depth (which quantifies macro-texture only) because friction can be affected by changes in micro-texture.

Reference #24

G. Maycock

"Studies on the Skidding Resistance of Passenger Car
Tires on Wet Surfaces"

Proceedings of the Automobile Division of The Institution
of Mechanical Engineers, 1965-66, Volume 180, Part 2A,
pp. 122-157.

Goal of Tests

The effects of tread pattern, tread rubber composition, surface texture, and speed upon peak and locked wheel brake force coefficients on wet roads were investigated.

Equipment

A front wheel braked car was used for these tests. The vehicle was modified so that brake torque could be applied at a controlled rate only to the front wheels where the test tires were mounted. The vehicle was instrumented to measure speed and deceleration, and test wheel angular velocity.

A sprinkler system was used to provide a consistent wet surface.

Road Surfaces

Seven surfaces at the Road Research Laboratory test track, representing a wide variety of surface textures, were tested: (1) mastic asphalt, (2) polished concrete, (3) fine cold asphalt, (4) asphalt with chippings, (5) rounded gravel carpet, (6) mixed aggregate, and (7) quartzite. For a description of the textures of these surfaces, see Reference 27.

Water depth was .04-.08 inches.

Tires Tested

Two sets of tires were tested. The first set consisted of nine tires having three different tread patterns: (a) smooth, (b) six circumferential grooves, and (c) a regular production tread pattern with six grooves and siped, each of which was available with three different rubber compounds: (a) natural rubber, (b) oil-extended SBR, and (c) oil-extended high-styrene SBR. These three compounds had resiliences of 48.5%, 28%, and 23.5%, respectively, but about the same hardness (67 Dunlop scale). All tires were 6.40 x 15 cross ply.

A second set of eight tires, all made of the same SBR rubber compound, were designed to study the effect of tread pattern variations. Six tires had ribbed and siped patterns and two had block-type patterns. All were of radial ply construction except one five-rib, siped pattern was bias ply.

Test Procedure

Vehicle speed and deceleration was recorded as the front brakes were gradually applied until lockup occurred.

The first set of tires was tested on all seven surfaces at speeds from 25 to 65 mph. The second set of tires was tested only on surfaces (2), (3), and (4) at speeds from 25 to 80 mph.

For all tests, tire load was 900 lbs and inflation pressure was 24 psi.

Method of Analyzing and Presenting Data

Values of peak and locked wheel BFC were computed from vehicle deceleration. Linear equations of the form BFC = $C_1 - C_2V$ were fitted to the data by least squares. Plots of peak and locked wheel BFC versus speed are presented for each tire-surface combination.

Conclusions

(1) Even the simple straight groove, unsiped tread pattern gives a large improvement in friction over the smooth tread.

(2) Tread pattern effects are most significant at high speeds.

(3) Sipes give significant improvement on smooth surfaces.

(4) Tread pattern design is important on smooth surfaces but has no effect on rough surfaces.

(5) Increasing the number and width of grooves improves friction.

(6) Tread pattern variations have a greater effect upon peak BFC than on locked wheel BFC.

(7) Rubber compounds having low resilience (high hysteresis) gave large improvements in peak BFC (20-50%) over natural rubber on all surfaces. Less improvement was obtained for locked wheel BFC except on surfaces having a harsh micro-texture.

(8) Both peak and locked wheel BFC decrease with increasing speed and the rate of decrease with speed is greatest on smooth surfaces. Locked wheel values decrease more rapidly than peak values so that the ratio of peak to locked wheel BFC increases with increasing speed.

(9) Radial ply construction provides somewhat higher peak BFC than bias ply construction.

Reference #25

G. Maycock

"Experiments on Tire Tread Patterns"

Road Research Laboratory Report LR 122, 1967.

Goal of Tests

The effects of tread groove width and rib width upon peak and locked wheel BFC on wet surfaces were investigated.

Equipment

The test tires were fitted to the front wheels of a test car with the brake system modified so that brake torque could be applied at a controlled rate to the front wheels only. The test car was instrumented to measure vehicle speed and deceleration and test wheel rotational speed.

A sprinkler system was used to wet the road surfaces.

Road Surfaces

Six different surfaces at the RRL test track representing a wide variety of macro- and micro-textures were used.

A	Polished concrete	Concrete flooring, specially polished and having very small asperities.
B	Fine Cold Asphalt	Cold asphalt to B.S. 1690 using blast furnace slag aggregate - a 'sandpaper" texture.
C	Asphalt with chippings (White)	Hot rolled asphalt to B.S. 594 with $\frac{1}{2}$" Meldon white chippings rolled into the surface.
D	Rounded Gravel Carpet	Bitumen gravel carpet with [illegible] Bridport gravel. Tops of stones rounded and highly polished.
E	Asphalt with chippings (Black)	Hot rolled asphalt to B.S. 594 with $\frac{3}{4}$" pre-coated chippings rolled into the surface.
F	Brushed Concrete	

For a more detailed description of surfaces A, B, D, and E see Reference 27.

Water depth varied from surface to surface due to differences in texture. On the smooth surfaces, water depth was estimated to be .02-.04 inch above the asperities.

Tires Tested

All test tires were 185 x 15 radials, moulded with a smooth tread. Straight, circumferential grooves were then cut by hand to a depth of 8 mm.

Two sets of experimental tires were produced. For one set, the number of ribs was varied while total rib area (number of ribs x rib width x contact length) and the ratio of rib width to groove width was held constant.

Dimensions of Tread Patterns Used in Experiment 1

Number of Ribs	Groove Width (in)	Rib Width (in)	$\frac{\text{Groove Width}}{\text{Rib Width}}$
5	0.28	0.9	0.31
7	0.20	0.65	0.31
9	0.16	0.52	0.31
13	0.12	0.36	0.33

For the other set of tires, groove width was varied while number of ribs and rib width were held constant.

Dimensions of Tread Patterns Used in Experiment 2

Nominal Groove Width (in)	Number of Ribs	Groove Width (in)	Rib Width (in)	Groove Width / Rib Width
0.02	5	0.02	0.5(Nominal)	0.04
0.1	5	0.10	0.51	0.20
0.2	5	0.215	0.49	0.44
0.3	5	0.29	0.52	0.55
0.4	5	0.36	0.54	0.67
Additional tyre:				
0.19	5	0.20	0.52	0.38

Test Procedure

Test vehicle speed and deceleration, and rotational speed of each front wheel were recorded as the front brakes were gradually applied.

Tests were done at speeds of 20 to 105 mph.

Inflation pressure was 24 psi cold and tire load was 800 lbs for all tests.

Technique for Analyzing and Presenting Data

Peak and locked wheel BFC were calculated from vehicle deceleration, taking into account load transfer and aerodynamic drag.

Plots of peak and locked wheel BFC versus speed with tread pattern as a parameter were presented for each surface.

Conclusions

(1) Increasing the number of ribs from 5 to 13 did not improve either peak or locked wheel BFC, except on the smoothest surface (polished concrete) on which the five-rib tire shows a somewhat greater rate of BFC reduction with speed.

(2) For a given rib width, groove depth, and water depth there is a groove width above which no further increase in BFC is obtained.

(3) Tread grooves are very important on surfaces of smooth macro-texture, but show little or no effect on coarse textured surfaces.

(4) Locked wheel BFC shows a greater reduction with increasing speed than does peak BFC.

Reference #26

J.K. Meades

"Braking Force Coefficients Obtained with a Sample of Currently Available Radial Ply and Crossed Ply Car Tires"

Road Research Laboratory Report LR 73, 1967.

Goal of Tests

The wet road braking performance of a sample of ten commercially available cross ply and radial ply tires was evaluated.

Equipment

The RRL front wheel braked car was used for these tests. This vehicle was modified so that brake torque can be gradually applied to only the front wheels on which the test tires are mounted. The vehicle is instrumented to measure vehicle deceleration, vehicle speed, and test wheel angular velocity.

A sprinkler system was used to provide a consistent wet surface.

Road Surfaces

Tests were performed on four surfaces at the Road Research Laboratory test track.

(1) Polished concrete: very smooth in both macro- and micro-texture. Average texture depth = .4 mm

(2) Quartzite carpet: very rough macro-texture and harsh micro-texture. Average texture depth = 2.4 mm

(3) Asphalt with pre-coated chipping to motorway specification: rough macro-texture and harsh micro-texture. Average texture depth = 1.5 mm

(4) Brushed concrete: moderate macro-texture and harsh micro-texture.

Water depth was maintained between .02 and .04 inch.

Tires Tested

A sample of five bias ply tires of size 6.40 x 15 and five radial ply tires of size 185 x 15 were tested. These tires were all commercially available and in common use on European roads. Photographs of the tire treads are presented.

Test Procedure

Test vehicle speed, vehicle deceleration, and test wheel angular velocity were recorded by an oscillograph while the front brakes were gradually applied.

On surfaces (1), (2) and (3) speeds from 25 to 80 mph were used. On surface (4) speeds up to 125 mph were used.

Tire load was 800 lbs and inflation pressure was 24 psi for all tests.

Technique for Analyzing and Presenting Data

Values of brake force coefficient were computed from vehicle deceleration data taking into account aerodynamic drag and weight transfer.

Plots of peak and locked wheel BFC versus speed with tire type as a parameter is presented for each surface.

Conclusions

(1) At low speeds, radial and bias ply tires show about the same braking performance. However, radial tires suffer less reduction in BFC with increasing speed except on the very coarse surface.

(2) At low speeds the ratio of peak to locked wheel BFC was about 1.5 for all tire-surface combinations tested. However, this ratio increases with increasing speed, and at 80 mph it can range from 2.0 to 8.0 depending on the surface.

Reference #27

J.K. Meades

"The Effect of Tire Construction on Braking Force Coefficient"

Road Research Laboratory Report LR 224, 1969.

Goal of Tests

The wet road braking performance of bias ply and radial ply tires having the same tread pattern and rubber compound was compared.

Equipment

The RRL front wheel braked car was used. This vehicle was modified so that brake torque can be gradually applied to only the front wheels where the test tires are mounted. The vehicle is instrumented to measure vehicle speed, vehicle deceleration, and test wheel angular velocity.

A sprinkler system was used to provide a consistent wet surface.

Road Surfaces

Tests were performed on seven surfaces at the Road Research Laboratory test track, representing the full range of surface textures.

(1) Mastic asphalt: smooth in both macro- and micro-texture, average texture depth = .1 mm.

(2) Polished concrete: smooth in both macro- and micro-texture, average texture depth = .1 mm.

(3) Fine cold asphalt: moderate macro-texture and a very harsh micro-texture, average texture depth = .4 mm.

(4) Rounded gravel macadam: coarse macro-texture but a highly polished aggregate (smooth micro-texture), average texture depth = 1.5 mm.

(5) Asphalt with pre-coated chipping to motorway specification: a coarse macro- and harsh micro-texture, average texture depth = 1.5 mm.

(6) Mixed aggregate (Bridport gravel and crushed quartzite): coarse macro-texture and moderate micro-texture (stones somewhat polished), average texture depth = 1.7 mm.

(7) Quartzite macadam: very coarse and harsh in macro- and micro-texture, average texture depth = 2.4 mm.

Water depth was .5-1.0 mm.

Tires Tested

Four different tires were tested:

(1) Bias ply, size 5.90 x 14, snow tread pattern, winter tire rubber compound.

(2) Radial ply, size 165 x 14, tread pattern and compound same as (1).

(3) Bias ply, size 155 x 13, circumferential grooves and sipes.

(4) Radial ply, size 155 x 13, tread pattern and compound same as (3).

Test Procedure

Test vehicle speed and deceleration, and test wheel angular velocity were recorded as the front brakes were gradually applied until lockup.

Speeds from 30 to 80 mph were used. Tire load was 800 lbs and inflation pressure was 24 psi for all tests.

Technique for Analyzing and Presenting Data

Values for peak and locked wheel brake force coefficients were computed from the vehicle deceleration records.

Plots of peak and locked wheel BFC versus speed for each tire-surface combination are presented. Straight lines were fitted to the data by the method of least squares.

Conclusions

(1) The radial ply tires gave higher peak BFC on all surfaces. The differences were small on surfaces having coarse macro-texture and were greatest on surfaces with smooth macro-texture and harsh micro-texture.

(2) The difference between radial and bias ply tires for locked wheel BFC is small.

(3) The conclusions stated above apply to both snow treaded and regular highway treaded tires.

(4) Locked wheel BFC decreases more rapidly with increasing speed than does peak BFC, and peak values were higher than locked wheel values.

Reference #28

Samuel Mercer, Jr.

"Locked Wheel Skid Performance of Various Tires on Clean, Dry Road Surfaces"

Highway Research Board Bulletin No. 186, 1958, pp. 8-25

Goal of Tests

Locked wheel brake force coefficients on dry road surfaces of several different tires as affected by speed and tire load were evaluated.

Equipment

Tests were performed using:

(1) a two-wheel skid trailer

(2) a 1956 Chevrolet station wagon

(3) a 1956 Chevrolet four-door sedan.

Road Surfaces

Tests were performed on three surfaces:

(1) Bituminous asphalt

(2) Portland cement concrete

(3) A 500-ft. section of a heavily traveled asphalt public highway.

Tires Tested

Firestone, Goodyear, U.S. Royal, and B.F. Goodrich each contributed twelve 6.70 x 15 bias ply, synthetic rubber, tubeless tires. Tread patterns were somewhat different, but all had circumferential grooves and sipes.

Test Procedure

For the friction trailer tests, the tires were mounted in pairs and loaded to 1000 lbs at an inflation pressure of 28 psi. Four test runs were made for each combination of test conditions. Speeds of 10-50 mph were used. Road surface temperature was measured and one set of tires was tested periodically as a control. With one set of tires, the effect of load was investigated by testing at loads from 770 to 1500 lbs per tire.

Locked wheel stopping distance tests were performed using initial speeds of 30, 40, 50 and 70 mph.

All test tires were broken in by 200 miles of normal driving prior to testing.

Technique for Analyzing and Presenting Data

Braking force readings from the friction trailer rose rapidly at the instant of lockup, stabilized for a short time, then decreased as the skid progressed. The high initial value was recorded as data and the results of four runs were averaged.

From the locked wheel stopping distance data, average values of braking force coefficient were computed. The data is tabulated and plots of friction coefficient versus speed for the various test conditions are presented.

The stopping distance data was analyzed to determine the accuracy with which initial speed can be determined by measuring the lengths of skid marks on a dry surface.

Conclusions

(1) On dry surfaces, locked wheel braking force increases with increasing speed.

(2) Locked wheel braking force coefficient decreases with increasing tire load.

(3) Differences of 10% in braking performance were found between tires of different brands.

(4) Only small differences in dry friction were found between the three surfaces.

(5) No significant changes in dry friction with changing surface temperature was detected in the range of 65-110°F.

(6) Speed estimates based on the length of skid marks on dry pavements are accurate to within 10%.

REFERENCE #29

A. H. Neill, Jr.

"Wet Traction of Tractionized Tires"

National Bureau of Standards, Technical Note 566, 1971

GOAL OF TESTS

To determine the effect of sipes upon cornering traction and locked wheel stopping distance on wet road surfaces.

EQUIPMENT USED

A diagonal braked, 1968 Chevrolet was used for both stopping distance and cornering traction tests.

A watering truck was used to wet the road surfaces.

ROAD SURFACES

		SN Value	
Pavement No.	Description	Stopping Distance Pads (50-20 mph)	J-Curve Pads (40 mph)
1	Rounded Siliceous Gravel	42-46	50
2	Crushed Siliceous Gravel	43-49	51
4	Slag and Limestone Screenings	7-18	24
5	Rounded Siliceous Gravel (P.C. Concrete)	42-61	43

Surfaces 2, 4, and 5 were used for braking tests and surfaces 1 and 2 for cornering tests.

Average water depth was maintained at approximately .05 inch. The same volume of water per unit surface area was used for all surfaces. Due to differing texture depths, the depth of water above the asperities was not the same for all surfaces.

Ambient temperature varied from 73-87°F with a mean of 81°.

Surface texture was not described and values for average texture depths are not given.

TIRES TESTED

Twenty-four bias-belted tires, all of the same size, rubber compound, and tread pattern (not specified), some siped and some unsiped, were tested.

Two methods of siping were used: (1) eight cuts per inch at 90° to the direction of travel; (2) seven cuts per inch to a depth of 7/32 inch at 65° to the direction of travel.

All tires were run in with 100 miles of driving, except eight tires siped by method (2) were driven for 8000 miles after which the sipes were 4/32 deep.

All tires were statically balanced and the high spots were cut off to make the tires round.

There is no indication whether or not the sipes open into a groove.

TEST PROCEDURE

Locked wheel braking traction was evaluated by measuring stopping distance of the diagonal braked automobile. Cornering traction was evaluated by measuring speed at breakaway on a skid pad of 288-foot radius.

Four test runs for each combination of speed, tire, and surface were made. The speed, tire, and surface combinations were tested in random order to minimize extraneous effects such as temperature.

Speeds of 20, 30, 40 and 50 mph were used.

Tire load was 1270 lbs. for all tests.

TECHNIQUE FOR ANALYZING AND PRESENTING DATA

The results were presented in a table giving stopping distance and speed at breakaway for both siped and unsiped tires for each speed-surface combination. Also, a plot of stopping distance versus speed for each surface is presented.

Each data point is an average of four test runs.

CONCLUSION

Sipes neither improve nor degrade the wet traction performance of tires.

Reference #30

B.E. Sabey

"Road Surface Texture and the Change in Skidding Resistance with Speed"

Road Research Laboratory Report No. 20, 1966.

Goal of Tests

Locked wheel braking force coefficients were measured on several road surfaces for which texture was also measured. The degree of correlation between the rate of decrease of braking force coefficient with increasing speed and surface texture depth and profile ratio was investigated.

Equipment

A single-wheel skid trailer was used to gather locked wheel braking force data.

Road Surfaces

A large sample of concrete and asphalt surfaces having various textures were tested.

Tires Tested

All tests were performed with a smooth tread tire.

Test Procedure

Braking force tests were done at 30, 50, and 80 mph. Surface textures were measured using two methods: (1) the sand patch method which measures average texture depth, and (2) a stereo photogrammetric technique from which the profile ratio can be derived. The profile ratio is defined as the ratio of the length of surface profile to the length of the baseline. The value of this ratio depends both upon texture depth and the shape of the asperities.

Technique for Analyzing and Presenting Data

Five types of correlations between skid resistance in the speed range 30 mph to 50 mph and surface texture were investigated:

(1) the decrease of BFC versus average texture depth

(2) the percentage decrease of BFC versus average texture depth

(3) the decrease of BFC versus profile ratio

(4) the percentage decrease of BFC versus profile ratio

(5) the percentage decrease of BFC versus the logarithm of the profile ratio.

Plots of these correlations are presented; linear regression lines are plotted; and correlation coefficients are computed.

Conclusions

(1) A knowledge of the decrease in braking force in the speed range 30 mph to 50 mph is not sufficient to predict the friction performance of a surface at 80 mph.

(2) A significant correlation was established between the percentage decrease in BFC in the speed range of 30 mph to 80 mph and average texture depth. From this correlation, two conclusions can be made:
(a) if average texture depth is less than .01 inch, low values of BFC will be obtained at 80 mph even

if the value at low speeds is high, and (b) an average texture depth of .025 inch will restrict the decrease of BFC in the speed range 30 mph to 80 mph to 25% or less of the 30 mph value.

(3) The profile ratio is a somewhat better measure of surface texture than average texture depth because it depends to some extent upon the sharpness of the asperities. Somewhat better correlations were obtained using profile ratio.

Reference #31

K. H. Schulze and L. Beckman

"Friction Properties of Pavements at Different Speeds"

Skid Resistance, ASTM Special Technical Publication No. 326, 1962.

Goal of Tests

To measure wet skid resistance of a large sample of public road surfaces; to correlate average surface void width with the speed dependency of BFC; to correlate BFC with a surface wear index; and to correlate peak and locked wheel BFC.

Equipment

A single wheel skid trailer.

Tires Tested

Not specified.

Road Surfaces

A total of 48 fine asphaltic concrete, mastic asphalt, and Portland cement concrete surfaces were tested.

Mean void width, determined from stereo photographs, was used as a measure of surface texture.

Water depths and method of wetting the surfaces were not specified.

Test Procedure

A total of 600 locked wheel BFC measurements were made. Twenty peak BFC measurements were made.

Speeds of 20, 40, 60 and 80 km/hr were used.

For the surface wear study, locked wheel BFC was measured on both lanes of four-lane roads and traffic density data was gathered for each lane.

Techniques for Analyzing and Presenting Data

Statistical methods were used to perform the correlations. Data is presented in both tabular and graphical form.

Conclusions

A significant correlation was found between slope of the BFC versus speed curve and mean surface void width (correlation coefficient = .87).

The surface wear study shows that the effect of surface wear is to increase the slope of the BFC versus speed curve. This study also revealed that mastic asphalt surfaces wear more rapidly than cement concrete surfaces; but since asphalt has higher friction when new, they both tend to approach the same skid resistance in the worn state.

Peak and locked wheel BFC correlate sufficiently well that the above conclusions derived from locked wheel tests should also be valid for peak BFC.

Reference #32

L. Segel

"Tire Traction on Dry, Uncontaminated Surfaces"

Paper presented at a Symposium on the "Physics of Tire Traction, Theory and Experiment" at the General Motors Research Laboratories, Oct. 1973.

Goal of Tests

The traction fields* of several tires on two dry road surfaces were measured to investigate the effects of the following variables:

(1) road surface
(2) speed
(3) carcass construction (bias, belted bias, radial)
(4) aspect ratio
(5) tread shoulder wear

Equipment

The mobile tire tester of the Highway Safety Research Institute was used for these tests.

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*A "traction field" for a given tire-surface-load-inflation pressure-speed combination is a collection of data which defines the following functional relationship:

$$F_x, F_y = f(S_x, S_y)$$

where

F_x = longitudinal (braking) force
F_y = lateral (cornering) force
S_x = longitudinal (braking) slip
S_y = lateral slip ($\tan\alpha$, α = slip angle)

Road Surfaces

Two surfaces at the Automotive Proving Grounds, Inc., in Pecos, Texas were tested:

(1) a coarse aggregate bituminous concrete (asphalt) surface with slight macro- and moderate micro-texture

(2) a brushed Portland cement concrete surface with slight macro- and moderate micro-texture.

Tires Tested

Traction fields were obtained for a sample of eleven commercially available tires selected to provide a systematic variation in aspect ratio and carcass construction while having similar longitudinal groove tread patterns.

Tire Size	Aspect Ratio	Carcass Construction	Number of Tread Ribs	Tread Width
F78-14	.80	Bias	7	6.00
F78-14	.80	Bias	7	5.75
F70-14	.74	Bias	7	6.50
F78-14	.80	Belted-Bias	7	5.75
F78-14	.80	Belted-Bias	7	5.70
F78-14	.80	Belted-Bias	7	5.75
F70-14	.74	Belted-Bias	7	6.30
F70-14	.74	Belted-Bias	7	6.50
F60-14	.59	Belted-Bias	9	8.00
FR70-14	.71	Radial	5	6.50
FR70-14	.71	Radial	7	6.50

A sample of twelve tires were tested for the effect of shoulder wear. These were original equipment tires on the vehicles used in a study of limit handling performance as influenced by degradation of steering and suspension systems, and represent a wide variety of sizes, construction, and tread profiles.

Test Procedure

To obtain the traction field data, longitudinal slip was varied from 0 to 1.0 (free-rolling - lockup) while the test tire was run at constant slip angle. This procedure was repeated for several slip angles up to 16 degrees for each tire and surface at speeds of 20 and 40 mph. Inflation pressure was 28 psi for all tests and tire loads between 800 and 1100 pounds were used. Braking force, cornering force, aligning moment, and test wheel rotational speed were recorded on magnetic tape.

For the tread wear study, free rolling cornering force was recorded on a strip chart recorder while the test tire was run at a slip angle of 20 degrees, at 40 mph, under a load of 1550 pounds. Tread profile shape was recorded at regular intervals during this test.

Technique for Analyzing and Presenting Data

The traction field data stored on magnetic tape was processed using a hybrid computer on which it was digitized, filtered, averaged, and plotted.

The tread wear data was analyzed by plotting cornering force coefficient versus distance traveled which was also correlated with the amount of tread wear.

Conclusions

A. Influence of Speed and Surface

(1) Brake force versus longitudinal slip characteristics are highly sensitive to speed and surface, but lateral force versus slip angle characteristics are relatively unaffected.

(2) Peak longitudinal force and the value of slip at which the peak occurs both decrease with increasing speed.

(3) The value of slip at which peak longitudinal force is obtained is very sensitive to surface characteristics. On the asphalt surface the peak occurs at 20-30% slip, while on the concrete surface maximum force is obtained at lockup.

B. Influence of Carcass Construction and Aspect Ratio

(1) No clear trends with respect to carcass construction or aspect ratio were established. Systematic testing using specially constructed tires is necessary to study these tire design variables.

C. Influence of Tread Shoulder Wear

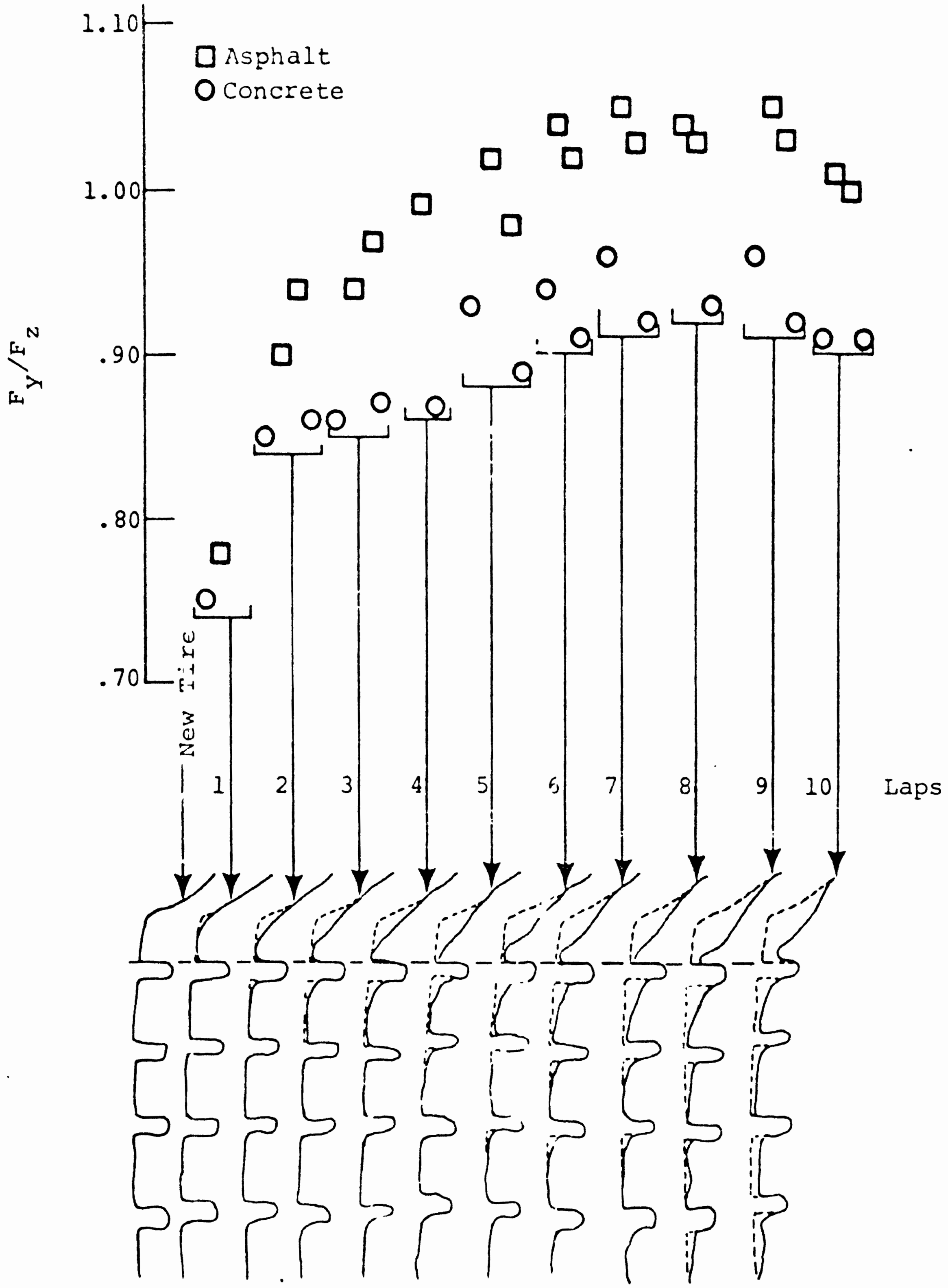
(1) Tires having sharp corners at the tread shoulder show a high degree of sensitivity of peak cornering force to small amounts of shoulder wear. (See the illustration on following page.)

(2) The amount of change in peak cornering force due to shoulder wear can be sufficient to have a significant affect upon the limit handling characteristics of a vehicle.

(3) It seems reasonable to hypothesize that this sensitivity to shoulder wear is due to a large variation in contact pressure distribution due to small amounts of shoulder wear.

D. Combined Longitudinal and Lateral Slip

(1) The limiting shear force capability of pneumatic tires cannot generally be described using the "friction ellipse" concept. Real tire behavior is often more complex.



Tread Profile - Outside Shoulder

$\alpha=20°$ $F_z=1550$ Uniroyal L78-15 Fastrak

Tire Sample No. 1

Reference #33

F.D. Smithson and F.H. Herzegh

"Investigation of Tire-Road Traction Properties"

SAE Paper No. 710091, 1971

Goal of Tests

The effects of road surface texture, tread pattern, and rubber compound upon peak and locked-wheel brake force coefficient on wet surfaces were investigated.

Equipment

The tests were performed with the General Motors friction test trailer and with a B.F. Goodrich front wheel braked car.

Tires Tested

Four different bias ply tires were tested:

(1) A standard B.F. Goodrich production tire having six circumferential grooves and siped, and made of Styrene-Butadiene rubber (SBR).

(2) Same as (1) but made of natural rubber.

(3) An unsiped tire having four straight circumferential grooves, and made of SBR rubber.

(4) Same as (3) but made of natural rubber.

Road Surfaces

Fourteen different road surfaces were tested; eight special test surfaces and six public highway surfaces known to be sites of frequent skidding accidents. These surfaces represent a wide variety of macro- and micro-textures.

Test Procedure

Peak and locked wheel braking force coefficients were evaluated for each tire-surface combination at 20, 40, and 60 mph.

Method of Analyzing and Presenting Data

Braking force values were obtained directly from the friction trailer and derived from vehicle deceleration of the front wheel braked car. Each data point is an average of 10 test runs.

For each surface, plots of peak BFC and locked wheel BFC versus speed with tire type as a parameter are presented.

Conclusions

(1) Tires having different rubber compounds show different friction values only on surfaces having harsh micro-texture. Hence, a surface having a harsh micro-texture must be used in tire traction tests if compound differences are to be accounted for.

(2) Sipes improve both peak and locked wheel BFC only on smooth polished surfaces.

(3) The typical slippery public highway surface has a coarse macro-texture but relatively little micro-texture. Sipes and high hysteresis rubber compounds both improve traction on these surfaces.

(4) For the purpose of defining the traction properties of a surface, it is proposed that the surface be tested with the following four special tires:

   (a) ribbed but unsiped tire of SBR compound

   (b) ribbed but unsiped tire made of natural rubber

   (c) smooth tread tire made of natural rubber

   (d) a ribbed and siped tire made of natural rubber.

Reference #34

G.C. Staughton

"The Effect of Tread Pattern Depth on Skidding Resistance"

Road Research Laboratory Report LR 323, 1970

Goal of Tests

The effects of tread groove depth, speed, and surface texture upon peak and locked wheel brake force coefficient on wet surfaces were determined.

Equipment

The test tires were fitted to the front wheels of a test car (E-type Jaguar) with its brake system modified so that brake torque could be applied at a controlled rate to the front wheels only.

A sprinkler system was used to wet the surfaces.

Road Surfaces

Six surfaces at the Road Research Laboratory test track were used. These surfaces represent the full range of textures found on public roads.

Surface		Texture		Average Texture depth μm
		Macro	Micro	
Smooth concrete	Monolithic Granolithic concrete flooring specially polished and having very small asperities	Smooth	Polished	100
Mastic asphalt	Smooth fine textured surface	Smooth	Polished	100
Fine textured asphalt	Fine cold asphalt with blast furnace slag aggregate – harsh sandpaper texture surface	Smooth	Harsh	400
Mixed aggregate macadam	Bitumen macadam with 60% Bridport gravel and 40% crushed quartzite – coarse texture	Rough	Semi-Polished	1700
Bridport gravel macadam	Bitumen macadam with 100% Bridport gravel – tops of stones rounded and highly polished – coarse textured	Rough	Polished	1500
Asphalt to Motorway Specification	Hot rolled asphalt with pre-coated chippings rolled into surface – coarse textured	Rough	Harsh	1500

Water depth was maintained constant throughout the test program for each surface, but varied from surface to surface due to texture differences.

Surface	Water depth μm
Fine textured asphalt	630
Mastic asphalt	1170
Smooth concrete	680
Asphalt to Motorway specification	410
Bridport gravel macadam	480
Mixed aggregate macadam	380

Tires Tested

Two commercially available 5.60 x 13 tires of cross ply construction were tested.

Test Procedure

Vehicle deceleration and speed, and the rotational speed of each front wheel were recorded as the front brakes of the test vehicle were gradually applied.

Traction tests were done at intervals of 5,000 km of normal driving until the tread was worn to a depth of 2 mm, after which tests were run at 500 km intervals.

Concurrently with the test tires, traction measurements were made with a smooth tread control tire to compensate for variations in surface temperature and water depth, and for seasonal effects.

Tread depth was evaluated by taking the average of 16 points around the tire.

Tests were done at speeds of 50, 80, and 130 km/hr. Tire inflation pressure was 16.5 N/cm^2 (cold) for all tests.

Technique for Analyzing and Presenting Data

Brake force coefficients were calculated from the recorded values of test vehicle deceleration, taking into account load transfer and aerodynamic drag. These BFC values were adjusted according to the control tire data, then plotted. Data is presented in the form of plots of peak and locked wheel BFC versus tread depth for each surface with speed as a parameter.

Conclusions

(1) Surface texture and speed interact with tread pattern depth to determine skid resistance.

(2) Tread wear has little effect on surfaces having coarse macro-texture.

(3) Tread wear has a significant effect on smooth textured surfaces and BFC drops very rapidly for tread depths below 2 mm.

(4) On smooth surfaces at high speed, locked wheel BFC was very low even for the new tire with full tread depth. Hence, tread grooves cannot completely compensate for lack of surface texture.

Reference #35

G.C. Staughton and T. Williams

"Tire Performance in Wet Surface Conditions"

Road Research Laboratory Report LR 355, 1970.

Goal of Tests

Locked wheel braking force coefficient (BFC) and hydroplaning speed as affected by tire construction, tire load, inflation pressure, tread pattern, surface texture, water depth, and speed was investigated.

The effects of inflation pressure and water depth are stressed.

Equipment

Most of the tests were done using a single wheel skid trailer operated in the free rolling and locked wheel modes. Some data was taken with a front wheel braked car and the RRL braking and cornering machine.

Road Surfaces

Three surfaces at the Road Research Laboratory test track were tested:

(1) smooth concrete - smooth macro-texture, harsh micro-texture, average texture depth = .4 mm.

(2) rolled asphalt with precoated chipping - rough macro-texture, harsh micro-texture, average texture depth = 1.5 mm.

(3) quartzite macadam - very rough macro-texture, harsh micro-texture, average texture depth = 2.4 mm.

Texture depths were measured using the sand patch method.

Water depth was maintained by damming up a .46 x 21.5 meter section of each surface to form a trough. Water depths from "just damp" to 10 mm were used. Water depth was measured using a calibrated needle probe at several points in the trough.

Tires Tested

The main body of tests with the skid trailer were done using the following tires:

Tyre No.	Tyre construction	Tread Details	Tyre size	Tread rubber hardness Dunlop scale @ 20°C
1	Radial	Full patterned tread	145 x 10	68
2	Radial	Full patterned tread	"	68
3	Crossply	Full patterned tread	5.20 x 10	69
4	Crossply	Full tread depth smooth	"	60
5	Crossply	Worn smooth	"	69

A few supplementary tests using the front wheel braked car and the RRL braking and cornering machine were done using regular production radial and bias ply tires of larger size.

Test Procedure

Hydroplaning speed and locked wheel BFC were measured for each tire-surface combination at water depths from "just damp" to 10 mm. BFC values were measured at speeds of 20 to 130 km/hr.

Tire variables investigated were:

(1) tire construction - radial or bias ply

(2) tread pattern - fully patterned and smooth

(3) tire load - 665 to 2265 Newtons

(4) inflation pressure - 55 to 330 kN/cm^2.

Hydroplaning speed was determined by measuring the speed at which spin down of the free-rolling wheel occurred.

Technique for Analyzing and Presenting Data

Plots of locked wheel BFC versus speed and water depth, and plots of hydroplaning speed versus inflation pressure and water depth are presented. The data is also tabulated.

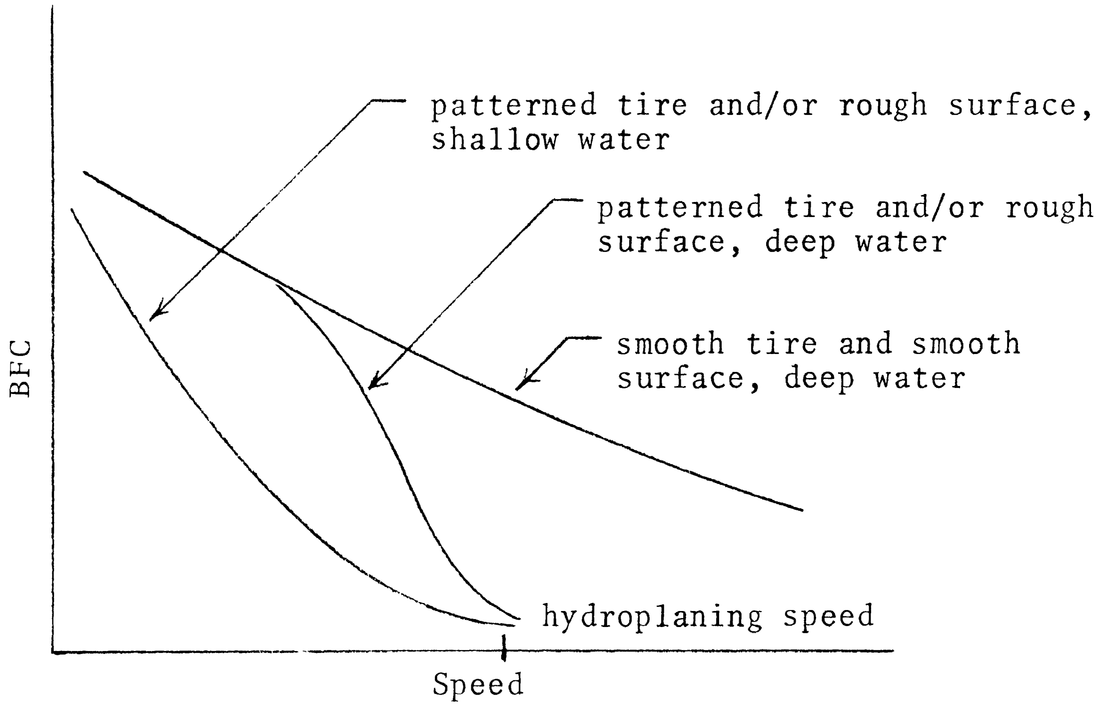
Conclusions

(1) In deep water, hydroplaning speed depends primarily upon tire inflation pressure. Tread pattern, tire construction, tire load, and surface texture have only a small effect. Hydroplaning speed increases with increasing inflation pressure.

(2) Hydroplaning speed decreases with increasing water depth up to a certain depth (5 mm for all but one test tire) above which no further decrease occurs.

(3) For water depths below 3 mm hydroplaning speed, even for the worn smooth tires, is so high that it will rarely occur in practice.

(4) At low water depths, locked wheel BFC is strongly affected by tire tread pattern and surface texture, especially at high speeds. In deep water, tread pattern and surface texture have a large effect only at speeds below the hydroplaning speed.



(5) At low water depths, locked wheel BFC is not significantly affected by inflation pressure.

(6) Most of the decrease in locked wheel BFC with increasing water depth occurs in the first 3-4 mm.

Reference #36

T. Williams

"The Relation Between Braking Force Coefficient and
Slip for an Aircraft Tire Braked on Four Wet Surfaces"

Road Research Laboratory Report No. 50, 1966

Goal of Tests

The effect of speed, inflation pressure, and surface texture upon peak and locked wheel braking force coefficients developed by an aircraft tire on wet surfaces was investigated.

Equipment

The Road Research Laboratory heavy load test vehicle was used for these tests. For a description of this device see Reference #20. The surfaces were wetted with a sprinkler system.

Road Surfaces

Four surfaces at the Road Research Laboratory test track were tested:

(1) Smooth concrete - smooth macrotexture, polished microtexture, water depth .015-.03 inch.

(2) Fine cold asphalt - smooth macrotexture, harsh microtexture, water depth .005-.035 inch.

(3) Quartzite macadam - rough macrotexture, harsh microtexture, water depth .005-.045 inch.

(4) Rounded gravel macadam - rough macrotexture, polished microtexture, water depth .015-.035 inch.

Tires Tested

A 35 x 10 x 17 aircraft tire having five ribs 1 1/8 inch wide and four grooves 3/16 inch wide and .264 inch deep was tested.

Test Procedure

The test wheel brake was gradually applied until lockup while vehicle speed, test wheel angular velocity, and braking force were recorded. Tests were performed on each surface at speeds of 10, 30, and 56 mph and at inflation pressures of 40 and 160 psi. Tire load was 3.5 tons for all tests.

Technique for Analyzing and Presenting Data

Braking force coefficient and the corresponding values of wheel slip were derived from the recorded data. Plots of BFC versus slip for each combination of surface and inflation pressure with speed as a parameter are presented.

Conclusions

(1) The ratio of peak to locked wheel BFC increases with increasing speed and is higher on smooth textured surfaces.

(2) Peak BFC occurs at about 15-20% slip.

(3) On smooth surfaces at the speeds and water depths used in this work, an increase of inflation pressure causes a decrease in both peak and locked wheel BFC.

(4) Inflation pressure has no effect upon the initial slope of the BFC versus slip curve.

Reference #37

T. Williams, J.K. Meades, and B.S. Riley

"The Wet Road Grip of Lorry (Truck) Tires: A Comparison of Three Types"

Transport and Road Research Laboratory, Report LR 544, 1973

Goal of Tests

To evaluate the wet road cornering and braking friction of three types of truck tires and to compare these with a typical automobile tire.

Equipment

A truck, with only the front wheel brakes operative, instrumented to measure speed, lateral and longitudinal acceleration, roll and pitch angle, steering wheel angle, and vehicle side slip angle was used for these tests.

Road Surfaces

Three test surfaces at the Road Research Laboratory were used:

(1) Mastic asphalt, average texture depth = .04 mm.

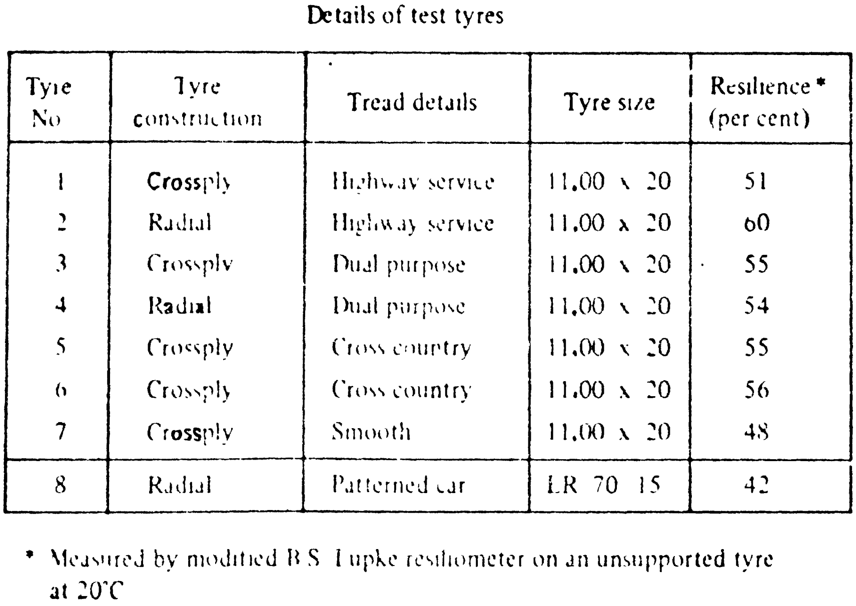
(2) Smooth concrete, average texture depth = .2 mm.

(3) Rounded gravel macadam, average texture depth = 1.5 mm.

Cornering tests were done on surfaces (1) and (3); braking tests were done on all three surfaces.

A sprinkler system was used to maintain a water depth of about .5 mm above the asperities.

Tires Tested



Details of test tyres

Tyre No	Tyre construction	Tread details	Tyre size	Resilience* (per cent)
1	Crossply	Highway service	11.00 x 20	51
2	Radial	Highway service	11.00 x 20	60
3	Crossply	Dual purpose	11.00 x 20	55
4	Radial	Dual purpose	11.00 x 20	54
5	Crossply	Cross country	11.00 x 20	55
6	Crossply	Cross country	11.00 x 20	56
7	Crossply	Smooth	11.00 x 20	48
8	Radial	Patterned car	LR 70 15	42

* Measured by modified B S Lupke resiliometer on an unsupported tyre at 20°C

Test Procedure

Cornering friction was evaluated by measuring maximum lateral acceleration obtainable at 15, 20, and 25 mph in a J-turn maneuver.

Peak and locked wheel brake force coefficients were obtained by measuring vehicle deceleration as the front brakes were gradually applied at a speed of 10 to 65 km/hr.

Inflation pressure was 75 psi for all tests.

Tire loads of 2450 lbs and 2800 lbs were used for the cornering tests. A load of 2450 lbs was used for all braking tests.

For purposes of comparison, brake force coefficients were measured for an automobile tire using a front wheel braked car.

Technique for Analyzing and Presenting Data

The cornering test data is presented in the form of plots of maximum lateral acceleration versus speed and plots of lateral acceleration versus slip angle.

The braking test data was presented in the form of plots of peak and locked wheel brake force coefficient versus speed.

Conclusions

(1) Marked differences in traction performance were found between the three types of truck tires, the order of merit being: (1) highway tires, (2) dual purpose tires, (3) cross country (off-road) tires.

(2) The automobile tire was far superior to the best truck tire. The peak brake force coefficient for the automobile tire on wet mastic asphalt was twice that obtained for the highway-type truck tire.

(3) These differences are due primarily to differences in tread pattern.

Reference #38

Report of the National Safety Council Committee on Winter Driving Hazards, 1967, 1968, 1969-1970.

Goal of Tests

To evaluate the braking, driving, and cornering performance of tires on ice. The effects of the following variables were investigated:

(1) studs

(2) tire load

(3) ice temperature

(4) tire construction (bias, belted bias, radial)

(5) studded tire wear

(6) sipes (knife-cuts on the tread).

Many experiments not concerned with tire friction, such as a test of an anti-jackknife device for trucks, were also performed. Only the tire friction experiments are discussed here.

Equipment

Instrumented automobiles were used to measure locked wheel stopping distances and cornering performance. Friction trailers were used to evaluate locked wheel friction and cornering friction. A dynamometer truck was used to evaluate driving traction.

Road Surfaces

All tests were done on smooth clear ice while ice surface temperature was recorded.

Tires Tested

Three regular highway tread, bias ply, tires; one new unstudded, one new with 80 studs in 4 rows, and one studded and worn by 2500 miles of driving on clear roads.

Three bias ply snow tread tires; one new unstudded, one new with 110 studs in 6 rows, and one studded and worn by 2500 miles of driving.

Nine unstudded, highway tread tires, one bias ply, one bias-belted, and one radial ply from each of three manufacturers.

Test Procedure

Tests with the cornering trailer and the locked wheel skid trailers were done at 20 mph with a tire load of 1085 lbs.

Cornering friction was evaluated by measuring the maximum speed that could be maintained on a 200 foot radius skid pad.

Tractive friction performance was evaluated by measuring draw bar pull force developed by an automobile pulling a dynamometer truck. Values of friction were measured at incipient wheel spin (peak value) and for a wheel spinning at 300% slip.

Locked wheel stopping distances were measured from an initial speed of 20 mph.

Ten runs were averaged to obtain each data point.

Ice temperature was recorded during all the tests.

A control tire consisting of an unstudded, bias ply, highway tread tire made from ASTM E-17 rubber was used to insure data reproducibility.

Conclusions

(1) The new studded snow tire having 110 studs developed about twice as much locked wheel friction as the new unstudded snow tire.

(2) A new studded highway tread tire having 80 studs developed 45% higher locked wheel friction than the unstudded highway tread tire.

(3) There is little, if any, difference in frictional performance on ice between unstudded highway tread tires and unstudded snow tires.

(4) After 2500 miles of normal uniform wear the studded tires lost about 15% of their friction relative to the new tire.

(5) On 25°F ice at 20 mph, an increase in tire load from 1085 to 1273 lbs. caused a loss of about 10% in locked wheel friction. Also, stopping distance tests show that heavier vehicles have longer stopping distances.

(6) On 25°F ice, studded tires on all four wheels improve cornering friction by about 50% over that for regular highway tread tires. This corresponds to a 24% improvement in cornering speed.

(7) Studded tires on the rear wheels only, or on the front wheels only, give no improvement in cornering.

(8) On 25°F ice a studded snow tire having 110 studs will produce about twice as much tractive (driving) force as a regular highway tread tire both at incipient spin (peak friction) and in the spinning condition. However, peak friction is about 10% higher than spinning friction for studded tires.

(9) There is no significant difference between unstudded bias ply, belted-bias, and radial ply tires on smooth ice.

(10) Skid trailer tests at 20 mph on 25°F ice show that siped tires produce about 20% higher values of locked wheel friction than unsiped but otherwise identical tires.

(11) Braking distance tests from 20 mph on 25°F ice show that the use of new studded snow tires on the rear wheels of a vehicle reduces stopping distance by 25% of that for similar unstudded tires. After 2500 miles of wear, the improvement is reduced to 19%.

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