Locked-Wheel Friction Tests on Wet Pavements

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The friction coefficient between a pair of locked automotive tires (running in the normal wheel tracks) and a wet highway surface was determined in an elaborate test program, using a specially constructed test trailer. This program provided data from more than 400 tested surfaces along approximately 6,500 route miles of rural sections of major transcontinental routes following the National System of Interstate and Defense Highways as nearly as possible. The data are tabulated, and cross-plots have been made to indicate the effects of age, wear (based on age and traffic volume), surface finish and aggregate composition on the friction coefficient exhibited by portland cement concrete roads. Summaries are made also for the comparative effects of age and wear on the friction coefficients of PCC and bituminous asphalt roads.

●THERE IS a correlation between the slipperiness of a highway and accident occurrences. The skid-resistance properties of the pavement surface are therefore vitally important in the design and construction of new highways and the refurbishing of older roads. Determination of friction coefficients along with an analysis of the road construction, material ingredients, and traffic use will indicate how the best surfaces have been attained.

In the late summer of 1959, the Vehicle Dynamics Department of Cornell Aeronautical Laboratory, Inc., undertook a program sponsored by the Portland Cement Association to determine locked-wheel friction coefficients on wet pavements. The results of this program (4) are reported herein. Data were obtained from more than 400 tested surfaces along approximately 6,500 route miles of rural sections of major transcontinental roads forming part of or closely paralleling the network known as the National System of Interstate and Defense Highways. Information was provided, therefore, on some sections of this network which have already been constructed, and on roads which will be superseded as major routes when the whole network is complete in 1970.

PROGRAM SUMMARY

The program objective was to determine the effect of surface finish and road construction on the friction forces attainable between a specific tire and various wet surfaces under steady-state nonrolling conditions.

The major pieces of equipment used in the field test part of the program consisted of a skid trailer designed, constructed, developed and proved in previous programs (1, 2) and a specially adapted tractor unit.

The route chosen and the sampling frequency for the tests are discussed later. Two months were required for the road test part of the program. This included time for tests, truck and trailer routine maintenance, minor repairs, and rest periods for the test crew of two men. The route mileage totaled 6,500 mi through 20 states, but the actual mileage covered by the truck and trailer was about 8,200 mi.

TABLE 1

DISTRIBUTION OF TESTS BY STATE

State	No. of Surfaces Tested
Arizona	12
Arkansas	34
California	11
Georgia	18
Illinois	18
Iowa	45
Kansas	58
Maryland	9
Missouri	18
New Mexico	8
New York	24
North Carolina	17
Ohio	9
Oklahoma	19
Pennsylvania	16
South Carolina	7
Tennessee	31
Texas	33
Virginia	18

At the time of each test, data acquired showed the location, basic surface material type, general description of road, ambient weather conditions, test speed (if other than 40 mph), and the average friction coefficient for the test surface. Table 1 gives the number of tests made in each state.

Subsequently, information was obtained on age, average daily traffic count, coarse and fine aggregate materials and surface finish. The portland cement concrete test sections were then divided into the various groups given in Table 2 according to the materials and surface finishes used.

TABLE 2

PORTLAND CEMENT CONCRETE SURFACE GROUPING

Group No.	Aggregate		Surface Finish	No. of Surfaces Tested
	Coarse	Fine		
1	Gravel	Nat. sand	Broom	18
2	Gravel	Nat. sand	Burlap	32
3	Gravel	Nat. sand	Belt	19
4	Limestone	Nat. sand	Broom	3
5	Limestone	Nat. sand	Burlap	41
6	Limestone	Nat. sand	Belt	4
7	Gravel and limestone	Nat. sand	Belt	2
8	Coarse grained igneous	Nat. sand	Broom	1
9	Coarse grained igneous	Nat. sand	Burlap	4
10	Coarse grained igneous	Nat. sand	Belt	10
11	Traprock	Nat. sand	Belt	1
12	Slag	Nat. sand	Burlap	6
13	Argillite	Nat. sand	Belt	2
14	Volcanic slate	Nat. sand	Belt	2
15	Serpentine rock	Nat. sand	Burlap	2
16	Limestone	Man. sand	Burlap	10
17	Slag	Man. sand	Burlap	1
18	Gravel and limestone	Mixed sand	Belt	3

Notes: Natural sand includes sand, siliceous sand, quartz sand, lake sand, concrete sand. Manufactured sand means manufactured or crushed limestone sand. Mixed sand means mixed natural and manufactured sand. Coarse grained igneous includes granite, diorite, syenite, granite gneiss.

TEST EQUIPMENT

The equipment used for road testing consisted of the test trailer and special bodied tractor shown in Figures 1 and 2.

The test trailer which has been fully described (1) consists of a two-wheel, low c.g.

unit in which the drag force acting through the two wheels into the axle is measured by strain gages mounted on aluminum cantilever beams. The trailer has a completely self-contained hydraulic brake system which in previous programs has been operated by a push-pull cable system from the towing vehicle. For this program an air-operated master cylinder was fitted to make use of the cab-controlled pneumatic trailer brake system fitted as standard on the tractor. Both trailer wheels are locked during a test run.

The direct reading friction coefficient measuring system has been improved since the trailer was built several years ago. A schematic of the system is shown in Figure 3.

The tractor used for this program was an International R-190 with 142-in. wheelbase and a gross vehicle weight of 15,840 lb. Mounted behind the cab was a 3½-in. diameter, 7½-ft long, 530-gal water tank with a 6-in. diameter filler cap on top. Behind the tank was a large wooden box with a rear opening door. The interior of the box was divided into three compartments for auxiliary equipment, spares, and crew's personal baggage. A special tow-hitch frame at the rear of the tractor matched the trailer attachment.

The auxiliary equipment included the motor-driven water pump used in previous programs, a battery box for the measuring system, and a shutoff valve operated from the cab.

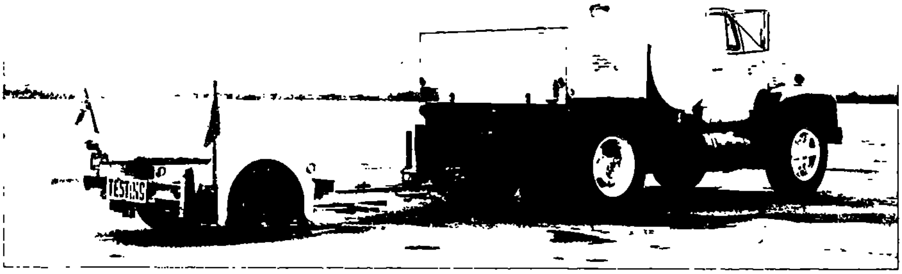


Figure 1. Tow truck and test trailer.

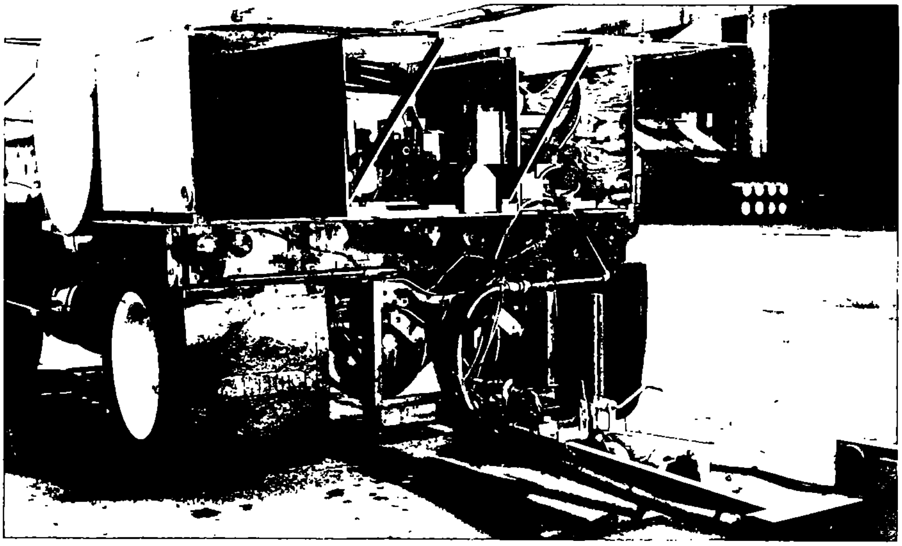


Figure 2. Rear of tow truck.

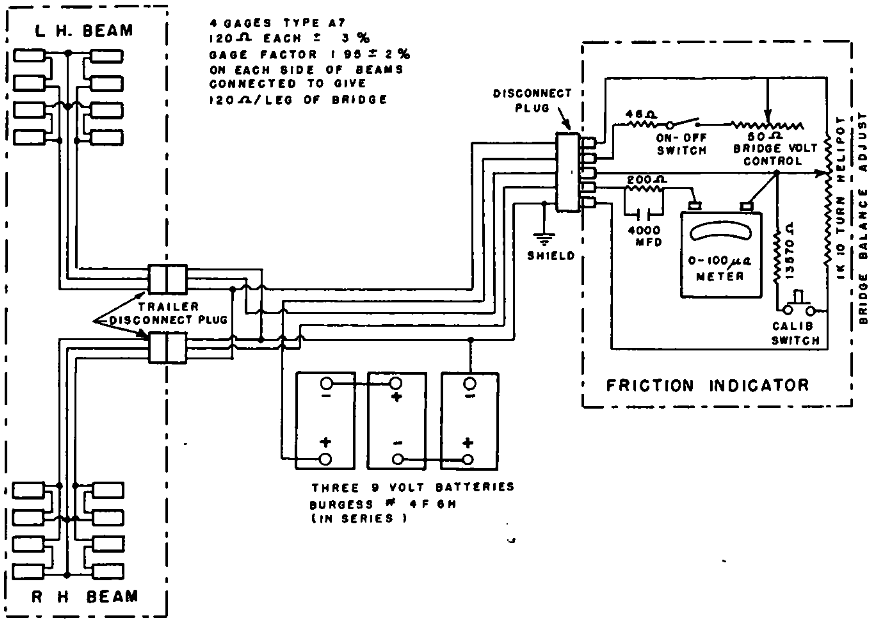


Figure 3. Schematic of friction force measuring system.

The major spares were two wheels and tires for the trailer (one being mounted on top of trailer) and an extra set of calibrated measuring beams with gages cemented in position and cables attached. A portable gas-driven water pumping unit was also carried, together with 15 ft of 1½-in. inside diameter delivery hose and 50 ft of 1-in. inside diameter suction hose. This unit was taken along as a precaution so that natural water supplies, such as creeks or ponds might be used, but was not, in fact, required at any time during the program because little difficulty was experienced in obtaining water from fire hydrants, water works, and private sources. An average of about 5 gal of water was required for each brake application test. Thus, a three-sample test required approximately 15 gal and a two-way or double-length test 25 to 30 gal.

CALIBRATION

Two sets of measuring beams, whose section sizes are slightly different and which have gages cemented in position and cables attached, are available for use on the PCA skid trailer. Both sets were calibrated before the program commenced. One set which was used for all but four test sections was recalibrated after the road test work was finished using the same calibration equipment as before. The "before" and "after" curves were virtually identical. The calibration curves for both sets of beams are shown in Figure 4.

The measuring system is calibrated by applying a horizontal load to the tongue while the trailer hitch rested on ball bearings on a weight scale platform. The trailer brake system is locked on during calibration. Inasmuch as the trailer weight is known and the load transfer to the trailer hitch equals the unloading of the trailer wheels, the normal force at the tires may be obtained. The friction coefficient between locked tires and ground is then the horizontal drag divided by the calculated normal load. It is necessary, of course, to have the trailer wheels standing on a high coefficient surface during calibration.

The accuracy of the microammeter readings is maintained by a simple procedure consisting of: (a) switching on the power, (b) adjusting the bridge balance helipot to obtain zero meter reading with no load on the trailer wheels, (c) pushing the calibration button which throws a known resistance into the circuit, and (d) adjusting the

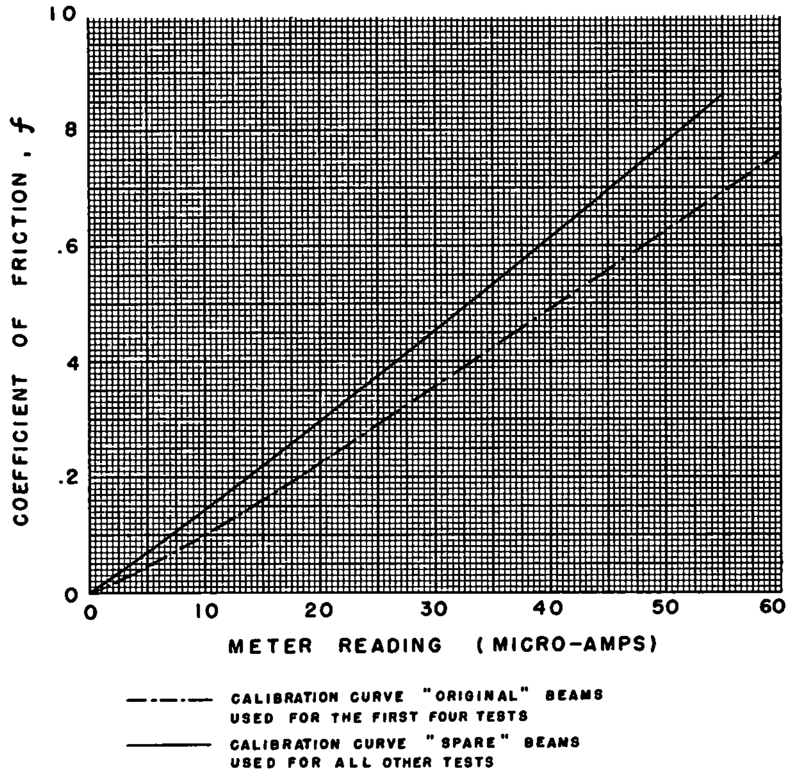


Figure 4. Calibration curve PCA skid trailer.

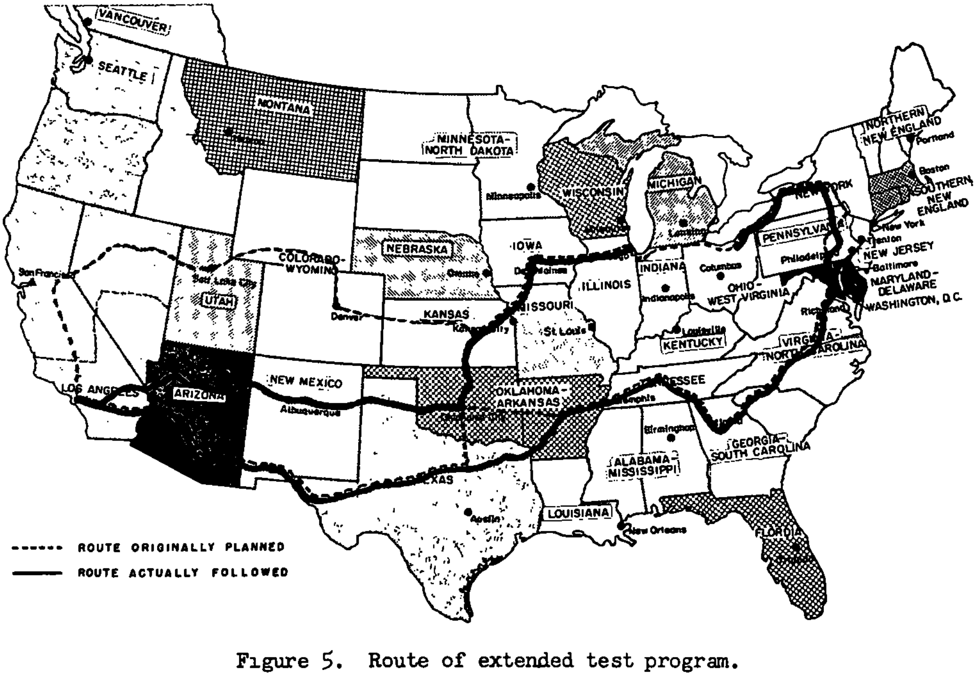


Figure 5. Route of extended test program.

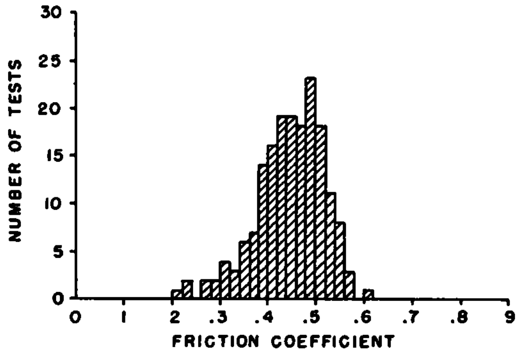
bridge voltage control to read 100 microamps. This meter calibration is standardized for all tests, both calibration and road. Thus, the accuracy of the road measurements is maintained.

ROUTE AND FREQUENCY OF TESTS

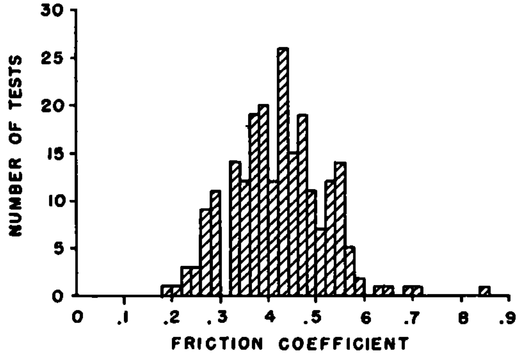
The program provided approximately 40 working days of field testing. The original planned route is shown in Figure 5 and proved to be somewhat optimistic. It covered 7, 156 mi through 25 states. However, by prior agreement with the sponsor, the routing could be modified during the program. The final route (Fig. 5) covered 6, 500 mi through 20 states. Table 1 gives the number of surfaces tested in each state.

At the beginning of the program, tests were made every 5 mi in the rural sections. If three consecutive sample checks showed that the test surface was appreciably above or below "normal", a further three sample tests were made in the opposite direction but aligned with the first tests. If the section tested in the "normal" range, no further samples were made until five more miles were covered. Later in the program the turn-around was eliminated to save time, and if the first three sample checks showed a coefficient outside the "normal" range, a further three checks were made in the same direction.

The "normal" range is defined as that in which the friction coefficient lies between certain values (see Fig. 6). These values were varied from time to time to maintain approximately 50 percent of the tests outside the "normal" range and are given in Table 3. The frequency at which tests were made was also varied from time to time to maintain a reasonable daily mileage.



a) PORTLAND CEMENT CONCRETE



b) BITUMINOUS ASPHALT

Figure 6. Distribution of tests over friction coefficient range.

TABLE 3

"NORMAL" COEFFICIENT RANGE AND FREQUENCY OF TESTS

From	To	Friction Coefficient, Normal Range	Miles Between Tests in Rural Areas	Tests Outside Normal Range (%)	Average Daily Mileage
Chicago	Oklahoma City	0.32 to 0.50	5	48.6	152.7
Oklahoma City	Dallas	0.225 to 0.54	25 plus	14.3	268
Dallas	Atlanta	0.32 to 0.50	5	41.1	190
Atlanta	Buffalo	0.32 to 0.48	5	56.3	190.2

DERIVATION OF SINGLE LINE CURVES

Close and Fabian (1) plotted the experimentally obtained friction coefficient data versus the logarithm of the Wear Index and the logarithm of road age, because the scattering of data points plotted in this form was more easily faired by a straight line. This indicated linear relationship between f and log (W) was assumed to exist for the purpose of fairing the data obtained in this series of tests. Accordingly, a straight line was fitted mathematically to the raw data by using a "least squares" or "linear regression" curve fitting procedure for the variables f, log (10W), and log (10A). At the specific request of the sponsor the resulting plots are presented here with linear scales for both friction coefficient and Wear Index or age. The resulting curves are not all-conclusive but indicative of general trends.

Figures 7 to 15 were made showing the average friction coefficient versus Wear Index. The latter is a function of age and the average daily traffic count for the lane tested. Additional plots, Figures 16 to 21, show comparisons between PCC and bituminous asphalt surfaces for friction coefficient versus age and friction coefficient versus Wear Index. Figure 22 shows the effect of surface finish.

Standard statistical analysis methods were used to derive single line curves from the masses of scattered data points. In several cases insufficient data exist for any conclusions to be drawn.

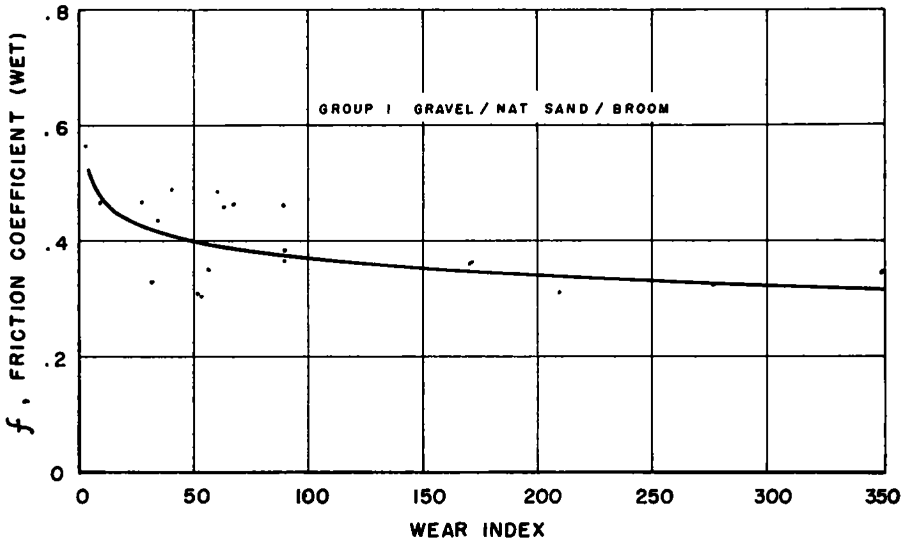


Figure 7. Effect of wear—PCC Group 1.

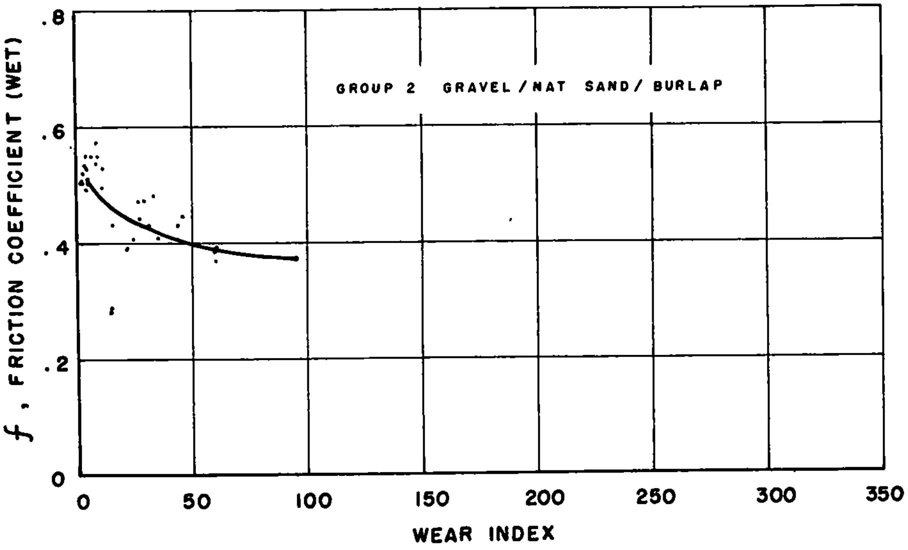


Figure 8. Effect of wear—PCC Group 2.

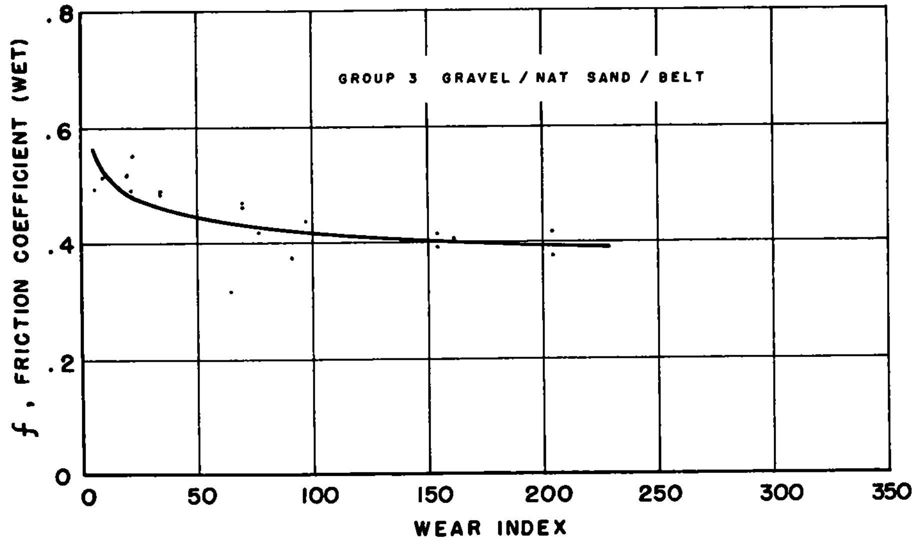


Figure 9. Effect of wear—PCC Group 3.

A total of 1,795 tests were made on 418 surfaces. However, complete data could not be obtained for a small number of surfaces and these were eliminated from the subsequent analysis.

DATA DISCUSSION

Wear Index Definition

To study the effect of wear on the surface characteristics the following Index has been used:

$$\text{Wear Index} = \frac{\text{ATL}}{1,000}$$

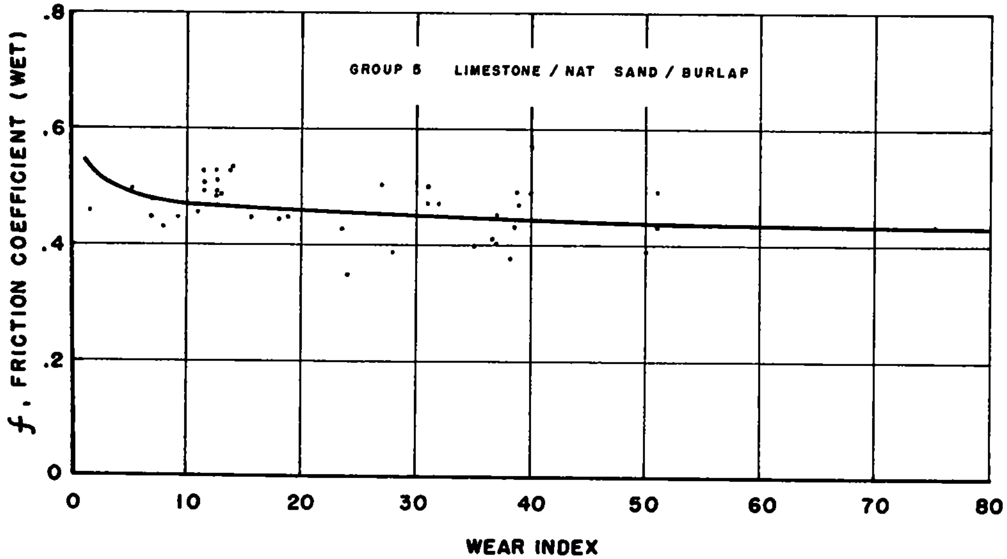


Figure 10. Effect of wear—PCC Group 5.

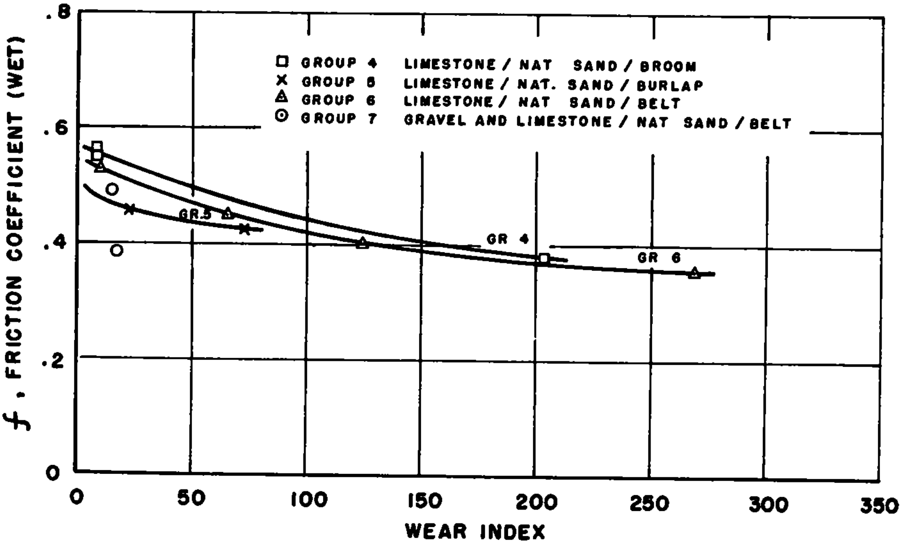


Figure 11. Effect of wear—PCC Groups 4, 5, 6, 7.

in which

A = age of pavement surface in years,
T = average total daily traffic count, and
L = correction factor for traffic distribution in lane tested.

A and T are derived from State Highway Authority data, and L is discussed in the next paragraph.

Traffic Distribution in Various Lanes

Where there are more than two lanes, observation shows that they will not all carry equal amounts of traffic. A few traffic counts have been made which show the traffic volume in various lanes but these data are somewhat scarce. Figures are given in Reference 3 for the percentage of vehicles using the right-hand lanes in a four-lane highway. These percentages vary with the total traffic volume.

A certain traffic distribution pattern was assumed as satisfactory for use in this program. The assumed distribution pattern is given in the text table on page 28.

For the Wear Index, the correction factor L is 2/100 of the percentage of the total traffic estimate for the appropriate lane in which testing was performed; for example, for a six-lane highway outside lane $L = \frac{2}{100} \times 20 = 0.4$.

The total traffic volume figures used in this report are based on recent traffic counts

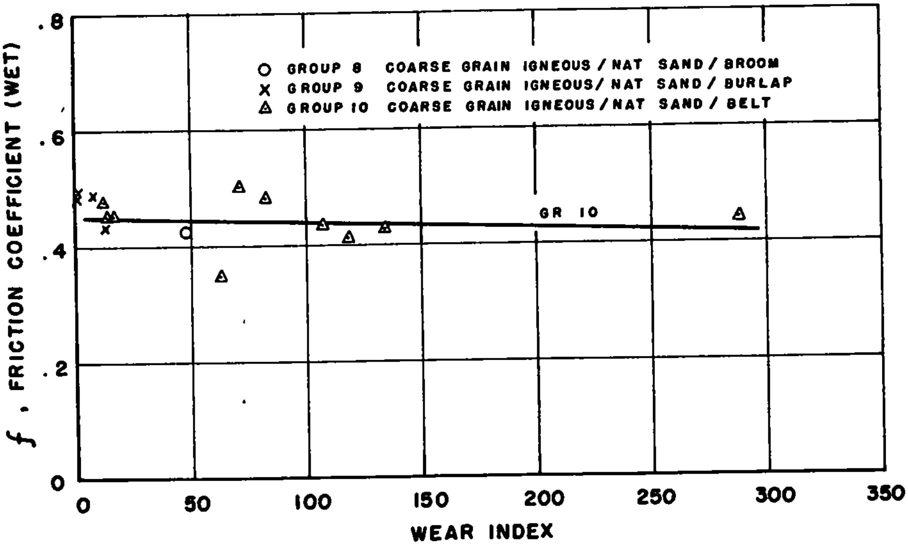


Figure 12. Effect of wear—PCC Groups 8, 9, 10.

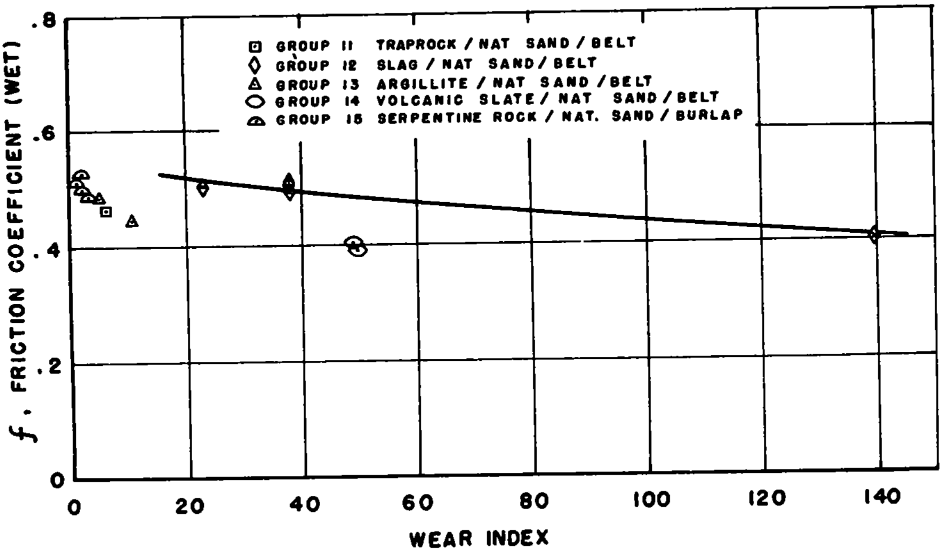


Figure 13. Effect of wear—PCC Groups 11 to 15.

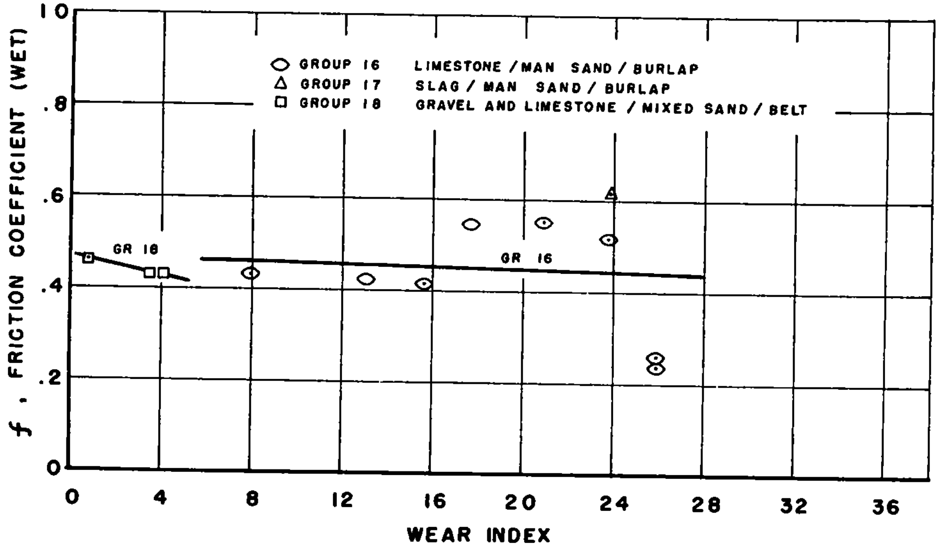


Figure 14. Effect of wear—PCC Groups 16 to 18.

No. of Lanes	Distribution per Lane (%)
2	50, 50
3	40, 20, 40
4	40, 10, 10, 40
6	20, 20, 10, 10, 20, 20
8	15, 15, 10, 10, 10, 10, 15, 15

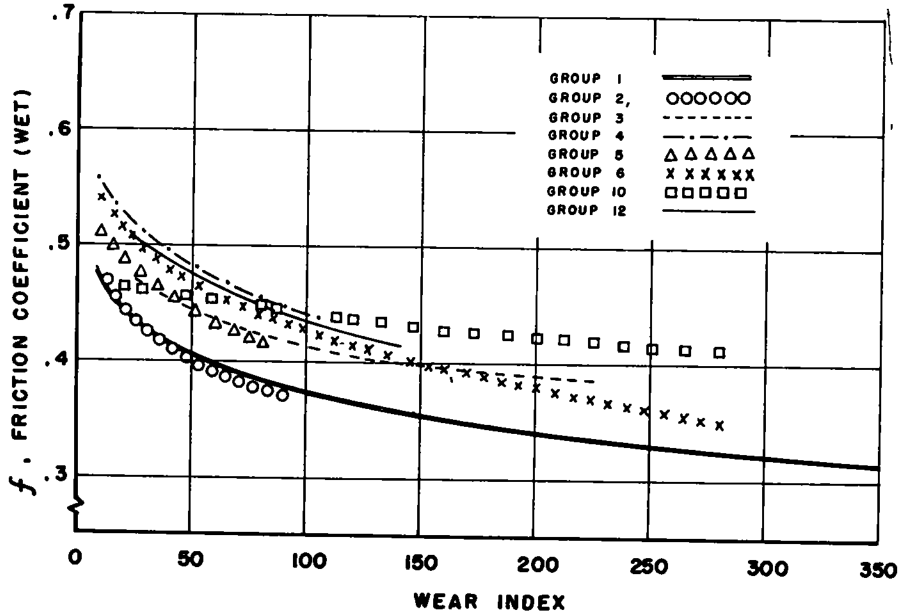


Figure 15. Effect of wear—PCC various groups.

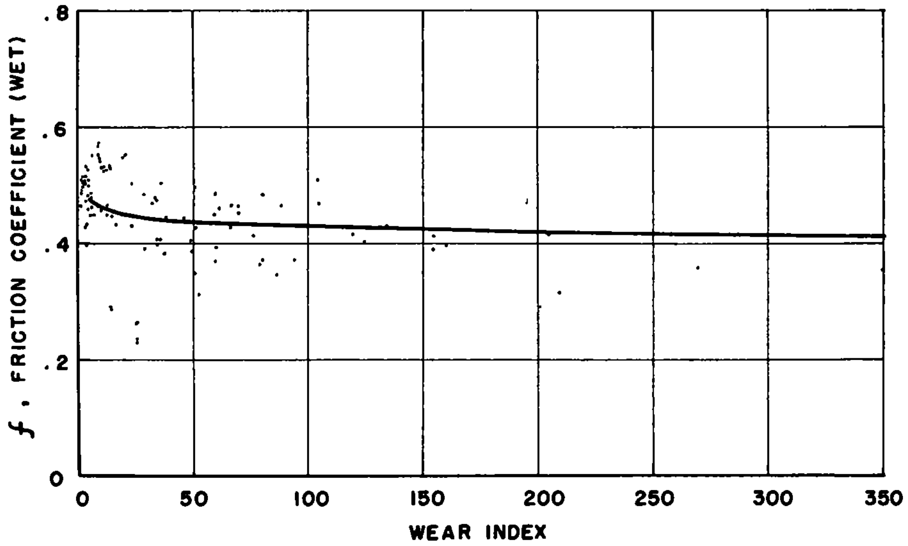


Figure 16. Effect of wear—PCC.

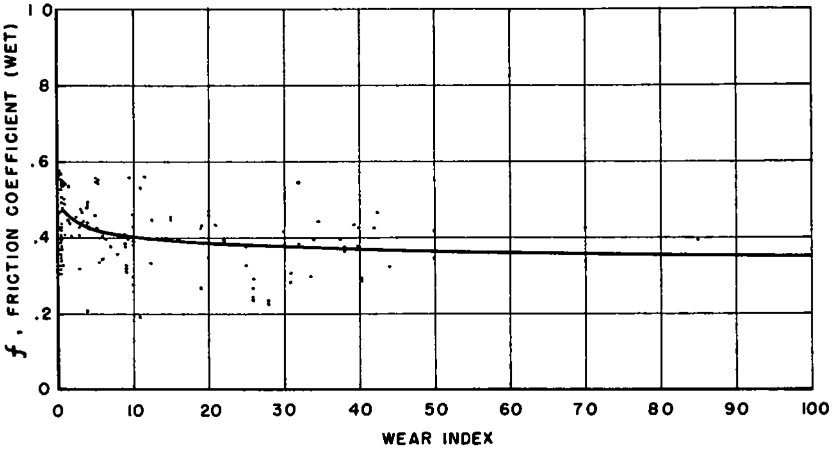


Figure 17. Effect of wear—asphalt.

over short periods. Because it is logical to assume traffic increases over the years, these traffic volume figures may give higher totals for the older pavements than is probably true. But there is no accurate way to correct these figures.

Tire Standard

The program was designed primarily to evaluate the variation in friction coefficient due to road surface alone. However, because measurements were being made of the friction coefficient between road surface and automotive tires, it was necessary that a "standard" tire be used for all tests.

The standard tires adopted for this program were similar to those used in the First International Skid Conference Correlation Study tests conducted in Virginia, August 1958. These tires (specially made by the Goodyear Tire and Rubber Company), are described fully in the Proceedings of the First International Skid Prevention Conference (2, p. 387).

Tire Wear Effects

Inasmuch as standard tires were used in all tests it might appear that the only source of major variation in the friction coefficient would be due to the road surface. However, it is recognized that tread wear is a factor influencing skid resistance of a tire (2, p. 159). In a test program of the long-distance type reported here, tire wear might have had some effect on the friction coefficient values measured. Two sets of standard tires were used, the first set covered 4,500 mi and the second set 3,700 mi. Although comparative tests were made on the same surface, when the former had 4,500 mi and the latter less than 100 mi, the variation measured was less than the known accuracy of the test trailer. No valid conclusion can therefore be drawn inasmuch as the two sets were

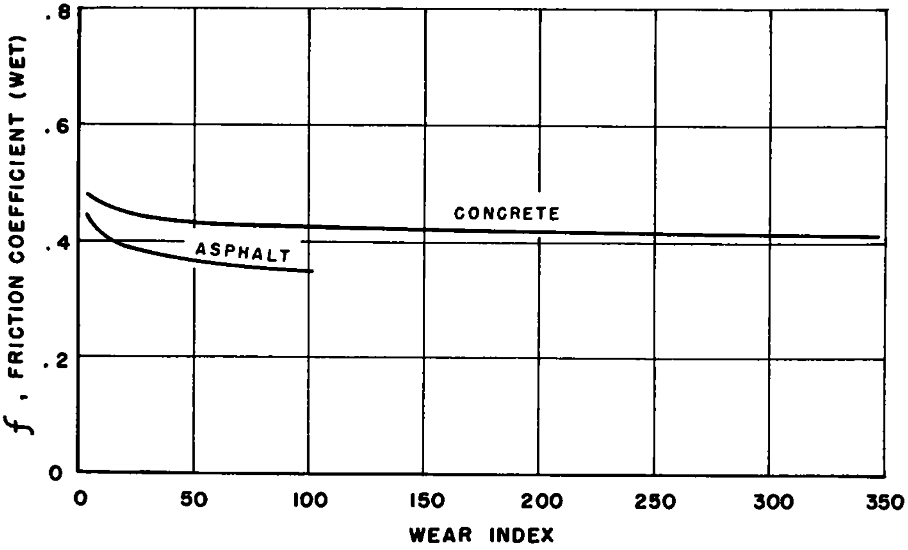


Figure 18. Effect of wear—comparison of PCC and asphalt.

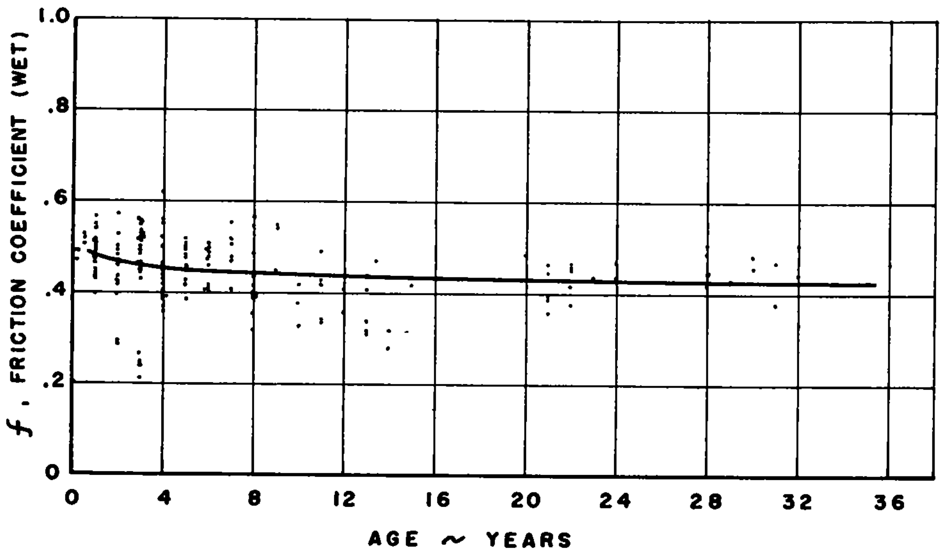


Figure 19. Effect of age—PCC.

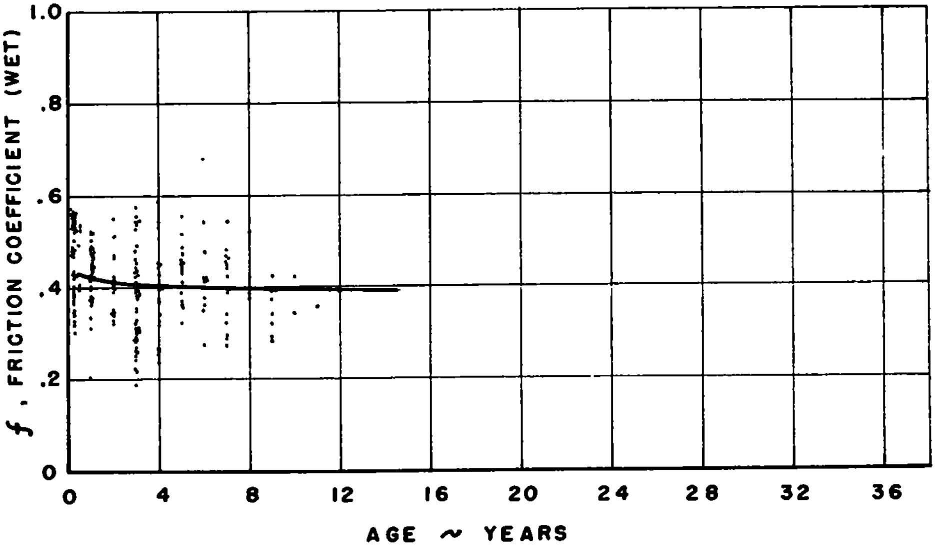


Figure 20. Effect of age—asphalt.

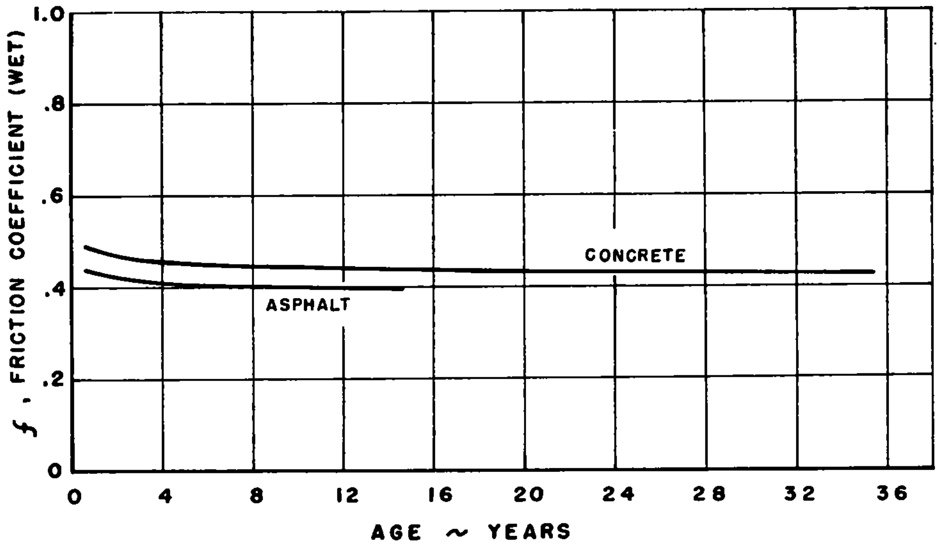


Figure 21. Effect of age—comparison of PCC and asphalt.

not tested on the same surface when all tires had almost zero mileage. It is possible that much greater mileages are required to demonstrate authentic measurable differences.

Effect of Grade

It was necessary to eliminate two-way runs early in the road testing, and accordingly, the effect of road grade on the accuracy of the measurement has to be assessed. An error is introduced when the trailer is stationary on a grade because the combined weight of the tires, wheels, axle, and springs has a small component (equal to the sine of the grade angle) which is "read" by the measuring system.

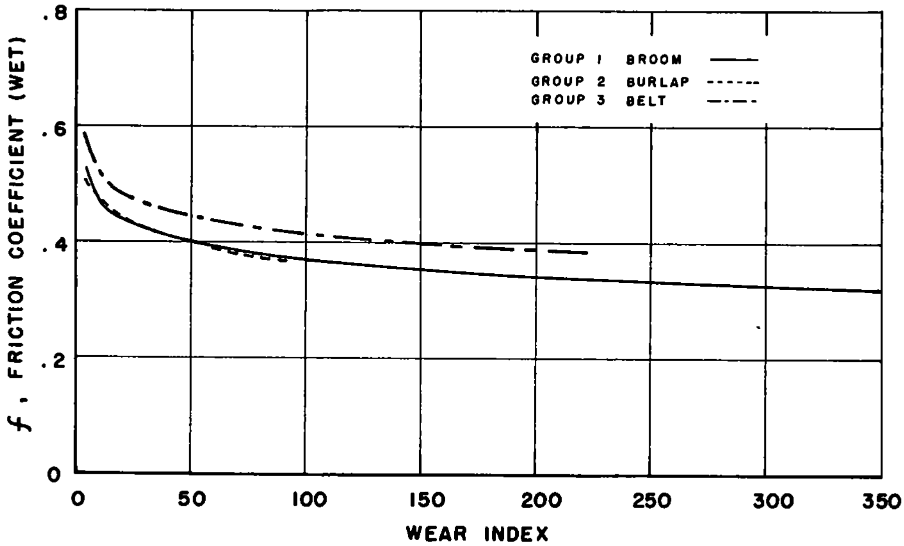


Figure 22. Effect of surface finish—PCC Groups 1, 2, 3.

Weight of tires, wheels, axle, springs = 300 lb
Static load on tires (level road) = 1,855 lb
Steepest grade tested = 4 deg 30 min
Component force due to grade = 300 x sine 4 deg 30 min
= 23.5 lb

Tire load normal to road (4½ deg grade) = 1,855 - (1,855 x sine 4 deg 30 min) = 1,709.3

∴ maximum theoretical error in friction coefficient $= \pm \frac{23.5}{1,709.3} = \pm 0.0137$

The measured error is actually less because of friction in the spring support link bearings. Tests show that on a 5-deg slope the actual reading in the measuring system is less than 1 microamp which is equivalent to a friction coefficient of 0.01.

Effect of Speed

The effects of speed shown in Figure 23 are derived from test runs made on a four-lane, asphalt-surfaced road in the vicinity of Lancaster, N.Y., at speeds of 30, 35, 40, 45, and 50 mph. It is interesting to compare these results with tests made at 20, 30, 40, and 50 mph on the New York State Thruway in November 1957, using the same equipment (1). The shape of the curve is identical in the speed range common to both.

Except in a very few cases, all tests in the program were run at a standard speed of 40 mph. Friction coefficients for these few cases have been corrected to 40-mph equivalent, using a calibration factor derived from the curves shown in Figure 23.

Apparatus Repeatability

A series of runs were made to show the repeatability accuracy of the measuring system. As reported in the original test result sheets, each set of four runs was made on the same piece of surface in the same direction, at the same speed on the same day. The over-all average for 16 runs gave a value of f = 0.322 and the individual tests average 0.313, 0.331, 0.320, and 0.324, giving deviations of -0.009, +0.009, -0.002, and +0.002. This demonstrates the claimed average friction coefficient accuracy of the PCA test trailer as being ± 0.01.

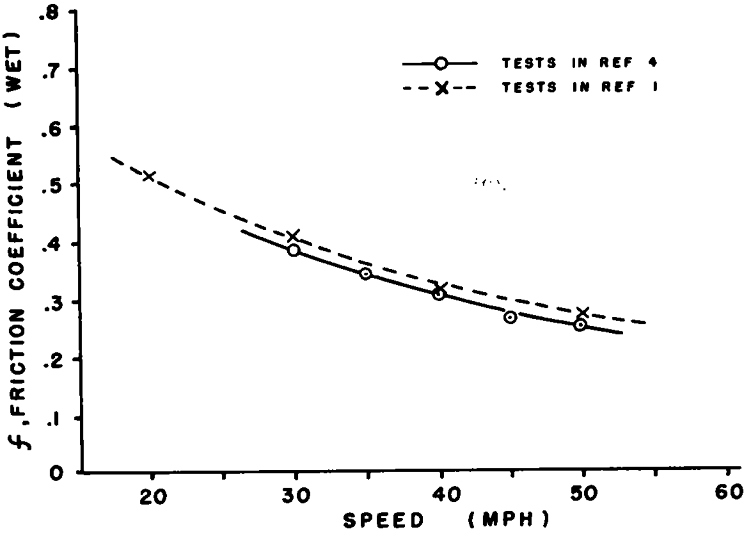


Figure 23. Effect of speed (locked wheels on wet surface).

Effect of Wear

A comparison of the effect of wear on the various groups of portland cement concrete surfaces is shown in Figure 15. This indicates that, of all the various groups measured in this program, the belt-finished, coarse-grained igneous/natural sand combination has the highest friction coefficient when the Wear Index exceeds 100, even though it is inferior to most of the other groups when first laid. It can be seen also that the belt-finished, gravel/natural sand combination and the belt-finished, limestone/natural sand combination are both superior to the broom-finished, gravel/natural sand group at all times.

The graphs shown in Figures 16 and 17 are combined in Figure 18 and show that on the average the PCC surfaces tested gave a higher initial friction coefficient which decreased less with wear than that of the asphalt surfaces tested in this program.

Effect of Age

Figures 19 and 20 show the effect of age on PCC and asphalt surfaces, respectively, whereas Figure 21 combines these graphs to give a direct comparison. The average age and friction coefficient for the 177 PCC surfaces tested in this program are 8.508 years and 0.45, respectively. For the 230 asphalt surfaces tested, the figures are 3.289 years and 0.42, respectively. In comparing PCC and asphalt-surfaced roads, it is interesting to note that only three asphalt surfaces tested in the program were more than 10 yr old. Of the PCC surfaces, 46 were more than 10 yr old and 31 were more than 20 yr old, with the oldest section being 36 yr.

Effect of Surface Finish

A comparison of broom-, burlap- and belt-type finishes on a gravel/natural sand combination is shown in Figure 22. It can be seen that although broom and burlap are virtually similar in effect, they are both inferior to a belt finish in maintaining a good friction coefficient. Figure 5 provides some comparison between broom, burlap and belt finishes on a limestone/natural sand combination. In this case, broom and belt give similar results with burlap slightly inferior. However, it is questionable whether there are sufficient data points for the broom and belt finishes for a reliable trend to be deduced.

RECOMMENDATIONS

More data are required for many aggregate combinations and surface finishes tested in this program. Only groups 1, 2, 3, and 5 have sufficient data points with groups 10 and 16 being marginal in this regard.

Examination of the remaining groups shows that further testing in the States of Arkansas, Georgia, Iowa, Maryland, North Caroline, Ohio, Oklahoma, Pennsylvania, South Carolina, Tennessee, and Texas is required to establish valid trends.

In this paper, all bituminous surfaces have been grouped together because of lack of information about materials used and fabrication methods. It would be desirable to hav such information so that these surfaces can be analyzed in the same manner as the PCC surfaces.

For future studies that use Wear Index as a measure of surface wear, more accurate estimates of average daily traffic counts over periods of several years are required. Better data on traffic distribution in various lanes of wide highways is also required.

ACKNOWLEDGMENTS

The research on which this paper is based was sponsored by the Portland Cement Association under Contract Number CC-93, with the Cornell Aeronautical Laboratory, Inc.

REFERENCES

1. Close, W., and Fabian, G. J., "Locked Wheel Friction Coefficient on Wet Surfaces." Cornell Aeronautical Lab. Report No. YD-1197-V-1 (March 1958).
2. Anon, Proc., First International Skid Prevention Conference, Virginia Council of Highway Investigation and Research, Charlottesville (Aug. 1959).
3. Anon, "Lateral Placements of Trucks on Two-Lane Highways and Four-Lane Highways." Public Roads (Aug. 1958).
4. Barboza, G., and Close, W., "Extended Study of Locked Wheel Friction Coefficients on Wet Road Surfaces." Cornell Aeronautical Lab. Report No. YM-1372-V-1 (Aug. 1960).

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