LABORATORY APPARATUS FOR FRICTION TESTS BETWEEN TIRES AND PAVEMENTS

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SYNOPSIS

A machine has been built to measure in the laboratory the following characteristics of iron paving blocks: (1) the coefficient of friction between the paving blocks and rubber tires for straight skidding and for sideways skidding, (2) the stopping distance of a car on such a pavement, and (3) the tire noise. The machine consists of two six-foot flywheels, on the periphery of which are bolted the paving plates to be tested. An automobile is mounted such that its front wheels rest on these flywheels. The flywheels are rotated by a 15 horsepower motor to top peripheral speeds of 60 miles per hour. Hydraulic traction dynamometers are connected to the center of gravity of the car and serve to measure the braking force and the sideways force when the brakes are applied or when the front car wheels are turned through an angle. A high-speed motion picture camera is used to record the dynamometer readings, the time, and the motion of the flywheels and of the front car wheels. Examples of the curves so obtained are given. It has been found that by changing the design of the surface pavement corrugations, the coefficient of friction may be changed by more than 100 per cent.

If cast iron is to be used as a surfacing material for pavements, it is imperative that it have a corrugated or studded surface. While rubber tires on wet, polished, smooth iron have a coefficient of friction of only about 0.2, it has been found possible to increase this value greatly by using a roughened surface. Since iron can be cast into a large variety of designs, there is the possibility of developing a surface having very large coefficients of friction. In attempting to devise such a surface it was necessary to have a rapid and cheap method of testing pavement surfaces.

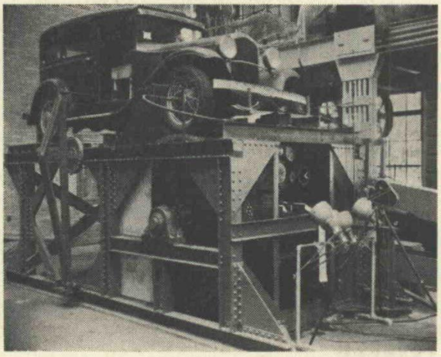

Figure 1

A laboratory testing machine was built to measure the following functions of the relative speeds of the pavement surface and automobile: (1) the coefficient of friction both for skidding and skidding impending; (2) the stopping distance of a car; (3) the coefficient of side friction (steering response); and (4) the noise generated by the interaction of the pavement surface with the automobile tires. While the absolute magnitudes of these quantities as measured in the laboratory may differ from those which would have been obtained if the tests had been made on a highway of the same material, the measurements serve as a basis for comparison of the experimental surfaces. It is planned to correlate our laboratory measurements with highway measurements later.

APPARATUS

Figure 1 is a photograph of the testing machine. It is essentially a device for moving the pavement surface while the test car is at rest. The cast steel paving

surface is bolted to the periphery of two 6-ft. flywheels which are keyed to a 5-in. axle mounted in roller bearings supported by a heavy steel frame. The method of mounting the pavement plates is shown in Figure 2. By means of a 15 hp. slip-ring motor and a belt drive the flywheels can be given peripheral speeds up to 60 m.p.h. A 1931 Plymouth car is mounted so that its front wheels rest on the paving surface, while its rear wheels are supported by a platform. The car is held in place by two cables at right angles fastened to its center of gravity. The cables are about 3 ft. long and, therefore, permit the car to bounce up and down as it would under actual driving conditions. The master cylinder of the hydraulic brake system of the car is mounted near the bottom of the machine frame with a lever to operate it. Copper tubing and a short section of reinforced rubber tubing connect the master cylinder to the front brakes. The car wheels are made to track straight on the pavement by means of a lever attached to the tie-rod, pivoted at the axle, and held between two clip angles.

An attempt was made to simulate as nearly as possible the actual driving conditions on a highway. When an automobile is driven around a curve or when it is decelerated by the application of its brakes, the inertial force acts as though it were all concentrated at the center of gravity. For this reason, the restraining forces in the laboratory set-up are applied and measured at the center of gravity of the car.

The second condition of similarity to driving conditions to be fulfilled is that the kinetic energy of the flywheels at a peripheral speed v shall be equal to the energy normally dissipated at the front wheels of a car when it is stopped on the highway from a speed v. If we assume a car (with all four wheels locked) skidding to a stop from a speed v, the energy dissipated at each wheel is proportional to the weight on that wheel provided that the coefficient of friction is the same at all four tires. Kinetic energy is also proportional to weight. Therefore, it can be shown that in such a case the energy dissipated at each car wheel is equal to the initial kinetic energy of the weight supported by that wheel. Therefore, the second condition to be fulfilled by the test machine can be expressed by the equation:

$$\frac{1}{2} I \frac{v^2}{R^2} = \frac{1}{2} m_f v^2,$$

Wherein I is the moment of inertia of the flywheels, v is the peripheral speed of flywheels, R is the flywheel radius, and m_f

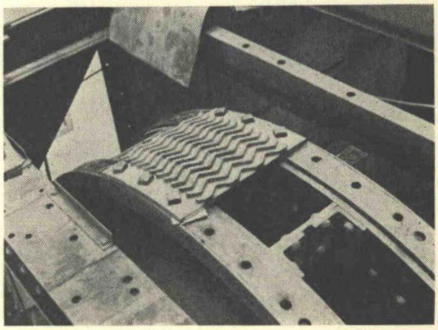

Figure 2

is the total mass supported by the front car wheels. Solving the equation for I, we have:

$$I = m_f R^2$$

However, in order to make the flywheels strong enough to stand the top operating speeds safely, it was found necessary to build the flywheels a little heavier than the weight obtained from the above equation. The only calculation in which I enters is that of stopping distance, and here the proper corrections for the discrepancy in I are made.

The iron pavement which has been in use on the University of Minnesota campus for the past four years has acquired a high degree of polish, and the edges of its surface lugs have been only

slightly rounded. To make the test surface in the laboratory set-up correspond to a pavement which has been in use for several years, the following "aging" process is used:

After the pavement plates have been bolted to the flywheels, a light cut is taken across their surface with a lathe tool which is carried in a portable lathe carriage bolted to the testing machine (the flywheels being rotated by a motor through a speed reducer) (see Fig. 3). Next a No. 80 grit emery wheel is mounted in the lathe carriage, and the flywheel surface is ground to eliminate the scratches made by the cutting tool.

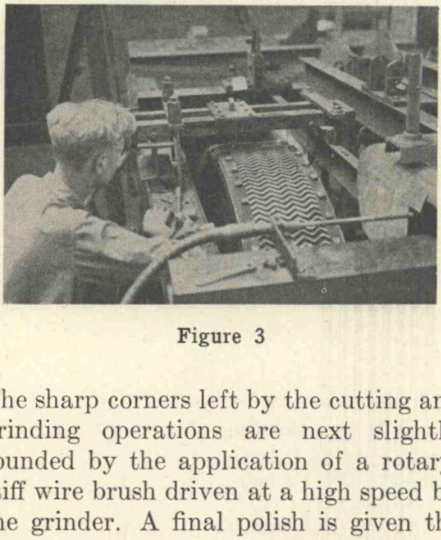

Figure 3

The sharp corners left by the cutting and grinding operations are next slightly rounded by the application of a rotary, stiff wire brush driven at a high speed by the grinder. A final polish is given the surface by the manual application of a fine emery cloth while the flywheels are rotated at a high speed.

All of the tests are run on a wet surface. Other investigators [1] have found that if a surface has satisfactorily high coefficients of friction when it is wet, it also will be satisfactory when it is dry. The water is sprayed on the surface at the rate of about 1½ gal. per minute.

[1] Moyer, *Proceedings,* Highway Research Board, Vol. 13, p. 123 (1933) and Stinson & Roberts, p. 169.

Both new and old tires are used for all of the tests. The procedure is generally to use a new nonskid tread tire until it is slightly worn, and then to cut off its tread to make it correspond to an old tire. The tire tread is cut off on a lathe by the use of a sharp, flat knife which is constrained to move in a special templet to give the correct curvature to the cut. This curvature was determined from measurements on several old tires. The tire size is 4.75 by 19 in., and the tire pressure used is 35 lb. per sq. in.

MEASURING INSTRUMENTS

For the computation of the coefficients of friction, the braking force and the side force acting on the car are measured through the anchoring cables by hydraulic dynamometers, which were designed and constructed in this laboratory. The side cable-lever-dynamometer set-up can be seen in Figure 1. Each dynamometer consists of a bourdon tube pressure gauge connected through a ¾ in. copper tube to a water-tight steel drum, one side of which is thin, flexible steel sheet. When the dynamometer is filled with water, it will accurately measure forces applied to the flexible face of the drum. The effective area of the dynamometer drum is about 100 sq. in., and since the displacement of the bourdon tube gage is less than ½ cu. in. for the maximum force recorded, the motion of the drum face is less than 0.005 in. Therefore, the measurement of the brake force and of the side force requires only a negligible motion of the center of gravity of the car. This is, of course, necessary in order to have as small a time lag as possible in the force measurements.

The rotation of the flywheels and of the front automobile wheels is indicated on special "clocks" made in this laboratory. These revolution indicators consist of an 8-in. dial with pointers driven

through a gear box. The flywheel indicator is coupled to the flywheel axle through a chain drive and can be read directly to 0.025 revolution. Each of the automobile wheel indicators is coupled to the automobile wheel through a flexible shaft, and can be read to 0.1 revolution.

Time is measured by a revolution indicator of the above type, driven by a 60 cycle synchronous motor. Time can be read directly to 0.025 sec. and estimated to 0.010 sec.

A standard automobile speedometer is coupled through a belt drive to the flywheel revolution indicator. It gives the operator the approximate speed of the flywheels when tests are being made. More exact determinations of the speed are made from the data on flywheel motion and time.

A pressure gauge indicates the oil pressure in the hydraulic brake line.

Two recording vibrographs were built to show the vertical and horizontal motion of the automobile axle. The recording mechanism is driven by the same synchronous motor that marks the passage of time, so that the vibrograph readings can be correlated with the other data.

All of the instruments are mounted on a 3 by 4-ft. panel set in the front of the machine, as shown in Figure 1. This permits a motion picture record to be made of the instruments during a test.

A 16 mm. Eastman Ciné-Special motion picture camera is used to record the readings on the instrument board. For most of the work the camera is operated at 16 frames per sec. and ¼ shutter opening to give an exposure of 1/128 sec. This "stops" the motion of the pointers quite well. In some of the work, camera speeds as high as 64 frames per second are used. The negative panchromatic film is viewed in an Eastman "Recordak," and the instrument readings are transcribed to data sheets.

TEST PROCEDURE AND CALCULATION

Coefficients of Friction: The two brakes are first equalized so that when the hydraulic brake pressure is gradually increased the two wheels lock at as nearly the same instant as possible. This adjustment is always made before the coefficient of friction tests are made.

The test routine is as follows: The flywheels are brought up to the desired speed by the motor, the power is shut off, and one operator applies the brakes while the other operates the movie camera. The brakes are left on until the wheels have been locked for about 1½ sec. The tires are then washed with cold water (for cooling and for carrying off the small rubber particles that have been rubbed off), and the same procedure is repeated for another speed. Usually tests are made at the lower speeds first, because the greatest tire wear occurs at the high speeds. Tests are run from 5 to 60 m.p.h. at 5 to 10 m.p.h. intervals.

Next the brake force dynamometer is calibrated under the same conditions as those under which the tests were made. A rod is attached to each end of the front axle, and it is connected at the other end to the vertical arm of a right angle lever which is pivoted at its apex on the machine frame. To the horizontal end of the lever are hung the calibrating weights. The levers have a mechanical advantage of 5, so that the horizontal force applied to the car is equal to the total calibrating weight multiplied by five. Turnbuckles in the connecting rods serve to take up the "give" in the front springs when the force is applied. The readings of the dynamometer plotted against the corresponding known forces give the calibration curve. This calibration curve has been found to be a straight line.

After the film has been developed and the data transcribed, the dynamometer

readings are plotted against the time A typical curve is shown in Figure 4 The peak in the curve is the value of the frictional force for skidding impending, while the average force over a ½ sec interval, beginning ¼ sec after the peak position, is taken as the value of the frictional force for the wheels locked From the calibration curve, the frictional force in pounds is calculated The corresponding speed of the pavement surface with respect to the car is calculated from the flywheel-time data

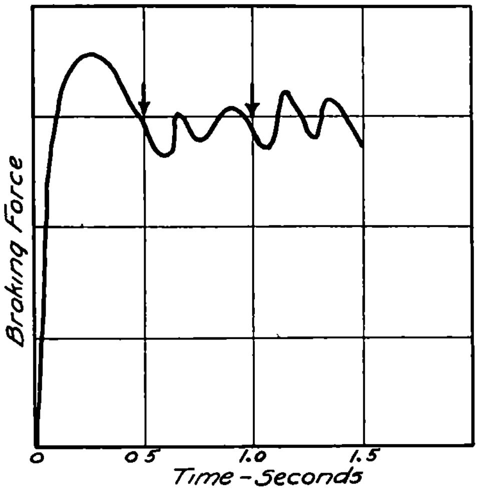

Figure 4

The coefficient of friction is calculated from the following formula

$$u = \frac{F}{W + 0\ 198F}$$

Wherein F = frictional force
W = static load on the front wheels of the car

The factor 0 198F in the denominator is the increase in the weight on the front wheels of the car when the force F is applied It has been shown by Moyer [1] that due to the couple acting on a car when the brakes are applied, the effective weight on the front wheels is $W + \frac{HF}{L}$ where H is the height of the center of gravity, and L is the wheelbase

It was found that when a braking force was applied, the car wheels would be forced back a little due to the elasticity of the springs This displacement was never more than ¼ in It can be shown that if the car wheels are displaced by this amount, the increase in the observed coefficient of friction is to the order of 0 005 or less than 1 per cent

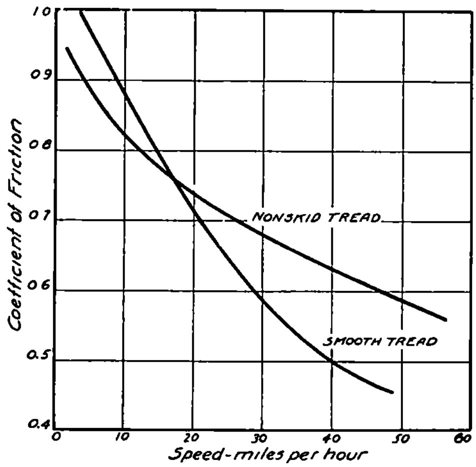

Figure 5

of most measurements The effect was compensated for, however, by initially setting the car so that the front wheel centers were $\frac{3}{16}$ in ahead of the vertical through the flywheel centers

The resulting coefficients of friction were plotted as a function of the flywheel peripheral speed in the usual manner Such curves are shown in Figure 5

Stopping Distance The test procedure for determining the stopping distance is as follows The flywheels are brought up to the desired speed, the power is cut off, the brakes are applied to lock the car wheels, and the flywheels are thereby brought to a complete stop A motion

[1] Moyer, *Bulletin* No 120, page 76, Iowa Engineering Experiment Station

picture record over the same range of speeds as before is made of the instrument board.

From the motion picture record, the initial speed v and the distance d travelled by the periphery of the flywheel are determined. The equivalent stopping distance of a car is calculated from the formula:

$$d_c = \frac{WR^2}{I} d + \frac{0.198v^2}{2g}$$

Where g is acceleration of gravity, v is the initial speed in feet per second, W is the static mass supported by the front car wheels, R is the radius of the flywheels, and I is the moment of inertia of the flywheels. This serves to reduce all stopping distances to the same moment of inertia, and also to approximate the stopping distance of a car on a highway of the same surface as that tested.

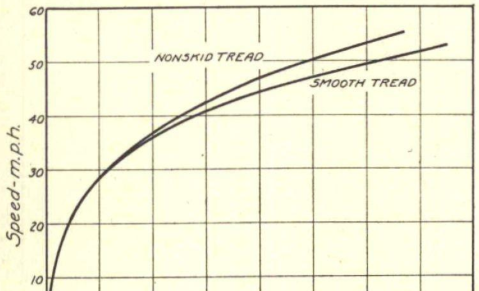

Figure 6

The stopping distance is plotted against the initial flywheel speed. This curve is, then, a characteristic of the pavement surface. Figure 6 is an example of such a curve.

Coefficient of Side Friction (Steering Response): For the tests on side friction, the clip angles are removed from the automatic steering device in order that the car wheels may be turned through some steering angle ϕ. The steering apparatus is equipped with a stop that can be clamped at any desired steering angle within the range of the steering gear of the car. A picture of this set-up is shown in Figure 7.

The following procedure is used for making the tests: The clamp on the steering mechanism is set at the desired steering angle ϕ, the flywheels are brought up to the desired speed v, and the power is cut off. One operator turns the steering wheel until the stop is hit, while the other operator gets the motion picture record of the instruments. After about a second, the wheels are straightened and the procedure is repeated for some other speed. Generally for each angle ϕ tests are made at 10 m.p.h. intervals up to 60 m.p.h. This is done for steering angles over the range available (about 22 deg.) at about 4 deg. intervals.

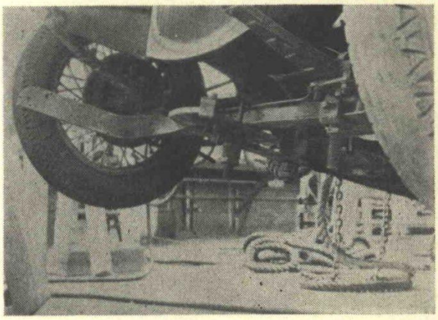

Figure 7

This side force dynamometer is calibrated for the conditions under which it is used. The known calibrating force is applied in line with the front axle by a lever-weight system, similar to that used for the brake-force calibration. In this case each front wheel is made to rest on two horizontal plates with rollers between in order that they may be free to move. The tires are deflated enough to bring the axle down to its normal level. The readings of the dynamometer plotted against the known force gives the calibration curve and serves as a basis for

the calculations of the side force of friction It, too, is a straight line

From the motion picture record of the side force dynamometer, the average force acting is calculated for the angle ϕ, and the speed v which is determined as before The coefficient of side friction, or the steering response, is then

$$u = \frac{\text{force of side friction}}{W}$$

A small correction is applied to this value to compensate for the effect of the displacement of the car wheels when they are turned through an angle Figure 8 shows the type of curve obtained for side coefficient as a function of speed

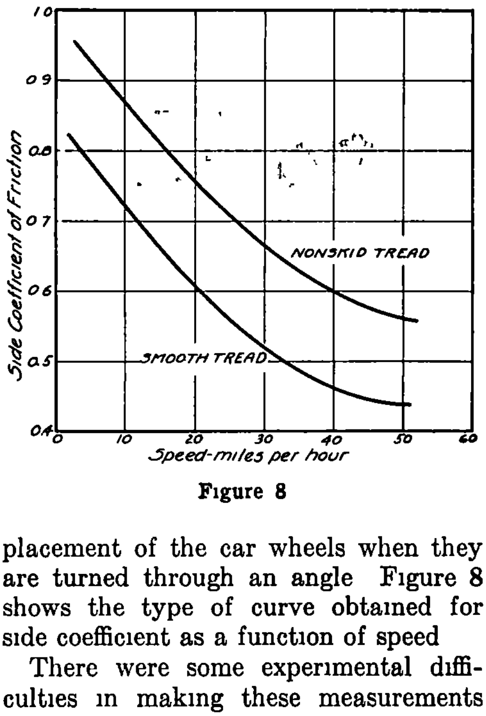

Figure 8

There were some experimental difficulties in making these measurements due to the flexibility of the car and its tendency to tilt under a side force The tilting was largely eliminated by introducing a torsional stabilizer at the rear springs The difficulties due to the flexibility of the car were reduced by tightening the side dynamometer cable to introduce an initial side force on the car somewhat less than that to be measured, the car being pulled up against a stop When the front wheels were turned through an angle, the car would pull away from this stop, so that the force registered was the one actually acting at the front wheels In this way it was possible to cause the car wheels to track near the center of the rotating pavement even under very high side forces The dynamometer was always calibrated under the same conditions as it was used

Noise Measurements A General Radio Type 559B noise meter was used to measure the noise generated by the tires on the pavement surfaces The noise meter is set about 20 in from the tire and pointing toward the point of contact between tire and pavement Readings are then taken as a function of the flywheel speed The background noise is next measured as a function of speed with the car jacked up so that the tires are not in contact with the pavement The noise intensity in decibels is plotted against velocity, both for the background and for the tire noise The difference between the two curves gives the noise due to the interaction of tires with the pavement Figure 9 is an example of such a noise

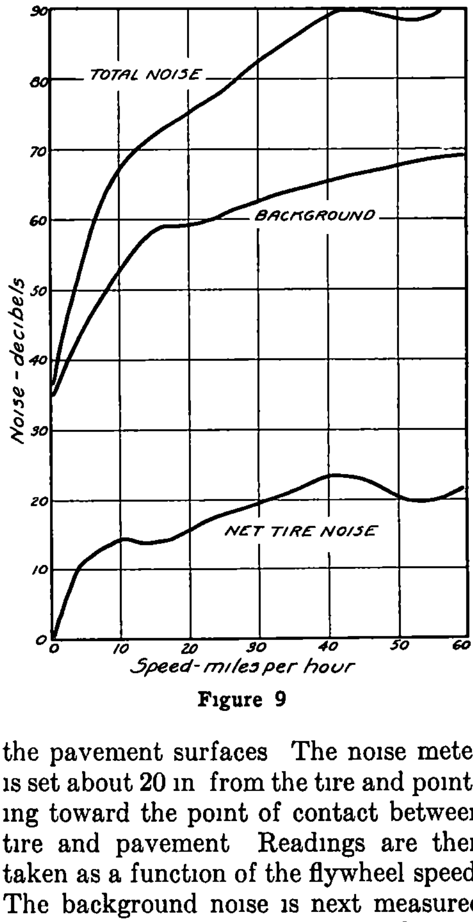

Figure 9

curve Similar procedure is used to obtain the noise inside of the car Since the background noise is substantially the same for all of the test surfaces, the method indicates the relative "noisiness" of the pavements tested

CONCLUSION

Very marked changes can be produced in the coefficients of friction of tires against a wet, cast steel pavement by simply altering the design of the pavement surface Seven designs of a roughened surface have so far been tested, and the range in value of the coefficients for these surfaces is given in Table I

It should be emphasized again that these values may not be the same when they are measured on a flat surface The correlation of the values as measured on a flat surface (a highway), and the values as measured on the curved surface in the experimental set-up, is to be carried out this summer (1938) An iron pavement one-half block long is at present being laid on a campus street, and the identical design of surface used on this street is also being tested in the laboratory It is hoped that by comparing the values of the coefficients of friction and the stopping distances as measured on the street to those measured on the laboratory test machine, some conclusion may be reached as to the relation existing between the two methods of measurement More can be said about the absolute magnitudes of these values after the correlation tests have been carried out

TABLE I

(All values given for 30 m p h peripheral speed of flywheels, and for a wet surface)

	Coefficients of friction		Coefficient of side friction	Stopping distance, feet
	Skidding impending	Wheels locked		
Nonskid tires				
High	83	70	91	90
Low	46	34	49	44
Smooth tires				
High	86	66	75	104
Low	32	24	48	40