Research Report 255

ROAD SURFACE FRICTION FROM THE STANDPOINT OF AUTOMOTIVE AND HIGHWAY ENGINEERS

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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 our highways. Nothing is so important for the safe, effective use of our highway system, and it is the opinion of the authors that a joint effort to determine the reasons for poor friction characteristics and to develop solutions is a matter of paramount importance.

In the discussion, we are 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.

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. This is almost certainly the result of inherent characteristics of the pneumatic tires as successive segments pass through the contact area.

Figure 1 is a reproduction of a single frame of a high-speed motion picture showing the contact area of a tire running over a piece of tempered glass. It is noted that the total width of the tire in the contact area is less than the projected width of the undeflected tire. This apparently results from the flattening out of the compound curved tire surface as it is deflected under load.

This high-speed motion picture makes 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 5/16", which means that each outer rib moved approximately 5/32" toward the center and back. Compression in the longitudinal direction causes a movement of as much as 1/8".

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.

Without analyzing this movement in detail, it seems clear that 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 within the contact area between the tire and the road will also wear off tread rubber. Since the tire manufacturers are deeply concerned about tread wear rates, they have always devoted a large amount of development work in designing treadpatterns and contact shapes to minimize total wear and to distribute the wear evenly across the tread. It must, therefore, be concluded 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. It seems evident that the most hopeful steps for significant progress lie in the area of developing pavement surfaces which do not become polished under abrasive wear.

Test observations discussed later in this paper and other observations reported by other writers give a strong basis for the assumption that both Portland 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 very much pleased at the opportunity to cooperate with the Michigan State Highway Department in performing the brief tests discussed here.

Our 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 2) 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, we used a Servo type of indicator, developed and constructed by the Proving Ground, but 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 Buick test car was towed behind a truck.

As a source of water to wet the surface, we used a tank truck. It was fitted with a valve so that water could be sprayed on the road just ahead of the test car during the time each observation was made.

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 permits safe test performance at normal traffic speed without disturbance of the traffic stream and yields test results which are not influenced by possible changes in coefficient of friction with speed.

A further advantage from this 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, it is our opinion that 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 State Highway surfaces, a heavy rain had fallen; the pavement surface appeared to be clean, and we were reasonably sure 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 shown later 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 elevated speeds the reaction developed by the air resistance couple may become significant.

Figure 3 shows the tow truck and the test car in the relative positions occupied during the test.

Figure 4 shows the strain indicating meter mounted in the front seat compartment of the car and a portable radio used for communication with the tow truck.

Figure 5 shows the location of the strain gauges mounted on the torque tube.

Prior to the formal test program, a series of evaluation tests were made on parts of the Proving Ground road system.

Figure 6 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 ± .01 and the incipient slide is consistent within a range of coefficient of friction approximately ± .02. The accuracy with which the strain indicator could be read is not much better than this.

The Test Track surface is a bituminous concrete material corresponding to Michigan State 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.

Figure 7 shows comparable observations at a speed of 50 mph. The effect of speed is not significant statistically on these observations.

Figure 8 shows test results on another bituminous concrete used on the Military Proving Ground Straightaway. 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. The uniformity of the results is not quite as close as on Figure 6 or 7, possibly because the surface variation may be somewhat greater.

Figure 9 shows results 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. Consistency here 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 shown in Figures 6, 7, and 8.

Figure 10 shows the results on a sheet asphalt surface with extremely low traffic volumes and of about six years service.

Figure 11 shows results of tests on a public highway adjacent to the Proving Ground. This is surfaced with an oil aggregate type surface with about two years service under light traffic.

Figure 12 and Figure 13 show dry friction measurements on the surfaces shown under wet conditions in Figure 6 and 9 respectively.

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

In the following four charts, the test results are shown 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 1000 to express the index in convenient numerals.

Figure 14 shows the results for bituminous concrete with limestone aggregate.

Figure 15 shows the results for bituminous concrete surface with gravel aggregate.

Figure 16 shows the results with Portland cement surface, and Figure 17 is a composite of the three.

It is conceded that the individual relationships are rather poorly correlated because there are many other variables to be studied including the type of filler, sand, and possibly cementing media, but there is a strong indication of a predominant type of grouping which points out distinctly that the three basic types of surface give distinct wear index behavior patterns.

A study of certain apparent abnormalities in Figures 14 and 15 has uncovered facts which are believed significant to the problem of constructing highway surfaces which will maintain a high degree of skid resistance throughout their useful life. For instance, point 20 in Figure 14, and points 3, 5, and 7 in Figure 15 represent projects constructed prior to 1944 involving 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 below. While these material differences are not great they should be investigated.

	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	Fly Ash
Coarse aggregate	100% pass. 1/2" sieve 15 - 45% pass. No. 4 Dept. Spec. 26A	90-100% pass. 1/2" sieve 0 - 25% pass. No. 4 Dept. Spec. 26A mod.	90-100% pass. 1/2" sieve 0 - 25% pass. No. 4 Dept. Spec. 25A

Further, with reference to photographs in Figures 18 and 25, 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 will need careful study.

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

Coarse Aggregate (retained on No. 10 sieve)	50 - 55 percent
Fine Aggregate (passing No. 10, retained on No. 200 sieve)	30 - 35 percent
Filler (passing No. 200 sieve)	5.5 - 6 percent
Asphalt cement	5.5 percent
Marshall Stability	1500 - 3000 lbs

Figures 18 and 19 present photographs of the surface in the traffic lanes of gravel projects 3 and 5, respectively, constructed prior to 1948. In both cases, note 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 shown in Figures 20 and 21. The two surfaces illustrated are at different ends of Project 12, 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 that in one case it was 0.48 (Figure 20) and in the other, 0.39 (Figure 21). 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 (Figure 21), 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.

Figure 22 shows comparative results for 8 projects including one bituminous surface with gravel aggregate, four surfaces containing limestone aggregate, and three Portland cement concrete pavement surfaces. In these comparisons, differences in coefficient of friction values between the two lanes amounted to as much as 36 percent.

Figures 23, 24, 25, and 26 show typical pavement surfaces in the traffic and passing lanes of two bituminous concrete projects containing different types of coarse aggregate. Photographs taken on many other projects show similar surface conditions in adjacent passing and traffic lanes. It is to be noted that, in the traffic lanes, the coarse aggregates, both gravel and limestone, have become worn and polished to varying degrees and that 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, while in the passing lanes, 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 presented in Figure 16 indicate clearly that Portland cement concrete surfaces, irrespective of mixture composition, can become increasingly slippery with time when subjected to heavy traffic conditions.

SUMMARY

This work is to be considered a progress report pointing up the need for a large scale study of the highway system in order that the factors mentioned above can be correlated into future highway design to provide for maximum safety.

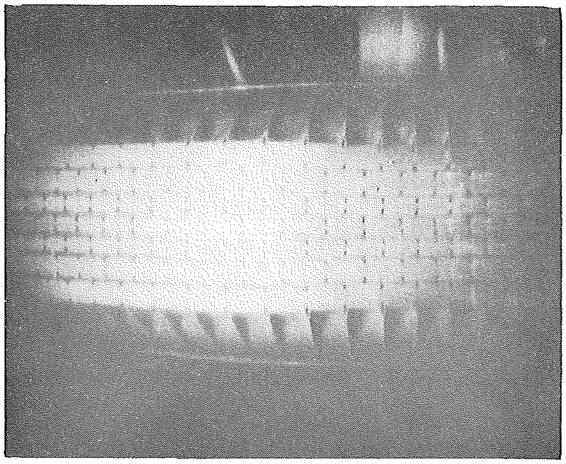

Figure 1—Single frame of high-speed motion picture showing contact area of a tire running over a piece of tempered glass.

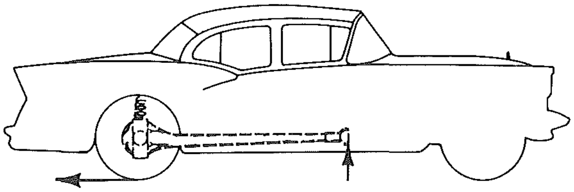

Figure 2—Schematic diagram illustrating bending moment in torque tube.

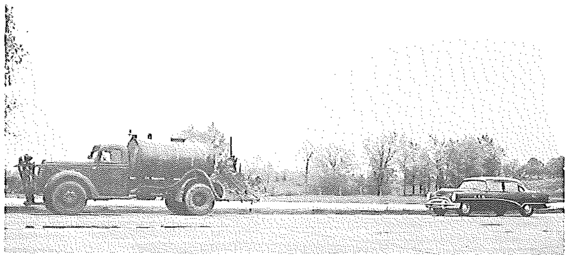

Figure 3—Test car being towed by tank truck with water control valve.

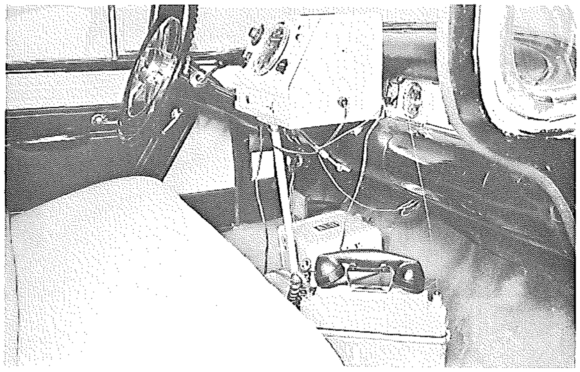

Figure 4—Strain indicating meter mounted in the front seat compartment and portable radio used for communication with the test operators in the tow truck.

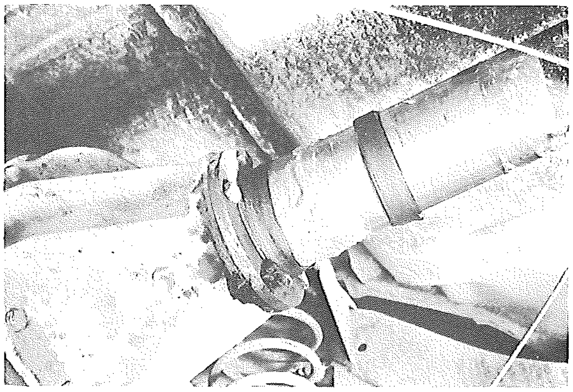

Figure 5—Buick torque tube with strain gauges installed under protective cover.

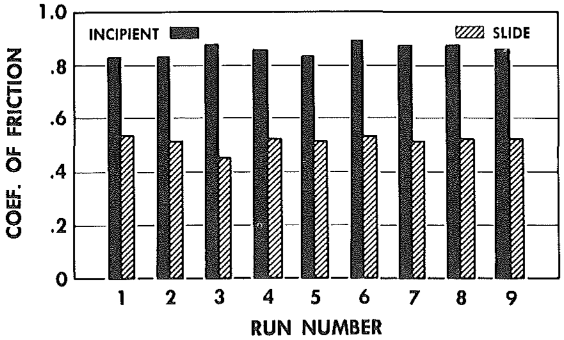

Figure 6—Incipient and sliding coefficients of friction observed on the 40 mph lane of the Proving Ground Test Track—Bituminous concrete surface.

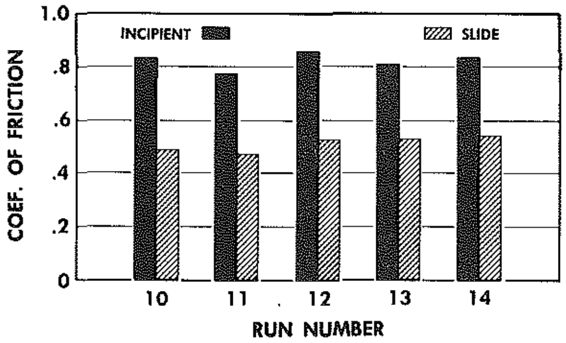

Figure 7—Incipient and sliding coefficients of friction observed at 50 mph on the Proving Ground Test Track—flooded bituminous concrete surface.

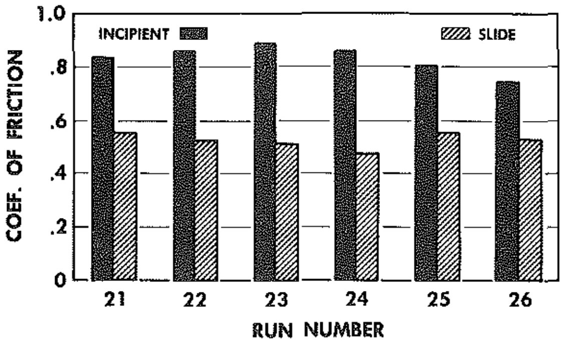

Figure 8—Incipient and sliding coefficients of friction on Military Straightaway at 40 mph flooded bituminous concrete surface.

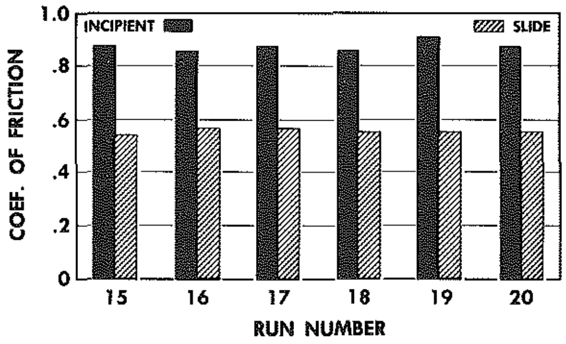

Figure 9—Incipient and sliding coefficients of friction observed on Engineering Straightaway at 40 mph—flooded Portland cement concrete surface.

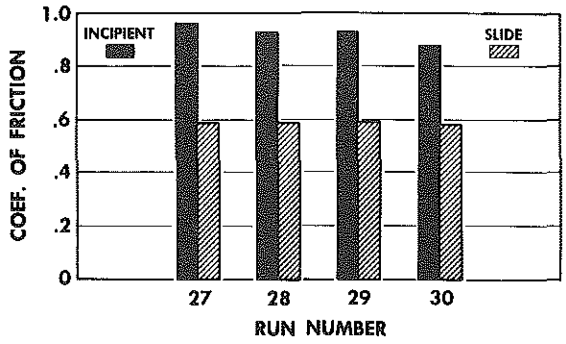

Figure 10—Incipient and sliding coefficients of friction at 40 mph—flooded sheet asphalt surface.

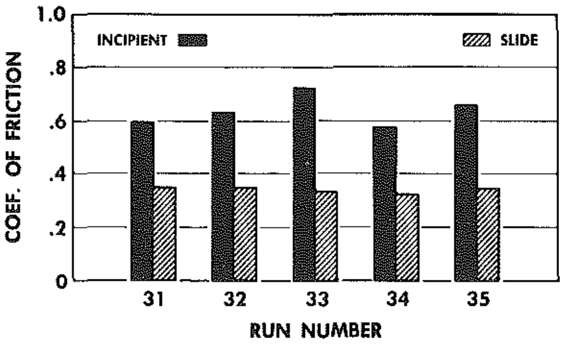

Figure 11—Incipient and sliding coefficients of friction observed at 40 mph on a public highway—flooded oil aggregate surface.

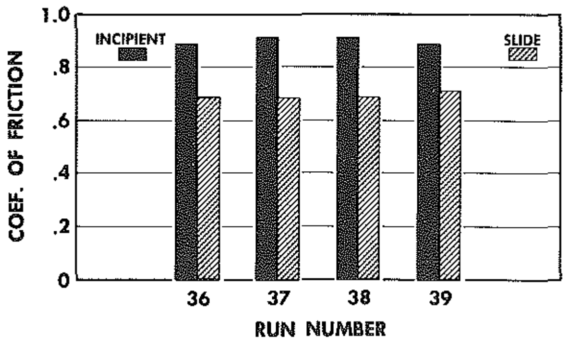

Figure 12—Incipient and sliding coefficients of friction at 40 mph on dry bituminous concrete on Proving Ground Test Track.

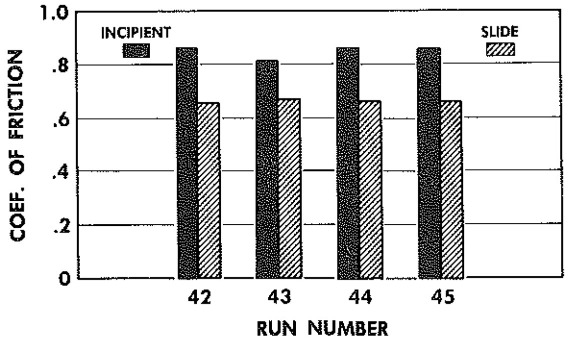

Figure 13—Incipient and sliding coefficients of friction at 40 mph observed on dry Portland cement concrete straightaway.

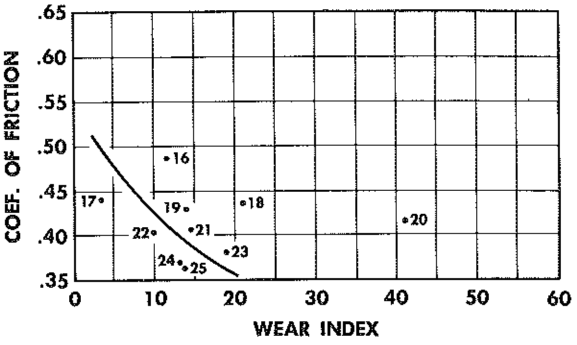

Figure 14—Sliding coefficient of friction at 40 mph as a function of wear index, various Michigan State Highways of bituminous concrete using limestone aggregate—flooded surfaces.

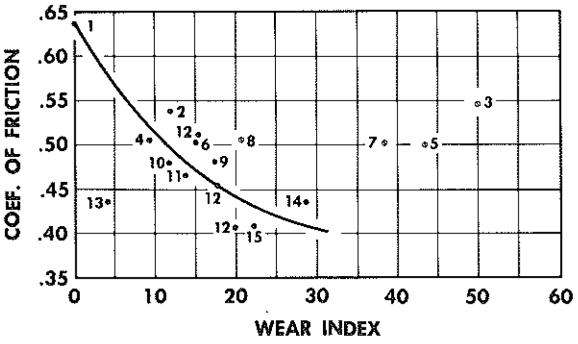

Figure 15—Sliding coefficient of friction at 40 mph as a function of wear index, various Michigan State Highways of bituminous concrete using gravel aggregate — flooded surfaces.

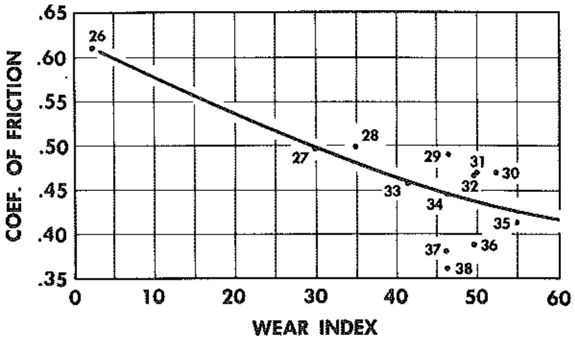

Figure 16—Sliding coefficient of friction at 40 mph as a function of wear index on Michigan State Highway roads paved with Portland cement concrete — flooded surface.

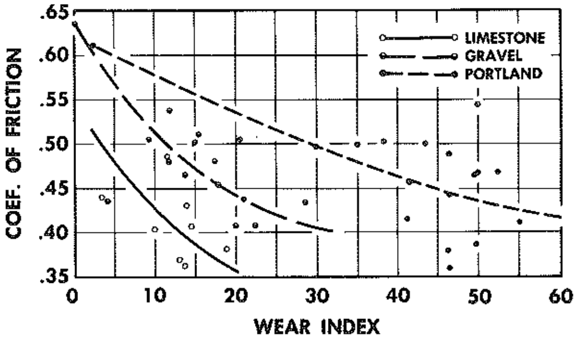

Figure 17—Comparative coefficients of sliding friction as a function of wear index observed on Michigan State Highways at 40 mph, on pavements of bituminous with limestone and gravel aggregate and Portland cement concrete—flooded surfaces.

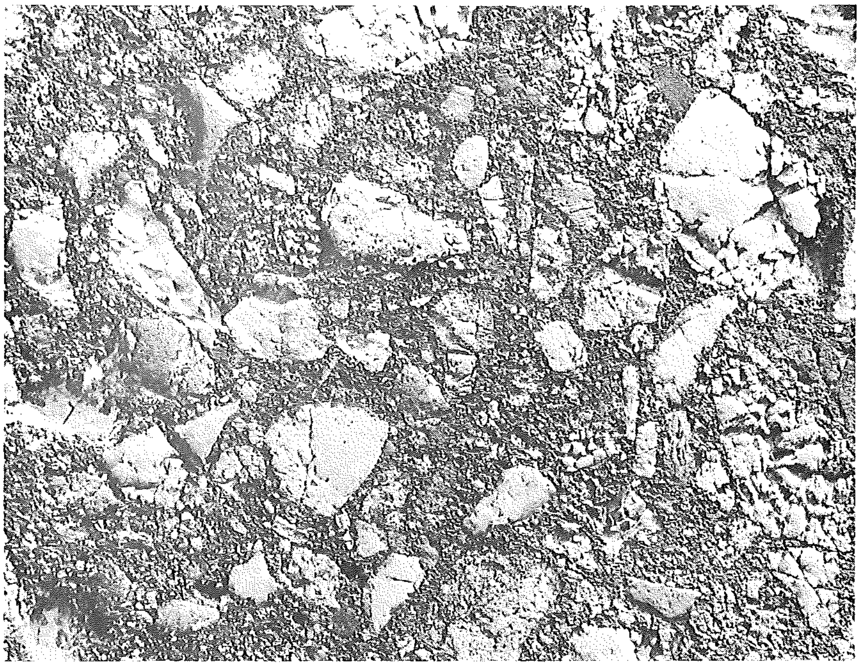

Figure 18—Project 3, Gravel aggregate 26A, Traffic Lane, coef. 0.545. Age 13 years. Average daily traffic, 3860. Wear factor 50.2.

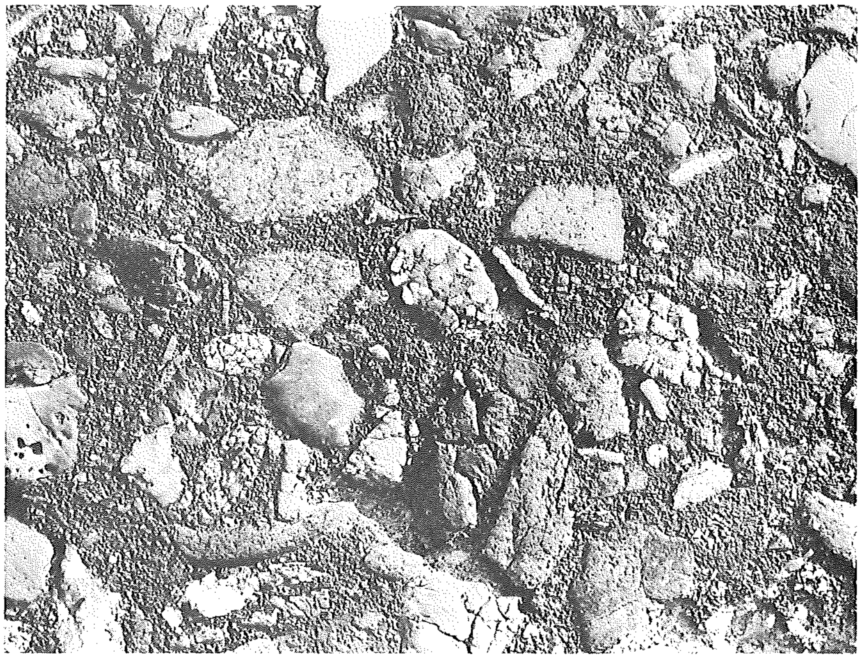

Figure 19—Project 5, Gravel aggregate 26A, Traffic Lane, coef. 0.50. Age 11 years. Average daily traffic, 3920. Wear factor 43.6.

Figure 20—Project 12, Gravel aggregate 25A, Traffic Lane coef. 0.50. Age 3 years. Average daily traffic, 12,000. West end of project. Wear factor 15.5.

Figure 21—Project 12, Gravel aggregate 25A, Traffic Lane, coef. 0.405. Age 3 years. Average daily traffic, 16,000. East end of project. Wear factor 20.0.

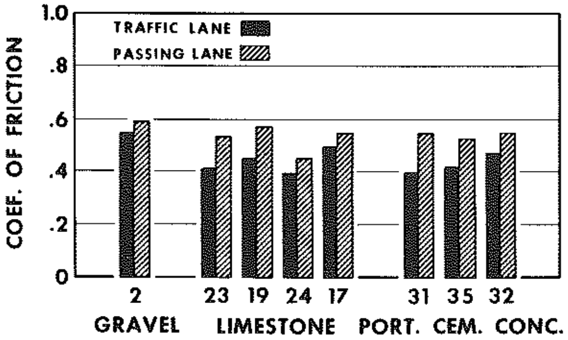

Figure 22—Comparative coefficient of sliding friction at 40 mph, on eight Michigan State Highway projects with various types of surfacing materials—flooded surfaces.

Figure 23—Project 2, Gravel aggregate 25A. Traffic Lane, coef. 0.545. Age 4 years. Average daily traffic, 3120. Wear factor 12.1.

Figure 24—Project 2, Gravel aggregate 25A. Passing Lane, coef. 0.59.

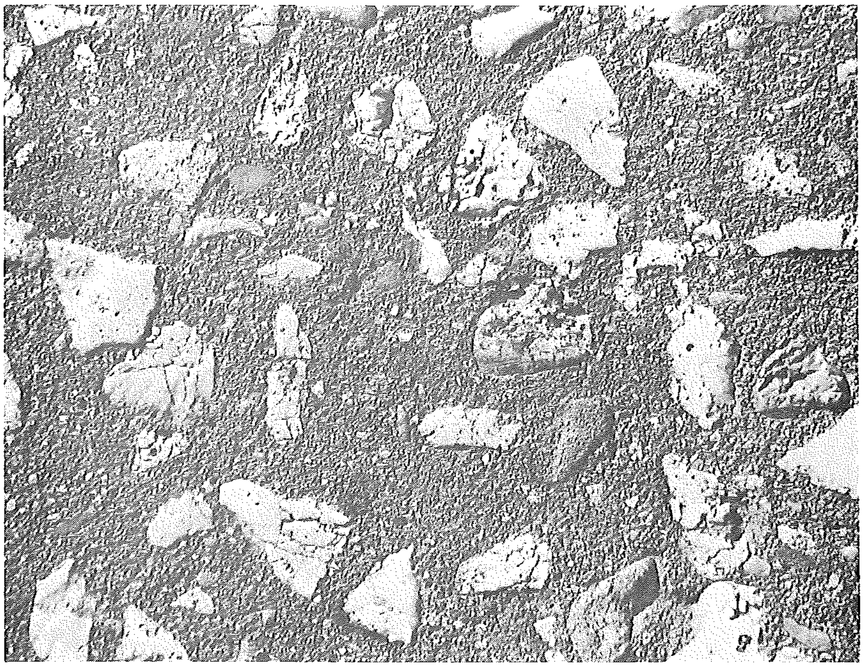

Figure 25—Project 18, Limestone aggregate 25A. Traffic Lane, coef. 0.425. Age 4 years. Average daily traffic, 2940. Wear factor 20.8.

Figure 26—Project 18, Limestone aggregate 25A. Passing Lane, coef. 0.57.

APPENDIX

Figure 27 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, which is 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 F_1H_1. The force moment equations are as follows, with the forces as indicated in Figure 27 and with positive moments in clockwise sense:

$$\sum F_x = 0 = -F_1 + F_6, \text{ therefore } F_1 = F_6$$

$$\sum M_A = 0 = F_5L_w - F_3L_w + FH_1$$

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

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 28 shows the coefficient of friction as a function of the tractive force.

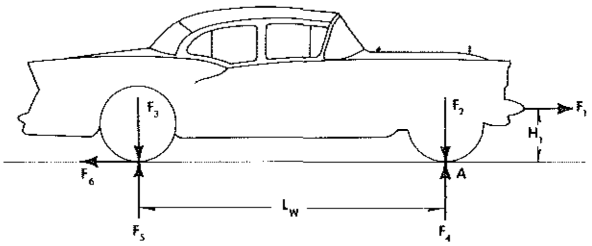

Figure 27—Force diagram of car.

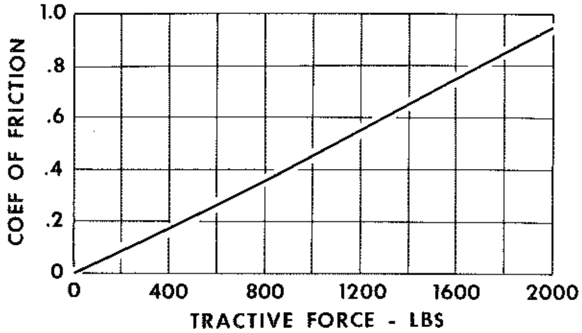

Figure 28—Calibration curve for coefficient of friction from tractive force readings.