Development of Skid Testing in Indiana

H. L. MICHAEL, Assistant Director, and
D. L. GRUNAU, Graduate Assistant
Joint Highway Research Project, Purdue University

Many studies have been made in recent years with various types of skid equipment to evaluate skidding characteristics of pavement surfaces. This paper briefly summarizes the equipment used and the results found in these studies and presents a detailed description of a semi-automatic braking device used on a conventional automobile in Indiana.

The device is electrically operated and when activated applies the brakes and initiates measurement of stopping distance simultaneously. The speed at which the brakes were activated is also recorded. The method used eliminates much of the human variable from the measurement of stopping distance and makes it possible for the good reproduction of stopping distance.

The skid testing program in Indiana is also outlined and preliminary results are presented. A number of experimental surfaces were tested along with four major surface types used in Indiana. These four were rock asphalt, portland cement concrete, bituminous concrete, and other bituminous surfaces. A total of 233 different roads were tested; each road being tested at three locations with two skids being performed at each location.

The skidding properties of the various roads were compared in terms of mean skid distances at 30 mph. Variability of the skid distances was determined along with the means.

The tests showed that rock asphalt had the best skidding properties of all the surfaces tested with respect to both average distance and variability. Its mean skid distance changed little between the wet and dry condition. Portland cement concrete surfaces provided relatively good skid characteristics but were subject to some polishing by traffic during the first few years of their life. The bituminous concrete surfaces tested had poorer skid characteristics than any other major type considered. The bituminous surfaces tested, other than rock asphalt and bituminous concrete, had a relatively low mean but were extremely variable. This variability was almost invariably associated with bleeding. Those roads with no bleeding yielded a mean 18 feet less than those that displayed some bleeding. The bituminous roads constructed with limestone aggregate had a lower mean than those containing gravel, although the limestone in some cases polished extensively under prolonged heavy traffic.

● IN 1954, drivers in the United States became involved in 30,800 fatal and 1,276,700 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. Seventeen percent of the fatal and nineteen percent of the non-fatal accidents in 1954 occurred on wet pavements. When consideration is given to the fact that pavements are wet for less than nineteen percent 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 as many accidents involve some type of skidding, the number is undoubtedly of considerable magnitude.

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.

Only a few organizations or individuals have undertaken extensive programs of research to determine the skidding characteristics of pavements. Possibly the most complete data have been obtained by Professor 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. 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.

One of the first detailed reports on another method of test, the automobile stopping-distance method, resulted from work conducted in Virginia by T. E. Shelburne and R. L. Sheppe, reported in 1948. 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 computing the coefficients of friction at speeds of 10, 20, 30, and 40 mph. The coefficient of friction was computed by the standard formula $F = \frac{V^2}{30S}$, where F equals the average coefficient of friction, V equals the initial speed in mph 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.

Other methods of test, such as a motorcycle sidecar used in England and a trailer with pivoted wheels used in France, have been reported and numerous conclusions from these skid studies have presented valuable information on skid characteristics. Much remains to be done in this area, however, and in order to obtain estimates of the skid characteristics of Indiana road surfaces and to investigate some of the factors that affect skid resistance a long-range study was undertaken.

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 driver 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 determined to be advisable.

DEVELOPMENT OF A PROGRAM

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 even though the towed-trailer method was found to have some advantages. The latter method is certain to give very accurate results as it uses sensitive instruments and results are averaged over a considerable length of pavement. Tests can be run fast and safely as the unit is self contained and does not require that traffic be stopped. The towed-trailer method, however, has definite disadvantages. It is expensive to build; there is a possibility of differences in skidding characteristics between a towed object and a freely skidding unit; and there is some doubt that the "hot spot" developed underneath one wheel of a towed trailer as it is dragged over a long distance will give performance characteristics similar to those obtained from four locked wheels skidding over a shorter distance. Finally, several investigators have indicated that there is a difference between the skidding resistance of a pavement in the initially wet stage and of one in a flushed condition. This presents a possibility that wetting a surface at high speed immediately before a skidding wheel might give unrealistic results.

Because of these considerations the Joint Highway Research Project adopted the basic concept of using the stopping distance of a freely skidding vehicle to compare skidding properties of pavements. In its original form this method of test consisted of a standard 1951 Ford equipped with a chalk-marking device mounted on the rear 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 and load the chalk marker with a chalk cartridge. He would then bring the vehicle to a speed slightly in excess of the test speed, disengage the clutch, 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.

It was felt at the outset of this survey that this method in its initial form was too crude and presented several disadvantages. Some of these were:

1. The driver may differ in his reaction time from skid to skid and day to day.
2. The driver may differ in his brake-pedal pressure from skid to skid.
3. The driver may miss the test speed by a considerable amount.
4. The "pull-apart" connector for the chalk marker did not release at the same instant for each brake application. This error would not necessarily be corrected by connecting the marker to the brake-light system as this system has large variations in "tripping" pressure.
5. The considerable time required to measure each skid with a tape created serious traffic problems and evaporation often made it impossible to run more than one skid at a site on hot days without rewetting. Wetting a surface before each skid would impose a problem in the procurement of sufficient water and require much more testing time.

It was thus decided to modify the test car to minimize or eliminate these disadvantages. 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 automatically close the braking circuit at a predetermined test speed and then measure the distance required to stop.

Letters explaining the problem were sent to many major concerns dealing with the manufacture of power brakes and speedometers. It soon became apparent that a speedometer that would close a circuit at a predetermined speed would be difficult to construct, and the necessary centrifugal switch would have a rather wide range of closing values. An alternative electrical speedometer could do the job accurately, but proved too expensive and would not measure distance. It was therefore decided to close the brake circuit manually and to find an instrument that would record the speed as the brakes were applied. The "Wagner Stopmeter" manufactured by the Wagner Electric Company of St Louis, Missouri, fulfilled this requirement and was available at a reasonable cost. A unit was subsequently purchased.

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 very 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 1. The heart of the system is the vacuum unit that operates a Ford master cylinder (E) through a simple lever system (F). The vacuum chamber (A) 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 a 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.

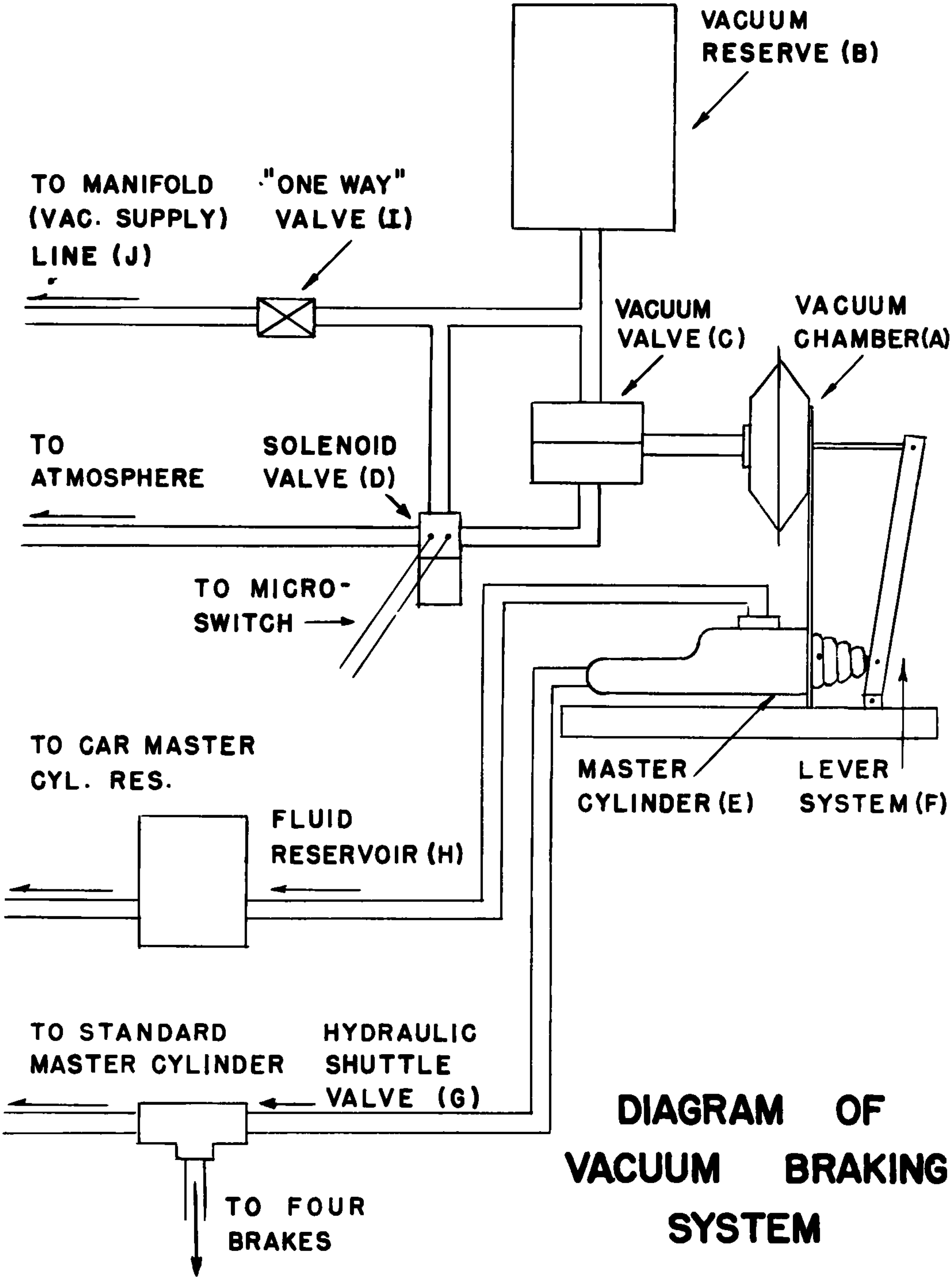

Figure 1.

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 brake

will transfer the shuttle valve (G) and allow normal operation of the brakes. The diameter of the shuttle valve was reduced from ½ in. to ¼ in. 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 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 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 3) to the solenoid valve and 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 it 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.

The preliminary tests indicated a problem with the brake-backing plates. The manufacturer, however, supplied the project with special reinforced plates and no further difficulty of this type was encountered.

Method of Testing

Each selected road is tested in at least three locations, with two skids performed at

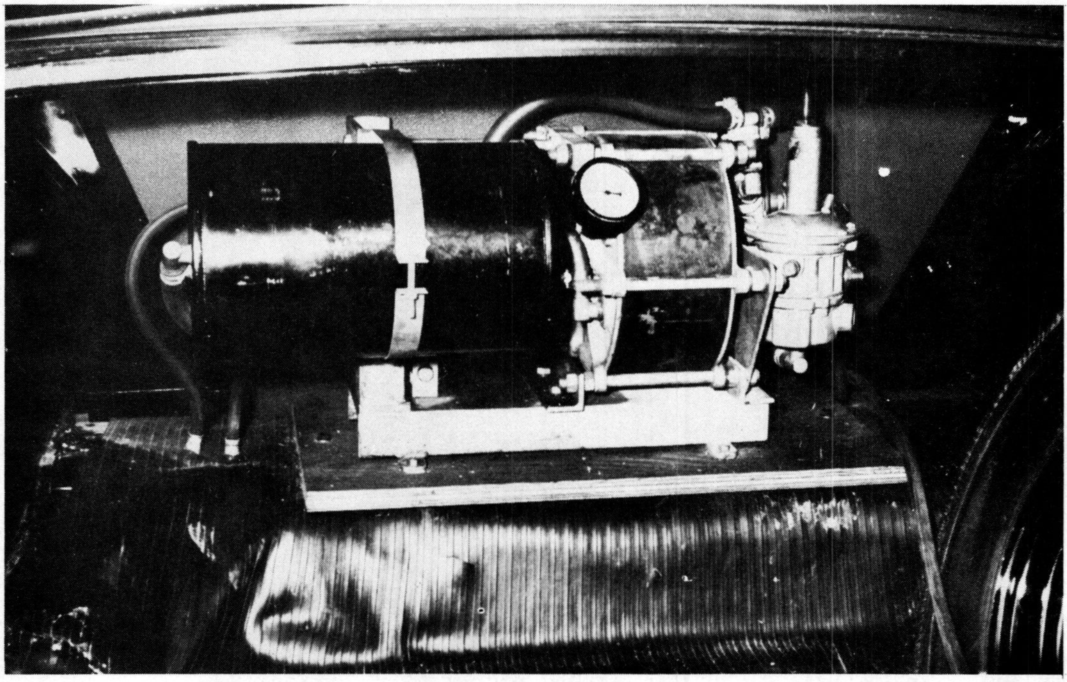

Figure 2. The Special Bendix Vacuum Braking Unit was installed in the trunk of the test vehicle.

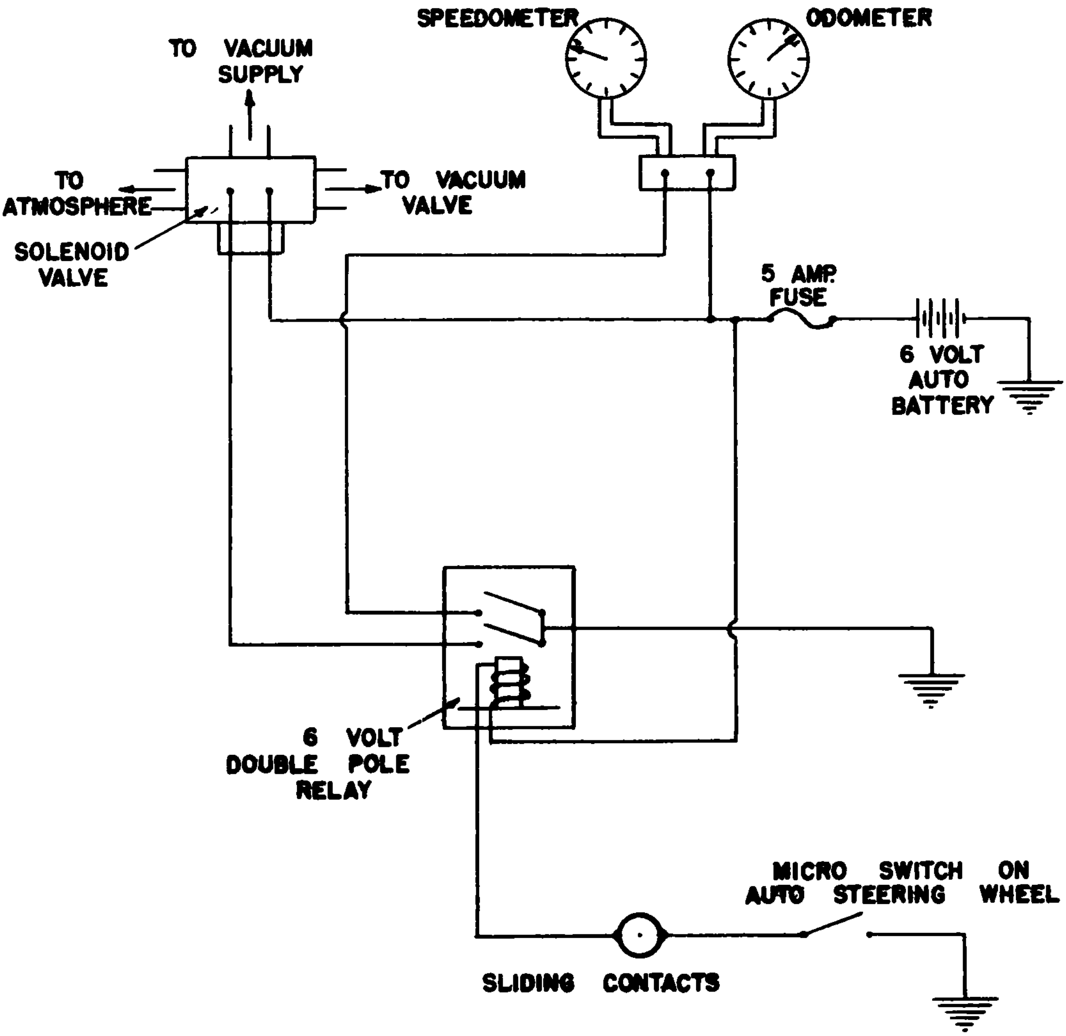

Figure 3. Wiring diagram of braking circuit.

each location. A location is a level, straight stretch of pavement 200 to 300 feet in length and located anywhere on the road. It is usually possible to select the locations in such a manner as to allow adequate sight distances for flagmen to stop traffic safely.

Most skids are run at 30 mph. The primary reason that one speed was chosen was that the interest is 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 allows more roads to be tested in the available time. Thirty mhp was selected as it was considered to be the highest speed that could safely be used over the wide range of road types that exist in Indiana. The fact that the test car left the road many times during the testing to date indicates that a greater speed would be quite hazardous.

The purpose of these tests is to investigate the skidding properties of roads and since the wet condition is the most critical, almost all of the tests are run under wet conditions. The only equipment necessary is the test vehicle, a water truck, two red flags, two thermometers, data sheets, clipboard and pencil. The usual crew consists of four men; the test car driver, an assistant, a water truck driver and a flagman. The four man crew is sufficient for most roads, but an additional flagman is desirable on highly congested routes.

After a location is selected on a particular road, the test car and flagman stop at a

point 400 to 500 feet in advance of the test section and the flagman halts all traffic approaching from the rear. The water truck and test assistant proceed ahead to the test site and begin wetting without interferring with oncoming traffic. The test assistant controls the water from the truck. When a sufficient strip (200 to 300 feet) is thoroughly wetted the assistant remains at the site and the water truck driver pulls the truck

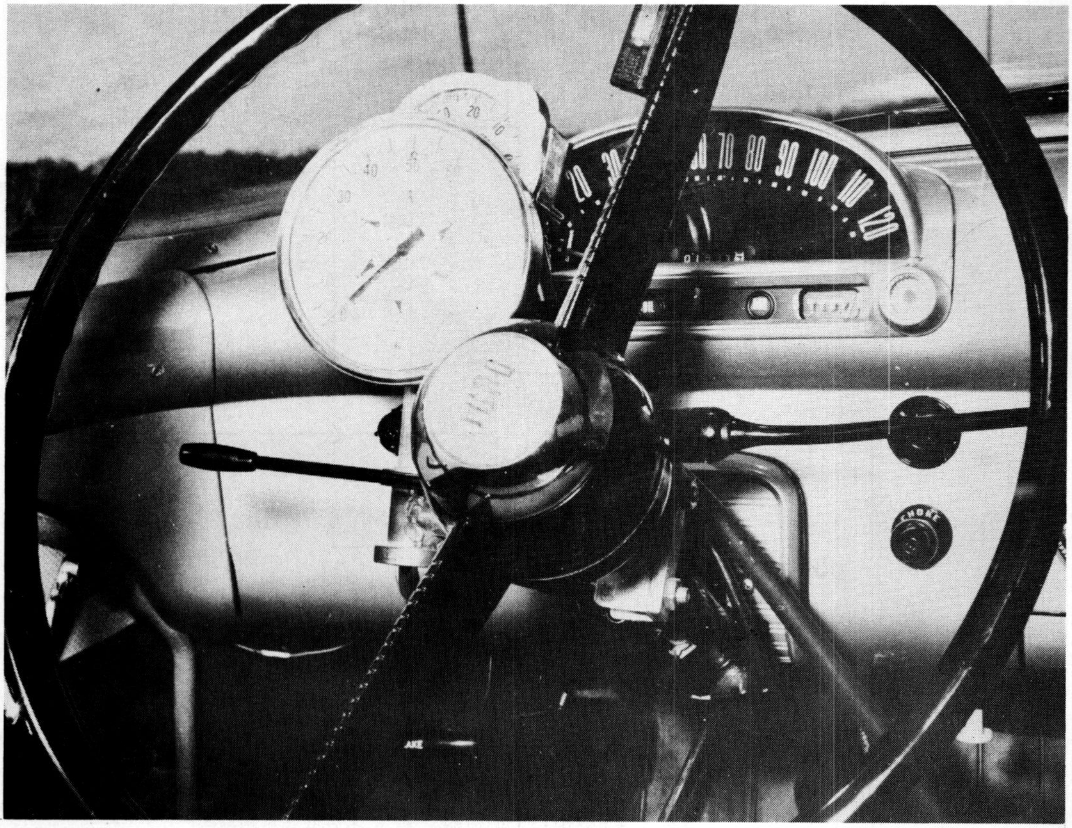

Figure 4. The speedometer and odometer dials of the stopmeter were mounted inside the skid vehicle.

Figure 5. The pavement was thoroughly wetted before each series of skids.

Figure 6. After the pavement was wetted, the skids were performed.

several hundred feet ahead, dismounts and stops oncoming traffic. The two skids are then run in quick succession, with the assistant and flagman raising and lowering the fifth-wheel as necessary, as it is not possible to back the car with this wheel down. It is generally possible to run both skids in less than two minutes after completion of wetting thus keeping the effects of evaporation and runoff to a minimum. The speed to the nearest 0.25 mph and distance to the nearest 0.25 foot are read from the stopmeter dials and recorded by the driver after each skid.

THE PRESENT PROGRAM OF TESTING

The skid project in Indiana developed along several lines. Two hundred thirty-three roads were tested during the summer of 1954. The roads tested were selected as a sample of the state highways in every part of Indiana and included roads of various surface types, different volumes of traffic, and various ages. The data obtained during this program have been analyzed and the results are indicated later in this paper.

Indiana also has several experimental pavements and on some of these periodic skid tests are continuing. An annual skid test is performed on a surface containing silica sand to determine the long-term skid characteristics of this surface type. Semi-annual skid tests, one in the summer and the other in the winter, are also conducted on the US 31 Test Road. A section of this road near Columbus, Indiana, is constructed for a long-term comparison of the characteristics of portland cement concrete and bituminous concrete. One of the characteristics being compared is that of skid resistance.

Another use of the skid equipment is in evaluating reported "slick" sections of highway. As the state police or highway department receives complaints of "slick" highways, the location is referred to Purdue and a skid test is scheduled for the reported location. A confirmation of the hazard by the test initiates activity by the responsible agency to eliminate the hazard.

DISCUSSION OF RESULTS FROM STATEWIDE STUDY

Four major construction types were investigated: 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

Figure 7. The Wagner Stopmeter was attached to the rear of the skid vehicle.

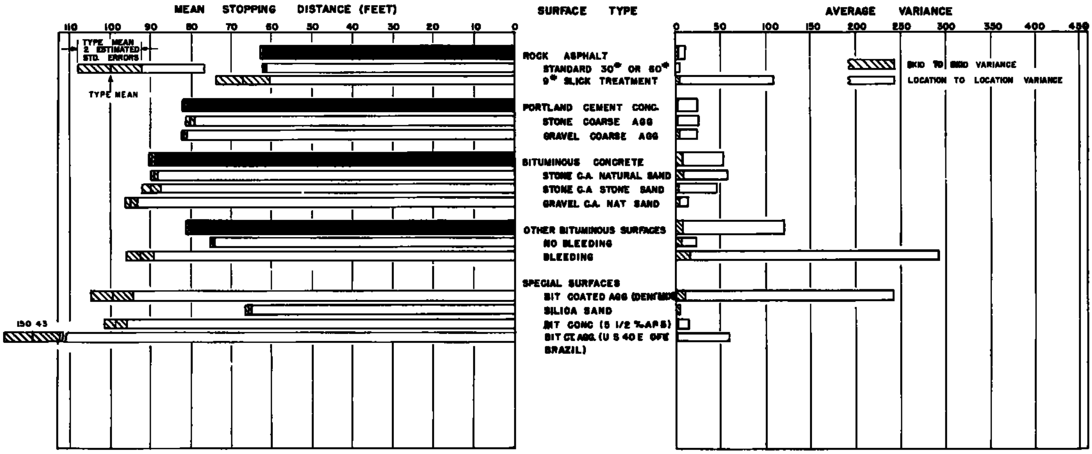

Figure 8. Estimated means and variances for the survey roads.

two skids were taken at each location. All tests were made at a brake-application speed of 30 mph. All distances indicated in this report are average stopping distances from the instant of brake application and were obtained using the same skid vehicle.

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.

TABLE 1

SUMMARY OF MEAN SKID DISTANCES, AVERAGE VARIANCES, AND STANDARD ERRORS

(1) CODE NO	(2) SURFACE TYPE	(3) MEAN SKID DISTANCE (FEET)	(4) NO OF ROADS	(5) AVERAGE VARIANCES: SKID TO SKID	(6) LOCATION TO LOCATION	(7) ROAD TO ROAD	(8) STD ERROR OF THE MEAN * (FT.)	(9) STD. ERROR OF THE MEAN ** (FT)
1XX	ROCK ASPHALT	62 56	32	1 02	11 39	34 23	0.24	043
111	STANDARD 30* OR 60*	62 25	30	0.84	4.98	25.51	0 17	0.36
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 84	292.26	1,428.55	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

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 variances represent differences that arise from variation in the surface properties of a particular road, from place to place, probably due to such factors as construction differences, varying traffic, and bleeding. Road-to-road variances, within a given type or subtype, 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.

The results of the tests for each road type are discussed in the following sections 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 must also be noted that the difference in skidding distance between two roads or road types is given in this study for a speed of 30 mph. A much greater difference in distance would be obtained at higher speeds and could be a very critical element, certainly a very dangerous one.

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 feet, a value significantly lower than that for any other major type, 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 found to be 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 are, then, not apparently 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 "deslicked" by a thin 9 lb rock asphalt treatment were 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 9 lb treatment is an effective method of temporarily "deslicking" surfaces. The type and condition of the previous surface is probably an important factor governing the service of the "deslicking" treatments.

These tests on rock asphalt surfaces serve to substantiate the conclusions of many other experimentors that those surfaces with a harsh, gritty, sandpaper 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 over-all mean of 276 skids run 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.

Although the average skid-to-skid and location-to-location variance for these roads were over twice as high as those for rock asphalt, and the road-to-road variance was over 10 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 average to be considerably older and have car-

ried more traffic than any of 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: 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 pre-1945 group indicated that there is 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 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 portland cement concrete roads tested in the survey were also divided according to the type of coarse aggregate (gravel or stone) used in the mix, but no over-all 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 stone coarse aggregate and stone sand, those with stone 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 on 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. 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 over-all 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 these roads 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 stone aggregate, and those containing gravel. Those road surfaces containing gravel were found to have a significantly higher mean than those surfaced with stone. 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 construction history 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. These bleeding sections made it necessary for friction to be developed primarily between the bituminous material and the tire, as the aggregate was usually 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 the full length of skid.

In order to evaluate the effects of bleeding and to make further comparisons, these bituminous surfaces were again 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 made within each of the two groups. The gravel roads were found to have a significantly higher mean within both the bleeding and non-bleeding groups, although the difference was much more pronounced for the bleeding group. This contrast further indicates that stone has better initial skidding properties even if no bleeding occurs. The variances within both groups were quite homogeneous, and neither aggregate appears to give more consistent surface than the others.

Contrasts among the three prevalent sizes 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 stone. Thus, for these roads, aggregate size does not appear to affect the skid distance to any measurable degree.

Special Sites

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 US 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, is of an especially low value, indicating consistency similar to rock asphalt.

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 No. 14 sand, No. 11 gravel or stone 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 US 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 had worn off 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 has the best skid characteristics when wet, both as to average distance and variability.
4. A thin application of rock asphalt is a good but temporary method of deslicking 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 Indiana limestone aggregate exhibited better skidding characteristics than those constructed with Indiana 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. 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 give excellent skidding characteristics.

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The authors also wish to express their thanks to the district engineers and other state highway department personnel who cooperated with this study. Their aid in the

location of test sections and cooperation in supplying men and equipment at the test sites were extremely valuable. Without such assistance this extensive testing program would have been impossible.

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Discussion

P. C. SKEELS, Head, Experimental Engineering Department, K. A. STONEX, Head, Technical Data Department, General Motors Proving Ground, and E. A. FINNEY, Research Engineer, Michigan State Highway Department — Engineers in the automotive industry are as much concerned as the highway engineers in the problem of maintaining high and consistent road surface friction characteristics on highways. Nothing is so important for the safe, effective use of the highway system, and a joint effort to determine the reasons for poor friction characteristics and to develop solutions is a matter of paramount importance.

This discussion is concerned primarily with the decrease in wet friction characteristics which results from a polishing action of the components of the pavement surface as a fundamental cause. The problem related to contamination of the surface by traffic slick or other factors is considered supplementary, however important it may be. The discussion is essentially as contained in a paper* by the writers presented at a meeting of the Association of Asphalt Paving Technologists.

It is evident to the eye and by feel that the aggregate in pavement surfaces does develop a high degree of polish in many instances. High-speed motion pictures showing a tire running over a piece of tempered glass make it clear that there is an appreciable movement of the portions of the tire as each section rolls through the contact area. The total movement of the ribs increases from the center to the outside; on the particular tire observed the contact area narrowed $\frac{5}{16}$ inch, which means that each outer rib moved approximately $\frac{5}{32}$ inch toward the center and back. Compression in the longitudinal direction causes a movement of as much as $\frac{1}{8}$ inch.

There are other components in this complex motion. It should be pointed out that this configuration is that of a free rolling front tire and that tires under braking, or rear tires driving, will have other slight longitudinal motions at the trailing edge. This continuous scrubbing action repeated thousands of times a day upon a heavily traveled road must inevitably wear away the pavement surface, and produce a high degree of polish on pavement surface components susceptible to polishing.

This relative motion between the tire and the road will also wear off tread rubber. This has lead the tire manufacturers to devote a large amount of development work to designing tread patterns and contact shapes that will minimize total wear and distribute the wear evenly across the tread. It must be concluded, therefore, that this wiping action is an inherent characteristic of an annular tire deflected by reaction with the road surface, and that everything possible is being and will continue to be done to minimize the amount of this polishing action. The most hopeful steps for significant progress seem to lie in the area of developing pavement surfaces which do not become polished under abrasive wear.

Test observations give a strong basis for the assumption that both portland cement and bituminous concrete surfaces become increasingly slippery when wet as total traffic and wear accumulate, and that this deterioration in friction capacity is related to the degree of polish of the components of the surface.

Because of the deep interest of the automobile manufacturers in the whole highway program, the General Motors Proving Ground Section was pleased at the opportunity to cooperate with the Michigan State Highway Department in performing the brief tests discussed here. The writers' part in the cooperative test was to develop inexpensive and simple instrumentation which could be used at an early date to survey selected road surfaces without interrupting normal traffic flow.

The basis of the design is that rear wheel torque reactions developed by driving or braking forces on a car equipped with a torque tube drive are transmitted through the torque tube and produce a deflection proportional to the wheel reaction (Figure 1). A 1954 Buick Special was selected for the test, and wire resistance strain gauges were cemented to the torque tube in such a manner that deflection of the tube would be indicated by appropriate strain measuring instruments. In this application a Servo-type indicator, developed and constructed by the Proving Ground, was used. However, any other type of strain indicator could be used equally as well. The same set of production tires was used throughout the test program; these tires were thoroughly broken in, but the treads were in good condition.

The hydraulic brake lines to the front wheels were fitted with valves, so that the front brakes could be blocked out and the braking reaction be developed by the rear wheels only. To avoid the hazards of sliding stops in traffic and to simplify the problem by making measurements at constant speed, the test car was towed behind a truck.

A tank truck fitted with a valve so that water could be sprayed on the road just ahead

*Skeels, P.C., Stonex, K.A., and Finney, E.A., "Road Surface Friction from the Standpoint of Automotive and Highway Engineers." Presented at a meeting of the Association of Asphalt Paving Technologists, Cleveland, Ohio, Feb. 13-15, 1956.

of the test car provided a source of water to wet the surface.

The outstanding advantage of this instrumentation was that it used existing components which were adapted to this survey with comparatively little effort. The chief advantage from an operating standpoint is that the speed of the vehicle train is not changed as the test observation is made, this uniformity of speed permitting safe test performance at normal traffic speed without disturbance of the traffic stream and yielding test results which are not influenced by possible changes in coefficient of friction with speed.

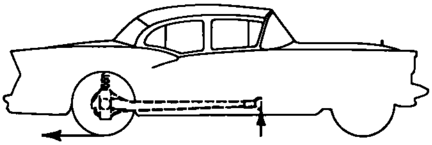

Figure 1. Schematic diagram illustrating bending moment in torque tube.

A further advantage from the point of view of a quick survey is that the use of an indicating type of meter gave immediate results, so that the test program was flexible and could be adjusted in the light of the continuing flow of results.

However, a comprehensive program on a continuing basis might be served better by the use of a trailer fitted with a controllable braking system and probably by the use of recording rather than indicating instrumentation.

The test procedure consisted of towing the car along the roadway at a speed of 40 mph; at the desired test site, the water was turned on to flood the pavement.

The driver applied the brakes slowly up to the point of skid, the car was dragged momentarily with the rear wheels sliding, and then the brakes were released and the water was stopped until the next test observation was made. In the meantime, the test observer watched the strain indicator as the brake reaction rose to the maximum at the point of incipient slide and then fell away abruptly to a more or less stable point during the slide. The incipient sliding value and the sliding value were both noted. Repeat tests were made throughout the length of any given project to average out local irregularities and variations of coefficient of friction; on occasions the train was disconnected and the vehicle brought back to the beginning so that check runs could be made over the same course. The consistency of test results under similar circumstances led to the belief that the spray of water was sufficient to flood the paved surface completely and to give reproducible test conditions.

Immediately prior to the tests on the Michigan highway surfaces, a heavy rain had fallen; the pavement surface appeared to be clean, and there was a reasonable certainty that the surfaces tested were as free from contamination of traffic slick, oil drippings, and dirt as is ever apt to be found. Therefore, the results are considered applicable to surfaces as clean as found normally.

Prior to the test observations, the strain indicator was calibrated by locking the brakes with the test car stationary and observing the relative readings of the strain indicator and a traction dynamometer in the tow cable under an extended range of values.

Since the tow cable is attached some distance above the ground, the force in the tow cable and the rear wheel friction force produce a couple which is balanced by an effective transfer of weight from the rear to the front wheels. The weight transfer is computed from the height of the tow cable and the wheel base of the car, and the coefficient of friction determined from the indicated reactions is adjusted to take into account this transfer of weight. The coefficient of friction is defined here as the ratio of the horizontal force and the vertical reaction at the rear wheel. Derivation of the formula is given in the Appendix. At increased speeds the reaction developed by the air resistance couple may become significant.

The strain indicating meter was mounted in the front seat compartment of the car and a portable radio was used for communication with the tow truck. Prior to the formal test program, evaluation tests were made on parts of the Proving Ground road system.

Figure 2 shows the incipient and sliding coefficients of friction observed in the 40-mph lane of the Proving Ground test track with the pavement as described before. With one exception, these results are consistent within a range of coefficient of friction of ±0.01 and the incipient slide is consistent within a range of coefficient of friction approximately ±0.02. The accuracy with which the strain indicator could be read is not much better than this.

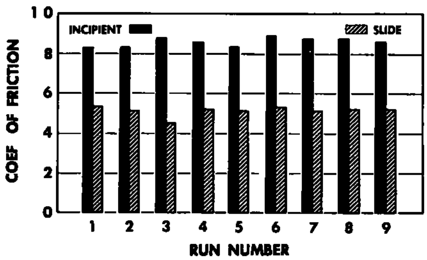

Figure 2. Incipient and sliding coefficient of friction observed on the 40-mph lane of the Proving Ground test track (bituminous concrete surface).

The test track surface is a bituminous concrete material corresponding to Michigan highway Class 1 with 25A coarse aggregate specification. At the time of this test, the surface had been in use for approximately two years under extremely light traffic volume by normal highway standards.

Comparable observations at a speed of 50 mph show that the effect of speed is not significant statistically.

The uniformity of test results on another bituminous concrete used on the Military Proving Ground straightaway is not quite as close, possibly because the surface variation may be somewhat greater. This surface was about four years old at the time of the test and had been subjected to a very light volume of military vehicles, both wheeled and track laying.

Consistency of observations made on a portland cement concrete engineering test straightaway, which has had a very light traffic volume during a period of about eight years service, is within the accuracy of observation of the strain indicator, and the mean values of a sliding coefficient appear to be measurably higher than those of the bituminous concrete surface.

Other tests were made on a sheet asphalt surface with extremely low traffic volumes and of about six years service, and on a public highway adjacent to the Proving Ground and surfaced with an oil aggregate type surface with about two years service under light traffic. Also recorded were dry friction measurements on both the bituminous and portland cement concrete surfaces.

The areas tested on the Michigan highway system were selected earlier by a visual survey. These test situations included variations in aggregate type, traffic volume, and length of service. Although they were confined to bituminous concrete surfaces in the original objectives of the survey, several portland cement surfaces were included for comparative purposes.

By plotting the coefficient of friction observed against a wear factor determined by multiplying the average daily traffic volume per traffic lane over the period since construction by the length of service in years and dividing by 1,000 to express the index in convenient numerals, the results for bituminous concrete with limestone aggregate, bituminous concrete with gravel aggregate, portland cement surface, and the composite of the three, there is a strong indication that the three basic types of surface give distinct wear index behavior patterns.

A study of certain apparent abnormalities in the bituminous surface plottings has uncovered facts believed to be significant to the problem of constructing highway surfaces which will maintain a high degree of skid resistance throughout their useful life. For instance, projects constructed prior to 1944 involve material specifications different in certain respects from those of the balance of the projects, which were constructed since 1944. The differences in material specifications are described as follows:

	Projects Prior to 1944 3 - 5 - 7 - 20	Projects 1944 - 1948 8 - 9 - 14 - 15 - 18	Projects Since 1948 Balance Studied
Asphalt cement	Pen. 85-100	Pen. 85-100	Pen. 60-70
Mineral filler	Limestone dust	Limestone dust	Flyash
Coarse aggregate	100% passing ½-in. sieve 15-45% passing No. 4: Dept Spec 26A	90-100% passing ½-in. sieve 0-25% passing No. 4: Dept Spec 26A mod	90-100% passing ½-in. sieve 0-25% passing No. 4: Dept Spec 25A

While these material differences are not great, they should be investigated.

Further, possible differences in weathering of asphalt-sand mortars and their subsequent abrasion by traffic, as well as the manner in which the coarse aggregates polish or disintegrate with age and traffic, are other important factors which need careful study.

The bituminous mixture design for all projects studied falls in the following category:

Coarse aggregate (retained on No. 10 sieve)	50 - 55 %
Fine aggregate (passing No. 10, retained on No. 200 sieve)	30 - 35 %
Filler (passing No. 200 sieve)	5.5 - 6 %
Asphalt cement	5.5 %
Marshall stability	1,500 - 3,000 lb

Photographs of the surface in the traffic lanes of the two gravel projects constructed prior to 1948 show the preponderance of coarse aggregate particles which are in various stages of disintegration. This gradual aggregate disintegration process has evidently caused the continual exposure of new projections with sharp edges which have imparted high skid resistance properties to the surface, irrespective of age and traffic load.

Further evidence of the effect of aggregate performance is supplied by the two surfaces at different ends of one project, which was built since 1948 with 25A specification aggregate under supposedly similar conditions. The coefficient of friction of the two surfaces is decidedly different; in one case it was 0.48, and in the other 0.39. Here again the surface with the better skid resistance characteristics has a higher proportion of coarse aggregate particles in various stages of disintegration, while in the case of the surface with the lower coefficient of friction the aggregate particles appear sound and smooth with less evidence of disintegration and displacement.

The effect of traffic on the skid resistance of pavement surfaces can be understood readily by comparing the results of sliding tests made in adjacent passing and traffic lanes where all factors may be assumed reasonably constant except for the extent of traffic coverage.

Comparative results for eight projects, including one bituminous surface with gravel aggregate, four surfaces containing limestone aggregate, and three portland cement concrete pavement surfaces, show differences in coefficient of friction values between the two lanes amounted to as much as 36 percent.

Typical pavement surfaces in the traffic and passing lanes of several projects show similar surface conditions in adjacent passing and traffic lanes. In the traffic lanes the coarse aggregates, both gravel and limestone, have become worn and polished to varying degrees and the bituminous matrix is only slightly depressed around and between the coarse aggregate particles. The coarser sand particles in the matrix are also worn smooth and flat. In the passing lanes, however, the coarse aggregate particles and the sand particles in the matrix still retain a high degree of angularity and the difference in elevation of the projections of the coarse aggregates and matrix is much more pronounced. The pictorial evidence clearly demonstrates the effect of heavy traffic on bituminous concrete surfaces and why, in many cases, they become slippery when wet.

Portland cement concrete pavement surfaces were not included in the original purpose of the investigation. However, sliding tests were made on several such projects in the course of the work for comparative study. Data indicate clearly that portland cement concrete surfaces, irrespective of mixture composition, can become increasingly slippery with time when subjected to heavy traffic conditions.

Appendix

Figure A shows the force system on the car under the conditions of calibration and test. It was shown in Figure 1, that the stress in the torque tube depends upon the value of skid resistance F_6. Thus, for calibration purposes, the stress in the torque tube is read for a range of values of F_1, measured independently by a traction dynamometer.

However, when the rear wheel is sliding, and the coefficient of friction is being measured, it is evident that the reaction F_5 varies, owing to the effect of the couple

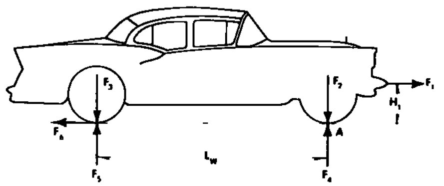

Figure A. Force diagram of car.

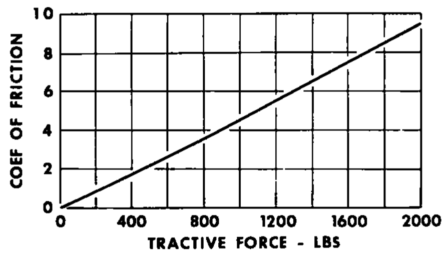

Figure B. Calibration curve for coefficient of friction from tractive force readings.

F_1H_1. The force moment equations are as follows, with the forces as indicated in Figure A and with positive moments in clockwise sense.

$$\Sigma F_X = 0 = -F_1 + F_6, \text{ therefore } F_1 = F_6$$

$$\Sigma M_A = 0 = F_5L_W - F_3L_W + FH_1$$

$$F_5 = F_3 - \frac{H_1}{L_W} F_1 = F_3 - \frac{H_1}{L_W} F_6$$

Coefficient of friction is defined as:

$$\mu = \frac{F_6}{F_5} = \frac{F_6}{F_3 - \frac{H_1}{L_W} F_6}$$

With known constant values of F_3, H_1, and L_W with this vehicle, the coefficient of friction is calculated for values of tractive force, F_6, indicated by stress observations. Figure B shows the coefficient of friction as a function of the tractive force.

HAROLD L. MICHAEL, Closure — The material presented by Skeels, Stonex, and Finney is valuable and, in effect, is a paper itself rather than a discussion.

As pointed out in the discussion and in the paper, one of the factors contributing to pavement slipperiness is the polishing action of the pavement surface. The discussers present concrete evidence of how and why this occurs. As stated, "the most hopeful steps for significant progress lie in the area of developing pavement surfaces which do not become polished under abrasive wear." This certainly is an important factor.

The tests referred to in the discussion develop comparisons similar to tests being performed in Indiana by the Joint Highway Research Project in cooperation with the State Highway Department. These semi-annual tests on a portland cement concrete and a bituminous concrete surface were initiated in 1954 when the surfaces were new. The information to date confirms the observations noted by the discussers, specifically that the surface becomes increasingly slippery with the passage of time and travel and that the traffic lane on dual-lane divided-lane highways is less skid-resistant than the passing lane. These tests are planned for continuance for several years and more information will be developed.

The Indiana studies also have shown that aggregates tend to polish and become slippery in varying amounts: some polish easily, others remain almost unaffected by traffic action. As the discussers indicate, much information is still required before maximum safety can be designed into highways.