FURTHER COEFFICIENT OF FRICTION TESTS

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SYNOPSIS

At the Thirteenth Annual Meeting of the Highway Research Board, the authors reported on tests to determine the coefficients of friction between automobile tires and road surfaces for straight-away rolling and for skidding [1] The study has been continued during the past year and three sections of the work are reported in this paper

A method is submitted for calculating the theoretical stopping distances of automobiles by averaging the coefficients of friction on the basis of the square of the speed The results point out the lower coefficients generally found at the higher speeds

Successive tests on vertical-fiber wire-cut lug brick roads with asphalt filler have shown a continued decrease in both the maximum rolling and the sliding coefficients of friction due to the extrusion of the asphalt

In tests on snow, non-skid tires showed an advantage of 7 to 27 per cent over smooth tires at speeds between 20 and 40 miles per hour Rolling coefficient for the 5 00 inch non-skid tire was 12 per cent better than for the 6 50 inch tire when stopping from 40 miles per hour but showed no difference when sliding For smooth tires, the 5 00 inch tire had an advantage of 8 and 14 per cent over the 6 50 tire for rolling and sliding respectively

The study of the coefficient of friction existing between tires and wet road surfaces with the variable factors involved has been continued during the past year

This report presents (1) a method of calculation of stopping distances from the coefficient of friction curves, (2) the effect of time, weather and traffic upon the coefficient of friction of several vertical-fiber wire-cut lug brick roads, (3) the variation of the coefficient of friction on snow with variation of tire sizes, tread, and inflation pressures The results submitted in this report are on the basis of stopping distances as well as coefficient of friction

STOPPING DISTANCE CALCULATION

On practically all roads the coefficient of friction decreases as the speed increases This factor is more important, however, than is

[1] Coefficient of Friction Between Tires and Road Surfaces, Karl W Stinson and Charles P Roberts, Proceedings Highway Research Board, Vol 13, page 169

indicated by the coefficient of friction curves, due to the fact that the theoretical stopping distance varies with the square of the speed

The idea of calculating the stopping distances from the curves of the coefficients of friction was suggested by Mr C G Hoover of the Firestone Tire and Rubber Company With his cooperation a method was devised for making these calculations Due to the low coefficients of friction at the higher speeds, the stopping distance from thirty miles per hour was found to be more than four times that required from fifteen miles per hour averaging about five and sometimes being over eight The method of calculation is as follows:

$$ds = vdt$$

where s = stopping distance, v = average velocity in feet per second; t = time in seconds

$$a = \frac{dv}{dt}$$

where a = acceleration in feet per second per second,

or

$$dt = \frac{dv}{a}$$

Then

$$ds = \frac{vdv}{a}$$

and

$$s = \int_{v_0}^{v_1} \frac{vdv}{a}$$

$$F = Ma$$

where F = force, M = mass

Since

$$w\mu = \frac{wa}{g}$$

where w = weight, μ = coefficient of friction, g = 32 2 feet per second per second,

$$a = \frac{w\mu g}{w} = \mu g$$

and

$$s = \int_{v_0}^{v_1} \frac{vdv}{\mu g}$$

If a curve is plotted with $\frac{v}{a}$ or its equal $\frac{v}{\mu g}$ as ordinate and V as the abscissa, the area under the curve will represent the stopping distance and the stopping distance may be obtained by integrating the area in terms of the coordinates

The area under such a curve may be obtained by applying Simpsons' rule for the area of an irregular figure The figure is divided by vertical lines into an even number of strips "n" of equal widths "dv" or $\frac{\text{"V"}}{n}$, where V = the velocity from which the stopping distance is to be calculated, and the ordinates

$$\frac{V_0}{g\mu_0}, \frac{V_1}{g\mu_1}, \frac{V_2}{g\mu_2}, \ldots \frac{V_n}{g\mu_n}$$

are measured The stopping distance,

$$s = \frac{1}{3}\frac{V}{n}\left\{\frac{V_0}{g\mu_0} + \frac{4V_1}{g\mu_1} + \frac{2V_2}{g\mu_2} + \frac{4V_3}{g\mu_3} \quad \frac{2V_{n-2}}{g\mu_{n-2}} + \frac{4V_{n-1}}{g\mu_{n-1}} + \frac{V_n}{g\mu_n}\right\}$$

If an increment of five miles per hour or 7 333 feet per second is assumed as "dv" or $\frac{V}{n}$, it will be seen that $V_0 = 0$ feet per second, etc Since g = 32 2 feet per second per second the only variables in the formula are the values of "μ" at the different speeds It is therefore not necessary to plot a curve of $\frac{\text{"V"}}{g\mu}$ against "V" since the values of the variables "μ" can be obtained from the conventional curve of "μ" against "V", and these values substituted in the formula

In order to obtain a curve of the stopping distance from any speed under any given set of conditions, the stopping distances have been calculated for 10, 20, 30 and also 40 miles per hour when the value of "μ" was known These distances were then plotted as ordinates with speeds in miles per hour as abscissae

It is recognized the stopping distance thus calculated does not represent the true stopping distance due to the neglect of the rolling and air resistances These factors are practically constant for various tires when tested on different hard road surfaces and therefore are neglected since this is a relative comparison of the variable coefficients of friction rather than the calculation of actual stopping distances of an automobile

TIRES

The tests were made with the tires shown in Figures 1 and 2.

EG;—5 00 x 19, General, smooth, 6 ply.
FR;—5 00 x 19, Dayton, "Roll-on," 6 ply
HT,—5 00 x 19, Dayton, "Thorofare," 6 ply
NK,—5 00 x 19, Kelly-Springfield, 6 ply
TF-K,—6 50 x 16, Firestone, "K," 4 ply
UF-HS,—6 50 x 16, Firestone, "High Speed," 4 ply.
VF;—6 50 x 16, Firestone, "High Speed," smooth, 4 ply

All tests were made using a tire load of approximately 800 pounds with tire pressure of 32 pounds in the 5.00 x 19 tires and 18 pounds in the 6.50 x 16 tires, unless otherwise noted.

The FR and HT Dayton tires were donated for this work by the Dayton Rubber Company at the beginning of this project and, as a result, all comparative road tests have been made using the HT tire.

Figure 1. The 5 by 19-in. Tires Used in the Tests.

This HT tire is only slightly worn after several thousand tests. Comparative tests have also been made on many roads with other tires. The NK tire was donated by the Kelly Springfield Tire Company. The TF-K, UF-HS and VF tires were donated by the Firestone Tire and Rubber Company. The UF-HS is the regular tread manufactured by Firestone in 1934 while the TF-K is a special design developed for the more quiet operation of independently sprung front wheels.

ROADS

BA-3. Westerville Avenue, Columbus, Northeast from Cleveland Avenue. This road surface consisted of 3-in. vertical-fiber wire-cut lug bricks with asphalt filler Type F-1 (Ohio State Specification) laid on a 1-in. sand cushion. A white-wash coat was used to permit removal of the excess filler. The road was opened to traffic in the fall of 1933.

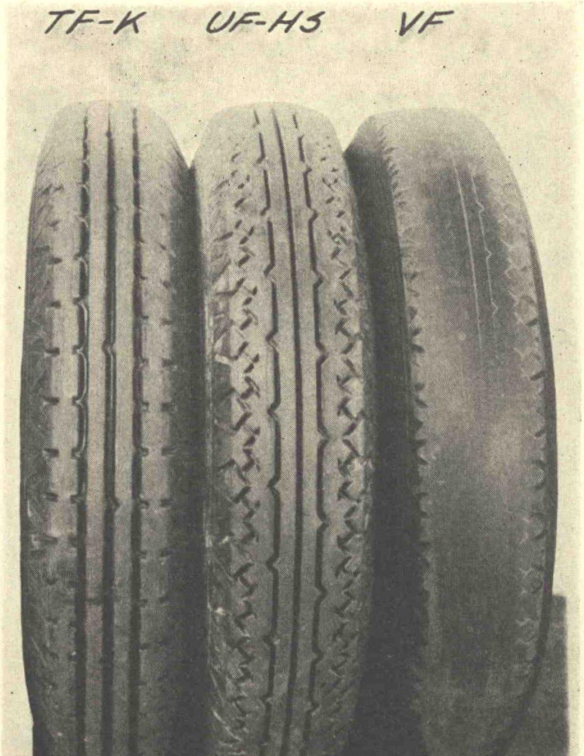

Figure 2. The 6.5 by 16-in. Tires Used in the Tests.

BA-22. East city limits of Circleville on U. S. Route 22. Three-inch vertical-fiber wire-cut lug bricks with asphalt filler Type F-1 were used for the surface. The surface of the bricks was white-washed before pouring the filler so as to permit removal of the excess. This road was opened to traffic late in the fall of 1932.

BA-31. State Route 31. Canal Winchester, Ohio, south to Fairfield County line. Three-inch vertical-fiber wire-cut lug bricks were used with asphalt filler Type F-1 and were laid on a three-quarter inch sand cushion. A white-wash coat was used to permit removal of the excess filler. This section was opened to traffic in the fall of 1933.

BA-40. East Main Street in Columbus and east of Bexley. This surface consists of a 3-in. wire-cut vertical-fiber lug brick filled and covered with type F-1 asphalt. The road was completed in November, 1931. Sand was placed on the asphalt during the summer of 1932.

BRICK

The results presented last year indicated that the exudation of the filler in brick roads prevented the tires coming in contact with the brick

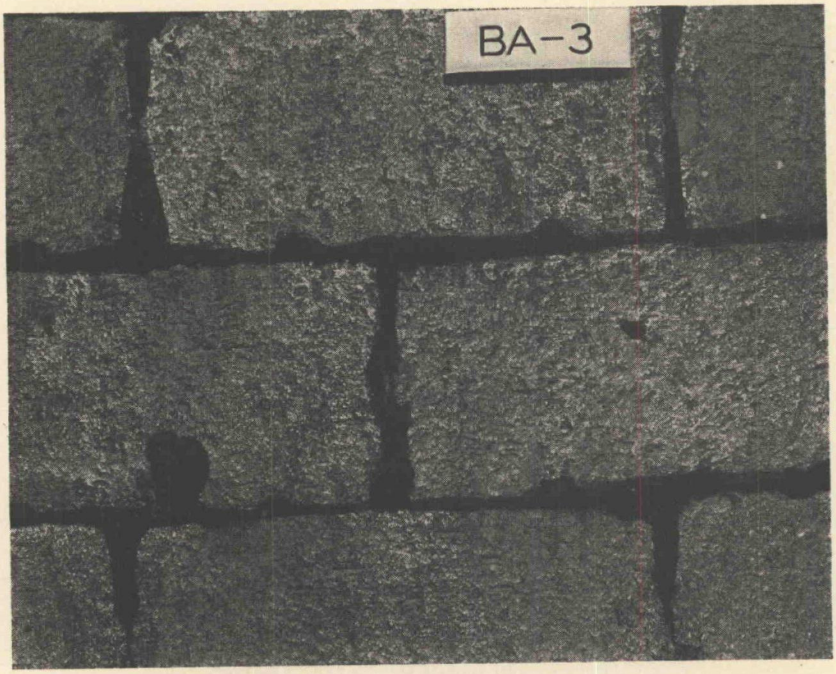

Figure 3. Vertical Fiber Brick Road, BA-3; April, 1934. Road Opened to Traffic in Fall of 1933.

surface. Therefore, even if the road was made with a wire-cut brick surface, the anti-skid feature was at least partially lost. During the past year this problem has been studied on the four vertical-fiber wire-cut lug brick roads described previously. The results of these tests are shown in Figures 10 to 18 inclusive. The photographs of the surfaces are shown in Figures 3 to 9, inclusive.

The first test on BA-22 was made immediately after completion of the road and gave very good coefficients of friction both for rolling and sliding with stopping distances of 36.5 and 47.3 feet, respectively from 30 miles per hour. The BA-3 and BA-31 roads were opened to traffic

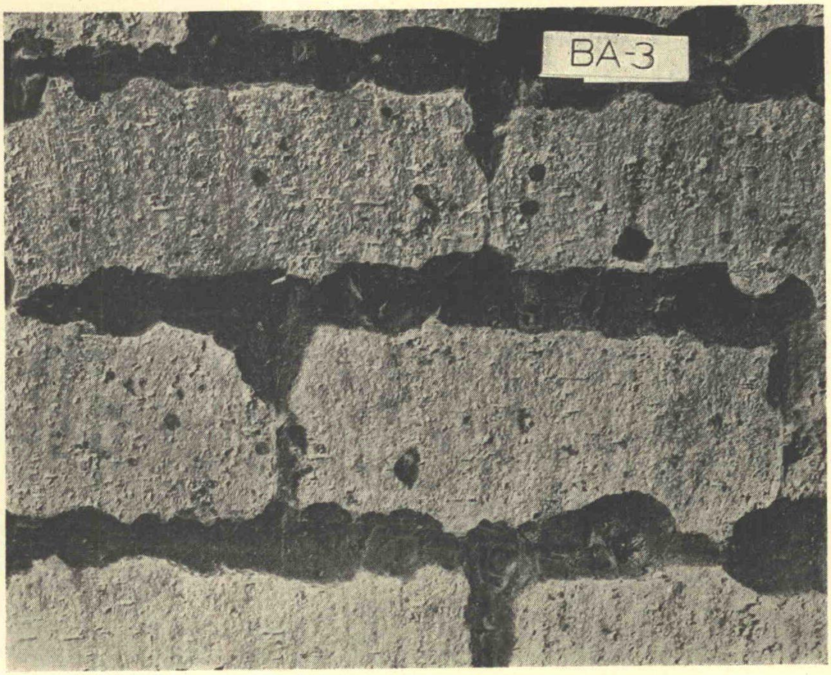

Figure 4. Same Road as Shown in Figure 3; October, 1934.

Figure 5. Vertical Fiber Brick Road, BA-22; April, 1934. Road Opened to Traffic in December, 1932.

Figure 6. Same Road as Shown in Figure 5; October, 1934.

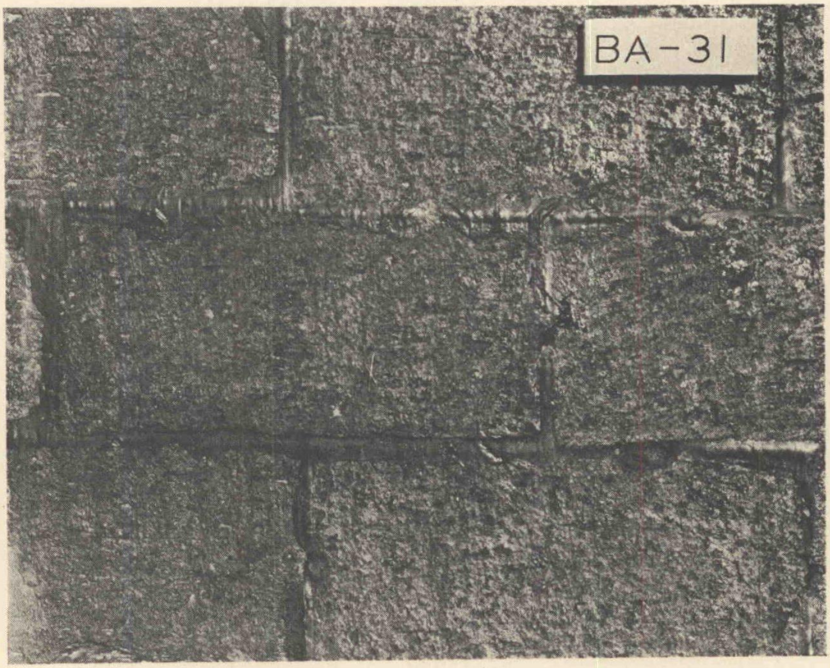

Figure 7. Vertical Fiber Brick Road, BA-31; April, 1934. Road Opened to Traffic in Fall of 1933.

Figure 8. Same Road as Shown in Figure 7; October, 1934.

Figure 9. Vertical Fiber Brick Road, BA-40; April, 1934. Road opened to Traffic in November, 1931.

in the fall of 1933 but no tests were made until the following spring of 1934 Although no hot weather intervened, a slight exudation had taken place when the tests were made with the result that the coefficients of friction were less than obtained on the first tests on BA-22 and gave rolling and sliding stopping distances from 30 miles per hour of 50 4 and 69 feet respectively for BA-3 and 47 8 and 68 8 feet for BA-31 These two roads were tested again in October 1934, the rolling and sliding

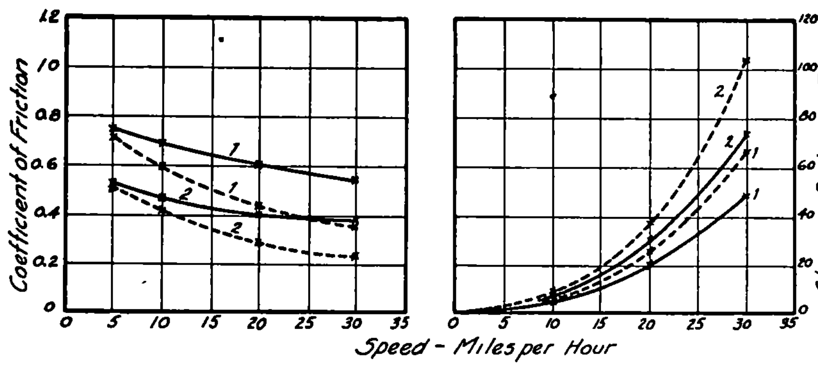

Figure 10. Friction and Stopping Distance Variations on Vertical Fiber, Wire-cut Lug Brick Road, BA-3, with Non-Skid Tire HT. Solid Lines, Rolling, Dash Lines, Sliding. (1), April, 1934; (2), October, 1934.

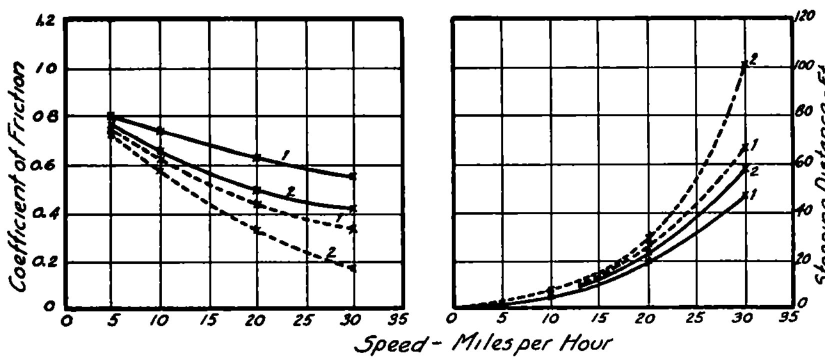

Figure 11. Friction and Stopping Distance Variations on Vertical Fiber, Wire-cut Lug Brick Road, BA-31, with Non-Skid Tire HT. Solid Lines, Rolling; Dash Lines, Sliding. (1), April, 1934; (2), October, 1934.

stopping distances had increased 50 and 55 7 per cent respectively for BA-3 and 24 and 50 3 per cent for BA-31 The results are shown in Figures 10 and 11.

Tests were made on BA-22 in December, 1932, October, 1933, April, 1934; and October, 1934. The results are shown in Figure 12 There has been a continued decrease in the coefficient of friction and a corresponding increase in the stopping distances required. It had been expected that one summer of exudation with the breaking off and wearing away of the filler from the top of the bricks during the following winter would cause the coefficient of friction curves to rise, approaching that for the original brick surface The filler has had a tendency to break off under service but many of these small pieces seem to have been rolled into the rough brick surface (Figure 6) and thus serve to increase the actual asphalt surface exposed to the tires rather than decrease it

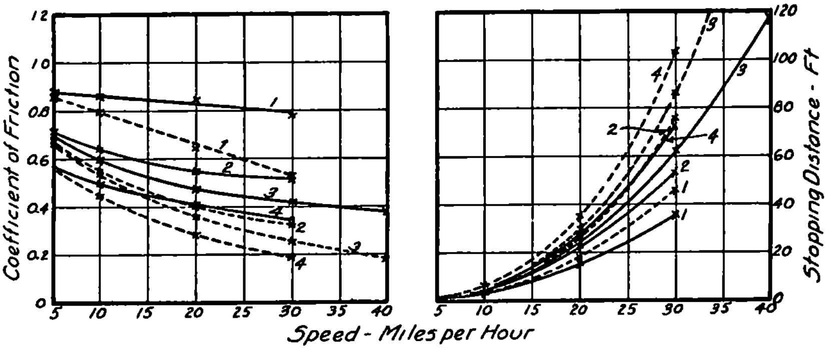

Figure 12. Friction and Stopping Distance Variations on Vertical Fiber, Wire-cut Lug Brick Road, BA-22, with Non-Skid Tire HT Solid Lines, Rolling, Dash Lines, Sliding. (1), December 30, 1932; (2), October 8, 1933, (3), April 25, 1934, (4), October 25, 1934.

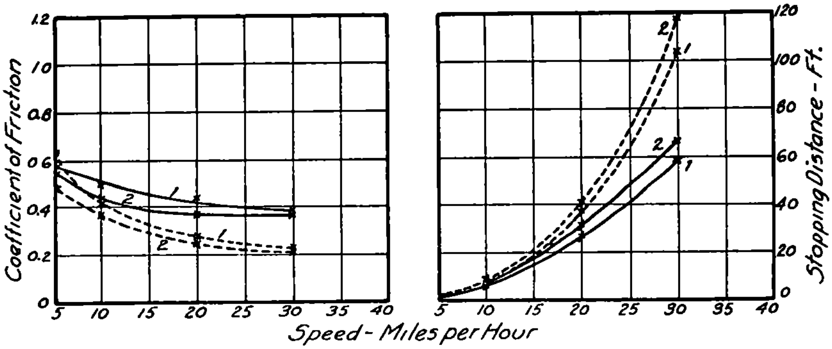

Figure 13. Friction and Stopping Distance Variations on Vertical Fiber, Wire-cut Lug Brick Road, BA-40, with Non-Skid Tire HT Solid Lines, Rolling, Dash Lines, Sliding. (1), December 7, 1932, (2), November 5, 1934.

Tests on BA-40 were reported last year. The asphalt had not been removed from the brick surface but sand had been rolled into the asphalt These first tests were made in December 1932 Since that time traffic has worn off much of the surplus asphalt exposing in many places over 50 per cent of the wire-cut brick surface This road was tested again in November, 1934 and the results are shown in Figure 13 There has been a small decrease in the coefficients of friction especially the rolling coefficients at slow speeds, with stopping distances when rolling and sliding from 30 miles per hour increased from 68 5 and 105 3 feet to 76 8 and 116 6 feet respectively This might be accounted for by wearing off or the submersion of the sand thus leaving the road more slippery although part of the brick surface was exposed

TABLE I

STOPPING DISTANCES IN FEET FROM 30 MILES PER HOUR

Road	Rolling				Sliding			
	December, 1932	October, 1933	April, 1934	October, 1934	December, 1932	October, 1933	April, 1934	October, 1934
BA-22	36 3	53 8	62 9	73 9	47 2	75 5	86 3	105 5
BA-3			50 3	75 5			69 2	107 7
BA-31			47 6	59 0			68 7	102 0
BA-40	68 5			76 8	105 2			116 6
BA-22	First rain			97 0				126 6

When the tests on BA-22 were made in October, 1934 there was an initial sprinkling that completely wet the road leaving water standing on it but there was not sufficient rainfall to cause the water to run off the road This was the first rain in over six weeks A series of tests was made before the accumulated dirt was washed off by additional rain The results are shown in Figure 14 in comparison with later tests on the same day after the road had been thoroughly washed by a heavy rain which continued throughout the testing The rolling coefficients of friction were much less as a result of the initial sprinkling while those for sliding were less also but mainly at the lower speeds, at thirty miles per hour they were 0 251 and 0 177 respectively The variations of stopping

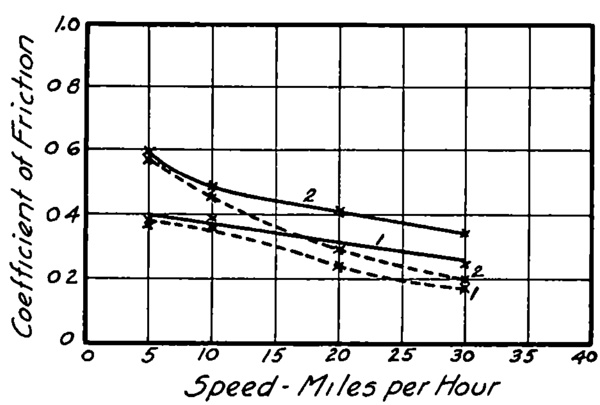

Figure 14. Friction Variation Between Initial Rain and After Thorough Washing on Vertical Fiber, Wire-Cut Lug Brick Road, BA-22, on October 25, 1934. With Non-Skid Tire HT. Solid Lines, Rolling; Dash Lines, Sliding. (1), Initial Rain; (2), After Heavy Rain.

distances from 30 miles per hour for rolling and sliding were 97.0 and 126.6 feet respectively for the initial sprinkling and 73.9 and 105.5 feet for the washed surface. This represents 31.3 and 20 per cent greater stopping distances which were required as a result of only an initial sprinkling on this road.

SNOW TESTS

During February and March 1934, over 1200 tests were made on snow with several different tires and at various tire pressures. Due to the difficulty of obtaining virgin snow for a large number of tests, packed snow was used. Most of the testing was made on two consecutive days

Figure 15. Packed Snow Used for Snow Tests.

when from 2 to 3 inches of packed snow was available on U. S. Route 40. Figure 15 shows the snow on this 50 foot road with a traffic lane cleared on each side. The testing was done on the 20 foot center strip of snow with the temperature varying between 20 and 27°F. during the two days.

Comparisons of smooth and non-skid tires on snow are shown in in Figure 16. In Figure 16 the rolling coefficient of friction was so nearly the same for the two 6.5 by 16-in. non-skid tires that only one curve was plotted. A second and lower curve shows the results for the smooth tire.

The sliding coefficient of friction curves have much greater variation with the UF-HS being the best and the TF-K tire at least half way down toward the curve for the smooth tire VF. At 40 miles per hour the coefficient of friction for the TF-K tire was 14 per cent less than that for the UF-HS

A comparison of the stopping distances is shown in Table II.

The variation of stopping distances while rolling is small but when sliding occurs the distance required for TF-K is 10 4 and 13 4 per cent greater than for UF-HS at 20 and 40 miles per hour respectively while the smooth tire VF requires 27 2 and 26 5 per cent greater distance

TABLE II

STOPPING DISTANCES ON SNOW (6 50 x 16)

Tire	Rolling		Sliding	
	20 mi per hr	40 mi per hr	20 mi per hr	40 mi per hr
	feet	*feet*	*feet*	*feet*
UF-HS	50 1	196 2	64 1	234 9
TF-K	50 1	196 2	70 8	266 4
VF	51 4	206 7	81 5	297 1

In Figure 16 the advantage of the 5 by 19-in non-skid tire NK over the smooth tire EG is very evident from both the rolling and sliding coefficient of friction curves A comparison of the stopping distances is shown in Table III The advantage of the NK tire is 6 6 and 8 8 per cent at 20 and 40 miles per hour respectively when rolling and 7 5 and 12 0 per cent when sliding

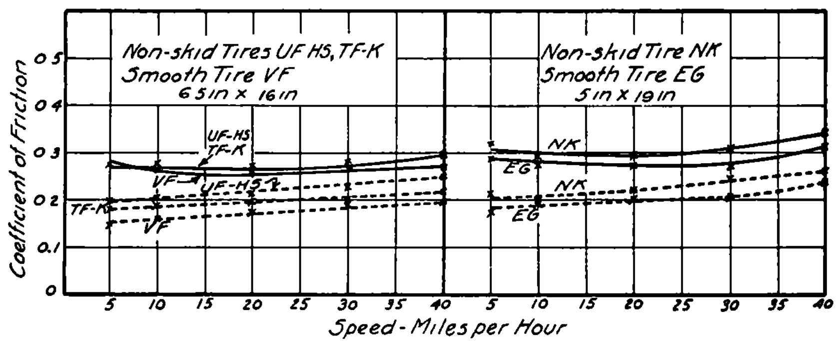

Figure 16 Friction Variation on Packed Snow With Smooth and Non-Skid Tires. February 2 and 3, 1934 Solid Lines, Rolling, Dash Lines, Sliding.

The variation between the 5 by 19 and 6 50 by 16-in tires is shown in Figure 17 The rolling coefficients of friction for the small diameter tires are better than for the large diameter, irrespective of the condition of the tread, but when sliding, the curves for the non-skid treads are approximately the same and better than the smooth treads

The tests just described were made using the recommended tire pressure for the 800 pound load on the tire In Figure 18 will be seen

TABLE III

Stopping Distances on Snow (5 00 x 19)

Tire	Rolling		Sliding	
	20 mi per hr	40 mi per hr	20 mi per hr	40 mi per hr
	feet	*feet*	*feet*	*feet*
Non-skid—NK	45 7	175 2	65 2	232 0
Smooth—EG	48 7	190 7	70 1	259 7

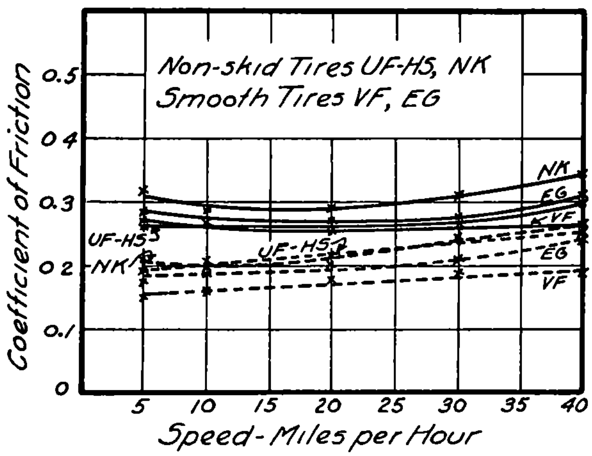

Figure 17. Friction Variation on Packed Snow With Smooth and Non-Skid Tires. February 2 and 3, 1934. Solid Lines, Rolling; Dash Lines, Sliding. UF-HS and VF, 6 50 in x 16 in , NK and EG, 5 in x 19 in

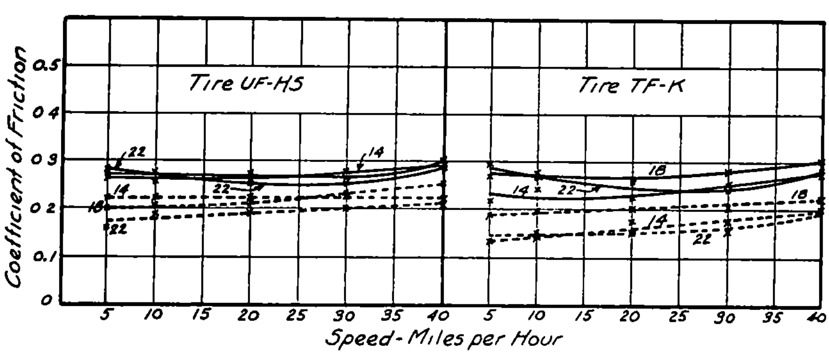

Figure 18. Friction Variation on Packed Snow With Variation of Tire Inflation Pressure. Tires UF-HS and TF-K February 2 and 3, 1934. Solid Lines, Rolling; Dash Lines, Sliding.

the results of tests where the pressure was varied four pounds above and below the recommended pressure of 18 pounds for the UF-HS and TF-K tires The UF-HS shows little variation when the pressure is below normal but the increased pressure produced a decided drop, especially of the sliding coefficient of friction.

The results when using the TF-K tire (Figure 18) show a decided advantage when using the recommended pressure of 18 pounds as they are highest both for rolling and sliding The variation of the inflation pressure caused a variation of the stopping distance as shown in Table IV

TABLE IV

EFFECT OF INFLATION PRESSURE ON SNOW

Inflation Pressure	Rolling		Sliding	
	20 mi per hr	40 mi per hr	20 mi per hr	40 mi per hr
pounds	*feet*	*feet*	*feet*	*feet*
14	59 0	218 4	90 6	315 8
18	50 1	196 3	70 8	266 4
22	51 7	211 7	89 1	327 1

DISCUSSION—FURTHER COEFFICIENT OF FRICTION TESTS

MR H P HAYDEN, *Barber Asphalt Company* The work of the authors of this paper as well as that of Professor Moyer has brought the attention of the highway engineers throughout the world to a consideration of the importance of the coefficient of friction between tires and road surfaces in highway design The data just presented magnify the importance of rather insignificant numerical differences in the coefficient of friction encountered in the study of various types of road surfaces by translating them into terms of stopping distances

Aside from the importance of this work in regard to the reduction of skidding hazards it seems evident a surface displaying a high coefficient of friction will result in a reduction in the slippage of tires under acceleration and thus effect large savings in fuel and tire wear

The effective coefficient of friction is no doubt reduced in case the road surface is so rough as to cause the tire to leave the surface momentarily at the speed of test It is conceivable the minute pulsation imparted to the tire by the extruded filler of brick pavements may be contributory to the reduction in coefficient of friction observed with increase in extrusion At the higher test speeds the tires only hit the asphalt coated high spots. This may explain the decrease in the coefficient of friction in Road BA-40 which, when originally tested, was entirely covered with type F-1 Asphalt which had been removed to the extent of about 50 per cent prior to retest

As any asphalt filler sufficiently fluid at the application temperature to permit of satisfactory penetration of the crack will be rich in bitumen, it is difficult to suggest a type of asphalt filler which will not have a low coefficient of friction after extrusion We may, however, expect the highly filled asphalts to give higher coefficients than those consisting of pure bitumen Although the sanding treatment given in the case of road BA-40 was not particularly successful, repeated sanding at maximum temperature should so fill the extruded filler as to increase the coefficient of friction substantially

MOTOR VEHICLE POWER REQUIREMENTS ON HIGHWAY GRADES

By R A Moyer

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SYNOPSIS

In order to get up to date information bearing upon the effects of highway grades on motor vehicle operating costs, six passenger cars and two trucks were used in a series of laboratory and road tests

In the laboratory, dynamometer tests were made on the rolling resistance, power, and fuel consumption characteristics of the vehicles

The road tests comprised gasoline consumption on various surfaces, gasoline consumption on grades, free wheeling tests; rolling, air and engine resistance, and acceleration and tractive effort

Some of the important points revealed by these tests are as follows In conventional gear the average gasoline consumption, ascending and descending grades at constant speed, increased uniformly with each per cent increase in grade above zero percent In free wheeling, fuel was saved when ascending and descending grades between 1 and 5 per cent, at speeds less than 48 miles per hour as compared to operation on level grades No advantage in gasoline mileage when operating in freewheeling as compared to conventional gear was obtained on a 10-mile hilly course at speeds greater than 52 miles per hour Savings in fuel costs, resulting from grade reduction, were greater for trucks than for passenger cars, on the same tonnage basis

Application of the test data to four typical grade reduction problems brought out these interesting relationships For passenger cars, operating in high gear at constant speed, the savings in fuel costs resulting from reducing a 9-per cent grade to a 6-per cent were ten times greater than in reducing from 6 to 3 per cent when the rise and fall were not affected and were four times greater when the rise and fall were changed Gently rolling grades of 3 per cent or less should cause only slight increases in fuel cost

For grades lower than 9 per cent, the time saving obtained from grade reduction is negligible for automobiles but is an important factor in truck operation on grades steeper than 3 per cent

INTRODUCTION

During the past fifteen years, great advances have been made in reducing highway transportation costs. Travel time has likewise been