Skid Characteristics of Pavement Surfaces in Indiana

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In 1953, drivers in the United States became involved in 31,450 fatal and 1,302,000 non-fatal accidents. Many of these accidents were primarily the fault of the drivers involved, but a great number might have been minimized or prevented by safer highways. Although many factors are involved in the building of safety into highways, one of the more important items is the resistance of pavement surfaces to skidding, especially when these surfaces are wet. Twenty per cent of the fatal and 23 per cent of the non-fatal accidents in 1953 occurred on wet pavements. When consideration is given to the fact that pavements are wet far less than 20 per cent of the time, and travel is usually reduced during wet periods, it is evident that a disproportionate number of accidents occur under these conditions. How many accidents could be avoided by better skidding characteristics is unknown; but since many accidents involve some type of skidding, the number is undoubtedly great.

In Indiana, it is generally recognized that certain types of pavements have better skidding characteristics than others, but few measurements have ever been taken on a comparative basis. Experimental sections have been constructed in the past few years, and several new surface types are being used. Some of these surfaces are quite economical and durable, but little is known of their skidding properties. If the new surfaces are dangerously slippery the reduced construction cost is of extremely dubious value, unless they can be redesigned so as to make them satisfactory.

The need for a method of determining skidding properties that is fast, safe, and accurate, and the determination of the skidding characteristics of pavement surfaces is, therefore, evident.

PREVIOUS INVESTIGATIONS

Only a few organizations or individuals have undertaken extensive programs of research to determine the skidding characteristics of pravements. Possibly the most complete data have been obtained by Prof. R. A. Moyer, formerly of Iowa State College and currently at the University of California in Berkeley. In his earliest tests, as reported in 1933, a two-wheel trailer towed by a water truck was used (15)*. The trailer was constructed so it could be used to measure impending skid, straight locked-wheel skid, and side skid. The skidding force was measured by integrating a dynamometer linkage to the towing truck. The wheels were locked or braked with Bendix self-energizing mechanical brakes which were manually operated. Two to four runs were made in each direction, wet and dry, at 3, 5, 10, 20, 30, and 40 mph and the dynamometer force was averaged over a distance of from 50 to 150 feet.

The more important conclusions of these earlier tests were:

1. There was a marked decrease in the coefficient of friction as speed increased although there appeared to be a definite similarity at higher levels.
2. Coefficients at low speeds were not a true indication of those for higher speeds (i.e. 30-40 mph).
3. High-type asphalt surfaces had the best coefficient of friction.
4. Portland Cement Concrete gave the most consistent results but averaged a slightly lower coefficient of friction than high-type asphalt.
5. At higher speeds, there was a marked increase in the coefficient of friction for sideways skidding as compared to that of straight skidding.
6. At higher speeds the coefficient of impending friction was greater than the sideways coefficient.
7. A slight decrease of the coefficient of friction was noted with an increase in weight.
8. Increase in tire pressure decreased the coefficient slightly.
9. Smooth treads gave consistently lower values for all three conditions of skidding, even though contact area was 50% greater.
10. With new treads, however, the coefficient of friction increased with contact area (i.e. soft balloon tires were considerably higher).

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* Numbers in parentheses refer to bibliography.

11. The difference between the coefficients of friction for wet and dry conditions increased with speed.
12. For a period of 30 minutes after a surface had been wetted there was no noticeable change in the coefficient of friction.
13. In a straight skid, differences of air temperature did not cause a significant change in coefficient.

The first detailed report on the automobile stopping-distance method of skid testing resulted from work conducted in Virginia by T. E. Shelburne and R. L. Sheppe, reported in 1948 (18). Here a standard, light-weight automobile was used with manually operated brakes. The skid distance was measured by taping the distance from a chalk mark fired from a device mounted on the running board. The roads were compared by comparing the coefficients of friction at speeds of 10, 20, 30, and 40 miles per hour. The coefficient of friction was computed by the standard formula $F = \frac{V2}{30\,S}$, where F equals the average coefficient of friction, V equals the initial speed in miles per hour at the time of applying brakes, and S equals the average stopping distance in feet. This formula has been used for almost all subsequent tests that have employed the stopping distance method.

This report summarized tests on only 32 different pavements so the results cannot be considered conclusive. Some of the more important conclusions were:

1. Results obtained on a wet surface at 30 or 40 mph can be used successfully to compare the skid resistance of various pavements.
2. Surfaces with harsh, gritty, sandpaper-like textures were found to give the highest coefficient of friction, these were followed by broom-finished portland cement concrete, and then the lower bituminous types.
3. All of the pavements tested in a dry condition were found to have a satisfactory resistance to skidding for speeds of 40 mph or less.

The results of skid tests performed in North Carolina were also found (11). Here the vehicle-stopping distance method was used exclusively and distances were taped from a chalk mark placed by activation of a device on the brake pedal. Tests were run on 42 pavement surfaces at speeds of 20, 30, and 40 mph. The conclusions corroborated those of other investigators and included:

1. Surfaces having a harsh, gritty, "sandpaper" texture were found to have short stopping distances.

2. A slight excess in asphalt will have a more pronounced effect in reducing friction values than the particle shape of the aggregate.
3. On relatively smooth level pavements, the stopping distance method is an excellent means of determining the average skid resistance. The data can be used to establish policies concerning the design, construction, and maintenance of surfaces with good non-skid characteristics.

A recent preliminary report from Moyer, based on the trailer method, reports a few new conclusions:

1. On Portland cement concrete, the coefficient of friction may decrease 30-50 per cent in two years because of oil slick.
2. Friction values in wet tests on ⅜-inch maximum size angular aggregate were 50 to 100 per cent higher than for smooth round gravel aggregate.
3. Heavy rains in November and December increased the friction values by 20 per cent to 60 per cent over those for the summer season.
4. Surfaces can be built that provide friction values for the wet condition that are nearly as high as the friction values for the dry condition, thereby reducing the skidding hazard to a minimum.

Research on skid-resistance was initiated by the Joint Highway Research Project in November 1950. At that time John F. McLaughlin presented a "Report and Annotated Bibliography on Skid Resistance". In 1951 field observations of vehicle reaction and reliability of test equipment were made. From June 1952 to the summer of 1953, further tests, using the automobile-stopping distance method, were conducted by John Baerwald. The primary purpose of these tests was to develop testing procedures and to provide data for comparison of the skid resistance qualities of pavement surfaces. From these preliminary tests a formal field study was developed and is the subject of this paper.

PURPOSE AND SCOPE

The primary purpose of this study was to obtain estimates of the relative skid resistance of Indiana road surfaces in the wet condition and to investigate some of the factors that affect their skid resistance. An important secondary purpose was the development of a fast, safe, and accurate method of estimating relative skid distance.

The actual field survey encompassed eleven weeks of testing in all sections of the State. Four major construction types were investigated:

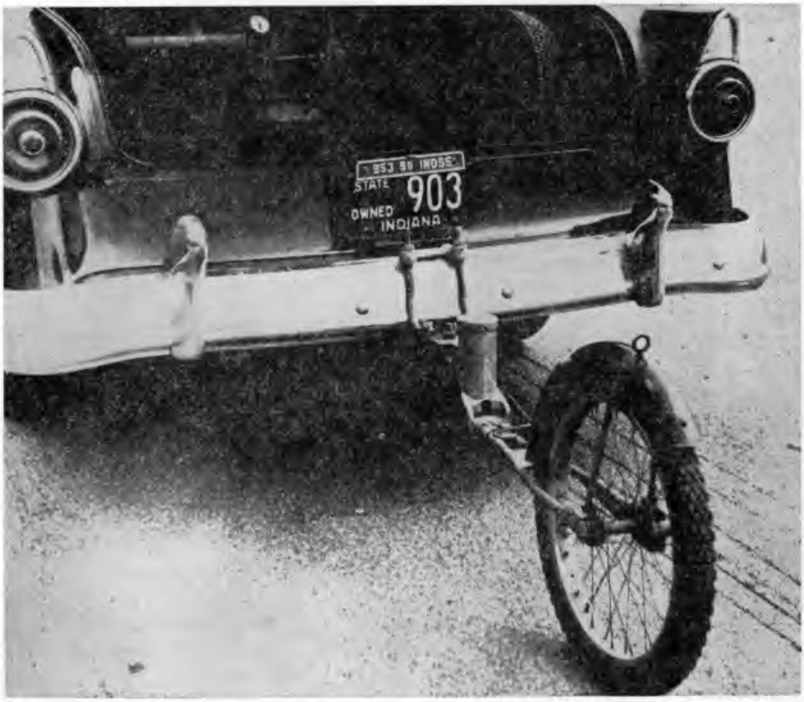

Fig. 1. The Wagner Stopmeter was attached to the rear of the skid vehicle.

Rock Asphalt, Portland Cement Concrete, Bituminous Concrete and Other Bituminous Surfaces. A total of 233 different roads were tested in a wet condition, and 20 in the dry condition. Each road was tested at three locations, and two skids were taken at each location. All tests were made at a brake-application speed of 30 mph.

PROCEDURE

Testing Device

A preliminary study was conducted in order to determine the testing method that would be the most satisfactory and that would be safe and economical. The vehicle-stopping-distance method was determined to be the best for this study and it was adopted. In its original form this method of test consisted of a standard 1951 Ford equipped with a chalk-marking device mounted on the back bumper, the wiring being attached to the brake pedal by a large clamp connected in series with a simple pull-apart connector. To run a test the driver would connect the proper wiring, load the chalk marker with a chalk cartridge. He would then bring the vehicle to a speed slightly in excess of the test

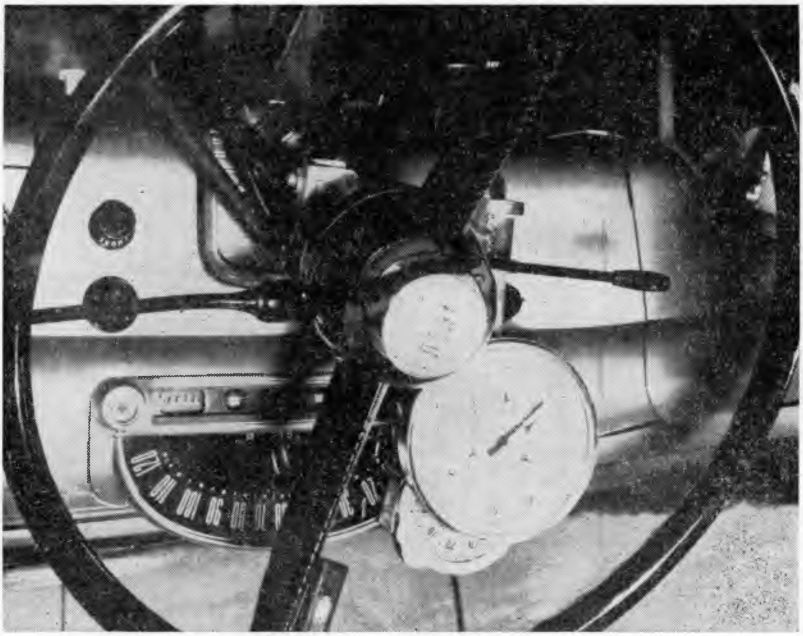

Fig. 2. The Speedometer and Odometer dials of the Stopmeter were mounted inside the skid vehicle.

speed, disengage the motor, let the vehicle coast to the proper speed and slam on the brake, bringing the car to a skidding stop. The movement of the brake pedal fired the chalk marker, and the distance from the mark to the final position of the car was taped.

Since this method depended on manual control of many variables, it was decided to modify the test car to minimize the human factor. The idea evolved to outfit the car with some type of electrically operated power brake that would give a constant braking pressure with each application. This could be connected with an accurate fifth-wheel speedometer-odometer that would record the test speed and measure the distance required to stop.

The "Wagner Stopmeter" manufactured by the Wagner Electric Company of St. Louis, Missouri, fulfilled this latter requirement and was available at a reasonable cost. A unit was subsequently purchased. (See Figures 1 and 2).

A study of possible braking systems revealed that a vacuum brake system would be the most practical and economical for test purposes. Air pressure and electrical brakes were investigated, but the cost of adapting either to the test car would have been far greater than that for the vacuum system. The Bendix Products Division of the Bendix Aviation Corporation of South Bend, Indiana, proposed a simple, electrically-operated, vacuum-braking unit. This unit was eventually constructed and installed in the test car by the Bendix Corporation.

The Bendix System is illustrated in Figure 3. The heart of the system is the vacuum unit that operates a Ford master cylinder (E)

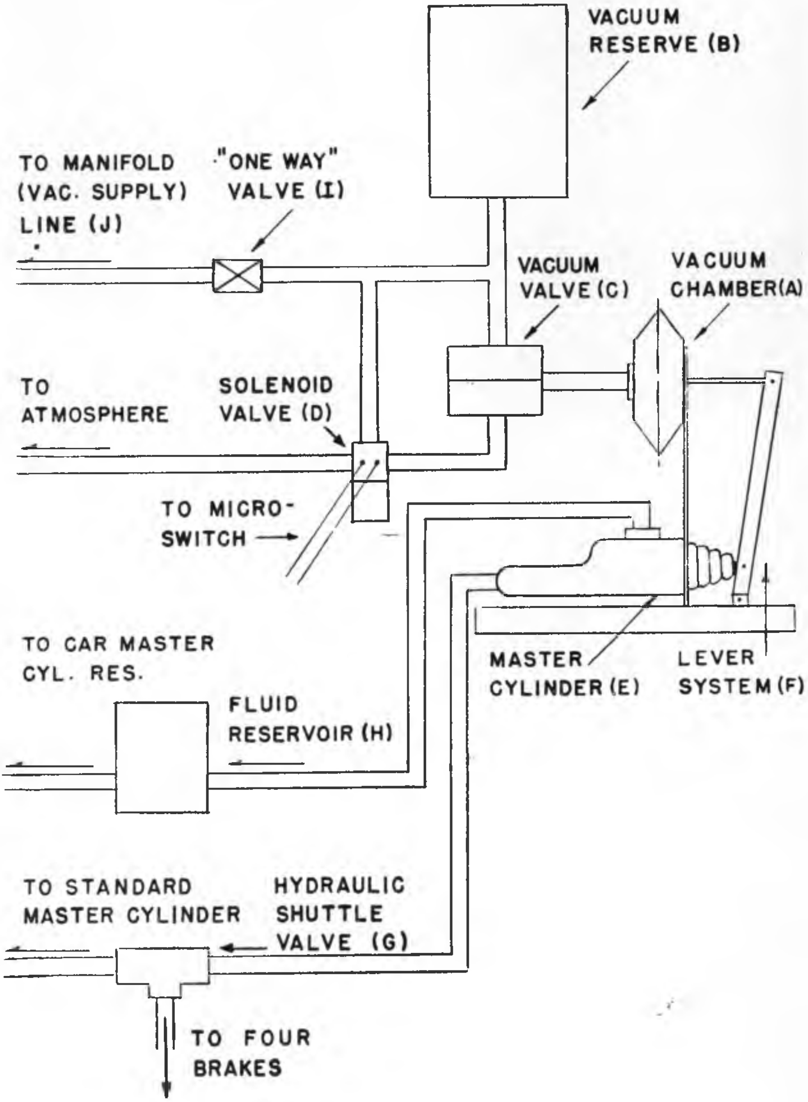

Fig. 3. Diagram of vacuum braking system.

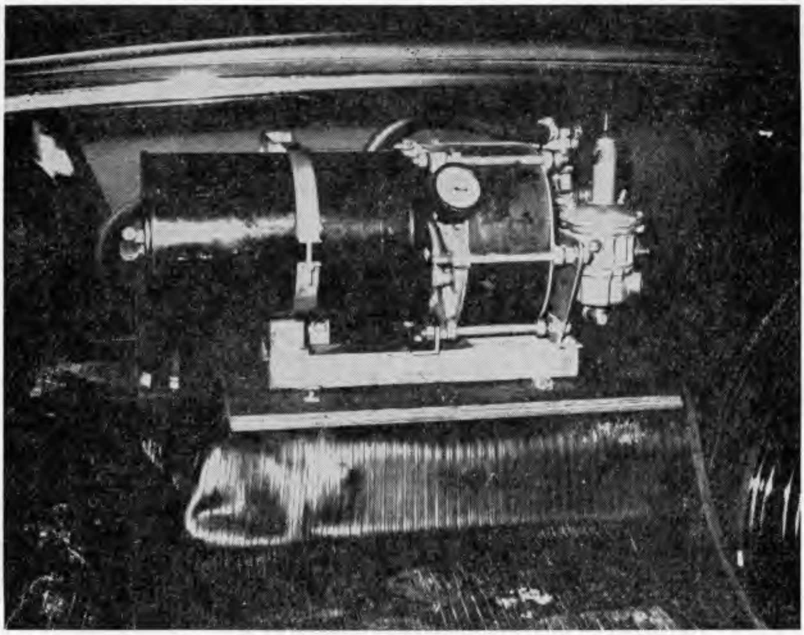

Fig. 4. The Special Bendix Vacuum Braking Unit was installed in the trunk of the test vehicle.

through a simple lever system (F). The vacuum chamber is activated when an electrical impulse opens the solenoid valve (D) which, in turn, opens the vacuum valve (C).

The vacuum thus created in the left side of the vacuum chamber causes atmospheric pressure to force the lever system (F) to the left, thus activating the master cylinder (E). The vacuum is supplied by the intake manifold of the engine through line (J). A one-way valve (I) was installed to eliminate any losses in the vacuum reserve tank (B) during periods of low manifold vacuum. A brake fluid reservoir (H) was included with lines running to master cylinder (E) and to the car master cylinder, so as to eliminate the possibility of pumping fluid between the car system and the power system.

Line pressure applied by master cylinder (E) causes the shuttle valve (G) to close the line to the standard car master cylinder and allows line pressure to be distributed to the individual wheels for braking. When the current to the solenoid valve (D) is discontinued the pressure is instantly relieved and application of the standard car

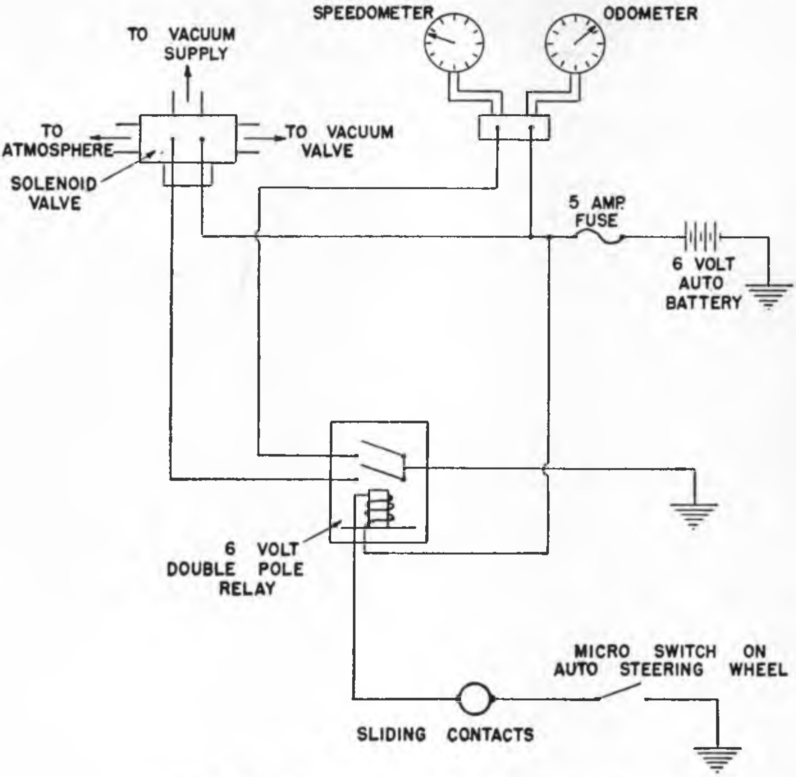

Fig. 5. Wiring diagram of braking circuit.

brake will transfer the shuttle valve (G) and allow normal operation of the brakes. The diameter of the shuttle valve was reduced from ½″ to ¼″ to eliminate the necessity of a large amount of fluid displacement when transferring from this special braking system to the normal method. The system, as outlined was installed in the trunk of the test car by Bendix personnel (See Figure 4) and operated without incident through the entire series of tests. The power system applies a brake line pressure of approximately 700 psi. and locks the wheels in less than 0.17 of a second.

With the braking problem solved, there remained a need for a method which would permit the driver to conveniently lock the brakes and activate the Wagner Stopmeter simultaneously and at the desired speed. After consideration of several types of foot switches, it was apparent that more positive and sensitive driver control could be realized by a hand-operated switch. A micro-switch was mounted on the steering wheel rim and connected to a circular copper contact plate at the wheel base. A carbon brush was set in the steering column so that it was in contact with the circular plate for all positions of the steering wheel and was connected into the coil of a 6-volt double-pole relay. The relay was connected as shown in the wiring diagram (Figure 5) to the brake solenoid valve and to the odometer and speedometer.

These modifications made skid testing quite simple and minimized the driver variable. In order to make a test run the driver merely has to let the car slow down to the test speed as indicated by the special speedometer and press the micro-switch. This action locks the brakes and at the same instant holds the speedometer and activates the odometer. At the end of the skid it is possible to record the braking speed and the skid distance from the stopmeter dials. This testing method has proven to be extremely consistent.

Selection of Test Roads

The term "road" in this paper will be used to define a section of pavement that is identical in age, volume, and construction over its entire length. These roads were generally between one and ten miles in length. Indiana pavement surfaces were divided into four major types: Rock Asphalt, Portland Cement Concerte, Bituminous Concrete, and Other Bituminous Surfaces; and these major types were divided into a number of sub-types. Roads of each of these types were selected from available records in the Joint Highway Research Project.

The 12 weeks set aside for the field study were initially divided so as to allow two weeks in each of the six highway districts. Progress, however, permitted the elimination of one week and a final count showed a total of 233 roads tested plus an extensive series of tests on the U. S. 31 Test Road near Columbus, Indiana.

It was also found necessary to eliminate some of the originally selected roads and to select replacements. A few had been resurfaced more recently than the available records indicated, and others had been resurfaced by maintenance forces of the Highway Department and the records of their construction were not complete. The selection of the actual roads tested was made in each district prior to the testing with the aid of district personnel.

Method of Testing

Each selected road was tested in three locations, with two skids performed at each location. A location was a level, straight stretch of pavement 100 to 200 feet in length and located anywhere on the road.

It was also possible to select the locations in such a manner as to allow adequate sight distances for the flagmen to stop traffic safely. Three adequate locations were available on most roads, even in hilly country, and it was necessary to eliminate only two roads because of a lack of suitable sites. It usually was possible to choose locations representing both directions or lanes of a road and this procedure was followed.

All skid tests were made at 30 mph. The primary reason that one speed was chosen was that the interest here was in comparing the skid resistance of the various road surfaces and not in studying the effects of various speeds. The selection of one speed also allowed more roads to be tested in the available time. Thirty mph was selected as it has been suggested by previous investigators as a speed that gives skidding properties that are representative of those that exist at the more commonly traveled higher speeds. Thirty mph was also considered as fast a speed as could safely be used over the wide range of road types that were covered. The fact that the test car left the road many times during the testing indicates that a greater speed would have been quite hazardous.

The purpose of these tests was to investigate the skidding properties of roads and since the wet condition is the most critical, almost all of the tests were run under wet conditions. The only equipment necessary for these tests was the test vehicle, a water truck, two red flags, two thermometers, data sheets, clipboard and pencil. The usual crew consisted of four men—the test car driver, an assistant, a water truck driver and a flagman. The four-man crew was found to be sufficient

Fig. 6. The pavement was thoroughly wetted before each series of skids.

Fig. 7. After the pavement was wetted, the skids were performed.

for most roads, but an additional flagman would have been desirable on highly congested routes.

After a location was selected on a particular road, the test car and flagman stopped at a point 400 to 500 feet in advance of the test section and the flagman halted all traffic approaching from the rear. The water truck and test assistant proceeded ahead to the test site and began wetting without interfering with oncoming traffic (See Figure 6). After thoroughly wetting the pavement and stopping oncoming traffic, the two skid tests were made in quick succession (See Figure 7). It was generally possible to make both skid tests in less than two minutes after completion of wetting, thus keeping the effects of evaporation and runoff to a minimum. Speed to the nearest 0.25 mph and distance to the nearest 0.25 foot were read from the stopmeter dials and recorded by the driver after each skid.

SUMMARIZATION OF THE OBSERVED DATA

Because it was impossible to make each skid test at exactly the designated speed of 30 mph, the raw data contained estimates of initial speeds from the Wagner Stopmeter in ¼ mph increments ranging from 29 to 31 mph. It was first necessary to adjust these distances to 30 mph. This was accomplished from an application of the physical relationship $F = \frac{V^2}{30\,S}$, where "S" is the skidding distance in feet, "V" the speed in mph, and "F" the coefficient of friction for the road.

Table No. 1. Summary of mean skid distances, average variances, and standard errors.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
CODE NO.	SURFACE TYPE	MEAN SKID DISTANCE (FEET)	NO. OF ROADS	AVERAGE VARIANCES			STD. ERROR OF THE MEAN * (FT.)	STD. ERROR OF THE MEAN ** (FT.)
				SKID TO SKID	LOCATION TO LOCATION	ROAD TO ROAD		
1XX	ROCK ASPHALT	62.56	32	1.02	11.39	34.23	0.24	0.43
111	STANDARD 30# OR 60#	62.25	30	0.84	4.98	25.51	0.17	0.38
121	9# SLICK TREATMENT	67.27	2	3.84	107.53	38.17	2.98	1.78
2XX	PORTLAND CEMENT CONCRETE	81.44	46	1.87	23.83	422.36	0.29	1.24
211	STONE COARSE AGG.	80.78	17	1.32	25.82	397.39	0.50	1.97
221	GRAVEL COARSE AGG.	81.83	29	2.06	22.67	446.28	0.36	1.60
3XX	BITUMINOUS CONCRETE	89.22	59	6.79	53.00	827.45	0.39	1.53
31X	STONE COARSE AGG.	88.78	55	6.99	55.65	830.02	0.41	1.59
311	NATURAL SAND	88.64	48	7.62	57.14	923.30	0.44	1.79
312	STONE SAND	89.80	7	2.64	45.43	199.99	1.04	2.18
321	GRAVEL C.A. + NAT. SAND	95.21	4	3.99	13.12	82.43	0.74	1.8[illegible]
4XX	OTHER BITUMINOUS SURFACES	80.83	47	8.20	119.97	1,304.50	0.21	2.15
41X	NO BLEEDING	74.06	30	5.11	22.34	508.30	0.35	1.68
411	ALL GRAVEL	77.86	12	6.43	19.10	618.22	0.51	2.97
412	ALL STONE	71.50	18	4.24	24.51	353.57	0.48	1.81
42X	BLEEDING	92.77	17	13.64	292.26	1,426.55	1.69	3.74
421	ALL GRAVEL	103.44	8	23.71	355.32	1,037.55	2.72	4.65
422	ALL STONE	83.28	9	4.69	236.41	672.01	2.09	3.53
5XX	SPECIAL SURFACES	—	14	—	—	—		
51X	BIT. CTD. AGG. (DENSE MIX.)	99.38	6	8.03	200.85	918.46	2.36	5.05
511	ALL GRAVEL	103.01	3	9.94	174.70	116.77	3.12	2.55
512	ALL STONE	95.76	3	6.12	226.99	1,942.84	3.55	10.39
52X	SILICA SAND	66.68	1	2.82	0.83	—	0.37	—
53X	BIT. CONC. (5 1/2 % AP 5)	98.35	1	1.85	13.74	—	1.52	—
54X	BIT. CT. AGG. (US 40 – 4 MI. EAST OF BRAZIL)	150.46	1	0.24	59.30	—	3.14	—

* BASED ON ONLY THOSE ROADS INCLUDED IN SURVEY

** REGARDING THE SELECTED ROADS OF EACH TYPE AS A RANDOM SAMPLE OF INDIANA ROADS

An approximate "F" for each major type of road was obtained by averaging all the speeds and skid distances for that type and placing these average values in the above relationship. With a knowledge of this average coefficient of friction, it was possible to estimate the difference in skid distance resulting from ¼ mph differences in speed. These estimated adjustments were applied to all skids with initial speeds other than 30 mph to render more comparable values. The average adjustment was about one foot for each ¼ mph.

For each selected location, any difference in the two skid distances gives rise to a variation which is called the skid-to-skid variance.

The three selected locations for a particular road always have somewhat different mean skid distances, and thus there is also a variation that arises from these differences. The measure of this variation is called the location-to-location variance.

Whenever more than one road has been selected in a given type or subtype, differences among the observed road means give rise to a third variance, the road-to-road variability.

Skid-to-skid variances are generally the smallest of the three types of variability since the two skids taken at the same location represent tests under the most similar conditions. The location-to-location variance represent differences that arise from variation in the surface properties of a particular road, from place to place, probably due to such items as construction differences, varying traffic, and bleeding. Road-to-road variances, within a given type or sub-type, reflect differences in skid resistance that must be associated, for the most part, with discrepancies in age or wearing, materials and methods of construction, and volume and type of traffic to which the roads have been subjected.

It is evident that the three types of variance are of considerable importance in the evaluation and comparison of the skidding properties of the various surface types. They indicate the degree to which a road type is affected by the variables of age, traffic, and construction. These affects are quite significant in evaluating the suitability of any particular surface type with respect to skid resistance, for a motorist will get little consolation from the fact that a particular road type has a very low overall mean if it has an extremely high location-to-location or road-to-road variance. Such a situation makes it quite possible for any section on which he has to stop to be considerably different from the average value.

Low variances, on the other hand, indicate that it is unlikely for any particular location on a road type to be greatly different from the overall type mean.

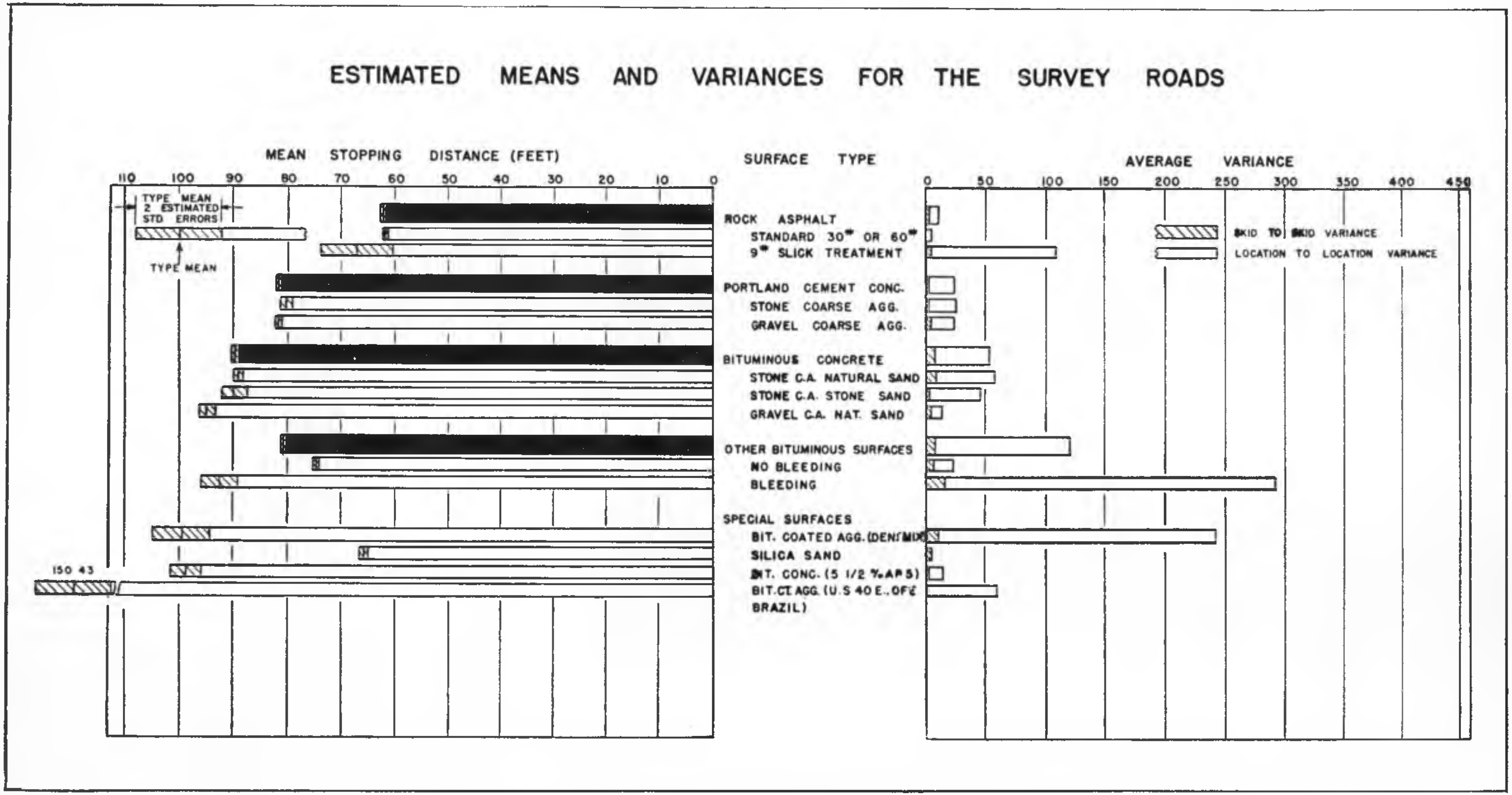

Fig. 8. Estimated means and variances for the survey roads.

RESULTS

The results of the tests for each road type are discussed in the following section and are summarized in Table 1 and Figure 8. All means stated are for a brake-application speed of 30 mph with the road surface in the wet condition. Significant differences are said to exist only when two-standard-error "regions of uncertainty" do not overlap. The standard errors used are based on only those roads included in the survey. The three variances, as previously discussed, are also shown in Table 1 and Figure 8.

It should also be noted that the difference in skidding distance between individual roads or road types is given in this study for a speed of 30 mph. A much greater difference in feet would be obtained at higher and more common speeds and could be of considerable magnitude and importance.

Rock Asphalt

The Rock Asphalt roads tested displayed excellent skidding properties in the wet condition. The mean of 180 skids on 30 different roads at 30 mph was 63.3 ft., a value significantly lower than that for any other major types, and only a few feet greater than the mean of the roads that were tested in the dry condition. The variability of the skid distances found on these roads was also of an especially low order, the road-to-road variance being on a par with the skid-to-skid variances for many other types and sub-types.

An attempt was made by rank order correlation and graphing to find a relationship between the small amount of variation existing between these roads and traffic volume, but no such relationship appears to exist. The skidding characteristics of Rock Asphalt surfacing is, then, apparently not affected by traffic volume and age; surfaces 14 and 15 years old were found to have about the same mean skid distance as many of those of recent construction.

Two roads that had been "de-slicked" by a thin nine-pound Rock Asphalt treatment was included in the survey. One of these roads was still completely covered, while a considerable portion of the resurfacing had worn off of the second. The former road displayed a mean and variance very similar to the conventional Rock Asphalt roads tested, while the latter had an exceedingly high mean skid distance and variance. It was concluded that the nine-pound treatment is an effective method of temporarily "de-slicking" surfaces. The type and condition of the previous surface however is probably an important factor governing the service of the "de-slicking" treatments.

These tests on Rock Asphalt surfaces serve to substantiate the conclusions of many other experimentors that those surfaces with a harsh, gritty, sand-paper finish have superior skidding properties in the wet condition. The only other surfaces tested that had similar properties were two sections constructed with Silica Sand, and they, too, had excellent skidding properties and small variances.

Portland Cement Concrete

The overall mean of 276 skid tests made on 46 roads constructed of Portland Cement Concrete was 81.4 feet. This value is significantly higher than that for Rock Asphalt, but significantly below the estimated mean for Bituminous Concrete.

Athough the average skid-to-skid and location-to-location variances for these roads were over twice as high as those for Rock Asphalt, and the road-to-road variance was over ten times as great, these variances were seldom more than half of those of the other major road types.

The comparatively small amount of variability on these roads is especially significant in view of the fact that these roads averaged to be considerably older and carried more traffic than any of the other major types, indicating that although the roads tested varied tremendously in both age and traffic volume, there was comparatively little variation in their skidding properties. An attempt was made to correlate the mean skid distances of all the tested roads with average traffic volume, age, and total traffic, but no significant relationships appeared to exist. The roads were then separated into two groups, these consisted of those pre 1945 and post 1945. Both of these groups were studied individually for a relationship between mean skid distance and both average volume and total traffic volume (the product of age and daily traffic). The data for the pre 1945 group indicated that there was no relationship between skid resistance and traffic for these older roads and thus their variability must arise from other factors not included in this investigation. The data for the post 1945 surfaces indicated a definite increase in mean skid distance with increases in both average daily traffic and total traffic. Another conclusion indicated by this study is that traffic tends to decrease the skid resistance of Portland Cement Concrete surfaces to a measurable degree for a few years after construction until they reach a point beyond which "polishing" action is greatly retarded. This premise was further substantiated by the fact that the post 1945 roads tested yielded a mean skid distance approximately 5 feet shorter than that for the older roads. The type and amount of brooming of the surface has also changed during the years and no doubt is also a factor in this decrease of skid resistance with an increase in traffic volume and age.

The Portland Cement Concrete roads tested in the survey were also divided according to the type of coarse aggregate (gravel or limestone) used with natural sand in the mix, but no overall differences in either means or variances were indicated between the two types.

Bituminous Concrete

The mean skid distance found for the 59 Bituminous Concrete roads tested was 89.2 feet at 30 mph. This mean is significantly greater than that for those roads tested in any other major type. These surfaces were also quite variable, yielding variances almost twice those for Portland Cement Concrete for each of the three sources of variation.

The Bituminous Concrete roads were divided into three major groups for comparison purposes: those constructed with limestone coarse aggregate and stone sand, those with limestone coarse aggregate and natural sand, and those constructed with gravel coarse aggregate and natural sand. Contrasts among these groups indicate that, for the roads tested, the roads containing stone coarse aggregate have a significantly lower mean skid distance than those constructed with gravel. Another contrast indicated that there was no significant difference between the roads constructed with natural sand and those containing stone sand. It is interesting to note that although the gravel-coarse-aggregate roads had the highest mean skid distance among the three sub-types studied here, the location-to-location and road-to-road variance is of an exceptionally low order, revealing consistency among these surfaces. It should also be pointed out that the road-to-road variances found for the stone-sand roads were also extremely small, being less than half those for Portland Cement Concrete, again suggesting a relatively consistent type of surface.

The effects of traffic on the three types of Bituminous Concrete were studied separately. The stone coarse aggregate, natural-sand fine aggregate roads gave indications of increasing mean skid distance with increasing total volume. The information of the other sub-types indicated no effect due to traffic volume.

Other Bituminous Surfaces

All the bituminous surfaces tested other than Rock Asphalt and Bituminous Concrete have been grouped together under the general heading of Other Bituminous Surfaces. This grouping includes to a large degree those surfaces in the State highway system that are designated as bituminous surface treatments and/or seal coats. These Bituminous Surfaces represent a considerable percentage of the total highway mileage in the State.

The 55 Bituminous Surfaces considered here yielded a comparatively low overall mean of 80.8 feet; a value almost identical to that of the Portland Cement Concrete roads, and significantly lower than that for the Bituminous Concrete surfaces tested. The variability among these roads was, however, of a large magnitude, far exceeding that of any other major type for each of the three sources of variation. Individual skids on the roads in this grouping ranged from 50 to 167 feet, displaying skidding properties anywhere from excellent to very poor. These high variances make it possible for any road or location to yield an average skid resistance value that is radically different from the comparatively low indicated mean.

For initial comparison purposes, the Bituminous Surfaces were divided into two groups, those surfaces containing limestone aggregate, and those containing gravel. Those road surfaces containing gravel were found to have a significantly higher mean than those surfaced with limestone. The gravel roads also displayed a greater road-to-road variance than stone, although the site-to-site and location-to-location variances did not differ to any great extent.

The inconsistent nature of these roads stems, to some extent, from the many variables inherent in these surfaces and from the many different combinations of aggregate and bituminous material that are present. The skidding properties are also influenced by the previous condition of any particular road.

The major cause of variability for these roads, however, appears to result from the bleeding of excess bituminous material, either from the current or previous construction. This bleeding causes "fat spots" to appear, usually along the wheel tracks, but often over the entire road. In these bleeding sections it was necessary for friction to be developed primarily between the bituminous material and the tire, as the aggregate was wholly or partially buried. High mean skid distances and high location-to-location variances were almost invariably associated with bleeding. Several bleeding roads were found to be too hazardous to test as it was impossible to keep the test vehicle on the road for a sufficient length of skid.

In order to evaluate the effects of bleeding and to make further comparisons, these Bituminous surfaces were divided into two major groups: those that evidenced some bleeding and those that were entirely free from bleeding. Comparisons were then made both within and between the groups.

The non-bleeding surfaces, as a group, displayed a mean of 74.1 feet, a value considerably below that for any major road type other than Rock Asphalt. The variances, too, were of a reasonably low order, especially the average location-to-location variance which was very close to the value for Portland Cement Concrete.

The group of bleeding surfaces, on the other hand, was found to have the relatively high mean of 92.8 feet, a figure significantly higher than that for the non-bleeding surfaces, exceeding this value by over 18 feet. The skid-to-skid variance was somewhat greater for the bleeding roads and the road-to-road variance almost three times as great, but a rather spectacular contrast was found in the location-to-location variances. The location-to-location variance for the bleeding surfaces was over ten times that for the non-bleeding ones. This indicates that a considerable portion of the variability and high means in these surfaces can be explained by bleeding. It may also be seen that these Bituminous Surfaces can have very good, consistent skidding properties if no bleeding occurs.

Comparisons among aggregate types, sizes, and bituminous materials were also made within each of the two groups. The gravel roads were found to have a significantly higher mean skid distance within both the bleeding and non-bleeding groups, although the difference was much more pronounced for the bleeding group. This contrast further indicates that limestone has better initial skidding properties even if no bleeding occurs. The variances within both groups were quite homogenous, and neither aggregate appears to give more a consistent surface than the other.

Contrasts among the three prevalent sizes (#9, #11, and #12) of aggregate in each group did not reveal any notable or significant differences in means or variances from size to size for either gravel or limestone. Thus, for these roads, aggregate size does not appear to effect the skid distance to any measurable degree.

Special Surfaces

Several surfaces were tested during the summer program that do not strictly fall into any of the previously discussed classes, and, therefore, merit individual consideration.

The first of these is a Silica Sand surface on U. S. 46 east of Greensburg. This road has an appearance and texture very similar to that of Rock Asphalt. The mean skid distance on this section was 66.7 feet, which was significantly lower than any road type except Rock Asphalt. The variability, especially that from location-to-location, was of an especially low value, indicating consistency similar to Rock Asphalt.

Another special road tested was a Bituminous Concrete section constructed with gravel coarse aggregate, and 5½ per cent AP 5 in place of the usual 6½-7 per cent. The section is located on S. R. 67 southwest of Indianapolis. The mean skid distance was 98.4 feet, and the variability, both skid-to-skid and location-to-location was of a low order. This mean is higher than that of the other Bituminous Concrete sections. It seems apparent, here, that the mere act of cutting the percentage of bituminous material from 7 to 5½ per cent in Indiana Bituminous Concrete pavements may be of little value in improving their skidding characteristics.

A group of six Bituminous-Coated-Aggregate surfaces was also included in the survey. These are designated as "dense mix" and had a plant mix surface composed of #14 sand, #11 gravel or limestone aggregate combined with either RC 5 or AE 90. The overall mean of these six roads was a comparatively high 99.4 feet and both the site-to-site and location-to-location variances were quite high. This mean was significantly higher than that for any of the major road types tested.

One surface tested clearly illustrated the seriousness of skidding due to polishing of aggregate. On a section of U. S. 40 near Brazil a Bituminous-Coated-Aggregate surface has been exposed to heavy traffic throughout its entire life. No bleeding was evident on the road and much of the seal aggregate was lost leaving a very coarse looking "open" surface. The mean skid distance on this road was 150.5 feet—the highest of any road tested in the survey. Close observation revealed each stone to be rounded and highly polished. Comparatively low variances on this road indicate this road was consistently slick from place to place.

CONCLUSIONS

The conclusions of this study are:

1. The vehicle stopping-distance method that utilizes an electrically controlled vacuum braking system and an integrated fifth wheel speedometer and odometer produces consistent and reproducible results.

2. The vehicle stopping-distance method is economical, rapid, and relatively safe at 30 mph.

3. Of all surfaces tested, Rock Asphalt had the best skid characteristics when wet, both as to average distance and variability.

4. A thin application of Rock Asphalt is a good but only temporary method of de-slicking a pavement.
5. Portland Cement Concrete surfaces provide relatively good skid characteristics but are subject to polishing by traffic during the first few years of their life.
6. Bituminous Concrete surfaces, as constructed in Indiana under present specifications, do not have as good skid characteristics as Rock Asphalt or Portland Cement Concrete.
7. Bituminous Surfaces other than Rock Asphalt and Bituminous Concrete have a relatively low average skid distance but are very variable.
8. Bleeding on Bituminous surfaces results in a significant increase in the stopping distance.
9. Bituminous surfaces constructed with limestone aggregate exhibited better skidding characteristics than those constructed with gravel aggregate.
10. Bituminous surfaces that were coarse and open exhibited poor skidding characteristics.
11. Although it cannot be considered conclusive because of the small number of roads tested, surfaces constructed with Silica Sand gave good results, comparable to Rock Asphalt.
12. A sample of Bituminous Coated Aggregate, dense mix, exhibited relatively poor skidding characteristics.
13. Since bituminous surfaces exhibited skidding distances when wet ranging from 50 to 167 feet, excellent to very poor, it is apparent that they can be designed and constructed so as to have excellent skidding characteristics.
14. It is recommended that this study be continued and that it concentrate on evaluation of the factors that affect the skid resistance of bituminous surfaces.

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