EFFECT OF ROAD ROUGHNESS ON VEHICLE BRAKING

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The loss of tire braking friction due to road roughness was simulated and measured experimentally in a test machine designed to produce simultaneous wheel slip and vertical vibration of the contact surface. Equivalent roughness amplitudes as great as 0.7 in. and roughness frequencies (velocity/wavelength) as high as 14 Hz were covered. Wheel slip was varied by discrete amounts to include the values normally associated with maximum friction. The dynamic friction force found in each test run was time-averaged and expressed as a percentage of the highest observed average to minimize the effects of temperature, surface conditions, and other secondary considerations. Results show simulated roughness amplitude and frequency to have a strong influence on the average force available for braking: Friction losses were 30 percent at 0.04 in. and 14 Hz, and 90 percent at 0.71 in. and 6 Hz. Wheel slip and the dead-weight load on the tires were found to have a less dramatic effect over the range tested. The most important conclusion reached is that friction predictions without road profile consideration can result in gross errors and may be one of the causes of lack of correlation of friction data.

•WITH THE exception of the body aerodynamic resistance, all other forces necessary for accelerating, braking, and steering a moving automobile depend on tire friction. Friction force is relatively large on a smooth, dry, plane pavement, but may be reduced on an uneven and undulating pavement. On a washboard road containing numerous holes and ruts that cause wheels to bounce and chatter, the accompanying loss of traction can be readily observed as the vehicle's brakes are applied without producing any noticeable deceleration.

Recent papers on tire friction indicate that most investigations focus on the microsurface structure of the pavement, that is, its texture and the polishing of the texture asperities. No work has been found that deals with effects of road roughness on tire friction, where road roughness refers to roughness amplitudes on the order of 1 in. and larger (what one feels as "roughness" when riding in a car).

This paper is concerned with the effects of bulk road roughness on the frictional forces developed by a tire operating in a slipping mode. A stationary test apparatus was employed to produce controlled sliding of a rotating tire against a vertically oscillating metal plate, simulating a tire operating under brake slip on a rough road. Tests were run over a range of 5 roughness amplitudes (0.041 to 0.707 in.) and a range of 10 roughness frequencies (0 to 14 Hz). Three measured sliding speeds—0.18, 0.30, and 0.46 mph—were tested that result in actual sliding speeds near and above the critical sliding speed of 0.1 mph at which the adhesion peak occurs.

The frictional force produced by the tire slipping against the plate was measured by a quartz load cell. The proportional output voltage was then averaged with an analog circuit and read from a digital voltmeter. The average normal force between tire and plate was measured by a strain gauge load cell. For a given roughness amplitude and normal preload, the average normal force was found to be essentially constant over the range of tested frequencies.

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The smallest amplitude of 0.041 in. produced a traction loss of about 30 percent at 14 Hz, and the largest tested amplitude of 0.707 in. produced traction losses greater than 80 percent at about 6 Hz, the exact values depending on the normal preload and sliding speed.

For larger amplitudes, the average deformation slip increased as the amplitude increased. This means that the average actual sliding speed decreased to a much lower value than the critical speed with the result that the frictional force decreased to a much lower value. On the other hand, the effects of increasing frequency at even relatively small amplitudes reduced the frictional force over the entire range of sliding speeds, the critical speed included.

To explain these conclusions, we briefly review the details of rubber friction.

RUBBER FRICTION

Rubber friction is a complicated viscoelastic process in which the friction force depends not only on the surface but also on load, temperature, and velocity (1). The total friction force developed by a tire slipping on a road surface is generally considered to be the result of 4 contributing factors: adhesion, hysteresis, tearing, and wear. The last 2 make very minor contributions compared to the first 2 and may, therefore, be neglected in most cases (2).

The 2 primary friction mechanisms, adhesion and hysteresis, appear to be different manifestations of the same basic energy dissipation process. The adhesion mechanism may be summarized as the component due to the shearing of molecular junctions at the tire-pavement interface. The hysteresis component is due to the "plowing" of the asperities of the rigid pavement surface through the soft rubber. On dry surfaces under normal conditions the adhesion mechanism is dominant, and hysteresis plays only a minor role. [A more detailed explanation of the friction mechanisms is given by Kummer and Meyer (3).]

For any given tire-pavement combination, there exists a particular sliding speed that produces the maximum possible traction force (Fig. 1). This sliding speed is called the critical sliding speed and has been experimentally determined to be on the order of 0.1 mph (3). Its exact value is influenced by rubber composition, surface parameters, and temperature.

The adhesion component, under normal conditions, provides the contol needed for braking, accelerating, and cornering because it increases rapidly to a high value in a sliding speed range (up to 0.1 mph) without producing noticeable vehicle drift speeds (3). Although the tire has to slip to develop this adhesion force, the slip speed necessary to produce a large friction force is small enough that there is no noticeable loss of control.

SLIDING SPEED

Of most importance is the actual sliding speed—the component of the tread speed tangential to the surface. However, because the tread elements in the contact area are distorted and undergo deformation slip (3), the actual sliding speed in the contact area is very difficult to measure; thus, "measured" sliding speed is commonly used. The measured sliding speed of the tire would be equal to the actual sliding speed if the tread elements in the rubber-pavement contact area were undistorted. In this paper "slip speed" refers to measured slip speed unless otherwise noted.

TEST APPARATUS

A detailed discussion of the test machine and its specifications and components is given by Leary (4). This paper describes only the machine's operational features.

The test machine is an uncomplicated, stationary piece of equipment capable of achieving the same relative velocity between the wheel and a simulated road surface that a given vehicle velocity and measured percentage of slip produce in the real case. This is accomplished by loading a rotating tire down against a vertically oscillating metal plate. (Figure 2 shows a schematic diagram of the test machine's important moving parts.) The rotation of the tire results in a relative sliding speed between the tread elements and the surface, while the vertical displacement of the plate simulates road roughness.

The tire is connected to a rotating axle that is restrained from any type of translational movement. Thus, effects on the tire load from the spring, shock absorber, and body mass are eliminated. All deflection produced by the vertical displacement of the table (metal plate) occurs in the tire. The amplitude of displacement of the table can be varied in 36 steps from 0 to 1 in. by changing an eccentric. The speed of the tire surface (the measured sliding speed) can be varied from 0 to 0.46 mph by adjusting the rpm of the dc motor that drives the wheel. Table oscillation frequency can be varied from 0 to 30 Hz. The tire is loaded against the table by an air cylinder to normal loads of 600 lb.

The instrumentation system employed monitors both the vertical normal force and the horizontal friction force. A strain gauge network in combination with an amplifier supplies an output voltage proportional to the normal load between the tire and the table. A quartz load cell in combination with a charge amplifier produces a voltage proportional to the horizontal friction force developed by the tire sliding against the table surface. Figure 3 shows the tire, table, load cell, and one of the strain-gauge-instrumented table support struts.

Because the 2 output voltages corresponding to the horizontal and normal forces in their unaltered forms vary periodically with time (Fig. 4), a small analog computer was used to time-average the 2 signals. The average values of normal and horizontal voltages obtained are then used as the inputs to a digital computer program that converts the voltages to pounds and calculates or plots the friction coefficients and percentage loss of friction.

The goal of this study was to investigate effects of road roughness on tire friction only; changes in frictional performance due to temperature and humidity were eliminated by normalizing all coefficients of friction in each group. All tests were made with a layer of water on the plate to reduce the temperature rise due to frictional heating and to reduce tire wear. In tests run earlier with both tire and plate dry, severe heating was noted and a sheet of rubber remained on the plate after the tire was raised. The water-film effects on traction are not at all like those on a real highway. In the real case, the slipping tire rotating at near vehicle speed is continuously moving forward on the film. On the machine, the tire slowly rotates while remaining in the same horizontal position and, as a result, experiences none of the "wedge" effects that tend to cause a real tire to hydroplane.

RESULTS

For a nominal load of 200 lb, the 2 smaller amplitudes of 0.041 and 0.084 in. produce a gradually decreasing friction force with increasing frequency. At 11 Hz the friction force levels off at 60 to 70 percent of its maximum value (a 30 to 40 percent loss). However, over the entire frequency range the highest friction force is produced by the lowest sliding speed. Figure 5 shows these trends for an amplitude of 0.084 in. Increasing the amplitude to 0.173 in. decreases the frictional force about 50 percent at 11 Hz (Fig. 6). In addition, a "crossover" occurs at about 4 Hz. At frequencies lower than 4 Hz, the highest friction force is produced by the lowest sliding speed, the same as with 2 smaller amplitudes; but, at frequencies above 4 Hz, the highest friction force is produced by the highest sliding speed.

At an amplitude of 0.342 in., the friction loss increases to about 80 percent at 9 Hz. The crossover now occurs at a much lower frequency, somewhere below the first test frequency of 2.2 Hz. At 0.707 in., the friction loss is about 90 percent at a frequency of 4 Hz, and the crossover again occurs somewhere below the first test frequency. At this large amplitude, the tread surface was observed to be leaving the table surface during the period that the table is moving through the lower portion of its travel.

For the 400-lb nominal load, the 2 smaller amplitudes exhibit friction losses of about 20 to 30 percent at the upper end of the test frequency range (around 11 Hz). As before with the 200-lb load, for the smaller amplitudes the highest friction force is produced at the lowest sliding speed at all tested frequencies. Increasing the amplitude to 0.173 in. increases the loss to about 30 to 50 percent depending on the sliding speed.

Figure 1. Speed dependence of adhesion coefficient on log of actual sliding speed.

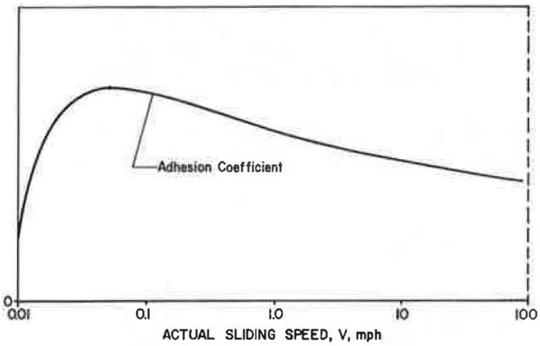


Figure 2. Schematic representation of tire friction test apparatus.

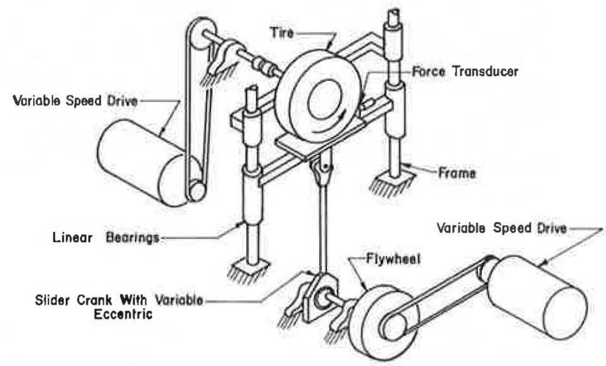


Figure 3. Tire, table, load cell, and strain gauge.

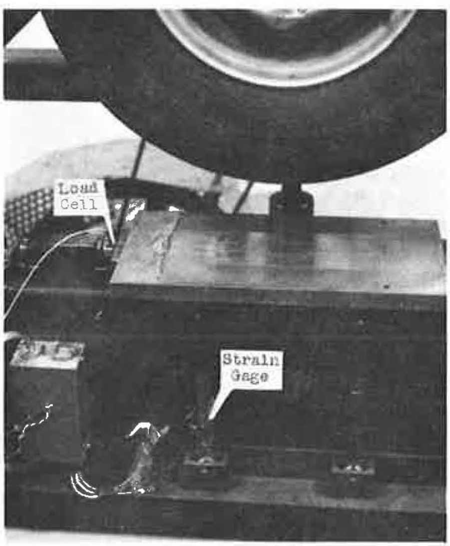
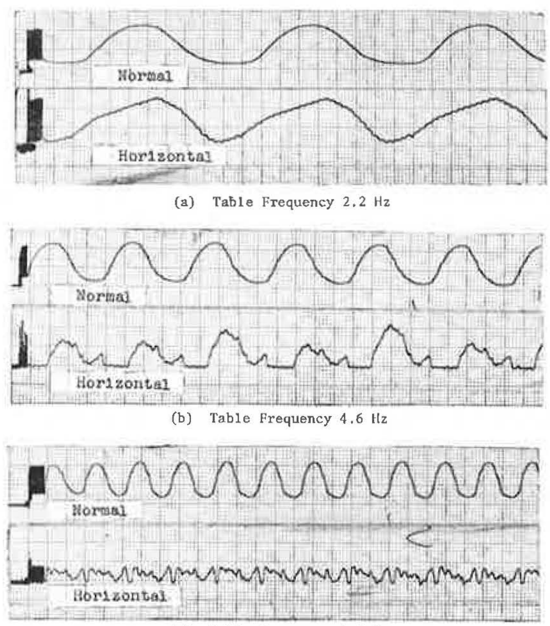


Figure 4. Unaltered normal and horizontal output voltages for measured sliding speed of 0.18 mph.



However, unlike the 0.173-in. amplitude at the lighter 300-lb load, no crossover is observed. At an amplitude of 0.342 in. the friction loss increases to about 65 percent at 10 Hz, and a crossover is now observed somewhere below the first test frequency. At the largest amplitude of 0.707 in. the loss is about 90 percent at a frequency above 8 Hz, and a crossover occurs at some very low frequency. As before, with the large amplitudes the tread surface separates from the table surface during part of the table's cycle.

A summary of these curves for the 400-lb nominal load is shown in Figure 7. The figure shows 5 curves, one for each amplitude tested, and each one is an average of the curves for the 3 sliding speeds.

INTERPRETATION OF TEST RESULTS

Mechanism of Friction

For this experimental case of a tire sliding at low speeds on a smooth, wet, flat plate, the dominant friction mechanism is adhesion; there is almost no hysteresis. Thus, a plot of the friction force as a function of the actual sliding speed is similar to that shown in Figure 8, which is valid for a constant sliding speed on a smooth surface.

Because the amount of deformation slip is unknown, the locations on the plot of the 3 actual sliding speeds that correspond to the measured sliding speeds of 0.18, 0.30, and 0.46 mph cannot be precisely determined. However, the 3 points must fall somewhere to the right of the adhesion peak because the lowest measured sliding speed is observed to produce the highest friction force and would appear in the approximate positions shown by points a, b, and c for the case of 0 frequency, 0 roughness.

Influence of Amplitude of Roughness on Friction Loss

For the case where a tire is operated on a rough surface, the amount of tread windup is constantly changing because the friction force is constantly changing. In the tests, as the table moves up against the tire, the tread elements wind up; then as the table moves away from the tire, the friction decreases and the tread elements easily snap forward. Thus, as the table oscillates at larger displacements, the net deformation slip remains about the same because the tread elements have the time required to wind up and then to unwind with less actual slip because contact is reduced as the table moves away.

In the tests, the rotating speed is held constant so that, as the displacement is increased, the actual sliding speed decreases. Thus, the points a, b, and c shift along the curve to the left and eventually reach positions such as shown by a′, b′, and c′. With the points shifted to the left of the adhesion peak, the higher measured sliding speeds now produce higher friction coefficient and there is an overall decrease of the friction coefficient for all 3 points.

Influence of Frequency of Roughness on Friction Loss

At the smaller roughness amplitudes, a loss of friction is still observed even though no crossover occurs to indicate that the actual sliding speed has shifted to the left of the adhesion peak. Thus, the primary mechanism that causes the friction loss cannot be attributed to the increase in deformation slip as in the case with the large roughness amplitudes described above. Instead of simply shifting on the curve on the coefficient plot as before, the operating points a, b, and c must somehow shift to a different curve that is valid for a tire sliding on a rough surface instead of a flat surface (the points a″, b″, and c″ located on a tentative "frequency roughness" curve). Because the adhesion force is dependent on the number and strength of interface junctions formed, the roughness frequency must reduce one or both of these factors to cause a loss of friction.

CONCLUSIONS AND RECOMMENDATIONS

The influence of frequency and amplitude on friction as separate effects was discussed. For the tests performed in this work, both effects occur simultaneously. Be-

Figure 5. Average maximum friction versus table frequency at amplitude of 0.084 in. and nominal load of 200 lb (curves normalized by dividing all coefficients by 0.59).

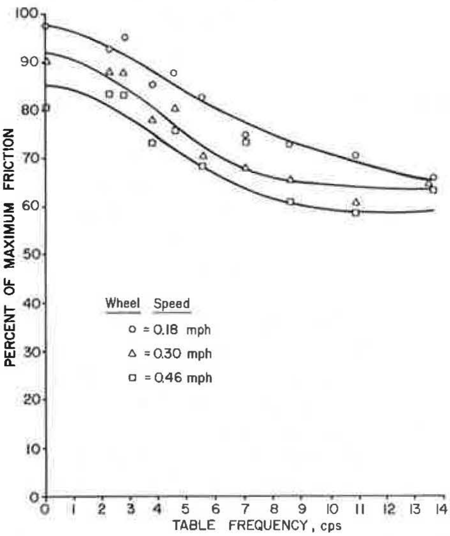


Figure 6. Average maximum friction versus table frequency at amplitude of 0.173 in. and nominal load of 200 lb (curves normalized by dividing all coefficients by 0.46).

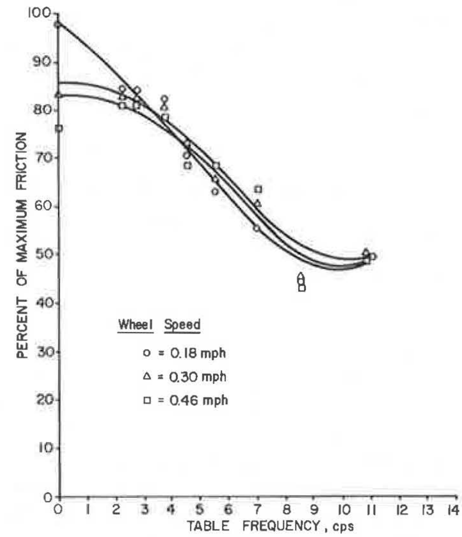


Figure 7. Average loss of friction versus table frequency at nominal load of 400 lb.

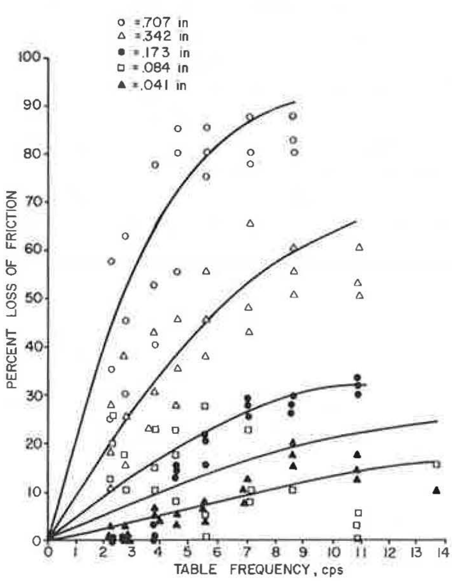
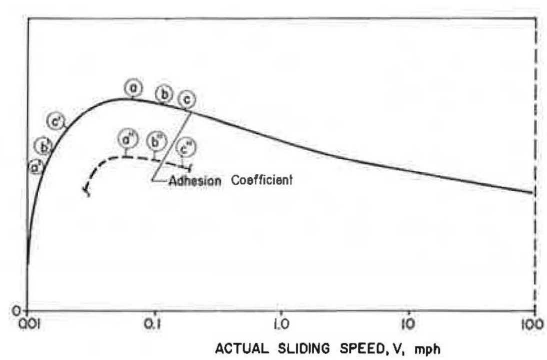


Figure 8. Influence of amplitude and frequency of roughness on friction loss.



cause each effect always occurs with, and influences, the other, no clear-cut observations can be safely made until one dwells on the combined effects.

The tests demonstrated that increasing roughness amplitudes (from 0.041 to 0.707 in.) and increasing roughness frequencies (from 0 to 14 Hz) result in a decrease in the average coefficient of friction for measured sliding speeds in the range from 0.18 to 0.46 mph. At small amplitudes producing barely observable gross movements of the tire tread, increasing the roughness frequency to 14 Hz causes a friction loss of approximately 30 percent. At a low roughness frequency of around 3 Hz, increasing the roughness amplitude to 0.707 in. can cause a friction loss of 60 to 80 percent, depending on the amplitude.

This loss of friction is due to 2 factors: a reduction of the actual sliding speed caused by the increased deformation slip, and an overall lowering of the coefficient of friction. The reduction of actual sliding speed and the resultant leftward shift on the adhesion coefficient curve due to deformation slip are caused most predominately by large amplitudes of roughness, and the lowering of the coefficient is caused mainly by frequency.

The test machine in its present form restrains the rotating wheel's axle from any vertical motion. Thus, the dynamic effects of the suspension and body are eliminated, and only the dynamic performance of the tire is tested. This departure from an actual car, though it makes an extension of the test observations to an actual driving situation difficult, is done for good reason. Testing performed in this manner can isolate the effects of the tire from the effects of the suspension and the effects of the body mass. If a quarter-car simulation had been done from the start, the separate effects on frictional performance due to the tire, suspension, and body mass could not have been separated. Also, for future study the test machine was so designed as to allow a more complete simulation of a quarter-car by adding a spring, shock absorber, and body mass.

Occasional occurrences of slip-stick and chatter have been noted. The fact that the friction force drops when the tire goes into a condition of chattering may warrant further investigation. For a particular test run where the slip-stick has been briefly explored, it is found that slip-stick is less likely to recur in the next run if there is a sufficient time interval between successive runs. This fact that the chatter can sometimes be avoided if the tire is given time to "rest" suggests the possibility that it may be undergoing some kind of recovery from a strain it undergoes during slip-stick.

Finally, it must be noted that these results clearly show that the traction available is highly dependent on the speed with which one traverses a rough road. Thus, if friction measurements are to be applied at speeds other than the test speed, road profile data must also be utilized. Therefore, friction predictions without profile consideration can result in gross errors and may be one of the causes of lack of correlation of friction data.

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