# Pavement Slipperiness in Tennessee

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This paper reports the results of a three-year study of pavement slipperiness in Tennessee. Throughout most of the study, slipperiness was measured through the use of a two-wheel trailer similar in many respects to those used by previous investigators. As a preliminary to the major investigation, comparisons were made of slipperiness of wet and dry pavements, clean and dirty pavements, and smooth and ribbed tread tires. In addition, the effect of load on the sliding wheel and of pavement and tire temperatures was investigated.

Toward the end of the study a number of pavements were tested for actual stopping distance with an automobile. A comparison of the two methods of test, trailer and automobile, is shown.

It is concluded that a major cause of pavement slipperiness in Tennessee is the susceptibility of certain limestone aggregates to polish under the action of traffic. It is also concluded that where such aggregates are used in portland cement concrete pavements these pavements have the same potentiality for becoming slippery as do bituminous pavements containing the aggregates. It is appreciated that the polishing action will take a considerably longer time in the case of the concrete pavements than the bituminous ones. Within the limitations of the equipment employed, it is concluded that stopping-distance tests performed on a series of pavements will rate them with respect to slipperiness in essentially the same order as skid trailer tests, provided similar tires are employed and the test conditions standardized to the greatest possible degree.

● THE State of Tennessee has for some time been concerned over the problem of slippery pavements. This concern is directed not so much toward secondary highways, many of which are indeed slippery, but toward highways in the primary system which, although built in accordance with presumably good specifications and under close inspection, appear to become slippery at a rapid rate. The magnitude of the problem is evidenced by its assignment in October, 1951, to the Tennessee Highway Research Program as one of the first investigations to be undertaken by that organization.

The "skid" or "non-skid" characteristics of pavement surfaces have been of interest to investigators since the early days of motor transportation. A report in 1924 by Agg (1), dealing primarily with the tractive resistance of roadway surfaces, describes tests conducted by the Iowa Engineering Experiment Station in which the skid coefficients of several pavement surfaces were determined by towing an automobile, applying the brakes to lock the rear wheels, and measuring the pull against the towing vehicle on a dynamometer. The value of these test results was limited as all tests were made at very low speeds (in the order of 3 to 5 miles per hour), but they serve to indicate the early interest in the problem. A subsequent comprehensive report by Moyer (2) describes additional work by the same organization. In these tests a two-wheel trailer was used as the skidding unit and coefficients of friction were determined between speeds of 3 and 40 miles per hour. This study, taking into account many of the variables affecting the coefficient of friction between tires and pavements and including investigations of side skids, is perhaps the most comprehensive in the field to date.

Subsequent to the early studies mentioned above, two-wheel trailers were used for making skid tests in Ohio by the Engineering Experiment Station of the Ohio State University (3), in Oregon by the State Highway Commission (4), in Kansas, Missouri and Wyoming by Moyer (5), and in California by the Institute of Transportation and Traffic Engineering, University of California (6). The equipment employed in these tests ranged from the rather simple trailer device developed by Moyer to a highly complex automatic system developed and built by the Institute of Transportation and Traffic Engineering.

In 1939 (7) a series of tests were performed in Cleveland, Ohio, in which a standard passenger automobile was employed for measuring pavement slipperiness. In these tests the automobile was driven at some selected speed, the brakes rapidly applied to lock the wheels, and the length of the ensuing skid measured. Since that time, tests of a similar nature have been made by the Virginia Department of Highways (8), the North Carolina State Highway and Public Works Commission (9), and the Institute of Transportation and Traffic Engineering at the University of California (6).

Reports of similar studies of pavement slipperiness are available from England (10), and other European countries.

During the study reported herein both types of measurements were made, and an effort has been made to determine the correlation between the two. A preliminary report of results of trailer tests was made in 1953 by Goodwin (11).

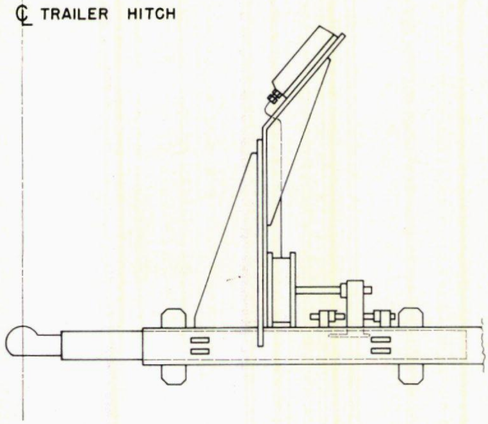



**Figure 1. Schematic diagram of drawbar assembly.**

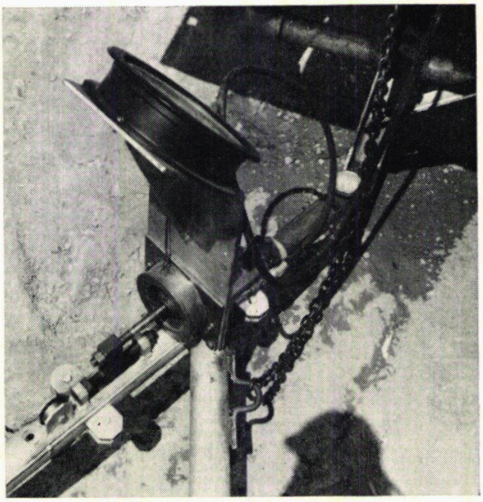


**Figure 2. Bellows-gage assembly.**

## EQUIPMENT AND TECHNIQUES

The great majority of tests conducted in this study have been made with a two-wheel trailer similar in many respects to those used by other investigators. The trailer consists of a 4- by 6-foot concrete slab mounted on the modified front axle assembly of a passenger car. The slab is six inches thick and provision has been made for the addition and securing of precast concrete blocks to permit variation in the axle or wheel load. The trailer is connected to the tow truck by an off-set drawbar which is in direct alignment, vertically and horizontally, with the center of the left, or inside, trailer wheel. The drawbar consists of two separate units as shown in Figure 1. The outer portion is a hollow shaft rigidly attached to the trailer. The inner unit is a solid steel shaft which floats inside the hollow unit on eight roller bearings. In operation, the end of the solid member is attached to the hitch of the towing vehicle. Connection between the two members is effected by a piston and bellows assembly. The piston, connected to the inner shaft, extends through a slot in the hollow shaft and makes contact with the bellows which is rigidly attached to the outer, hollow member. The bellows and a 10-inch bourdon type pressure gage, Figure 2, make up a closed pressure system. Any pull exerted on the drawbar will cause compression of the fluid behind the bellows and will give an indication on the pressure gage. Protective mechanical stops prevent the piston from moving far enough to rupture or seriously damage the bellows.

The test trailer is pulled by an F-5 truck

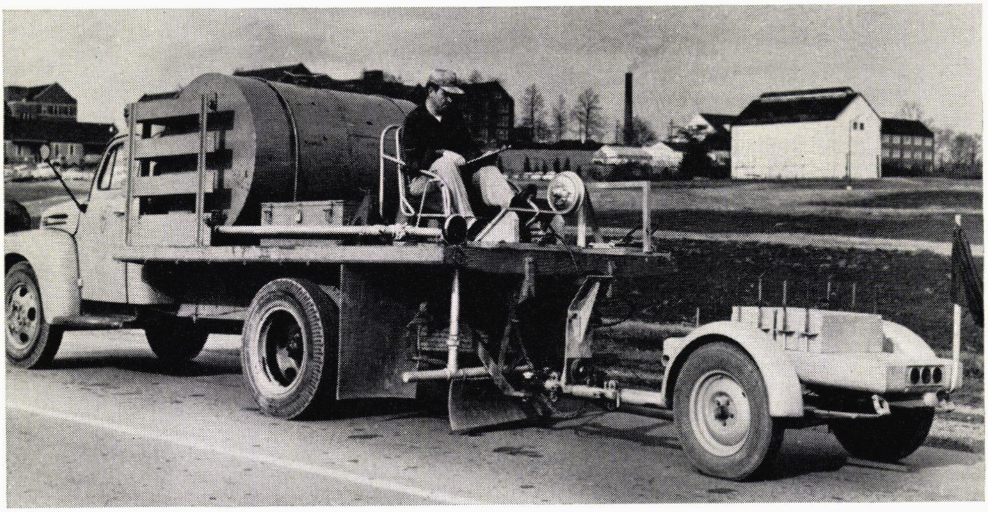


**Figure 3. Skid trailer and controls.**

provided by the Tennessee Department of Highways and Public Works. The truck is equipped with a 500-gallon water tank and a sprinkling bar so installed that a stream of water from six No. 5 sprinkling nozzles is directed at the pavement about five feet in front of the skidding wheel. This permits a two-foot strip of pavement to be wetted ahead of the test wheel in such a manner that the skid test is made in the center of the wetted strip. The operator is seated on the rear of the truck facing the trailer, Figure 3. From this position he can operate a quick opening valve which turns on the sprinkler system, depress the brake pedal which locks the brake on the left wheel of the trailer, and record the indicated drawbar pull as shown on the pressure gage. He can also check the speed at which the test is conducted by means of a speedometer located on the trailer.

Insofar as possible test sites have been selected on relatively flat stretches of highway at locations where good turn-around areas were available near each end of the section. Trailer tests have been made at speeds of 10, 20, 30 and 40 miles per hour in most cases. Readings are taken with the truck and trailer travelling in both directions on the section to eliminate the effect of grade, and sufficient tests are made to provide a good average value. A total of four tests at each speed, two in each direction, has generally been found to be sufficient for this purpose.

In the later phases of the study it was thought desirable that some stopping-distance tests be conducted and that efforts be made to determine the correlation, if any, between these and the trailer tests. These tests have been made with a 1952 Plymouth automobile weighing 3580 pounds and equipped with four 6.70 by 15-inch 4-ply Fisk tires in good condition. The car was equipped with an electric detonator, actuated by depression of the brake pedal, which discharged a .22 caliber blank cartridge firing a chalk bullet against the highway surface at the instant of brake application. This detonator, fabricated in the shop of the Engineering Experiment Station at the University of Tennessee, is shown in Figure 4. The design is similar to that used by the Council of Highway Investigation and Research, Charlottesville, Viginia.

The truck normally used for towing the test trailer was employed for wetting the pavement immeditately prior to stopping-distance tests. Its sprinkler bar was extended in both directions to permit wetting of a strip approximately 8 feet wide. Tests were again conducted at speeds of 10, 20, 30 and 40 miles per hour. As soon as the pavement surface had been wetted and the sprinkler truck moved out of the way, the test car was driven onto the wetted section at the selected speed. The brakes were applied forcefully to lock all four wheels. At this instant the chalk gun fired, leaving a mark on the pavement. When the

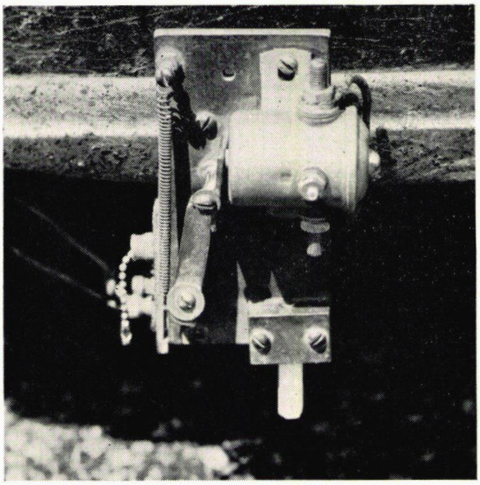


**Figure 4. Detonator and chalk gun.**

car had skidded to a stop the distance between the chalk mark and a point on the pavement immediately beneath the gun was measured with a tape, as shown in Figure 5.

Upon completion of a set of stopping-distance tests at any given location, one wheel was removed from the car and transferred to the skid trailer. Trailer tests were then conducted on the same section at the same speeds. In most cases sections selected for stopping-distance tests were very flat and the tests were conducted in only one direction. No correction was made for the influence of grade.

Considerable attention was directed toward selection of tires for use in this program. Results of correspondence with tire manufacturers and with those engaged in measuring the slipperiness of pavements, as well as the results of a few preliminary tests, indicated that the type and condition of tire tread, as well as the rubber composition of the tire, would have a marked influence upon test results. In an effort to minimize this influence a number of special recapped tires were obtained for the study. These were 6.00 by 16-inch 4-ply tires with a perfectly smooth recap of 14-gage cold synthetic rubber. Each tire was buffed with a wire brush before initial use and, subsequently, at the end of each day's testing or at more frequent intervals if the appearance of the tire indicated such treatment to be desirable. These tires were used throughout the study except as otherwise noted, with particular exception in the case of the direct comparison of trailer and stopping-distance tests mentioned above.

## RESULTS

At the beginning of this study it was appreciated that a number of variables would have some degree of influence upon the results of any type of skid measurements. The more important of these were believed to be speed of

**Figure 5. Measuring stopping distance.**

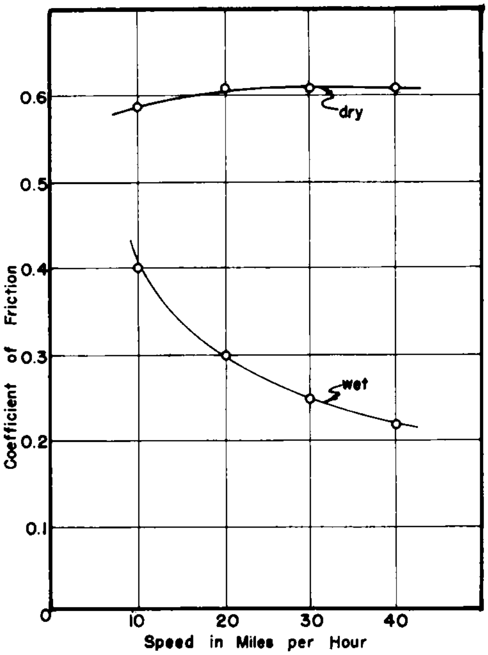



**Figure 6. Comparison of slipperiness of pavement in wet and dry conditions.**

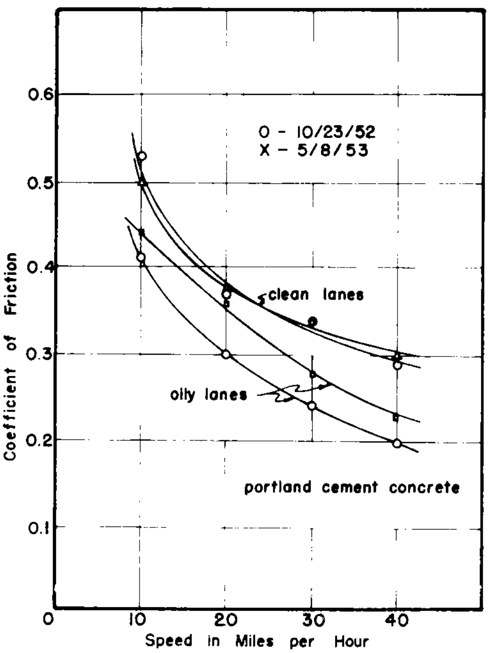



**Figure 7. Effect of oil deposits on pavement slipperiness.**

the vehicle, type of pavement surface, condition of surface (cleanliness, oil deposits, etc.), age of surface, traffic intensity, weight of the vehicle, condition of tire tread, air pressure in tires, adjustment of vehicle brakes, direction of skid and, possibly, tire and pavement temperature. It was the purpose of the study to determine the influence of pavement type, age and traffic intensity upon surface slipperiness. It was necessary that the other variables be evaluated and, insofar as possible, eliminated from the study.

*Skid Trailer Tests*

Preliminary tests showed the coefficient of friction of wet pavement surfaces to decrease very rapidly as speed of the vehicle increased, as reported by other investigators. No such tendency was observed, however, in tests made on dry pavements. Typical test results from a pavement tested in both wet and dry conditions are shown in Figure 6. In order that results of this study might be directly compared to other work in the field, test speeds of 10, 20, 30 and 40 miles per hour were selected.

The condition of pavement surface with respect to cleanliness and oil or other deposits is a factor which is largely uncontrollable. It was felt, however, that some determination of the effect of surface deposits should be made as an indication of the importance of these factors in the general problem of pavement slipperiness. A four-lane concrete pavement was located which offered an opportunity to investigate the effects of oil deposits. This pavement, approximately six years old, was made with sand and gravel aggregates, and had a broomed surface texture. There was no perceptible difference in wear between lanes but the outer lanes had been considerably darkened by oil deposits. The inner or passing lanes showed no such depositions. The results of trailer tests on the two lanes are shown in Figure 7. The clean lane may be seen to be distinctly less slippery than the oily one. The average difference in coefficient is in the order of 0.05. A second series of tests made approximately seven months later shows little change to have occurred in the clean lanes but a further decrease averaging approximately 0.03 to have taken place in the oily lanes.

In an effort to determine further the effect of pavement cleanliness upon resistance to skidding a series of tests was performed on a bituminous pavement located near a heavy construction area. Considerable dust and dirt had been tracked onto the pavement. At the end of these tests a section of the pavement was scrubbed with water and stiff bristle brooms. No detergent of any kind was employed. When the scrubbed pavement was tested it was found to have a coefficient of approximately 0.04 greater than the pavement in its initial condition at all speeds except 40 miles per hour, at which speed only slight improvement was noted. Results of these tests are shown on Figure 8.

Due to limitations in size of equipment available it was decided that wheel loads would be restricted to those normally encountered in automobiles. It was found that the static load on the skidding wheel, with no load-blocks applied to the trailer, was 670 pounds. With four blocks added the wheel-load was 838 pounds and with eight blocks 1000 pounds. A series of tests was performed under these three load conditions. Results are shown in Figure 9. It may be observed that at speeds of 20 miles per hour or more only very minor differences were measured. The use of four blocks was selected as the standard test condition, as the resulting wheel load approximated that of an average automobile. Minor variations in load occurred when different skidding wheels and tires were employed. All loads fell within the range of 821 to 843 pounds.

Limited tests making use of the two tires shown in Figure 10 were conducted to determine the influence of tire tread upon measured coefficients of friction. The static contact area of the ribbed tread tire was 18.0 inches and that of the smooth tread was 19.0 inches. Results of tests on two pavements are shown in Figures 11a and 11b. In the first case relatively small differences were measured while in the second the average difference was in the order of 0.10. The surface texture of the first pavement was rather coarse and open while that of the second was more closed. Analyses of cores removed from the two surfaces showed the fineness moduli of the aggregate in the surface coarses to be 4.48 and 3.92, respectively. Apparently, as the pavement surface becomes very smooth, a ribbed tread tire has considerable advantage over the smooth tread in providing channels through which the water may escape from between tire and pavement. Water

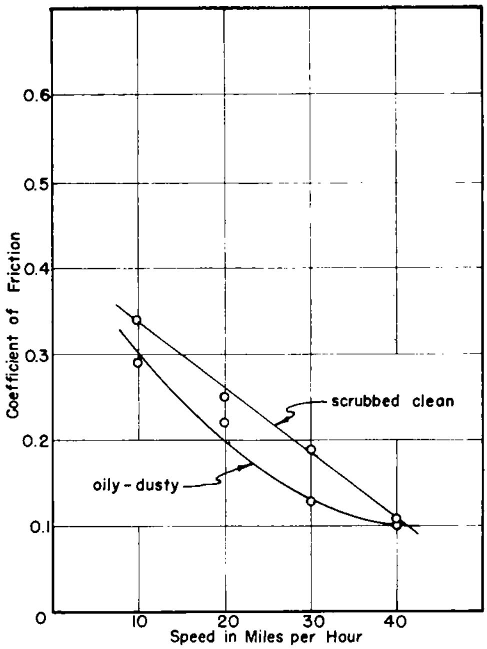



**Figure 8. Effect of dust deposits on pavement slipperiness.**

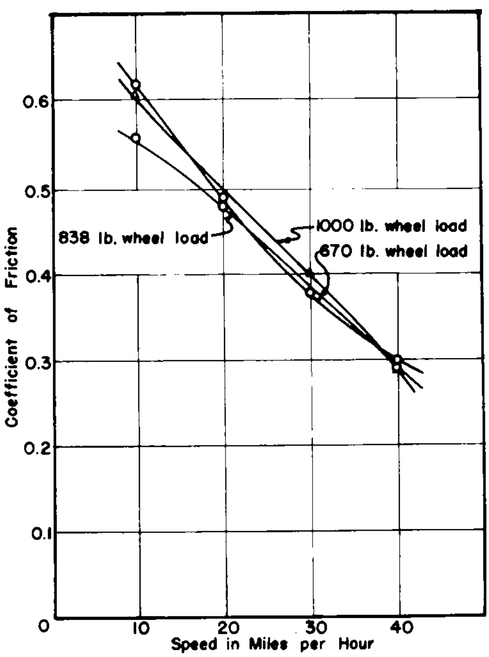



**Figure 9. Effect of wheel load on coefficient of friction.**

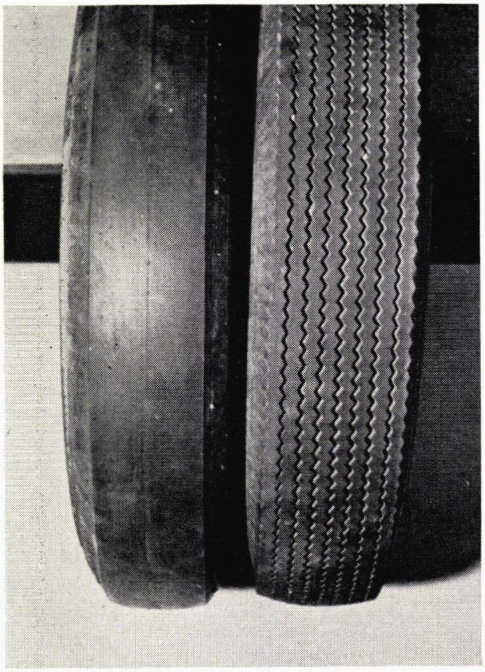


**Figure 10. Typical test tires.**

at any given point under the tire need move only to the nearest groove in order to be relieved, where in the case of the smooth tread tire water located near the center of the tread must move half the width of the tire for release. As the pavement texture becomes coarser sufficient channels are available within the surface itself to facilitate the movement of such water, and the benefit of the rib tread is proportionately reduced.

Because in these early tests considerable difficulty was encountered in maintaining the rib tread tires in a relatively uniform condition, smooth tread tires frequently subjected to wire brushing were used throughout the majority of the investigation.

A few tests have been performed to investigate the effect of pavement and tire temperature upon the surface coefficients. In a typical case a bituminous pavement was tested in the morning and again in the afternoon of the same day. In the morning the temperature of the wetted road surface was 96.5° F and that of the tire 97° F. In the afternoon the respective temperatures were 120.5° F and 113° F representing a temperature differential of 24° F for the road and 16° F for the tire. The average difference in coefficients determined on these tests was 0.02 with the lower coefficient associated with the higher temperature. Because the effect of temperature upon the coefficient appeared to be small no effort has been made to evaluate this effect throughout the remainder of the study, although pavement and tire temperatures have been recorded regularly.

The remaining three variables mentioned above have, insofar as possible, been eliminated from the study. Air pressure in the test tire has been maintained at 30 psi at all times. Since only one wheel is braked in these tests the adjustment of the brake becomes relatively unimportant. It is only necessary that the wheel be locked during the test. Because of the nature of the equipment all skid tests have been made in a direction parallel to the center line of the road and approximately in the inside wheel track of the pavement lane tested.

With procedures standardized with respect to the variables enumerated above, tests were performed upon selected pavements throughout the State of Tennessee. Tennessee is divided from East to West into four more or less geographically equal State Highway Divisions. Conferences with personnel of the Tennessee Department of Highways and Public Works and the State Highway Patrol indicated that the problem of seriously slippery pavements was to a large degree confined to the Eastern one-third of the State. On the basis of these reports extensive tests were performed in Highway Divisions 1 and 2 and fewer tests in the two Western divisions. In Division 1 and 2 selected pavements included both those reported to be very good and very poor with respect to slipperiness. Only the pavements reported to be poor were tested in Divisions 3 and 4.

In comparing the relative slipperiness of pavements, two factors have been considered. One of these is the skid coefficient at 30 miles per hour, this speed being selected because in a few cases tests could not be made at higher speeds. The other factor is an "age-traffic index." The pavements tested varied widely in surface age and intensity of traffic. The age-traffic index has been obtained by multiplying the age of the surface in months, at the time of test, by the average daily traffic count and dividing the product by 100.

In the first state-wide series of tests 50 flex-

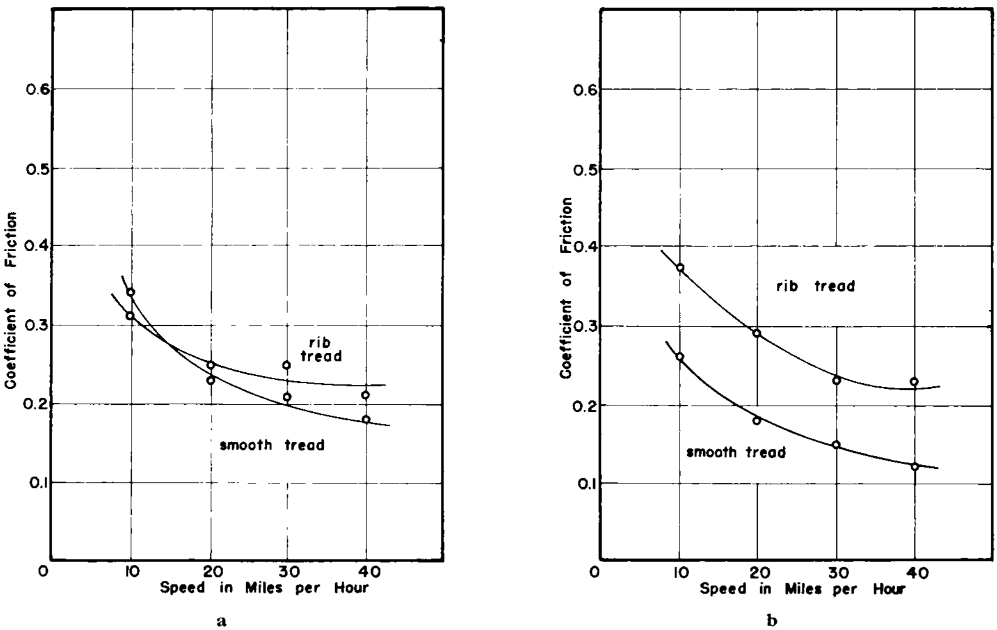



**Figure 11. Effect of tire tread on coefficient of friction.**

ible pavements were tested. Of these, 22 were in Highway Division 1, 13 in Division 2, 10 in Division 3 and the remaining 5 in Division 4. The average skid coefficients for pavements in the respective Divisions were 0.22, 0.21, 0.25 and 0.30, while their age-traffic indices were 694, 769, 487 and 322. The range of 30 miles per hour skid coefficients may also be of interest. For the pavements located in Division 1 the range was 0.43 to 0.09, in Division 2, 0.37 to 0.12, in Division 3, 0.39 to 0.15, and in Division 4, 0.39 to 0.18. It may be observed from these data that the pavements reported to give the most trouble in West Tennessee are as good as or slightly better than the average of both good and poor pavements in East Tennessee.

Four-inch cores were drilled at each test location and the samples brought into the laboratory for analysis. Such analyses revealed no apparent correlation between the coefficient of friction and the asphalt content, percentage of voids, or specific gravity of the aggregate. Samples of aggregate from the surface courses were subjected to abrasion tests in a small ball mill but no correlation was found between results of such tests and surface coefficients.

The most consistent relationship appeared to be that between coefficient of friction and type of aggregate in the surface course. Table I gives the average coefficient, the average age-traffic index, and the number of pavements tested for each of several combinations of aggregate. Although the number of pavements involved with certain types or combinations of aggregates is very small, it is apparent that the skid coefficient is reduced as the percentage of limestone or natural limestone rock asphalt (sometimes known as Alabama rock asphalt and referred to subsequently in this report as NLRA) is increased. It may be observed in Table I, however, that the average age-traffic index varies widely among the types of pavements tested.

In an effort to show this relationship more clearly, results of tests on a few individual pavements having age-traffic indices in the same order of magnitude are shown in Table II. Four of these pavements have indices between 275 and 310 and two between 160 and 180. The relationship between limestone aggregate and the coefficient of surface friction is quite pronounced in these cases.

In an effort to determine further the effect of surface aggregate upon pavement slipperiness, arrangements were made to test a few pavements in Kentucky and Virginia where surfaces different from those constructed in Ten-

TABLE I
SUMMARY OF SKID TRAILER TESTS IN TENNESSEE

| Type Surface Aggregate | Avg. Coefficient of Friction (30 mph) | Avg. Age-Traffic Index | No. Pavements Tested |
|---|---|---|---|
| 100% limestone | 0.20 | 745 | 29 |
| 70% limestone–30% sand | 0.22 | 1044 | 4 |
| 70% limestone–30% NLRA* | 0.22 | 143 | 2 |
| 70% gravel–30% NLRA* | 0.23 | 429 | 1 |
| 70% sand–30% NLRA* | 0.33 | 299 | 7 |
| 60% sand–40% NLRA* | 0.29 | 217 | 5 |
| 30% sand–70% NLRA* | 0.18 | 527 | 1 |
| 100% NLRA* | 0.12 | 1560 | 1 |

* Natural limestone rock asphalt (Alabama Rock Asphalt).

TABLE II
COMPARISON OF PAVEMENTS WITH SIMILAR AGE-TRAFFIC INDICES

| Type Surface Aggregate | Coefficient of Friction (30 mph) | Age-Traffic Index |
|---|---|---|
| 100% limestone | 0.19 | 162 |
| 70% sand–30% NLRA* | 0.43 | 180 |
| 70% sand–30% NLRA* | 0.37 | 298 |
| 60% sand–40% NLRA* | 0.36 | 288 |
| 70% limestone–30% NLRA* | 0.20 | 280 |
| 100% limestone | 0.16 | 306 |

* Natural limestone rock asphalt (Alabama Rock Asphalt).

TABLE III
SUMMARY OF SKID TRAILER TESTS OUTSIDE TENNESSEE

| Type Surface Aggregate | Ave. Coefficient of Friction (30 mph) | Avg. Age-Traffic Index | No. Pavements Tested |
|---|---|---|---|
| 100% limestone | 0.28 | 243 | 4 |
| 100% Kyrock* | 0.41 | 659 | 3 |
| 100% sandstone | 0.33 | — | 6 |
| 100% granite gneiss | 0.30 | — | 1 |
| 80% granite gneiss–20% sand | 0.25 | — | 3 |

*Kentucky Rock Asphalt.

nessee were available. Surfaces tested included those in which the surface aggregate was 100 percent limestone, 100 per cent sandstone, 100 percent granite gneiss, 20 per cent sand–80 percent granite gneiss and 100 per cent Kentucky rock asphalt (Kyrock). Results of the tests are shown in Table III. Age-traffic indices are not available for most of these pavements. The average age-traffic index for the 100 percent limestone aggregate surfaces, however, was 243 and for the 100 percent Kyrock 659. Two of the limestone and one of the Kyrock surfaces were only approximately one week old at the time the tests were performed. Results appear to emphasize the importance of type of aggregate in the surface course upon the resistance to slipping.

In order that the effect of surface aggregate upon pavement slipperiness might be clearly demonstrated, a test section was constructed in April 1953. In this project, known as the Rockwood Test Section, six different surfaces were laid. Aggregate combinations in the surface courses were 100 percent slag, 50 percent limestone and 50 percent slag, 50 percent limestone and 50 percent sand, 60 percent limestone and 40 percent sand, 75 percent limestone and 25 percent slag, and 75 percent limestone and 25 percent sand. The layout of these sections is shown in Figure 12. The slag employed had a specific gravity of 2.80 and a wear by modified Los Angeles Abrasion Test of 46.2 percent. The specific gravity of the limestone was 2.73 and its wear 21.2 percent. The sand was a relatively fine Cumberland Mountain sand, having a specific gravity of 2.65. An AC-8 (penetration 91) asphalt cement was used throughout the project.

Skid trailer tests have been performed on the six surfaces in this test section at intervals since immediately after its construction. Surface coefficients measured to date, at the speed of 30 miles per hour, are shown in Table IV. A recent set of test results are shown graphically in Figure 13.

The data presented in Table IV show that since the pavement was one month old Section D, containing 100 percent slag aggregate in the surface course, has shown a considerably higher resistance to skidding than any of the other sections. In general, it has been followed by Sections C and B, 50 percent slag–50 percent limestone and 50 percent sand–50 percent limestone, respectively, with some preference for Section C. These have been followed by Sections F and E, 25 percent sand–75 percent limestone and 25 percent slag–75 percent limestone, respectively, with Section F perhaps slightly superior to E. Section A containing 40 percent sand and 60 percent limestone has consistently showed the lowest coefficient of friction. To date the rea-

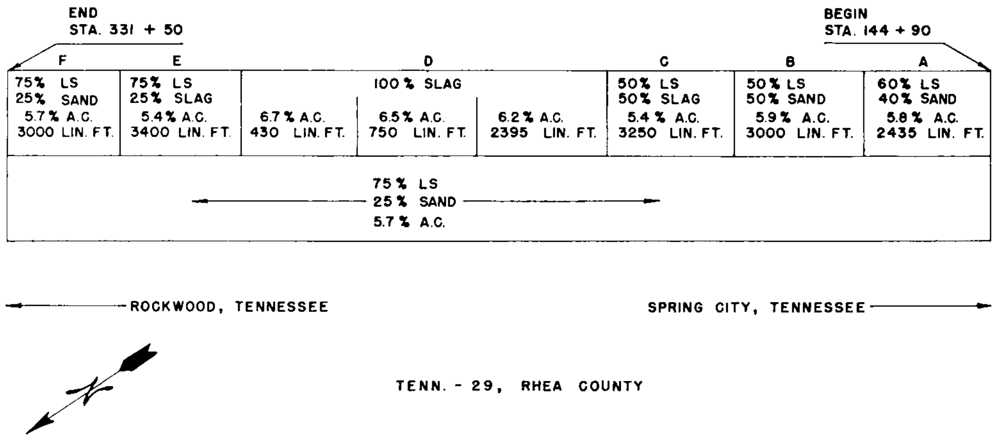



**Figure 12. Plan of Rockwood test section.**

son for this performance has not been determined. With the exception of Section A, it may be observed that the resistance to skidding increases as the percentage of limestone in the surface course decreases and that there appears to be no distinct preference between sand and slag as a partial replacement for the limestone. The outstanding performance of the surface containing only slag aggregate is most noteworthy.

One series of tests has been conducted on the Rockwood Test Section with the various surfaces in a dry condition. Results of these tests are shown in Figure 14. These show clearly that a series of pavements will not exhibit the same relative surface coefficients when in a dry as when in a wet condition. If the skid coefficient at 30 miles per hour is taken as the criterion of performance, the dry tests on these sections show them to be in decreasing order, Sections E, B, F, A, C and D. Thus the two sections performing best when the surfaces are wet appear to be the poorest when the surfaces are dry. It should be noted, however, that all six sections have coefficients of friction at 30 miles per hour of 0.80 or more when dry.

The implication is not intended that all limestone aggregates tend to produce highly slippery pavements. Several surfaces containing limestone aggregates have been found to be relatively skid resistant even after the passage of a rather considerable volume of traffic. In most cases where this has been observed, however, examination of exposed aggregate particles shows them to have a highly pitted appearance, and reference to construction records, where

TABLE IV
SUMMARY OF SKID TRAILER TESTS ON ROCKWOOD TEST SECTION

| Date Tested | Coefficient of Friction (30 mph) | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| 4-23-53 | 0.27 | 0.27 | 0.39 | 0.33 | 0.31 | 0.31 |
| 5-14-53 | 0.30 | 0.34 | 0.34 | 0.39 | 0.32 | 0.32 |
| 7-21-53 | 0.24 | 0.26 | 0.29 | 0.37 | 0.29 | 0.26 |
| 8-7-53 | 0.22 | 0.27 | 0.27 | 0.36 | 0.26 | 0.27 |
| 10-22-53 | 0.23 | 0.23 | 0.25 | 0.34 | 0.26 | 0.27 |
| 11-19-53 | 0.22 | 0.23 | 0.29 | 0.37 | 0.25 | 0.23 |
| 3-25-54 | 0.29 | 0.33 | 0.34 | 0.44 | 0.28 | 0.33 |
| 6-25-54 | 0.27 | 0.30 | 0.33 | 0.40 | 0.27 | 0.30 |
| 9-24-54 | 0.28 | 0.30 | 0.35 | 0.43 | 0.28 | 0.32 |

available, reveals that the stone involved contained fairly considerable quantities of shale. It is suspected that these inclusions may have resulted in a differential rate of wear in the aggregate exposed to traffic, which has resulted in the retention of a locally rough surface texture.

One pavement has been located in which the limestone aggregate used in the surface course was changed in the middle of the project. Coefficients of friction measured on the two sections at 30 miles per hour were 0.31 and 0.20. Analyses of small samples of aggregate taken from the two surfaces revealed that the aggregate present in the more skid resistant surface contained 13.64 percent $SiO_2$, 28.00 percent CaO and 15.31 percent MgO. The aggregate in the more slippery surface contained 3.60 percent $SiO_2$, 50.10 percent CaO and 2.09 percent MgO. Thus, it may be observed that the aggregate used in the less slippery surface was high in silica and magne-

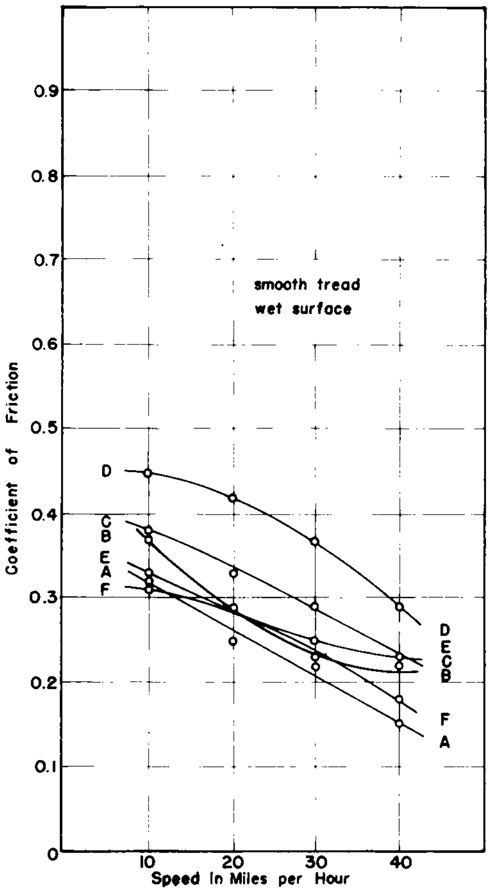



Figure 13. Results of typical tests on Rockwood test section.

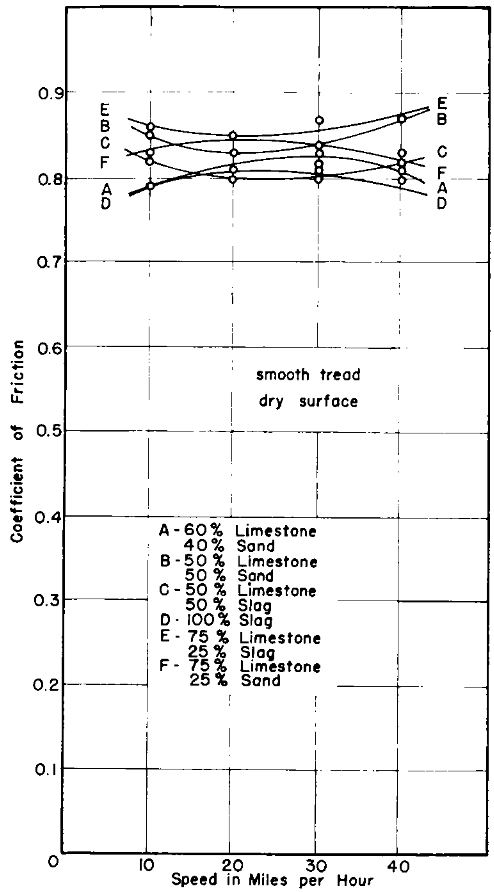



Figure 14. Results of test on Rockwood test section, dry surface.

sium while that in the more slippery surface was high in calcium. It is possible that some such chemical analysis may be useful in predicting the behavior of a given aggregate as a surface material. Insufficient tests of this nature have been performed, however, to confirm or disprove this possibility.

The foregoing discussion has dealt almost entirely with the testing of flexible pavements. The study has dealt primarily with such pavements because of their predominance in Tennessee and because they have been most frequently associated with the problem of slipperiness. Skid trailer tests, however, have been performed on eleven portland cement concrete pavements. Five of these contained limestone aggregates and the other six sand and gravel. The average age of the pavements containing limestone was 17.8 years, the average daily traffic intensity was 1965 vehicles (age-traffic index = 4198), and the average coefficient of friction at 30 miles per hour was 0.18 with the range extending from 0.09 to 0.32. The six pavements containing sand-gravel aggregates averaged 14.5 years in age, 1685 vehicles per day in traffic intensity (age-traffic index = 2932) and had an average 30 miles per hour coefficient of friction of 0.26 with range from 0.15 to 0.33. The youngest pavement included in the group was 4 years and 4 months old and the oldest was 24 years old. A few tests were attempted on very new concrete pavements having a broomed surface texture. The resulting wear on the test tires was so great that these tests were discontinued.

*Stopping-Distance Tests*

In the later phases of this study consideration was given to the desirability of conducting a limited series of stopping-distance tests. Although it was felt that the skid trailer had proved entirely satisfactory for evaluating pavement slipperiness, at least on a relative basis, it was appreciated that some benefits, particularly from a public relations point of view, would accrue from reporting the slipperiness, or lack thereof, of individual pavements in terms of stopping distances from given initial speeds. This would also permit direct comparison of the performance of a pavement surface with the safe stopping-distance specifications of the American Association of State Highway Officials. It was decided that an effort should be made to determine the correlation, if any, between the two methods of test in order that the results of skid trailer tests might be used to predict stopping distances.

Stopping-distance tests employing the equipment described previously have been performed on 18 pavements in addition to the six surfaces included in the Rockwood Test Section. In each case, both stopping-distance and trailer tests have been made on the same or consecutive days, and with one of the tires used on the stopping-distance vehicle transferred for use on the skid trailer. Where possible, stopping distances have been measured from initial speeds of 10, 20, 30 and 40 miles per hour on each pavement section, although in a few cases no satisfactory measurements could be made from the highest speed. In one case only, that of the slag surface on the Rockwood Test Section, stopping distances were also measured from an initial speed of 50 miles per hour.

Sufficient stopping-distance tests were performed from each initial speed to provide a good average result. From speeds of 10, 20 and 30 miles per hour three tests were usually sufficient. When the skid was started from a speed of 40 miles per hour, however, considerable variation was observed in the results obtained, and in some cases as many as six to eight tests were performed before a satisfactory average was determined. With the average stopping distances measured, a coefficient of friction from each initial speed was calculated through the use of the conventional stopping-distance equation:

$$S = \frac{V^2}{30f} \qquad (1)$$

where: $S$ = stopping distance, feet,
$V$ = initial velocity, mph, and
$f$ = coefficient of friction.

It was observed that these coefficients, when plotted against initial vehicle speed, produced curves generally similar in shape and approximately parallel to the curves developed from skid trailer tests, but the individual values were invariable considerably higher than those measured with the skid trailer. A typical set of test results is shown in Figure 15.

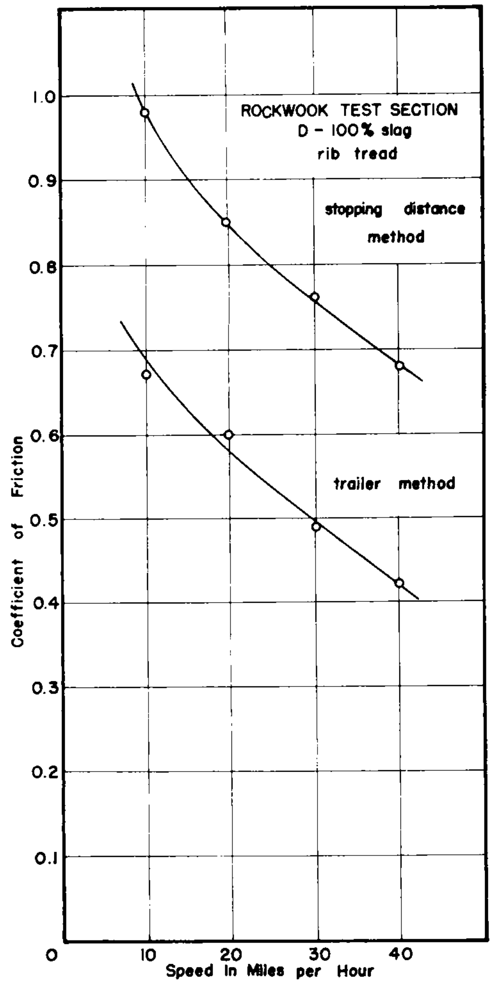



Figure 15. Comparison of skid trailer and stopping-distance test results.

With results of the two types of tests available for direct comparison, an effort was made to predict stopping distances on the basis of skid trailer tests. Two types of computations have been made and are referred to subsequently as Case 1 and Case 2. In the Case 1 analysis, the coefficient of friction versus speed curve is extrapolated to 5 miles per hour and the curve is broken into four segments, 0–10, 10–20, 20–30 and 30–40 miles per hour. The coefficient of friction for the median speed of each segment (5, 15, 25, 35 mph) is selected from the curve. The rate of deceleration through each 10 miles per hour increment in speed is then calculated from the relationship:

$$a = fg \qquad (2)$$

where: $a$ = rate of deceleration between initial and final velocity of the increment, ft. per sec. per sec.,
$f$ = median coefficient of friction,
$g$ = acceleration due to gravity = 32.2 ft. per sec. per sec.

Using this determined rate of deceleration for each velocity increment, the time required to decelerate through the increment is determined from:

$$t = \frac{V_1 - V_0}{a} \qquad (3)$$

where:
$t$ = time required for deceleration, sec.,
$V_1 - V_0$ = velocity increment through which deceleration occurs, ft. per sec., and
$a$ = rate of deceleration, ft. per sec. per sec.

From the values of "$t$" determined in this manner, the distance travelled while the deceleration takes place, may be obtained from:

$$S = Vt \qquad (4)$$

where: $S$ = distance travelled during deceleration, feet,
$V$ = median velocity of the increment (5, 15, 25 or 35 mph), expressed in ft. per sec., and
$t$ = time required for decleration, sec.

With the value of "$S$" determined for each of the four velocity increments between 0 and 40 miles per hour, stopping distances from any initial speed may be calculated by summing the appropriate increments of distance.

The computations designated as Case 2 are considerably less involved than those outlined above but, depending upon the shape of the coefficient of friction versus speed curve, may be appreciably less accurate. In this case, the median coefficient of friction between the selected initial speed and zero is taken from the curve and the stopping distance computed directly using the stopping-distance equation shown above (Equation 1). Thus, if the stopping distance from 30 miles per hour is desired the skid coefficient at 15 miles per hour is taken from the curve and used to compute the total stopping distance from the indicated initial speed.

As might be expected, since the coefficients of friction determined by the skid trailer are invariably lower than those determined by stopping-distance techniques, the calculated stopping distances based on skid trailer tests are always longer than stopping distances measured on the same pavements with the same tires. In an effort to compare the two methods directly, stopping distances calculated by Case 1 computations have been plotted against actually measured stopping distances on Figure 16. Similar results of Case 2 computations are shown in Figure 17.

It may be observed that a fairly good relationship exists between the stopping distances determined from the two methods of test. If straight line regression is assumed, the correlation coefficient in each case is approximately 0.98. The number of cases of comparison available is insufficient to permit the use of extensive statistical analyses. It may be observed from the plotted points, however, that the variance is relatively low through about the first two-thirds of the curve and becomes distinctly greater toward the upper limit of the curves. This bears out the observations of those conducting the stopping-distance tests that tests starting at speeds of 30 miles per hour, or less, were considerably more uniform than those in which the initial speed was 40 miles per hour.

From Figure 16 a relationship of true stopping distance equals 0.76; the stopping distance calculated from trailer tests may be inferred. On Figure 17 the relationship is true stopping distance equals 0.80 calculated stopping distance.

Among the stopping-distance tests performed, one particular series is worthy of mention as it bears directly upon the influence of pavement aggregate upon slipperiness. These tests were made on a concrete pavement which makes up a portion of Route Tenn-9 near Newport, Tennessee. A large portion of this pavement has been resurfaced. A short section of the original concrete remains uncovered. In the uncovered section, the northbound lane is made with a limestone aggregate and the southbound lane with natural sand and gravel. The two lanes were constructed at the same time by the same contractor and the age of the pavement is approximately 24 years. Upon several occasions when tests have been performed in this vicinity no notable differences in traffic in the two directions were observed.

Stopping-distance and trailer tests were made on both lanes of this pavement. The location is not ideal for stopping-distance tests as the only exposed concrete exists at the crest of a slight hill. In order that the tests might be as nearly comparable as possible, both lanes were tested with the vehicle sliding in a southerly direction. All tests were made in such location that the crest of the hill occurred approximately in the center of the skid so that the effect of grade and change in grade should be the same for the two lanes.

The results of these tests are shown in Figure 18. The difference in performance is quite outstanding. In the northbound lane, Figure 18a, constructed with limestone aggregate, the skid coefficients varied from approximately 0.62 at 10 miles per hour to 0.32 at 40 miles per hour when measured by the stopping-distance tests and from 0.37 to 0.17 between 10 and 40 miles per hour when determined from trailer tests. Actual measured stopping distances were 5.4, 36.1, 84.2 and 165.6 ft., respectively, from initial speeds of 10, 20, 30 and 40 miles per hour.

In the southbound lane, made from sand-gravel aggregate, shown in Figure 18b, the coefficients determined from stopping distance tests ranged from 0.95 at 10 miles per hour to 0.54 at 40 miles per hour and from 0.55 to 0.38 over the same speed range when tested with the trailer. Stopping distances were found to be 3.5, 17.7, 47.5 and 98.4 ft., respectively, from initial speeds of 10, 20, 30 and 40 miles per hour. The average difference between coefficients determined by stopping distances on the two pavements is approximately 0.25 and the average difference between trailer coefficients for the pavements is approximately 0.20.

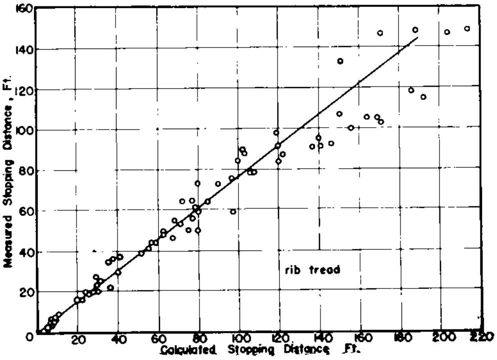



**Figure 16. Relationship of calculated to measured stopping distances, case 1 computations.**

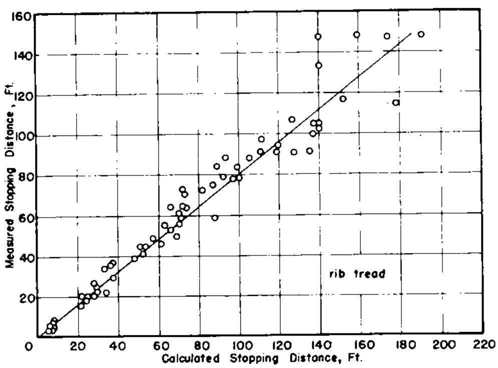
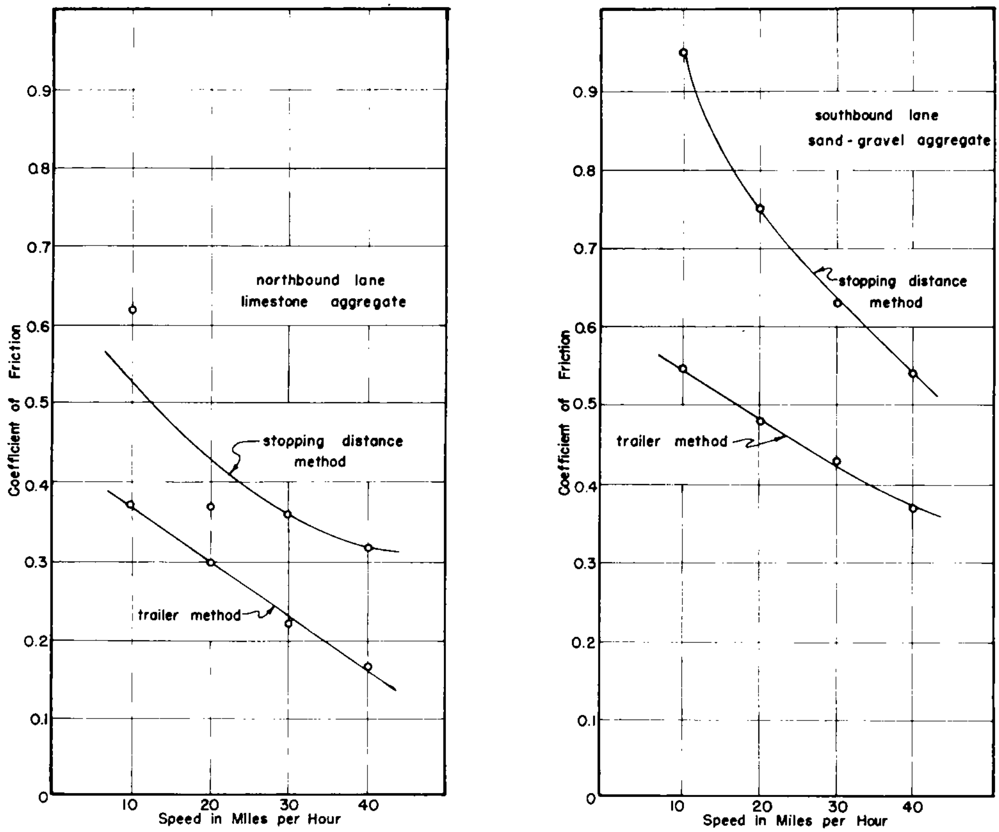



**Figure 17. Relationship of calculated to measured stopping distances, case 2 computations.**

Both of the surfaces exposed are quite worn in apperance. Most of the original surface mortar has been removed and large pieces of course aggregate are exposed and worn in both lanes. By AASHO standards, which require that a vehicle travelling at 40 miles per hour be able to stop within 113 feet, the southbound lane is clearly safe and the northbound lane is clearly unsafe. This appears to be one of the most notable verifications of the previously suggested theory that pavements containing certain types of limestone have a distinct tendency to become slippery when subjected to traffic.

A limited series of stopping-distance tests was performed to determine whether the re-




a b

**Figure 18. Comparison of slipperiness of concrete pavements having sand-gravel and limestone aggregates.**

lationship between measured and calculated stopping distances would remain the same if different tires were employed. Four smooth tires, similar to those generally used on the trailer, were obtained for the automobile. Stopping-distance and trailer tests were then performed on the six surfaces of the Rockwood Test Section. This provided 24 comparisons of the two distances. Graphical presentation of the data, similar to that shown in Figures 16 and 17, revealed a very similar relationship to exist. The slope of the line of regression was slightly less for the tests with the smooth tires.

## CONCLUSIONS

On the basis of the tests discussed above, as well as additional tests of a similar nature bringing the total number of pavements tested in Tennessee to approximately 80, it is concluded that the susceptibility of certain limestone aggregates to polishing under the action of traffic is a major cause of pavement slipperiness. This conclusion verifies opinions expressed by Gray (12) and Larson (13). It is appreciated that all limestone aggregates do not exhibit this tendency to the same degree. To date, however, no method has been evolved for predicting the potential behavior of an aggregate as a surface material. As a result of these investigations the Tennessee Department of Highways and Public Works now requires the inclusion of 40 per cent silica sand in limestone surfaces.

From the rather limited tests performed on portland cement concrete pavements, it is concluded that the slipperiness of such surfaces in Tennessee covers the full range of slipperiness of other types of pavements. It is believed that concrete pavements containing a limestone aggregate susceptible to polishing are potentially as likely to become slippery as are bituminous pavements containing the same aggregate. The difference in performance of the two pavements appears to lie in the rate at which the development of such slipperiness progresses. Since the particles of coarse aggregate are almost immediately exposed in a bituminous pavement while they are normally well protected by a coating of mortar in the concrete pavement, the concrete pavement may be expected to become slippery at a much slower rate than the bituminous pavement.

Within the limitations of the equipment employed it is concluded that stopping-distance tests performed on a series of pavements will rate them, with respect to slipperiness, in essentially the same order as skid trailer tests, provided similar tires are employed and the test conditions standardized to the greatest possible degree. Observations of those conducting both types of test are that the trailer type is more accurate, more reproducible, safer, and subjects traffic on the highway to much less inconvenience than the stopping-distance tests. The desirability of reporting pavement slipperiness in terms of stopping distances is appreciated. It has been demonstrated, however, that the results of skid trailer tests may be used to predict stopping distances through the use of computations somewhat in the order of those reported by Stinson and Roberts (14) or by the less complex stopping-distance equation. It is believed that stopping distances so estimated are as likely to reflect the true nature of the pavement surface in question as are actually measured stopping distances, particularly at speeds in excess of 30 miles per hour.

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