Measuring Tire Friction Under Slip With the Penn State Road Friction Tester

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Skid resistance measurements remain the most practical method for characterizing the frictional properties of highway pavements. Friction measurements with tires operating under slip are, however, needed for research purposes. The adaptation of the Penn State road friction tester, which was originally designed for measuring skid resistance with a full-scale tire, to the measurements of tire-pavement friction under slip is described. The method employed consists in gradually retarding the test wheel by an adjustable brake actuating system and measuring the forces in both horizontal arms of the test wheel parallelogram suspension. By electric addition of these forces and measuring vehicle speed and test wheel velocity the complete friction vs slip relationship of an individual test cycle is obtained.

•FRICTION studies of the tire-road interaction are essential to a better understanding of what happens to a vehicle in certain maneuvers. Experimental approaches under real road conditions are a necessary supplement to laboratory investigations and theoretical studies.

Friction is usually described by its coefficient, that is, the ratio of the friction force to the load of the bodies sliding on each other. The friction force in the tire-road contact area is highly dependent on a variety of factors, particularly temperature, sliding speed, surface texture and rubber composition, making its reliable and reproducible measurement rather difficult.

The friction forces measured at the tire-road interface give information about the performance of the tire and about the frictional properties of the pavement under stated conditions. This paper is concerned primarily with the latter use of tire-pavement friction data and therefore tire variables will not be considered.

SKID RESISTANCE

The simplest approach to the study of the frictional properties of the tire-road interface is to lock the tire and measure the friction force developed by the skidding tire. This procedure is used by highway departments to survey the frictional characteristics of pavements for the purpose of monitoring the condition of surface courses, scheduling resurfacing operations, etc. A standardized method for this purpose is available as ASTM Method E 274.

This test, however, simulates the frictional behavior of a pavement as it is seen by a skidding vehicle, a mode of operation which should be avoided at all cost because no control can be exercised over the directional movement of the vehicle while the tires are locked. It is preferable that the tire, when braking, driving or cornering

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forces are applied to it, continue to roll. Under these conditions, the tire is said to operate under slip because a certain amount of sliding is superimposed on the rolling mode whenever the tire transmits a force. As long as the tire only slips, directional control is maintained, and greater forces can be developed as well.

FRICTION UNDER SLIP

From theory and experiments, we know that the coefficient of friction of tire operating under slip is highly dependent on the amount of slip and that the maximum coefficient occurs at about 10 to 20 percent (the "critical slip"). The ratio between the coefficients at critical slip and during skidding is not constant, but depends on texture and microroughness of the surface and other factors. The relation between slip and skid coefficients and the processes controlling them are discussed in detail by Kummer and Meyer (1).

It is not the intent of the authors to promote at this time the measurement of slip resistance as a means of characterizing pavements for the purposes of the highway engineer. It is arguable that skid resistance is more significant from the safety standpoint than slip resistance, on the grounds that it is most important that a vehicle come to the quickest possible stop once it is out of control. On the other hand, one can take the stand that the critical slip resistance is more important because it defines the point up to which the vehicle will remain under control. Be this as it may, the purpose of this paper is to describe an apparatus for the measurement of tire-pavement friction under slip to enable us to carry out research to determine, among other things, the relationship between skid resistance and slip resistance.

Measuring Friction Under Slip

Several approaches to the measurement of tire friction under slip are possible and were considered. The method chosen simulates in the most realistic way the transient behavior of a braking tire and has the further advantage that it could be applied to our existing tester (2) with a minimum of changes. The chosen method has the additional advantage of fairly straight-forward conditions in the tire-pavement contact area. Therefore it is particularly suitable for research purposes.

Basically, the method consists in decelerating the test tire at a controlled rate and measuring friction force and slip during this process. A rapidly responding measuring and recording system is required. In this manner the friction coefficient over the entire slip range can be obtained from a single test cycle.

The Penn State Road Friction Tester as a Slip Tester

The concept described has been used to convert the Penn State road friction tester (1) from a skid into a slip tester. The tester, whose design dates back to 1958 (3), was built with some thought to its eventual adaptation to other studies on tire-road interaction than those concerned with skidding tires. Several changes and improvements have been made in the intervening years, but these did not change its operating mode or performance (4).

As a skid tester it has been used during the past four years by the Pennsylvania Department of Highways for regular pavement surveys throughout the state and by the University for research purposes. Its performance compares favorably with that of other testers (5).

DESIGN CRITERIA

All measurements should be direct to avoid errors and accuracy losses through computation or the application of corrections. It should be possible to calibrate the measuring system statically in order to keep the calibration procedure simple and permit frequent checks.

In keeping with the objective of creating a research tool, easy modification of the test cycle should be possible. This means that one should be able to modify the rate of brake application as well as alter the point at which the brake is released.

Figure 1a. The Penn State road friction tester.

The instrumentation system should allow measurement at normal travel speeds on all highways. All sensitive components should be protected against the environmental hazards to which they might be exposed on the road. The system should give meaningful data of adequate accuracy without making the equipment more sophisticated or expensive than absolutely necessary.

Basic Design

The Penn State road friction tester (1) consists of a $^3/_4$-ton truck as the towing vehicle with a single-wheel trailer attached to it (Fig. 1). The vehicle carries a 250-gal tank and a pump to deposit a film of water in front of the test wheel. The engine drives an air compressor and an oversize 12 VDC generator which through a 550 W inverter provides 115 VAC cycle power to the instruments.

Trailer Design

The heart of the tester is the trailer. Since it is of the single-wheel type it can be attached to a crossbeam at the rear of the towing truck in any desired relation to the

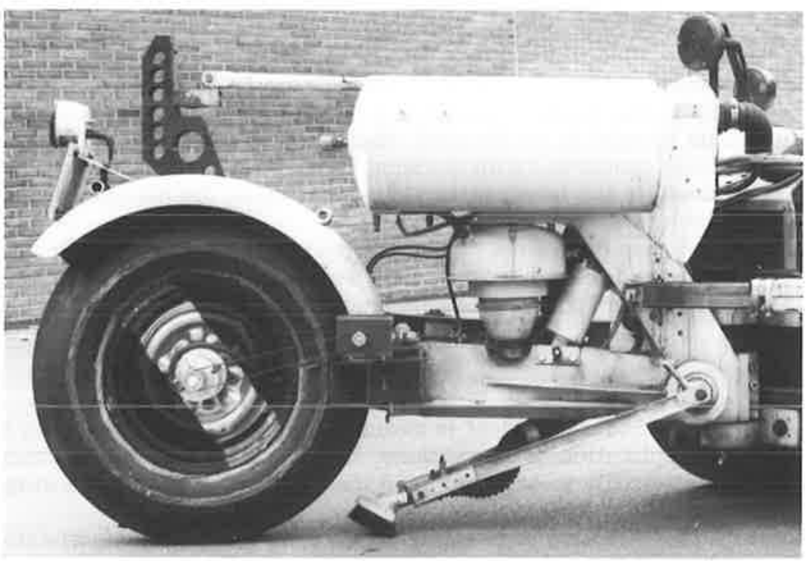

Figure 1b. The trailer with test wheel.

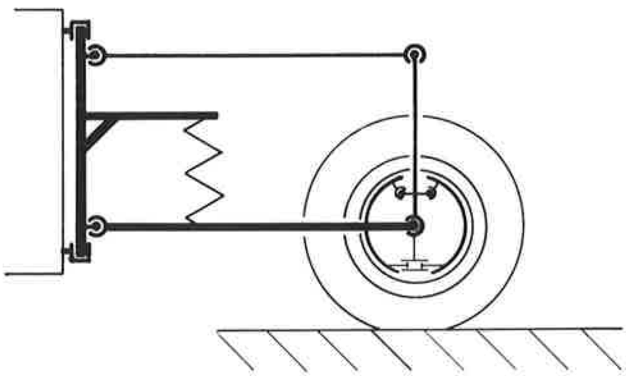

Figure 2. Trailer principle.

towing vehicle. The truck can therefore travel in the normal manner in a traffic lane, but measurements can be made in either wheel track or between them by changing the point of attachment of the trailer. The trailer consists basically of a wheel with brake, suspended on a horizontal arm pivoted to the towing vehicle and loaded through a spring abutting against the vehicle structure (Fig. 2). The spring, in effect, transfers part of the towing vehicle weight to the test wheel. By using an air spring the test wheel loading can be changed from the cab while the vehicle is in motion.

When the test wheel brake is applied, the friction force developed between tire and pavement produces a reaction torque at the brake. The brake mounting plate is free to rotate on the wheel axis, but is restrained by the upper horizontal arm pivoted vertically above the pivot of the main arm (Fig. 2). The suspension arm and the restraining arm are so dimensioned and attached that they form the long sides of a parallelogram.

The Test Wheel in the Slip Mode

When the brake is so applied that the wheel does not lock, the wheel will rotate at a lower velocity than that of free rolling. We say that the wheel operates with "slip." Slip is usually given as a percentage, obtained in the present case as

$$s = \frac{V - R\omega}{V} \times 100 \qquad (1)$$

where (with consistent units)

- V = vehicle speed
- R = effective tire radius (see Fig. 3)
- ω = angular velocity of the test wheel

The coefficient of friction is

$$f = \frac{F}{W} \qquad (2)$$

where (Fig. 3)

- F = force at the tire-pavement interface
- W = vertical load on the test wheel

Instead of coefficient the somewhat more convenient term "friction number" may be used:

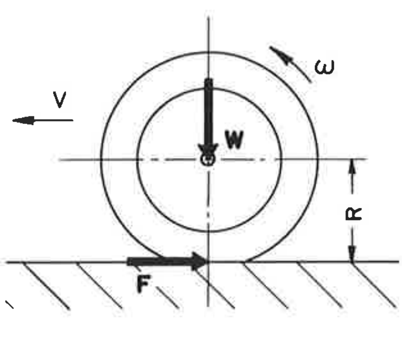

Figure 3. Forces acting on the test wheel.

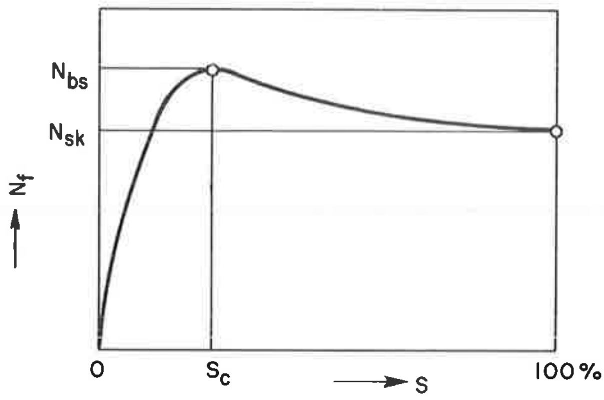

Figure 4. Friction number vs slip.

$$N_f = 100f = 100\frac{F}{W} \qquad (3)$$

A dictionary definition of "coefficient" states that "it is an unchanging ratio measuring some given effect or property in given conditions." In the case of tire-pavement friction, the description of the "given conditions" would be quite lengthy. To circumvent this problem one can agree on a set of conditions as they are specified in ASTM Method E 274 for the case of the locked wheel (100 percent slip) by defining the conditions under which the skid number N_{sk} is to be measured. Slip (brake or drive slip) numbers can be defined similarly. For the present purpose the maximum friction coefficient which occurs at slip s_c (the critical slip) will be called the brake slip number N_{bs} (Fig. 4). Except for the fact that the wheel is operating in the slip mode, the conditions of ASTM Method E 274 apply.

MEASUREMENT OF TIRE-PAVEMENT FRICTION

According to Eq. 2 the friction coefficient is proportional to the friction force as long as load W is constant. To obtain F any reaction force proportional to it may be measured. Under transient conditions, however, all reaction-forces in the parallelogram also contain a certain amount of inertia forces due to the deceleration or acceleration of the test wheel. Their effect can be neutralized by summing the forces in the two horizontal links of the parallelogram (Fig. 5):

$$D = \frac{I}{e}\frac{d\omega}{dt} + \frac{R}{e}F + \frac{x}{e}W \qquad (4)$$

$$E = -\frac{I}{e}\frac{d\omega}{dt} - \left(1 + \frac{R}{e}\right)F - \frac{x}{e}W \qquad (5)$$

where

I = moment of inertia of the rotating masses
e = length of the brake torque arm
t = time
x = displacement of the tire footprint center due to F relative to its static location

By addition:

$$E + D = -F \qquad (6)$$

As can be seen from Eq. 6, all influences due to pure moments and purely vertical forces on the measured friction force are automatically eliminated.

This means that by measuring the forces acting along the axes of the two arms the force at the tire interface can be obtained by simple summation and without regard to changes in wheel inertia or deceleration. Thus by decelerating the wheel a record of instantaneous slip and of the corresponding friction force (or coefficient of friction or friction number, if the wheel load remains constant) can be obtained without complex data processing.

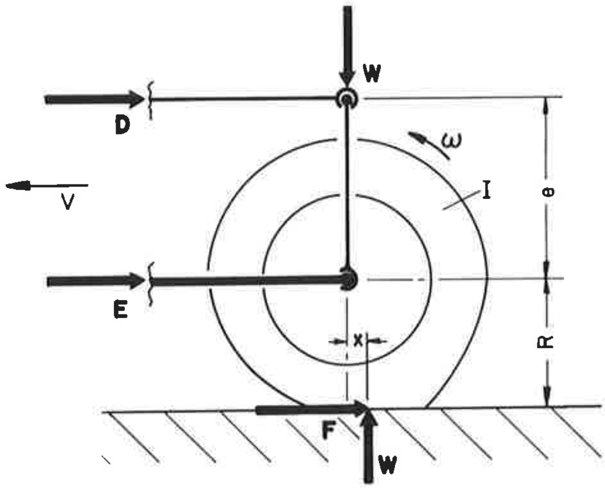

Figure 5. Forces on the trailer.

Measuring System

To measure the friction force F (or the friction coefficient) directly as the sum of forces E and D in the horizontal links of the trailer without additional computation, transducers of equal sensitivity are necessary. The main arm itself is used as mechanical part of the transducer for force E (Fig. 6) by measuring with strain gages attached to it the bending moment acting on it in its horizontal plane. This moment is due to the offset which puts the suspension arm pivot in the wheel plane. The gages are placed in the horizontal neutral plane of the main arm as close to the test wheel as possible to minimize influences from incidental side forces. To obtain maximum sensitivity the cross section of the main arm has been reduced as much as strength considerations permit.

Force D in the upper horizontal restraining link is also measured by strain gages. They are bonded to the tension side of a bar in which D induces a bending moment due to its offset to the neutral plane of the bar (Fig. 6). The offset can be adjusted to give the transducer the same sensitivity as the main arm has. Both strain gage bridges are combined to form a single one in such a way that the combined output is now directly proportional to the sum of the two forces and therefore to the friction force F. The bridge is operated with a carrier frequency of 20 kc and the output is amplified and recorded by a dry-writing Century Model 444 oscillograph.

The latter also records the output of a track wheel driven DC generator to indicate the vehicle speed (which is kept constant during a test). In addition, the test wheel speed is recorded. The wheel drives an impulse generator which produces 100 pulses per revolution. The output frequency, which is proportional to the angular velocity of the test wheel, is fed through a frequency-to-analog converter and an amplifier to the oscillograph.

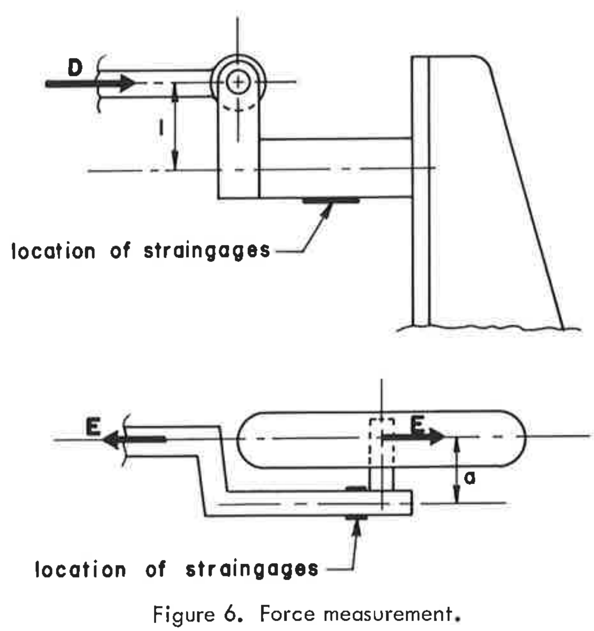

Figure 6. Force measurement.

TEST CYCLE CONTROL

The test wheel brake is a standard automotive hydraulic drum brake. The hydraulic system is pressurized by a pneumatic booster (2). Pneumatic system pressure is admitted to the booster by a solenoid valve which is controlled from the cab. By inserting an adjustable throttling valve in series with the solenoid valve the rate of brake application can be controlled and thereby the rate of increase of the slip.

When the critical slip has been reached, the friction force will be at its maximum. The brake force continues to increase, but the friction force decreases. The test wheel goes rapidly to 100 percent slip. Operating the wheel in the locked condition for any length of time may be undesirable, at least on high-friction surfaces, because it can cause tire flat-spotting. Flat spots would introduce noise into the force signal.

To control wheel lock, either limiting it to a predetermined period of time or preventing it altogether, the signal from the test wheel driven impulse generator is used to de-energize the brake system solenoid. This causes the brake to be released.

Several modes of operation can be achieved:

1. The brake can be actuated by a cycle timer at constant time intervals and be released automatically by the control system or the cycle timer.
2. The release signal can act as an override. In this case, the brake is actuated each time the test wheel speed increases above the setting point of the release control. Because of time delay in the control system and with a corresponding setting of the release point, the test wheel can be made to run up completely between individual test cycles. If only the friction at the critical slip is to be determined the release point can be so adjusted that complete spin-up does not occur.
3. Manual actuation and release is, of course, possible at any time.

For skid testing, the brake release can be bypassed. This permits the test wheel to be held in the locked condition until equilibrium at the tire-pavement interface has been attained. Thus the tester can be used to make skid-resistance measurements in accordance with ASTM Method E 274.

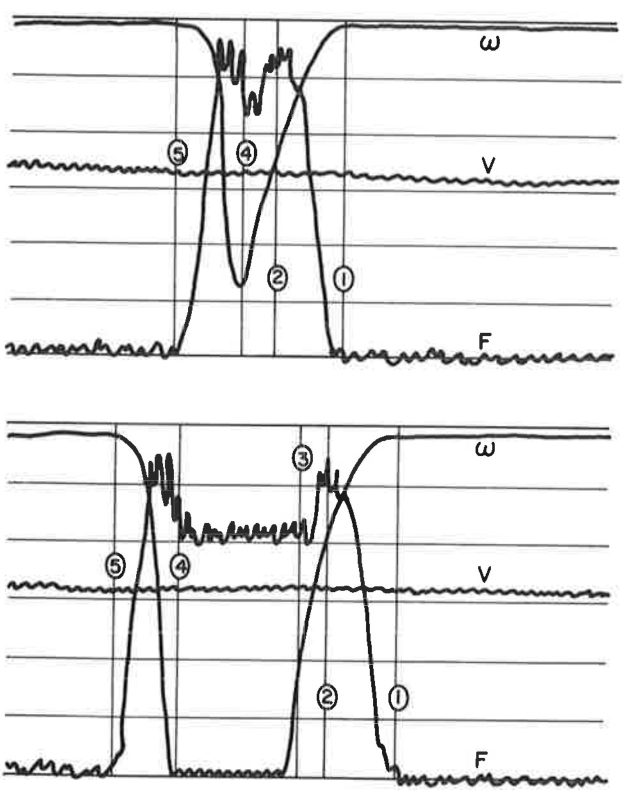

Figure 7. Replicas of typical oscillograms.

CALIBRATION

The static calibration procedures for wheel load and friction force used with the skid-resistance measurements are still applicable (2). To determine whether or not the indicated force is independent of wheel deceleration the wheel is raised off the ground—a lift cylinder which is a permanent part of the tester (2) makes this a simple matter—and with the vehicle at rest the test wheel is spun up by suitable means. The wheel is then permitted to run free and the brake is applied. No force signal should be generated as the wheel is decelerated.

Vehicle and test wheel speed are calibrated by driving a known distance at constant speed and measuring the time needed to traverse this distance.

TYPICAL RESULTS

In Figure 7 two typical oscillograms are reproduced. They are to be read from right to left. Vehicle speed, V, test wheel angular velocity, ω, and friction force, F, are recorded.

At point 1 brake application begins: the test wheel velocity begins to decrease slowly and the friction force increases. At point 2 the critical slip has been reached: the friction force is at its maximum. The test wheel velocity now decreases rapidly and the friction force decreases again.

At point 3 in the lower oscillogram, the test wheel velocity has become zero: the wheel is locked and the tire slides along the pavement. At point 4 dumping of the air from the brake application system allows the test wheel to spin up again. In the upper oscillogram this occurs before the wheel has come to a full stop. At point 5 the test wheel has regained its original velocity. The vehicle speed has remained constant throughout the cycle.

Scales are not given in Figure 7 for any of the variables because the intent is to show the results which are typically obtained. By filtering, most of the noise can be eliminated from the recorded signals. Since, however, a transient process is being recorded, filtering must be used with caution to prevent erroneous results. In skid testing there is, of course, no such limitation.

CONCLUSION

Although only a limited number of tests have been made so far, it is evident that the adaptation of the Penn State road friction tester to the measurement of tire-pavement friction in transient slip has been successful.

The conversion will be useful in many aspects of tire-pavement friction research where laboratory and theoretical studies require verification under real road conditions. The data which we are planning to obtain will also clarify how skid number and brake slip number are related (1) and to what extent the one can serve in the place of the other where safety is concerned.

ACKNOWLEDGMENTS

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