NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM 1416

TESTS TO DETERMINE THE ADHESIVE POWER OF PASSENGER-CAR TIRES

By B. Förster

Translation of "Versuche zur Feststellung des Haftvermögens von Personenwagen-Bereifungen," Deutsche Kraftfahrtforschung, Technischer Forschungsbericht, Zwischenbericht Nr. 22

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1. INTRODUCTION

The concept of the adhesive power of a tire with respect to the road involves several properties which result from the purpose of the tire; namely, connecting link between vehicle and road:

(1) The tire must transfer the tractive and braking forces acting in the direction of travel (tractive and braking adhesion).

(2) The tire is to prevent lateral deviations of the vehicle from the desired direction of travel (track adhesion).

Moreover, the rubber tire provides part of the springing of the vehicle. Above all, it has to level out the minor road irregularities; thus it smoothes, as it were, the road and simultaneously reduces the noise of driving. The springing properties of the tire affect the adhesive power.

The tests described below comprise a determination of the braking and track adhesion of individual tires. The adhesion of driven wheels has not been investigated so far.

*"Versuche zur Feststellung des Haftvermögens von Personenwagen-Bereifungen", Deutsche Kraftfahrtforschung, Technischer Forschungsbericht, Zwischenbericht Nr. 22.

NACA reviewer's note: The investigation reported herein is for automobile tires rather than airplane tires, and the tire sizes are not such as would be of general interest to the aeronautical industry. Nevertheless, the data do serve to indicate certain basic aspects of tire behavior and should be of interest to those concerned with the study of tire braking and cornering characteristics.

In braking a wheel with a rubber tire, the circumferential force may be increased to a maximum value at which the wheel is still barely rolling; if the brake is applied more strongly, the tire slides on the road without rolling. This condition is called "sliding friction" in what follows; the maximum value of the friction force for a rolling wheel is called "adhesive-friction value." Since in most cases the sliding-friction force is smaller than the maximum adhesive-friction force, the adhesive friction has to be regarded as a neutrally stable condition, the maximum value of which is attainable only under especially favorable circumstances. Otherwise, in the case of disturbances of the uniform run, for instance, due to road unevenness, a sudden transition to complete sliding takes place, at least when the customary types of brake construction are used, where locking of the wheel in the case of strong brake actuation can not necessarily be avoided.

In the case of rubber tires deformable in the transverse direction, forces acting laterally on the vehicle cause an additional motion of the wheel parallel to the axle, thus perpendicular to the intended direction of travel as indicated by the wheel plane. Such lateral forces appear in all steering motions, in the case of curvilinear travel, and also when the road is laterally inclined or cambered, and in the case of a cross wind. The actual direction of travel then results by geometrical addition of the lateral velocity and the traveling velocity of the wheel center point in the direction of the wheel plane. The angular deviations from the intended direction of travel may become so large under certain driving conditions, for instance, in sidewise skidding, that the sideward motion exceeds the forward motion of the wheel during the same time.

A number of factors affect the magnitude of the peripheral and lateral forces which can be transmitted between wheel and road, and of the friction coefficients which are to be determined by dividing these forces by the vertical force acting in the contact area between wheel and road:

(1) Properties of the tire:

Rubber mixture and vulcanization, admixtures, profile and state of wear, size and construction of tires, width and depth of rim, inflation pressure

(2) Properties of the road:

Material and type of construction of the road surface, wear and condition of surface (wetness, soiling, snow, ice)

(3) Cumulative effect of tire and road:

Wheel loading, traveling speed, mass relations, and springing of the vehicle.

As a result of the diversity of these influences, and because of considerations of the weather conditions, the investigations carried out by the Test Institute had to be limited to varying part of the parameters each time. Several hundred individual tests were performed in order to obtain a general picture of the dependence of the friction values and of the lateral forces on the test conditions.

In the present intermediate report we shall, after description of the test setup, first of all present a few test results.

2. EARLIER TESTS

For the determination of adhesive power, a number of investigations had already been carried out; their bases and results have been discussed and reproduced in part by G. Weil (ref. 1). However, the previous tests were carried out, for the greatest part, from the point of view of road construction and take, especially, related interests into consideration without discussing more closely the questions which are of interest to the manufacturer and user of tires. The tests of Schenck and Weil as well as the work of Agg and of Bradley and Allen always have been carried out only with a narrowly limited number of tires and, to some extent, with little used sizes of tires. The last mentioned tests are even limited expressly to smoothly worn motorcycle tires so that profile influences were not examined in these tests. Also, the velocity range investigated so far does not cover the speeds of normal driving traffic and is too narrow to allow conclusions regarding the behavior at higher speeds. The tests published by Kamm, which were carried out up to velocities of 160 km/h on the road, are deceleration braking tests. The braking decelerations attained in these tests could not be used for the determination of friction values between tire and road.

The following considerations governed the selection of the test method: Deceleration braking tests on standard motor vehicles require only little preparation and can be quickly executed; however, it is not possible, even for a skilled driver, to maintain the maximum attainable deceleration during the entire braking process. Thus, even when the brakes are adjusted so that the variation in wheel load with braking is taken into consideration and when, moreover, the deceleration is continually recorded instead of the mean deceleration being determined from initial velocity and braking, the adhesive-friction values appearing between tire and road cannot be calculated with certainty from these deceleration values. This is possible for sliding friction on all four wheels, that is, for locked wheels, within certain limits. However, here the tests are limited to moderate initial velocities because of the heat developed in the contact area and because of the wear of the tires. More reliable results may be obtained by towing tests, performed both with entire vehicles or with single wheels or pairs of wheels. However, towing tests with complete vehicles as carried out at Iowa University are also limited to relatively low speeds. Here also it is difficult to obtain uniform adjustment of all four wheels to the maximum possible braking moment.

Therefore it appeared most promising, also with regard to a quick change of tires, to perform the tests by means of a special single-wheel towing axle. This measuring arrangement also makes it possible to determine, in a simple manner, the lateral forces which are transferred and the lateral velocities which occur.

3. DESCRIPTION OF THE TEST SETUP

To a $2\frac{1}{2}$ ton Opel-Blitz truck, with a maximum speed of 85 km/h, a single-wheel towing axle is attached by means of a universal joint (fig. 1). In a steel frame, which may be loaded additionally by easily exchangeable weights, an automobile wheel runs on a swinging arm suspended on springs; a brake drum revolves with the wheel hub. The brake shoes are fastened to a brake support which is connected with the axle journel and is supported in ball bearings in the swinging arm. The braking moment transferred from the brake shoes, including the bearing friction of the hub, is transmitted to a measuring gage fixed on the swinging arm, which is connected to a recording manometer by a flexible pipe line. Gradually tightening the brake from the operator's position on the truck, permits increasing the braking moment until the wheel starts sliding. Thus, not the tractive force required for towing is measured, which would contain, in addition, mass forces in accelerated or decelerated driving as well as the air and climbing resistance on not-horizontal roads, but the braking moment including bearing friction. Thus, aside from the force required for overcoming the rolling resistance and the windage loss, the entire force effective on the circumference and utilizable for braking a vehicle is measured in this manner.

To the left side of the towing axle with the tire to be investigated there runs a bicycle wheel which is fastened in a swivellable arm, pressed against the road by a leaf spring, and, like the towed wheel, provided with an electrical-contact transmitter, so that the difference in the angular velocity of the two wheels and, thus, the slip of the braked wheel can be determined.

A lateral-traction device (fig. 1(a)) serves for determination of the lateral forces transmitted from the road to the tire, which are decisive for the safety from sidewise skidding. The frame of the towing axle carries, at the right, a cantilever beam; a cable acts on the latter through a hydraulic tension dynamometer; this cable is attached to a winch on the truck by means of which the wheel can be laterally deflected up to 30° from the direction of travel. By the attachment of a second cantilever beam which swivels about the vertical hinge axis, it is assured that the force on the frame always acts parallel to the wheeel plane and that the lever arm of the force indicated by the tension dynamometer always remains constant with respect to the hinge axis.

Since, in the case of a deflection of the towed wheel to the right, the rear end of the towing automobile is pushed a little to the left, the longitudinal axis of the automobile, then, does not coincide with the direction of travel. The deflection of the towed wheel from the direction of travel is therefore not equal to the angle formed by the towing axle and the truck. For this reason, the bicycle wheel serving for comparative measurements is also attached flexibly to the truck. The attachment arm indicates the actual direction of travel since, aside from the driving resistance of the bicycle wheel, only insignificant external forces act on this arm. The variation of the angle between the towing axle and the bicycle-wheel cantilever is transferred to the recording device by means of a rack and pinion gear transmission.

The places for the operating crew as well as the recording apparatus are situated on the platform of the truck. The latter carries, moreover, the tires to be investigated and a winch by means of which the towing axle can be raised to facilitate the changing of tires.

With this test setup one can therefore determine the maximum frictional force and the slip during braking of the wheel, the lateral force in lateral deflection, and the pertaining angle between wheel plane and direction of travel. The towed wheel, moreover, may also be simultaneously braked in the case of lateral deflection. Thus the conditions in braking, in driving around curves, and in sidewise skidding of the car may be reproduced, with the forces and motions being measured individually and recorded continuously. No measuring device has been provided for the tire loading ("wheel pressure"); it is determined for every single case from the weights of the towing axle, and the wheel with tire and balance weights. When the wheel is braked, the loading N of the tire becomes smaller than the initial loading N_0 since the moment of the friction force R acting in the road plane has an unloading effect with respect to the universal joint K as can be seen from figure 2. This unloading has been taken into consideration in the calculation of the friction values indicated below.

4. TEST MATERIAL AND TEST PERFORMANCE

(a) Tires

In view of the tire sizes used in Germany most frequently, the test apparatus was built for 16-inch and 17-inch rims which can easily be interchanged. Tires of the following dimensions were investigated:

4.50 × 17	5.25 × 17
4.75 × 17	5.25 × 16
5.00 × 17	

One may assume that with these tire dimensions at least 90 percent of the passenger cars in use in Germany are covered.

Within these dimensions a number of various tread patterns (profiles) were investigated, as manufactured by the tire firms Continental, Dunlop, Fulda, Metzeler, Englebert and Michelin.[1]

Tires with smooth tread, with commercial "standard" profiles, with cross-country profiles, and with nonskid-fine-section profiles of the Continental, Englebert, and Michelin firms were investigated; also tires with fine-section profiles subsequently cut or grooved according to the methods of Sommer-Tecalemit and Ölssner-Christophorus.

The test tires treated in this report are described in table I; some are shown in figures 3 to 5.

The influence of the rubber mixture was not especially taken into consideration in the present tests; however, tires with sago and with quartz admixture (Azo method) were used in the tests for comparison.

(b) Roads

In the tests, particular importance was attached to examining the nonskid properties on not especially prepared test sections; rather, the tests were performed on much travelled roads in and near Berlin. In order not to disturb the rest of the traffic too much, sometimes allowances had to be made for limitations, for instance, regarding speed; but this is outweighed by the advantage that the values determined in this manner are more realistic than would be possible on test sections which are not exposed to other traffic.

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[1]The Continental and Dunlop firms, in particular, supported the tests by furnishing tires; some of the wheels were made available, as a loan, by the Adlerwerken.

Also, the roads were not artificially dampened for the tests, for instance, by sprinkling, or made slippery in some other way. Rather, weather conditions suitable for the tests were awaited.

The following roads were mainly used for the tests:

(1) Charlottenburg Highway (various types of rough asphalt)

(2) Bellevue Avenue (tamped asphalt smoothly polished by traffic)

(3) Spandau Highway (granite small-unit paving bonded with cement)

(4) Military road near Pichelsdorf (sand asphalt, somewhat gripping)

(5) Avus (tarred fine-gravel surface)

(6) Avus (concrete)

(7) Masuren Avenue (rough asphalt)

(8) Reich automobile express highway, Berlin-Stettin (concrete)

A few separate tests were carried out on a number of other roads, particularly in order to determine the adhesive power on snow- and ice-covered roads, where the road surface underneath is only of secondary importance.

In order to limit the number of necessary test runs, the behavior of several tires on a number of road surfaces was first determined by preliminary tests; namely, braking tests without side force. A major number of tests were then carried out, under normal conditions, on two different road surfaces which may be regarded as typical and clearly show the properties of the tires, namely on Bellevue Avenue between Skagerrak Square and Charlottenburg Highway (tamped asphalt with a few patched-up spots) and on the Charlottenburg Highway between Bellevue and Sieges Avenues (coarse poured asphalt). Both roads are subject to a heavy traffic load, but still permitted performance of tests at speeds up to 60 km/h without any great disturbance by the remaining traffic since the sections used are not crossed by other roads.

(c) Loading and Pneumatic Pressure

The tire loading which can be varied in steps by additional weights was made to correspond to that of a 1.5 to 2 liter car for which the tires investigated are suitable, in empty and in occupied condition.

For the greater part of the tests, the tires were loaded to 300 to 310 kg which corresponds, for instance, to the front-wheel loading of an an Adler-Trumpf occupied by four passengers. Further tests were performed with loads of about 170 kg, 240 kg, and, in order to investigate tires also in overloaded condition, of 390 kg. The inflation pressure of the tires was adjusted according to the directions given by the manufacturers. For the normal loading of 305 kg an inflation pressure of 1.5 atmospheres gage was generally used. Moreover, the influence of the tire-inflation pressure was investigated in the range of 1.0 to 2.5 atmospheres gage.

5. TEST RESULTS

(a) Braking

Since the tires are deformable in the tangential direction, no significant circumferential forces between tire and road can be transmitted without a deformation of the tire occurring in entering and leaving the area of contact. Investigations of this subject were made by Schuster and Weichsler (ref. 2). The result found is that under the effect of circumferential forces a slip between tire and road appears which, in the case of small circumferential forces, is not caused by a sliding motion between contact area and road, but is to be explained solely by the elastic deformation of the tire. If larger circumferential forces are present, the adhesion between tire and road is not sufficient to prevent sliding at the points of the contact area where the bearing pressure is not sufficiently high in comparison to the shearing stress in the contact area. Finally, the tire slides within the entire contact area, but is still rolling with reduced angular velocity until at the very last, for the locked wheel, the sliding velocity in the contact area becomes equal to the velocity of travel.

In what follows, we shall understand by the slip σ: The reduction in the angular velocity ω of the wheel, in the case of transmission of circumferential forces, in comparison with the angular velocity ω_0 of the same wheel and for the same velocity of travel without braking, that is,

$$\sigma = \left(1 - \frac{\omega}{\omega_0}\right)100 \quad \text{in percent}$$

Since the speed of travel cannot be kept precisely constant during the braking in the test, the slip was determined by comparison of the number of revolutions of the test wheel and of the reference wheel during the braking with the corresponding number of revolutions before the braking. Since, when the single wheel is braked, the braking moment causes a reduction in tire loading and thus a slight increase of the rolling radius, the slip is seemingly increased. The unloading of the wheel must therefore be taken into consideration in the determination of the slip.

An example of the relationship between the transmitted peripheral force and the slip caused thereby is given in figure 6. In the ordinate the ratio of the peripheral force to the tire loading is represented, that is, the actually utilized interlocking-force coefficient. The maximum value of the transferable braking force is practically reached at slip magnitudes between 10 and 20 percent, and increases from then onward only very slightly. At half the maximum force, a slip of 4 to 5 percent is present. When the speed of travel is increased, the initial upward slope of the curves varies only imperceptibly, but the peak of the friction value $\mu_{\prime\prime}$ and the sliding-friction value μ_B (100 percent slip) are lower. On a wet asphalt road (fig. 7), all friction values are considerably smaller than on a dry concrete road.

Since the road surfaces are only in extremely rare cases completely uniform, scatter in the test values is unavoidable; this is particularly true when the roads are dirty or covered with snow. Uniform values with slight scatter were attained only on the Automobile Express Highway. In all other cases the measured values fluctuated in both directions, sometimes by more than 10 percent. The curves in the figures always indicate mean values.

(b) Dependence of the Lateral Force on the Sideslip Angle

Information regarding safety of the tires from sidewise skidding is given by the variation of the curves of the lateral force as functions of the sideslip angle. Figure 8 shows as an example the variation of the lateral force for a Continental-Record 4.75 - 17 tire for different tire loadings. The character of these curves shows a fundamental similarity: After a steep rise of the lateral force within angles up to 5° or 8°, there follows a flat gradually downward sloping part. For larger angles, one also finds to some extent a downward slope of the curves.

The steepness of the first part of the curve, that is, the increase in force for small angles is almost independent of the speed of travel, of the loading and of the road condition, except for particularly slippery road conditions. On the other hand one finds, as will be shown later, a high-degree dependence on the inflation pressure of the tire and - in the comparison of different tires under otherwise equal conditions - also on the form stiffness of the tire with respect to lateral stresses. As long as only slight lateral forces act on the vehicle, only small "crab angles" of the car appear, independently of the road condition.

One drives therefore comparatively safely even on a smooth road as long as one can avoid having major lateral forces affect the car, due to rapid steering motions, and as long as one drives around curves sufficiently slowly. The danger of sidewise skidding and the possibility of being thrown out of a curve appear when the lateral force acting on the tire, in the case of a major increase in the sideslip angle, does no longer increase at all or does so only insignificantly: In this case countersteering is no longer of help because for maximum wheel-steering angles the tire slides transversely on the road. Particularly dangerous are the road conditions where the rising slope of the lateral-force curve is flatter to begin with, for instance, in the case of light rain or tamped asphalt (figs. 20 and 21) and on glazed ice (fig. 22). For such conditions relatively small lateral forces, as may be caused, for instance, by lateral gusts from crossroads or forest firebreaks, or slight changes in course when encountering or overtaking another vehicle are sufficient to induce a sidewise skidding of the car which cannot be avoided by countersteering.[2] The braking friction, too, is only slight under these road conditions ($\mu_h = 0.09$ to 0.16 in the case of glazed ice) so that the car can be controlled only at small driving speeds.

It is known that braking while rounding a curve may lead to sidewise skidding because the cornering ability of the tire is reduced in that case. This phenomenon is represented in figure 9; the wheel has been braked twice with different amounts of force and has been laterally deflected. For a small amount of braking with 17 mkg ($\mu_B = 0.2$), the lateral force increases up to a sideslip angle of 16°, is therefore stable, with a maximum value of $\mu_s = 0.67$ which corresponds to a transferable lateral force of about 200 kg. The stronger braking with $\mu_B = 0.37$ in the second test reduced the lateral-force coefficient to $\mu_s = 0.46$ or 140 kg, respectively; the maximum value here is attained already at 10° deflection. Turning the steering wheel through a larger angle would therefore in this case no longer pull the car back into the curve; only releasing the brake can help. Both figures show the resultant of the interlocking-force (friction) coefficient obtained by geometrical addition of the two forces acting at right angles. It is notable that the maximum lateral-force coefficient without brake actuation lies at $\mu_s = 0.7$, thus as high as the resultant in the upper figure; in the case of a stronger braking the resultant drops to $\mu = 0.59$. For a braking without lateral force, an adhesive-friction coefficient of $\mu_H = 0.78$, and a sliding coefficient of $\mu_G = 0.62$ were measured on this road surface (smooth, dry tamped asphalt).

[2]The influence of the position of the center of gravity and of the wheel steering on sidewise skidding will be discussed in the next report.

(c) Influence of the Wheel Loading

In the range of small "crab angles" up to 4°, a variation in load is almost without influence on the magnitude of the lateral force, on a dry road as well as on a wet gripping road surface; however, in the case of smaller tire loadings, the limit of track adhesion is reached more quickly than in the case of a large load, as may be seen also from figure 8. However, expressing the lateral forces in terms of the corresponding tire loads one finds that the highest lateral-force coefficients deviate only slightly from one another. The same is true on a slippery road (fig. 10) and on solidified snow (fig. 11).

(d) Influence of the Speed of Travel

On a dry and on a wet gripping road, the traveling speed has only an insignificant effect on the lateral forces, that is, on the track adhesion, at deflection angles smaller than 6° to 8° (figs. 12 and 13). The maximum value of the lateral force decreases with the speed of travel; it became clear that tires permitting lateral deviation of the displaced air (C9, F2) were slightly less sensitive to speed than the tire D5 which was provided only with longitudinal grooves.

Braking tests on a dry level road (figs. 14 and 15) resulted only in a moderate reduction of the adhesive-friction coefficient for increasing speed; the sliding friction for locked wheels decreased even more. Whereas at low driving speeds, even on a slippery road, (cf. fig. 7), the difference between adhesive and sliding friction is only slight, a marked reduction of the interlocking-force coefficient in the transition to sliding was observed for higher speeds. This may be traced back partly to the heating in the sliding surface by which the rubber becomes smeary and finally burns; partly the reason is that the smallest road obstacles are no longer imbedded by the tire in sliding but that the tire jumps over them.

On a wet slippery road the transmitted brake and lateral forces decrease markedly with increasing traveling speed (figs. 16 and 17) so that above a certain velocity safe driving is no longer possible; however, this limiting speed may be influenced by the construction of the tire running surface. A fine-section profile tire, in particular, causes a smaller reduction of the friction coefficient with increasing driving speed.

At low speeds (6 to 10 km/h) where the tire has sufficient time to penetrate the smeary film on the road, only small differences can be observed between wet and dry roads, whereas on a solidified snow surface and on glazed ice the friction coefficients are small, even at low driving speeds.

(e) Influence of the Tire Size and the Pneumatic Pressure

Within the range of investigated tire sizes, an influence of the size on the adhesive and sliding-friction coefficients in braking, for otherwise equal test conditions, could not be determined. However, since larger tires have a smaller lateral flexibility, the rising slope of the lateral-force curves becomes steeper at small angles (fig. 12). The deformability of the tires depends especially on the number of cord layers in the sides of the tire. For a tire-inflation pressure of 1.5 atmospheres gage and a load of 300-310 kg, the following values were established for the rate of increase of the lateral force with the angle of deflection (as mean values from several tests):

Tire Size	Rate of increase in lateral force
4.50-17	25 kg/°
4.75-17	28 kg/°
5.00-17	33 kg/°
5.25-17	44 kg/°
5.25-16	30 kg/°
5.25-16 (Buna)	36 kg/°

These values apply, as can be seen from the lateral-force curves, only for small crab angles up to 2°, because larger angles between the direction of travel and wheel plane can no longer be taken up by deformation of the tire so that in this case sliding motions in part of the tire contact area occur.

Since an increase in inflation pressure hardens, aside from the vertical springing, also the lateral springing of the tire, this also becomes manifest in a stronger increase in lateral force at small angles (figs. 18 and 19). Under a loading of 305 to 310 kg, the following effect of the pneumatic pressure was determined:

Tire	Size	Increase in lateral force					
		Inflation pressure	1.0	1.5	2.0	2.5	Atmospheres gage pressure
C2	4.75-17		22	28	34	40	kg/°
C7	5.00-17		26	33	39	45	kg/°

This marked dependence on the inflation pressure corresponds to the phenomenon observed by any driver that, in the case of too low pressure, the car shows a tendency toward "crabbing" even on a dry road.

The limiting values of brake force and lateral force are likewise affected by the inflation pressure. On a dry tamped-asphalt surface, for instance, the following adhesive- and sliding-friction coefficients were measured in braking tests:

Tire C2 for 305 kg loading and 35 to 40 km/h

Inflation pressure, atmospheres gage pressure	1.0	1.5	2.5
Adhesion coefficient μ_H	0.85	0.77	0.73
Sliding coefficient μ_G	0.73	0.62	0.57

On a wet tamped-asphalt surface, also, an improvement in the interlocking forces was found when the inflation pressure was reduced:

Tire C7 with 307 kg loading at 30 km/h

Inflation pressure, atmospheres gage pressure	1.0	1.5	2.0	2.5
Adhesion coefficient μ_H	0.43	0.39	0.42	0.30
Sliding coefficient μ_G	0.35	0.30	0.33	0.30

The variation of the lateral-force values with the tire-inflation pressure on different road surfaces for the unprofiled tire C7 is represented in figures 19 and 20.

(f) Influence of the Road Surface

On dry roads, one finds considerable differences in the friction coefficients according to the type of construction and the age, that is, the previous traffic load the road surface had been exposed to. The adhesive-friction coefficients fluctuate in these tests from $\mu_H = 1.1$ on a gripping concrete or coarse-asphalt road to $\mu_H = 0.6$ on tamped asphalt made smooth by traffic.

The most marked differences, however, are caused by the various road conditions (fig. 21). The smallest friction coefficients were found on glazed ice (fig. 22), on snow covering made slippery by traffic, independent of the paving underneath (figs. 11 and 23), and on moist asphalt, particularly when it starts raining (figs. 20, 21, and 24). In the last case, the dust layer lying on the road after a long dry spell turns, when hit by a small amount of fluid, into a smeary film which cannot be penetrated by the tire at moderately high driving speeds, if the tire does not, due to a particular profile, have spots with high contact pressure and favorable possibilities for escape of the displaced fluid.

On the other hand, no danger exists due to wetness and smeary film on coarse road surfaces (concrete, small-unit paving, coarse asphalt), as can be seen from figures 8, 13, and 19. Obviously, here no continuous smeary film can develop, and the tire always finds spots where dry friction occurs.

An uneven road surface which when passed causes large fluctuations of the vertical force between tire and road, reduces the transferable circumferential and lateral forces, particularly at high speeds where the irregularities make the tire jump. This is mostly the case on non-filled-in small- and large-unit pavings.

(g) Influence of the Tire Tread

On a dry and rough road, the differences in the profile of the tires do not have a strong influence on the adhesive-force coefficients in braking as long as the remaining test conditions are kept constant. At a driving speed of 40 km/h, the adhesive-friction coefficients on these surfaces lie to the greatest part between 0.8 and 1.0, the sliding-friction coefficients between 0.65 and 0.85. On smoother road surfaces, the friction coefficients are smaller; dry tamped asphalt yields adhesion coefficients of 0.65 to 0.85 and sliding coefficients of 0.55 to 0.65, with the smaller values stemming from tires without profile or with large-area patterns. Tires with a fine-section profile or suitably subdivided profile can resist larger peripheral forces. This is true to an even higher degree in the case of a slippery road (fig. 24). The lowest values here are from the smooth tire; the highest lateral force was transmitted by the tire C12 which is provided with discontinuous narrow transverse grooves, similar to the Sommer process, and somewhat wider longitudinal grooves (fig. 4). This tire proved to be superior to the Sommer-type tire C9 and even more to the tire C8 which is provided with Christophorus-nonskid-tread (longitudinal cuts on the tire tread). On coarse asphalt, in contrast, tires without profile show the highest adhesion coefficients, especially at low tire-inflation pressure.

As a supplement to the lateral-force curves of figure 24, we shall give here braking-friction coefficients measured under the same test conditions:

Tire	C7	C8	C9	C12
Adhesion coefficient μ_H	0.19	0.37	0.8	0.85
Sliding coefficient μ_G	0.17	0.20	0.59	0.62

For this road condition, the braking-friction coefficients were therefore more than twice as large as the lateral-force coefficients for all tires, whereas otherwise on dry as well as on wet roads the maximum lateral-force coefficients generally lie between the adhesion and sliding coefficient of the same tire on the same road.

In the case of glazed ice (fig. 22), none of the tire treads which were investigated was sufficient for a force transmission that would be safe to an appreciable extent. The adhesive-friction values lie between $\mu_H = 0.13$ to 0.16; for sliding, these values dropped to $\mu_G = 0.09$ to to 0.14. Neither fine-section profile nor admixture of quartz (in the P-tires) could attain better adhesion.

On snow solidified by traffic, the interlocking forces are somewhat more favorable (fig. 23). The cross-country tire C5 which had been particularly effective on soft snow showed here too a certain superiority; however, on a dry road the greater deformability of the cross-country profile causes a slightly lesser increase in lateral force which for equal lateral forces brings about larger "crab" angles.

In the present investigations, the adhesive power of the tires was found to be influenced to a great extent by the design of the tire tread, by the tire inflation pressure, by the traveling speed, and by the road conditions. The influence of the springing of the vehicle, and the difference in the adhesive- and sliding-friction coefficients of two tires running behind one another in the same track have not been investigated so far.

Translated by Mary L. Mahler
National Advisory Committee
for Aeronautics

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TABLE 1

LIST OF THE TEST TIRES (AS FAR AS MENTIONED IN THIS REPORT)

Symbol	Manufacturer	Designation	Size	Remarks
C1	Continental	Aero	5.25-16	
C2	Continental	Balloon	4.75-17	
C3	Continental	Balloon	4.50-17	
C5	Continental	Type Aero (cross-country)	4.75-17	
C7	Continental	Test tire without profile	5.00-17	
C8	Continental	Test tire without profile	5.00-17	With Christophorus nonskid tread
C9	Continental	Test tire without profile	5.00-17	With Sommer nonskid tread
C12	Continental	"FP"	5.00-17	
D5	Dunlop	Magnos	5.25-16	
D8	Dunlop	Supra Gelände (cross country)	4.75-17	
F2	Fulda	Double balloon	5.25-17	
M1	Metzeler	Standard	4.75-17	
N1	Michelin	Super-Comfort-Stop	5.25-16	
P4	Peters Pneu Renova	Tread renewed (cross-country profile)	5.25-16	With Azo-quartz
P8	Peters Pneu Renova	Tread renewed (standard profile)	5.25-16	With Azo-quartz

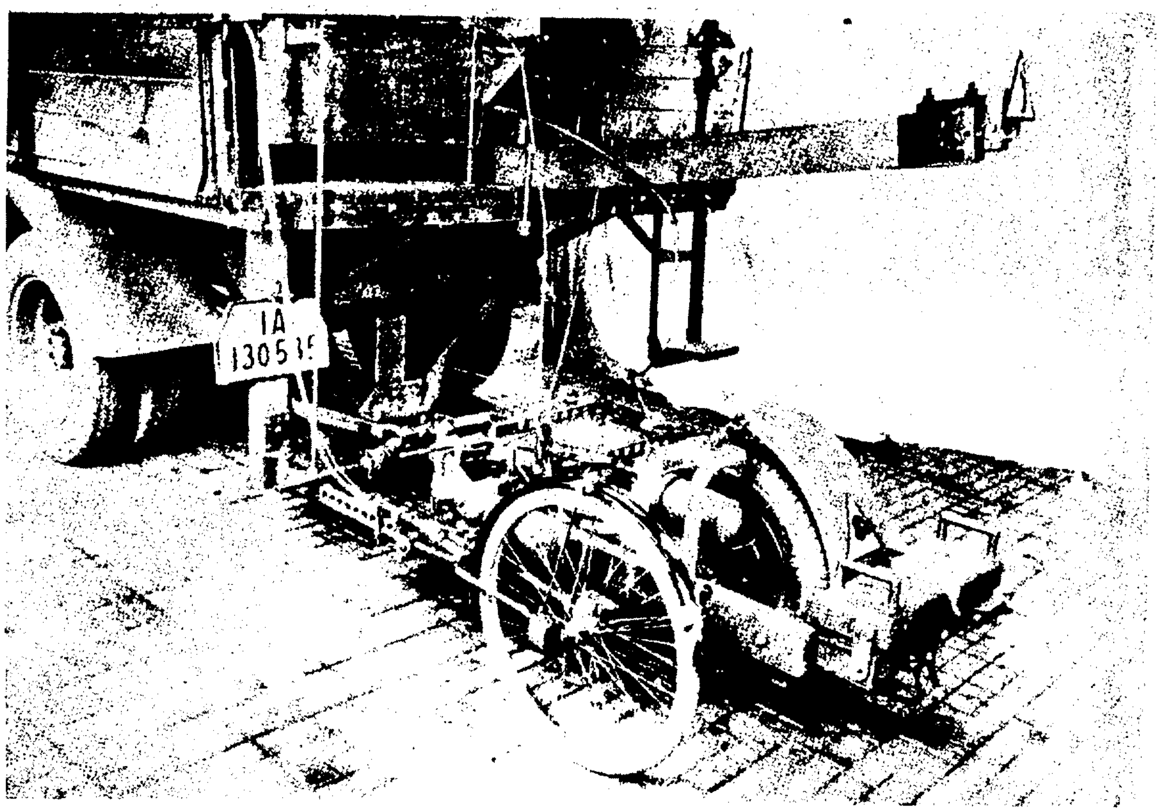


Figure 1.- Towed axle.

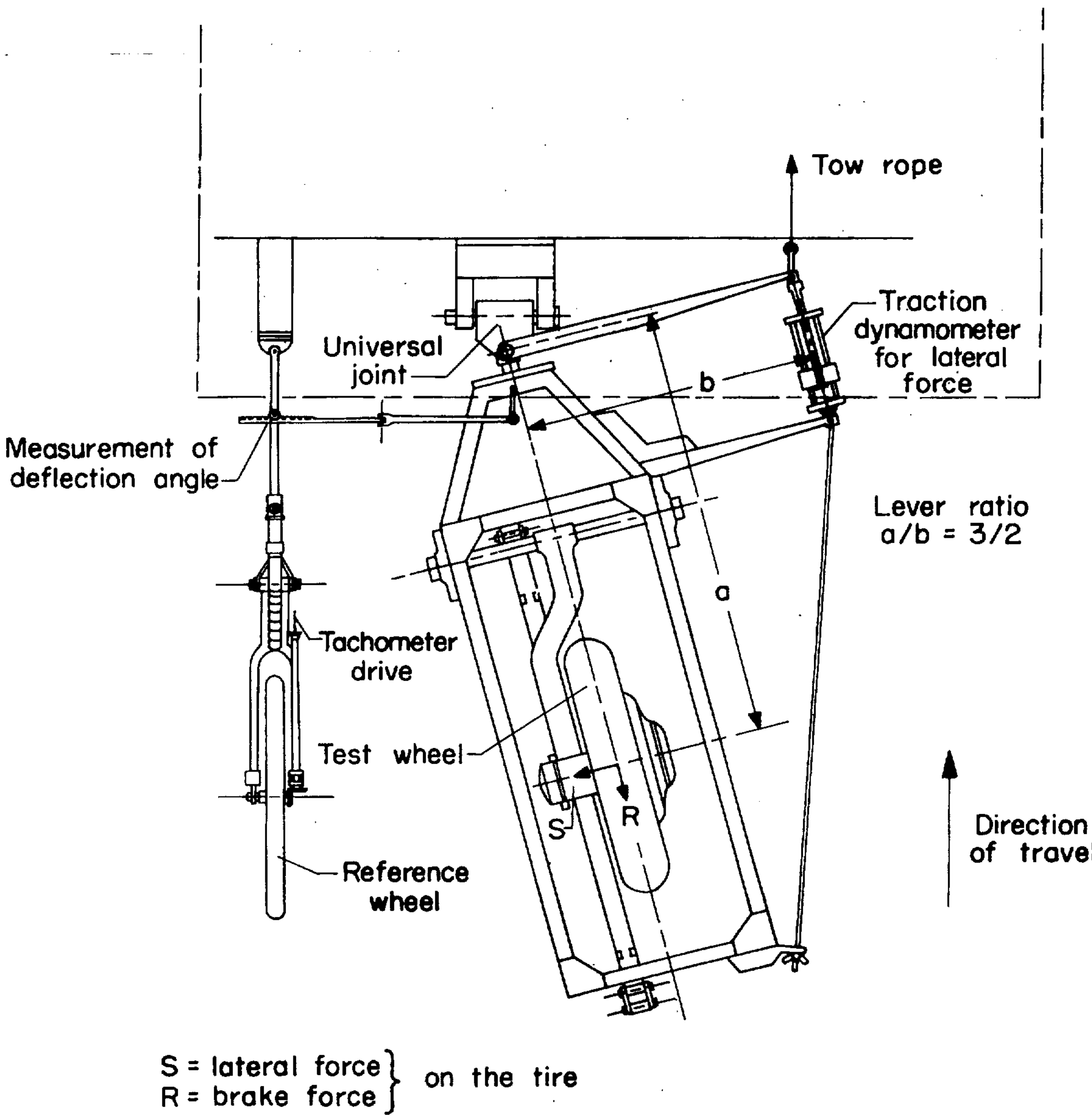
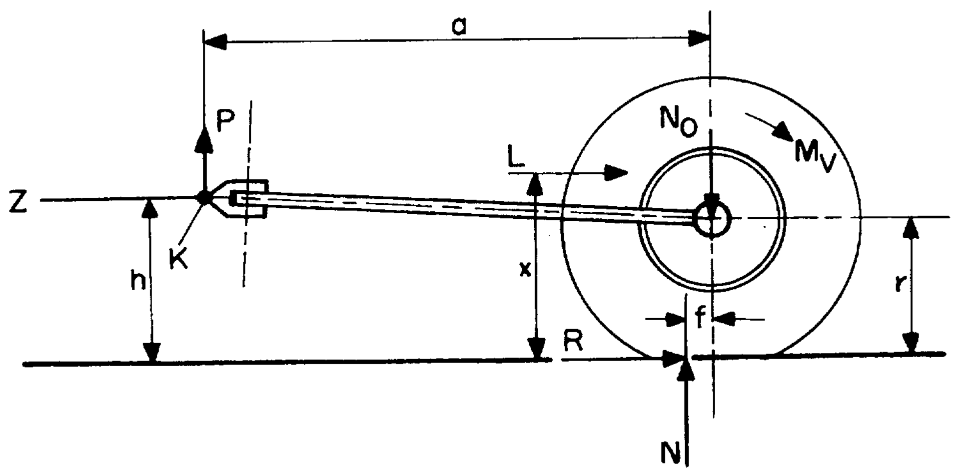


Figure 1(a).- Test setup for measurement of lateral force.



Friction coefficient (interlocking-force coefficient):

$$\mu = \frac{R}{N} \quad \text{where} \quad N = N_0 - P$$

Rolling resistance: $N \frac{f}{r}$

Air resistance: L; height of center of pressure x unknown

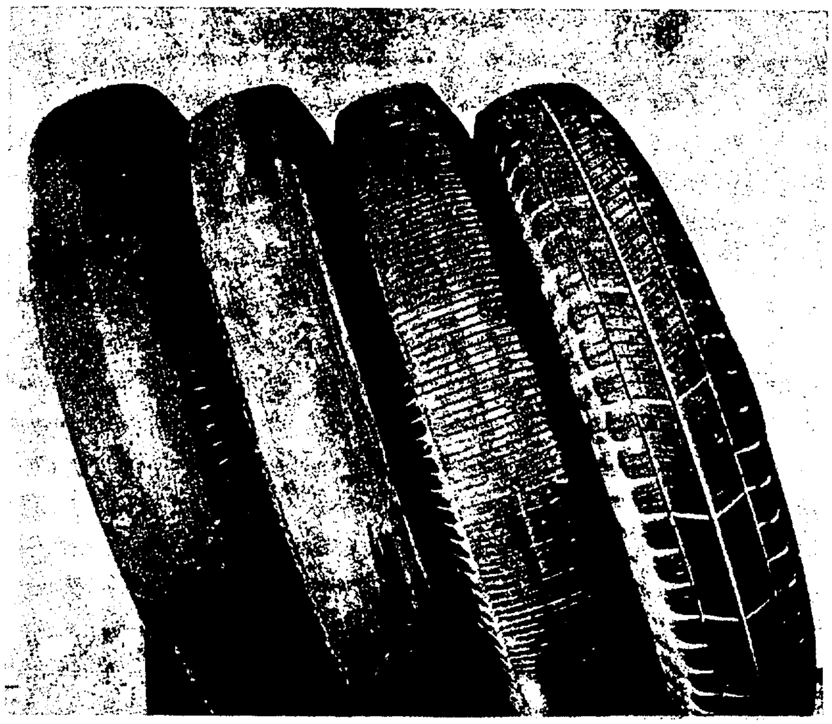
Windage moment: M_V

Unloading of the tire in braking: $P = \frac{1}{a}(Rh - Nf - L(x - h) - M_V)$

Figure 2.- Forces on the towed axle.

C 1	C 2	C 3	C 5
Continental	Continental	Continental	Continental
"Aero"	"Balloon"	"Balloon"	"Cross country"
5.25-16	4.75-17	4.50-17	4.75-17

Figure 3.- Test tires (standard and cross-country profiles).



C 7	C 8	C 9	C 12
Continental test tire 5.00-17 without profile	Continental test tire 5.00-17 with Christophorus nonskid tread	Continental test tire 5.00-17 with Sommer-type nonskid tread	Continental test tire 5.00-17 FP-tire

Figure 4.- Test tires (fine-section profiles).

D 5	E 3	N 2	F 3
Dunlop	Englebert	Michelin	Fulda
"Magnos"	"Supergrip"	"Super-Comfort-Stop"	"Balloon"
5.25-16	4.75-17	5.25-16	4.75-17

Figure 5.- Test tires (various profiles).

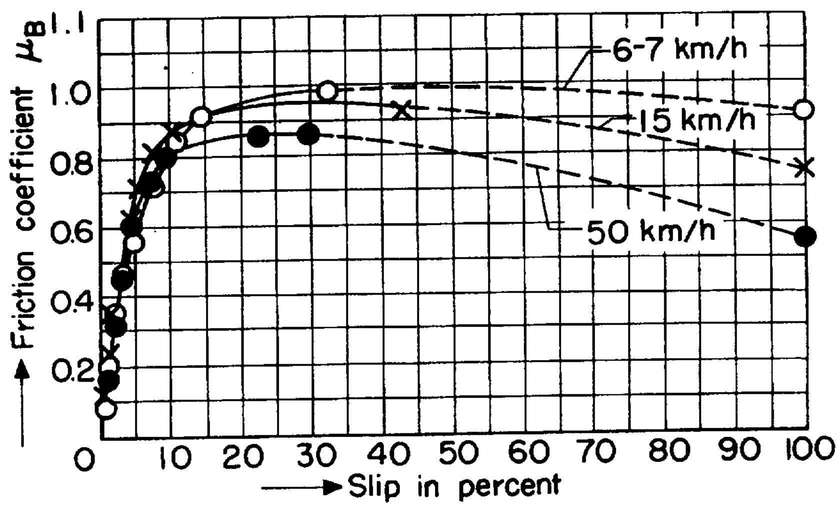


Figure 6.- Relationship between slip and friction coefficient at various driving speeds on the Berlin-Stettin Automobile Express Highway. Tires, C 3; tire inflation pressure, 1.5 atmospheres gage; tire loading, N_0 = 304 kg; concrete, dry.

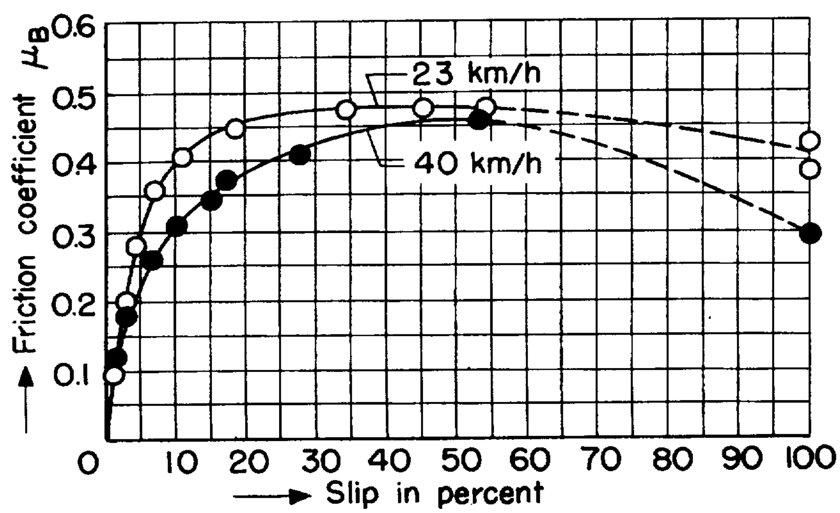


Figure 7.- Relationship between slip and friction coefficient at various driving speeds on a wet asphalt road. Tires, M 1; tire-inflation pressure, 2.5 atmospheres gage; tire loading, N_0 = 390 kg; tamped asphalt, wet.

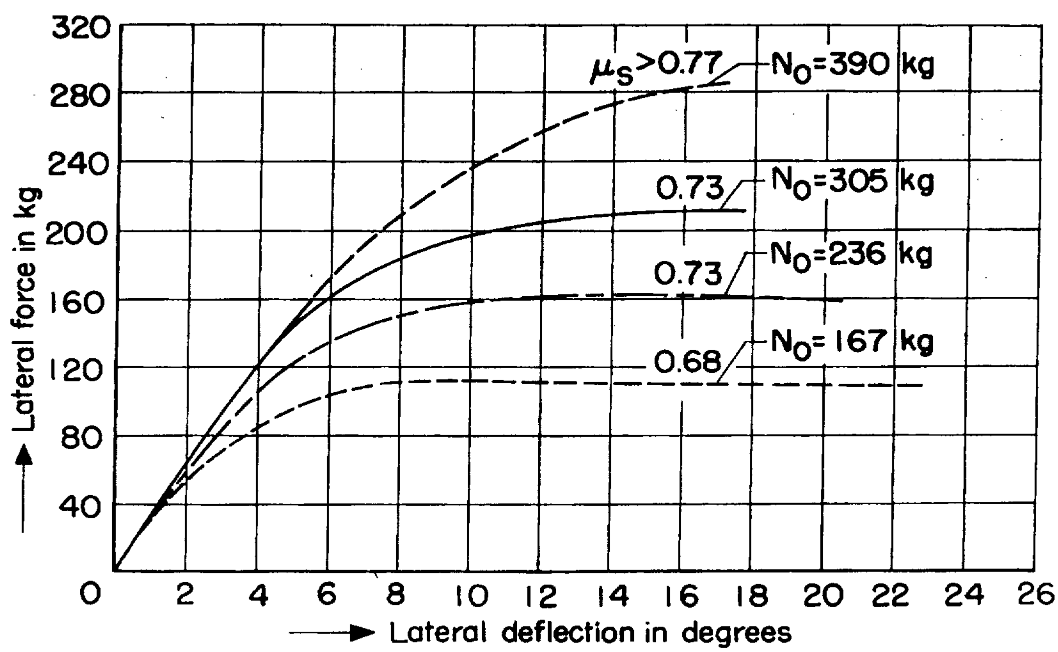


Figure 8.- Influence of the loading on the lateral force on a wet road. Tires, Continental-Record C 2 4.75-17; tire-inflation pressure, 1.5 atmospheres gage; traveling speed, 20 km/h; road, gripping asphalt, wet, light rain.

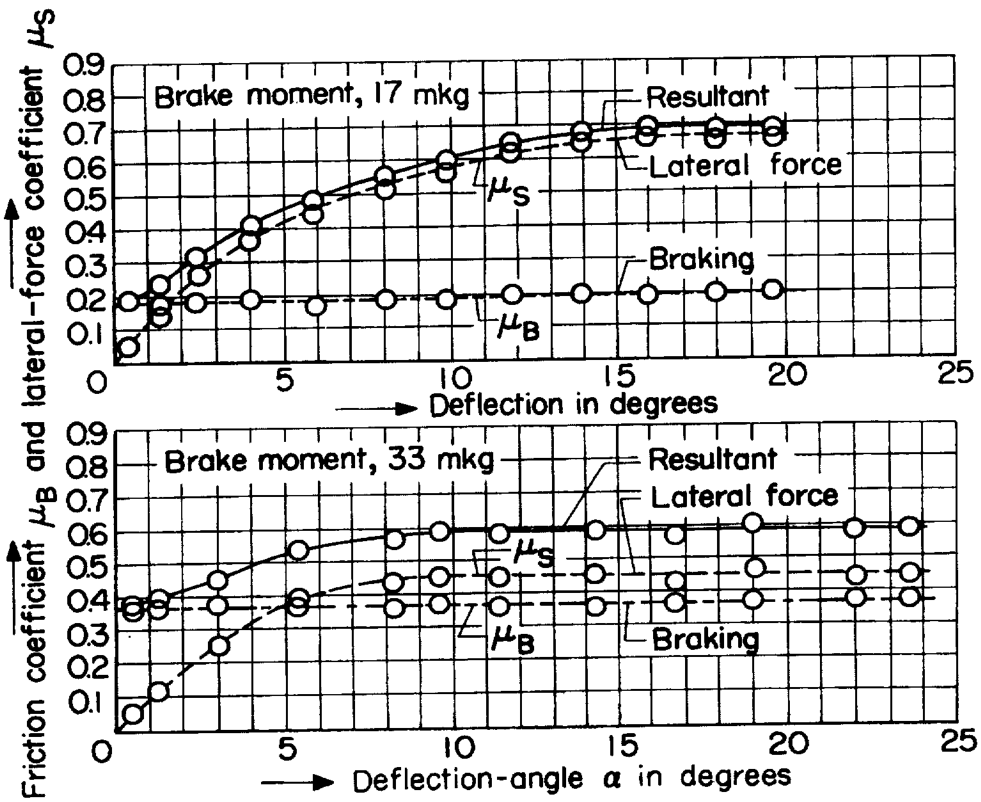


Figure 9.- Lateral force with simultaneous braking. Dependence of the friction coefficient on the lateral-deflection angle. Tires, C 2; tire-inflation pressure, 1.5 atmospheres gage; V = 30 km/h; N_0 = 305 kg; tamped asphalt, dry.

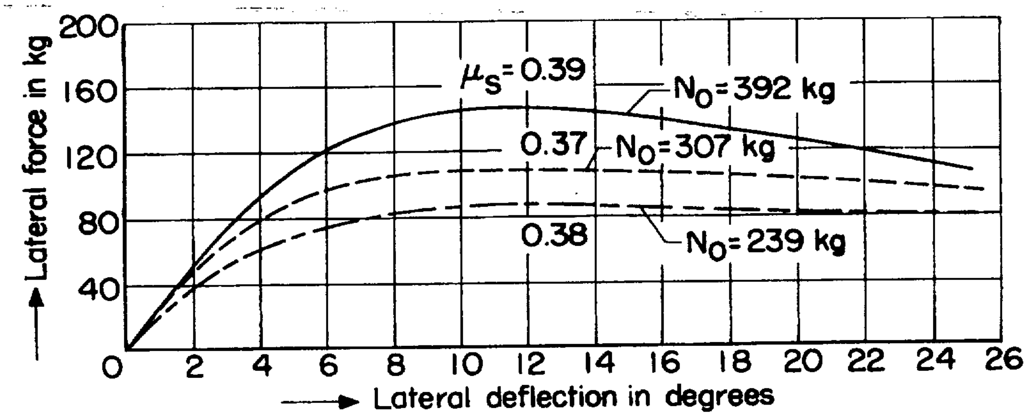


Figure 10.- Lateral force on a slippery road for various loadings. Tires, C 12 Continental FP 5.00-17; tire-inflation pressure, 1.5 atmospheres gage; V = 30 km/h; road, smooth tamped asphalt, moist, slippery.

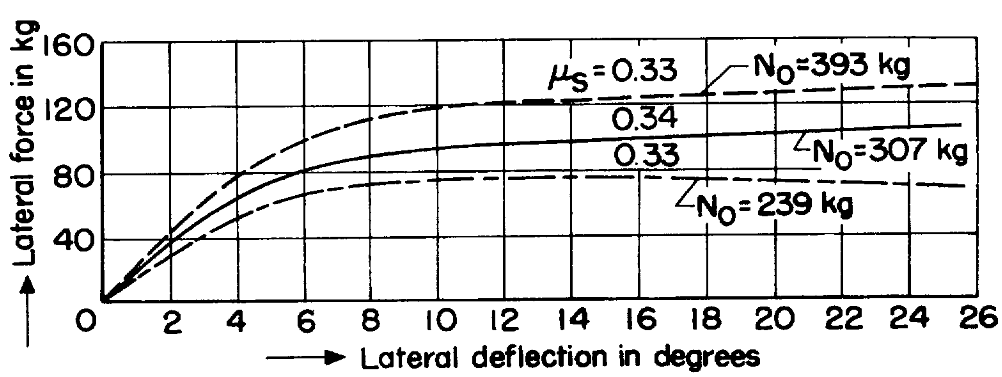


Figure 11.- Lateral force on snow solidified by traffic for different loadings. Tires, Continental Cross Country C 5 4.75-17; tire-inflation pressure, 1.5 atmospheres gage; traveling speed, 25-30 km/h; road, granite - small-unit paving with solidified snow surface.

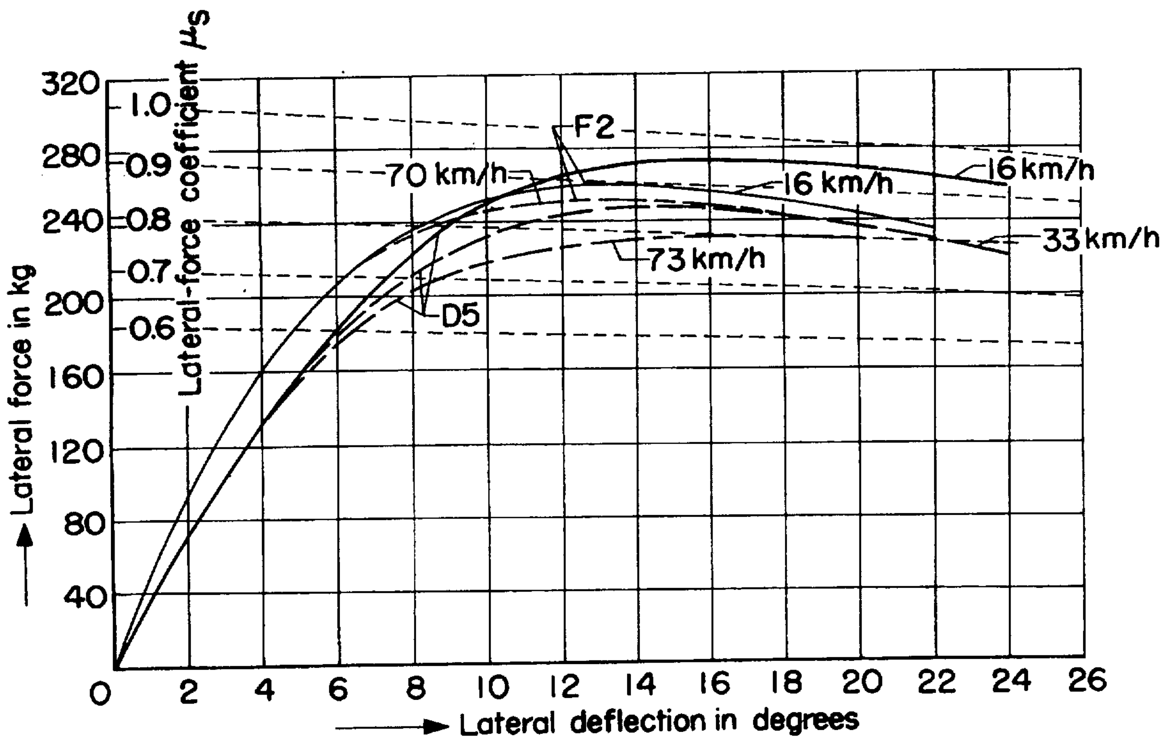


Figure 12.- Influence of the driving speed on a dry road. Tires, Dunlop Magnos D 5 5.25-16 and Fulda Balloon F 2 5.25-17; tire-inflation pressure, 1.5 atmospheres gage; loading, N_0 = 304 kg; road, Avus, tar - fine gravel surface, dry.

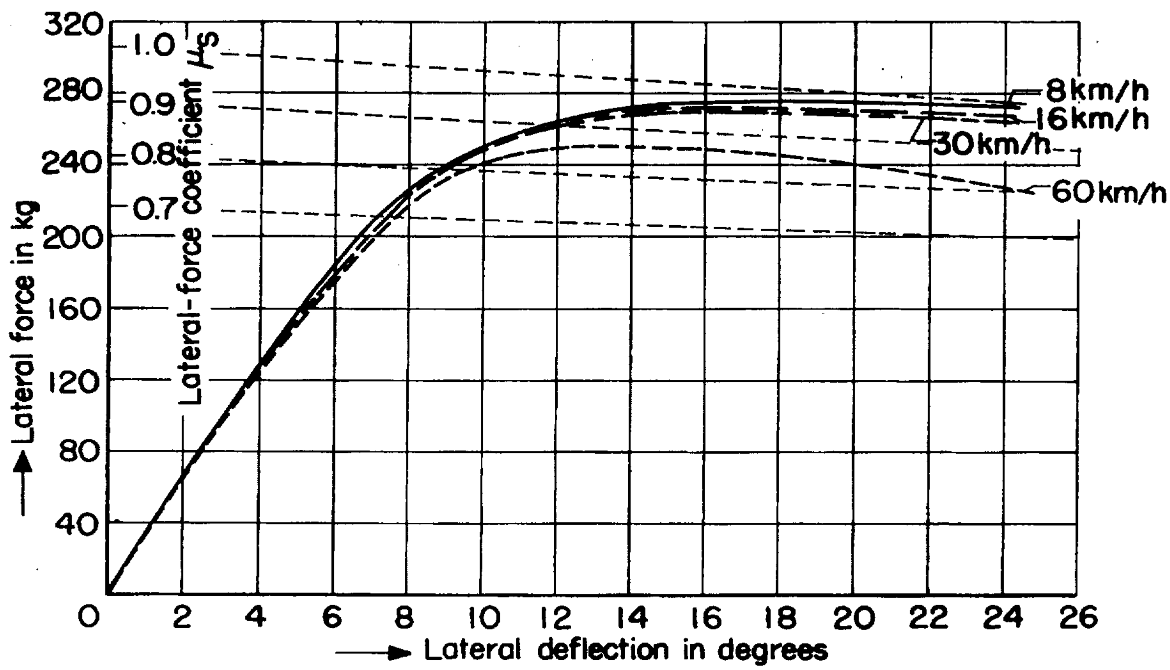


Figure 13.- Influence of the velocity on the lateral force on a wet gripping road. Test tires, Continental C 9 5.00-17 with Sommer-type nonskid tread; tire-inflation pressure, 1.5 atmospheres gage; loading, N_0 = 307 kg; road, rough asphalt, wet, dirty.

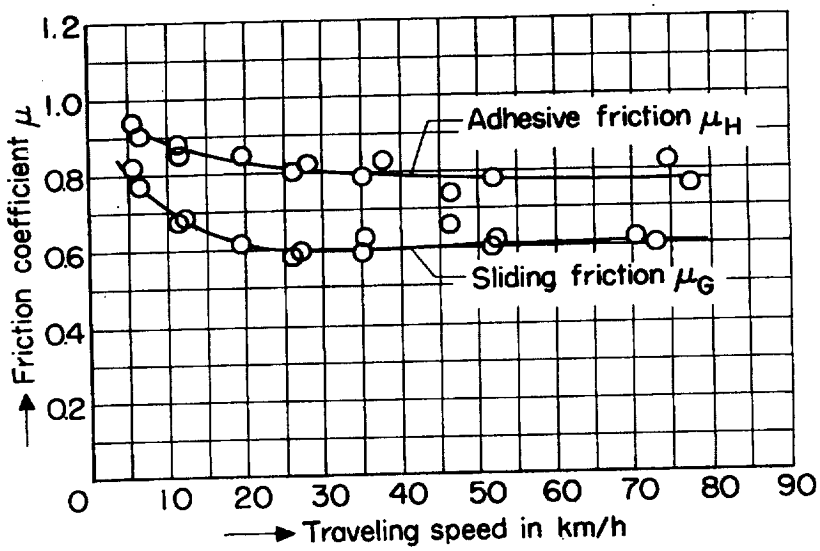


Figure 14.- Dependence of the adhesive- and sliding-friction coefficient on the traveling speed for a dry road. Tires, C 1 Continental 5.25-16; tire-inflation pressure, 1.5 atmospheres gage; N_0 = 305 kg; road, Avus, tar - fine gravel surface.

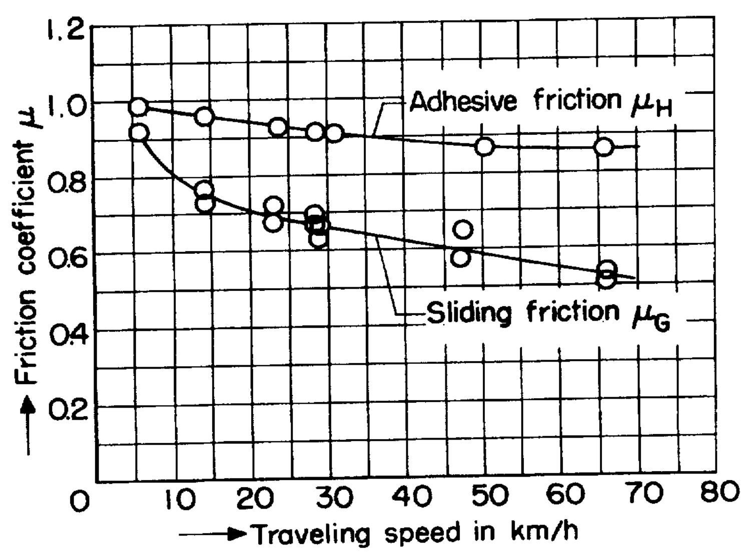


Figure 15.- Dependence of the adhesive- and sliding-friction coefficient on the traveling speed for a dry road. Tires, C 3 Continental 4.50-17; tire-inflation pressure, 1.5 atmospheres gage; N_0 = 304 kg; road, Automobile Express Highway, concrete.

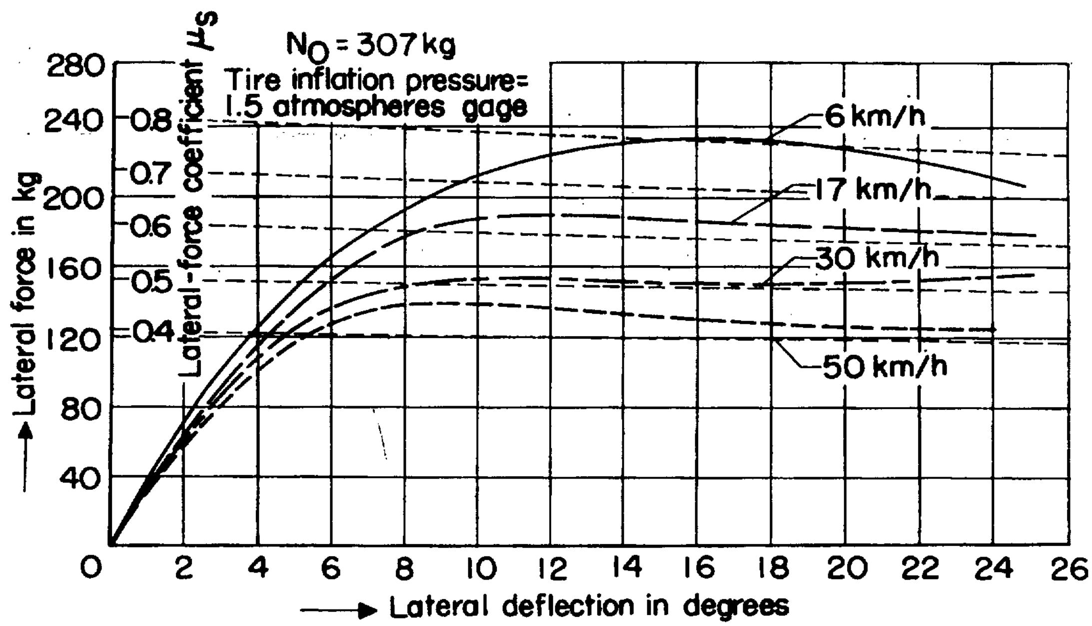


Figure 16.- Lateral force on a wet road for different traveling speeds. Test tires, Continental C 9 5.00-17, without profile, with Sommer-type nonskid tread; road, smooth tamped asphalt, wet, dirty.

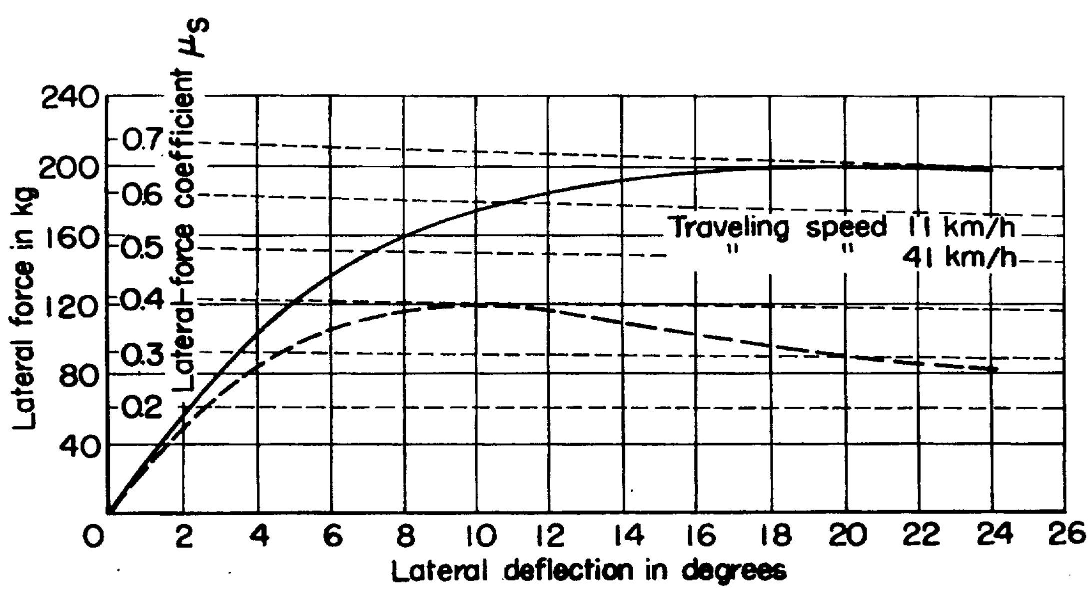


Figure 17.- Lateral force on a wet road at various speeds. Tires, Continental Aero C 1 5.25-16 without nonskid tread; 1.5 atmospheres gage pressure; N_0 = 305 kg; road, smooth tamped asphalt, wet, dirty.

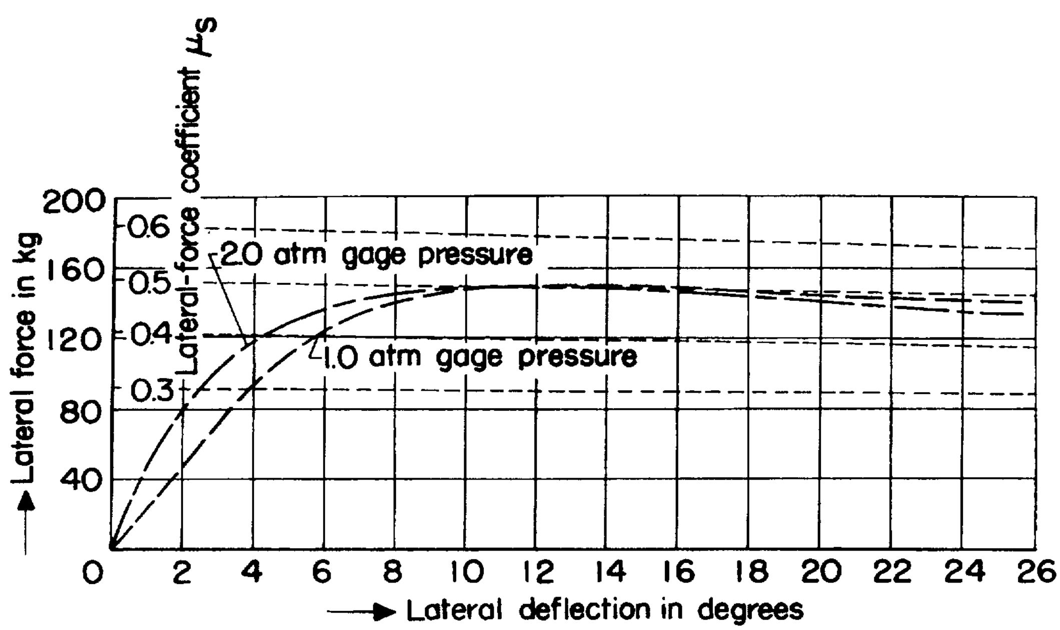


Figure 18.- Lateral force on a wet road for various tire-inflation pressures. Test tires, Continental C 9 5.00-17 with Sommer-type nonskid tread; N_0 = 307 kg; traveling speed, 28 km/h; road, smooth tamped asphalt, wet, dirty.

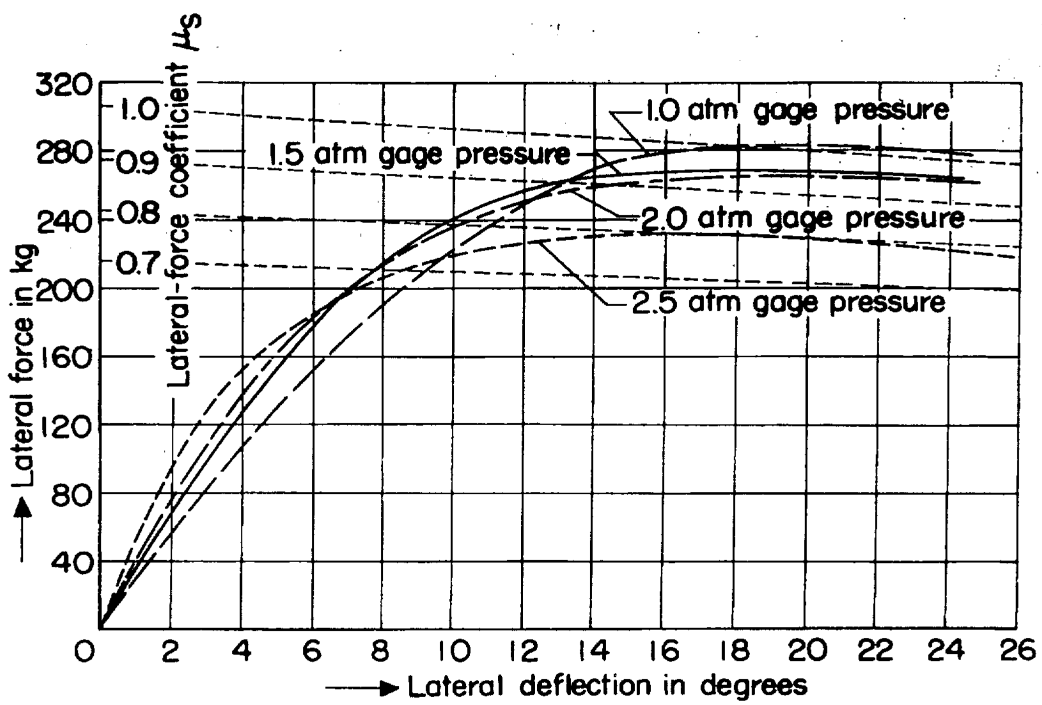


Figure 19.- Influence of the tire-inflation pressure on the lateral force in the case of a wet gripping road and a smooth tire. Test tires, Continental C 7 5.00-17, without profile; loading, N_0 = 307 kg; traveling speed, 30 km/h; road, coarse asphalt, wet, dirty (after night frost).

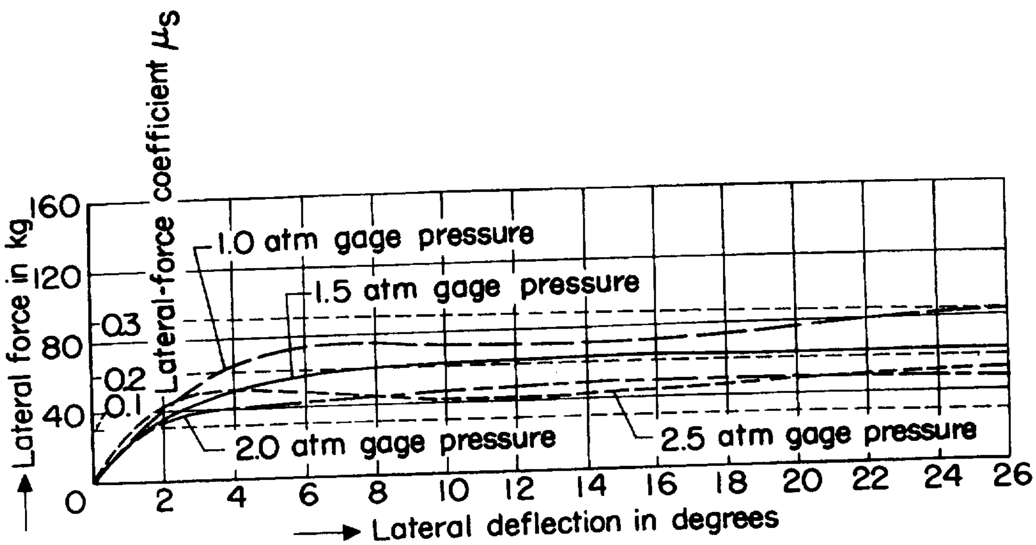


Figure 20.- Lateral force on a wet road for various tire-inflation pressures. Test tires, Continental C 7 5.00-17 without profile; N_0 = 307 kg; traveling speed, 28-30 km/h; road, smooth tamped asphalt, wet, dirty.

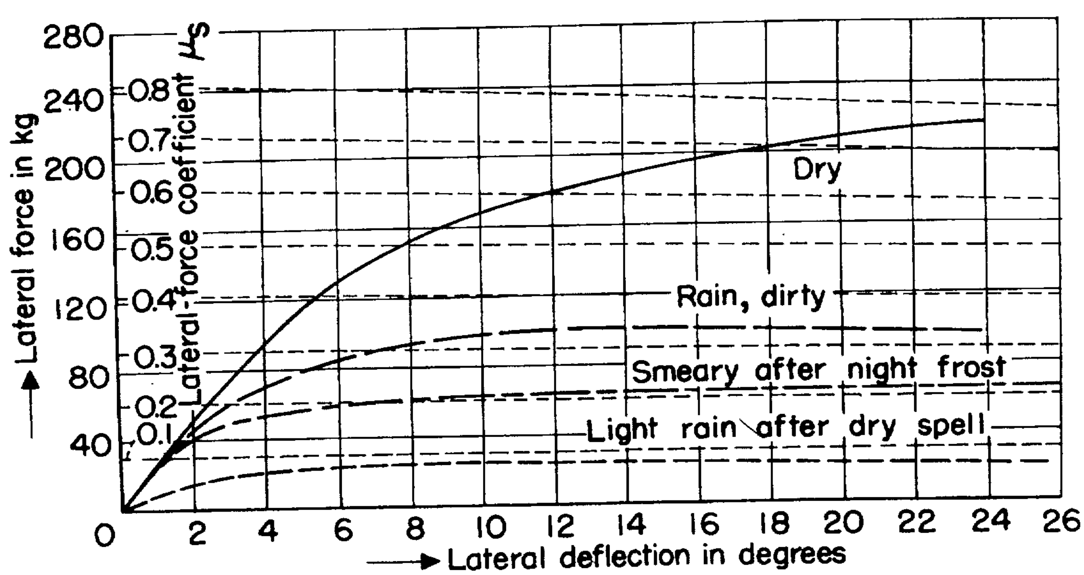


Figure 21.- Lateral forces under various road conditions. Tires, C 7 Continental 5.00-17 without profile; tire-inflation pressure, 1.5 atmospheres gage; N_0 = 307 kg; road, tamped asphalt.

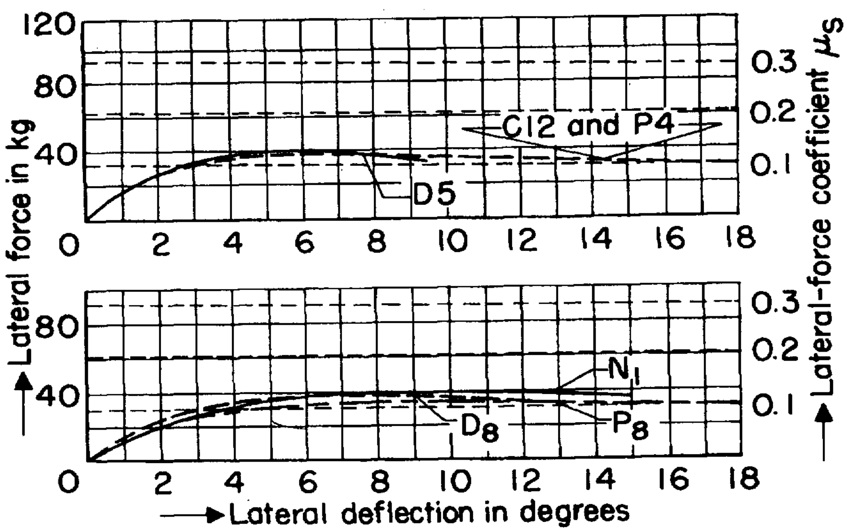


Figure 22.- Lateral force of various tires in the case of glazed ice. Tires, C 12 Continental FP 5.25-16, D 5 Dunlop Magnos 5.25-16, D 8 Dunlop cross-country 4.75-17, N 1 Michelin Super Comfort Stop 5.25-16, P 4 Peters Pneu Renova cross-country 5.25-16 with quartz, and P 8 Peters Pneu Renova Standard 5.25-16 with quartz; tire-inflation pressure, 1.5 atmospheres gage; loading, $N_0 = \sim 305$ kg; traveling speed, 25-30 km/h.

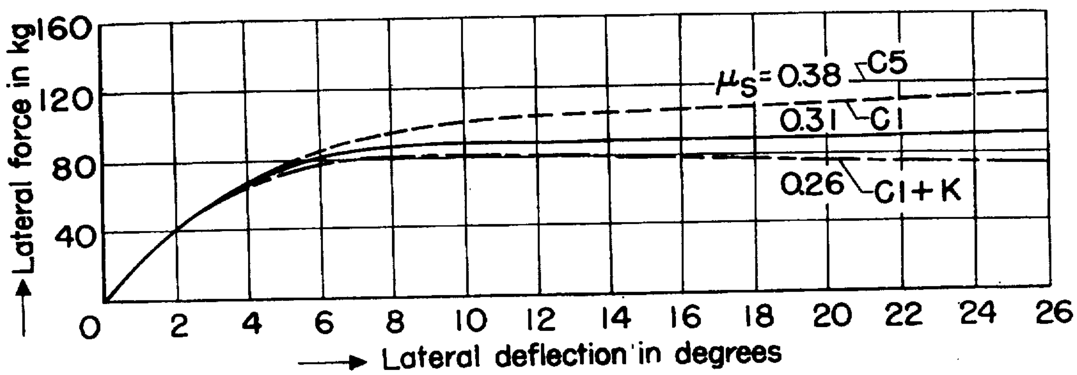


Figure 23.- Lateral force of various tires on solidified snow. Tires, Continental Aero C 1 5.25-16, C 1 + K the same tire with rubber cross - snow chain, and Continental cross-country C 5 4.75-17; tire-inflation pressure, 1.5 atmospheres; loading, N_0 = ~305 kg; traveling speed, 25-30 km/h; road, concrete with snow surface solidified by traffic.

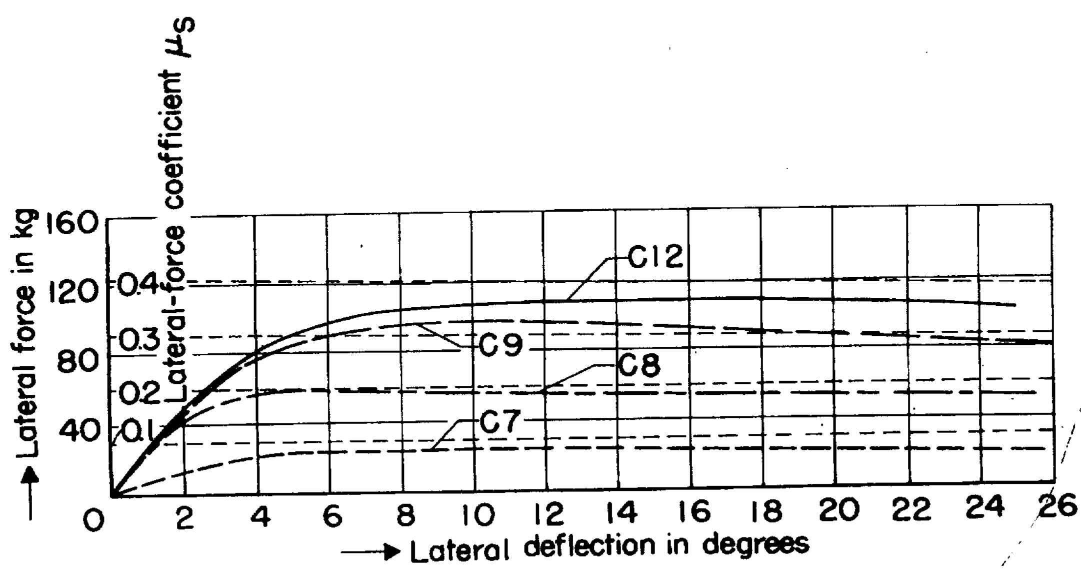


Figure 24.- Lateral force of various tire treads on a slippery road. Test tires, C 7 Continental 5.00-17 without profile, C 9 as C 7, with Sommer-type nonskid tread, C 8 as C 7, with Christophorus nonskid tread, and C 12 Continental FP 5.00-17; tire-inflation pressure, 1.5 atmospheres; loading, N_0 = 307 kg; traveling speed, 30 km/h; road, smooth tamped asphalt, moist, slippery.