State of the Art of Skid Resistance Research

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•ALL AGENCIES responsible for the construction and maintenance of roads and streets are faced with the problem of providing pavements on which adequate frictional resistance can be developed by vehicle tires. This frictional resistance is necessary to start, turn, accelerate, and stop a vehicle. The requirements are similar on airfields for the take-off and landing of airplanes.

Although the frictional resistance on modern roads is being gradually improved by appropriate construction and maintenance measures, the problems of the highway engineer are still unsolved because the required standards of frictional resistance are going up at an even faster rate due to the steadily growing volume of traffic and the increasing speed and performance of modern vehicles.

The final goal of any research effort in this field is to build roads that offer adequate pavement-tire friction under modern traffic conditions. To achieve this, it is necessary (a) to understand the fundamental concepts of road friction, (b) to measure this property effectively, and (c) to evaluate the results in terms of the individual factors involved. In this paper past research results, present research trends, and future research needs are discussed under these three headings.

PAST RESULTS

Highway engineers have been studying the problem of vehicle skidding and the resistance to skidding offered by pavement surfaces for several decades. In fact, early technical papers on the subject, which perhaps somewhat surprisingly touch on many of our present-day ideas, are about 30 to 40 years old. Other engineers (notably mechanical and aeronautical engineers), other scientists (notably physicists and geologists), and various other groups (automobile manufacturers, tire manufacturers, etc.) have also joined in the work. Understandably, only the major findings can be covered in this paper, and only in rather general terms.

A good percentage of the research results has been published under the auspices of the Highway Research Board, the American Society for Testing and Materials, the Permanent International Association of Road Congresses, and the British Road Research Laboratory. In order to correlate individual research efforts, an international conference (the First International Skid Prevention Conference) was held at the University of Virginia in 1958. This conference was successful in establishing contacts and working relationships among the leading investigators from several countries. Much of the present knowledge on skidding and skid resistance is consolidated in the two-volume Proceedings of the conference (12).

In addition to the United States, the major centers of skid resistance research have been Britain, Germany, Sweden, and France. Research reports from these countries and from Australia, Belgium, Canada, Czechoslovakia, Denmark, Holland, Israel, Italy, Japan, Poland, Russia, Spain, and Switzerland were covered in a literature review. This first section of the present paper is essentially a digest of that literature review. Past results of general interest are discussed here under three headings: nature of skid resistance, measurement of skid resistance, and skid resistance parameters.

Nature of Skid Resistance

The forces that are required in driving, steering, and braking an automobile are provided by the frictional resistance developed between the tires and the pavement surface. For any given tire and pavement combination there is a maximum friction potential; if it proves to be inadequate for the intended maneuver, the wheels begin to slide, the driver's control over the vehicle is drastically reduced, and the vehicle is said to be "skidding." The frictional resistance offered by the pavement surface to the sliding tires is called "skid resistance."

The most common example of vehicle skidding occurs during a panic stop, when all the wheels are locked and cease to rotate but the vehicle continues to slide. The implications of adequate skid resistance with respect to traffic safety are fairly obvious.

Skid resistance is usually considered to be a frictional force consisting of two components—the adhesion term and the deformation term. The adhesion term is the result of molecular forces, and its magnitude is determined by the nature of the two materials in contact, in this case the tire and the road surface, and by the normal force between them. Adhesion is usually the dominating factor on dry pavements; its effect diminishes with lubrication and becomes negligible on wet pavements. On wet pavements the deformation term is far more important. It is the result of the deformation of the tire rubber by the surface asperities and the ensuing energy dissipation in the rubber.

Under any given set of conditions the effective skid resistance (F) is the sum of the adhesion (F_a) and deformation (F_d) components; dividing it by the vertical load (L), it can be expressed in terms of an effective coefficient of friction (f): $f = F/L = (F_a + F_d)/L$. Since the adhesion term is greatly reduced (while the deformation term is essentially unaffected) by lubrication, the skid resistance of a pavement is always lower in the wet state than in the dry state. Typically, the difference may be of the order of 50 percent, depending on surface texture (higher on smooth pavements than on coarse ones) and testing speed (higher at high speeds than at low speeds). The great majority of wet-road skid resistance measurements are in the 0.30 to 0.70 range.

Measurement of Skid Resistance

In order to insure critical test conditions, skid resistance measurements are normally taken on wet pavements. Unfortunately, this has turned out to be practically the only standard feature of the procedures for measuring skid resistance. A number of diverse techniques and devices have been developed, and they each appear to have certain advantages. For the purposes of this discussion the various skid resistance measuring devices have been grouped into four classes—braking force trailers, other braking force methods, the sideway force method, and portable and laboratory instruments.

It should be noted that the indirect evaluation of skid resistance, by observation of the relative frequency of skidding accidents at certain sites, has also been attempted. Such data have been used to assess the significance of the problem of skidding, to validate skid resistance measuring techniques, to study the effect of individual skid resistance parameters, to locate accident black-spots, and to check the efficiency of corrective surface treatments.

Braking Force Trailers—This apparatus consists of a trailer with one or more test wheels and a towing vehicle which usually carries the recording instruments and a water tank. As the brake is applied on the test wheel, constant towing speed is maintained and the retardation forces acting in the plane of the test wheel are measured. Knowing the vertical load, the effective coefficient of friction can then be calculated.

If the brake is gradually applied on the test wheel, the percentage slip will gradually increase. (Percentage slip is defined as $s = (N_f - N_b) \cdot 100/N_f$, where N_f is the revolution rate of a freely rotating wheel and N_b the revolution rate of the braked wheel.) Generally, the measured frictional resistance will also increase up to a peak value obtainable at a critical slip percentage, and then it will decrease to the value of locked-wheel or sliding friction. The peak value of frictional resistance is usually called the "impending" or "incipient" friction; it is obtained at 5 to 20 percent slip, and it is likely to be about 50 to 100 percent higher than the sliding friction value.

The force-measuring instrumentation varies with trailer type, both in basic concept and in degree of sophistication. The parallelogram-type and torque-type systems are considered to be the best. Normally the coefficient of sliding friction is measured during automatically controlled brief periods of braking, and the results may be graphically recorded. Some trailers have been constructed to measure impending friction at a predetermined slip value.

Trailer tests provide a simple and direct approach to the problem of measuring skid resistance, they can be carried out at normal traffic speeds with minimum interference to traffic, and the procedure is fast and accurate (accuracy about ± 1 to 2 percent). While the initial cost of the equipment is relatively high, the unit testing cost (cost per test site) is usually very reasonable.

This testing technique has now become the most popular one in the United States, and over a dozen different skid-trailers are being used for routine testing. Advanced skid-trailers have also been developed in Sweden, Germany, Britain, France, Italy, and other European countries.

Other Braking Force Methods—Another technique based on the braking force concept is the stopping distance method. The test vehicle is accelerated to a predetermined initial speed, its wheels are then locked and the distance required for the vehicle to stop is measured. The effective sliding friction, corresponding to the speed range from the initial speed to zero speed, can then be calculated using the simple formula $f = V^2/30\,S$, where V is the initial velocity in mph and S is the stopping distance in feet.

Normally, slightly modified standard passenger cars are used for stopping distance tests. The stopping distance is measured either by means of a stopmeter with a fifth wheel (both the initial speed and the stopping distance being recorded on dials inside the car), or with a tape from a chalk-mark made by a brake-activated detonator. The braking system may also be modified in order to standardize braking conditions.

This is a relatively inexpensive testing method which closely simulates the critical conditions of emergency braking, and may be made realistic to the extent of reflecting changes in vehicle and tire design. On the other hand, it is normally limited to speeds below 30 to 40 mph, because there is an element of accident hazard involved and elaborate traffic control measures are required. The reproducibility of the measurements varies from ± 2 to ± 15 percent.

The stopping distance method has never been popular in Europe; it was favored by a majority of United States investigators up to a few years ago but is now gradually losing ground to the trailer method.

A decelerometer is used in a similar testing technique. As the brakes are applied, the deceleration of the vehicle is measured instead of the stopping distance. The coefficient of sliding friction is numerically equivalent to the deceleration expressed in g's. Actually, impending friction may also be measured if the brakes are gradually applied. The decelerometer is positioned either on the floor or on the dashboard of the test car.

The decelerometer method was developed in Britain, and has also been extensively applied in the United States. It is a satisfactorily accurate (typical reproducibility ± 2 to 3 percent), inexpensive, fast, and realistic testing technique, but it does require careful traffic control, and the testing procedure is rather difficult to standardize.

Sideway Force Method—The sideway force method is based on the contention that the critical maneuver with regard to skidding is cornering. The test wheel is set at a predetermined angle to the direction of travel, and the sideway force acting normal to the plane of the wheel is measured. The frictional resistance is then expressed in terms of the sideway force coefficient which is the ratio of the sideway force to the vertical load.

The maximum sideway force is obtained at a critical angle of inclination of the test wheel. This critical angle is a function of pavement surface parameters, and is usually slightly below 20 degrees. The instrumentation of the test vehicle usually involves electrical strain gages for measuring the axial force and an automatic system to obtain a continuous graphical representation of the test results.

The sideway force method is accurate (reproducibility ± 1 to 2 percent), yields continuous measurements along the road, and there are no accident hazards involved. Depending on the degree of sophistication aimed at, the initial equipment costs may be relatively high. The technique has been developed and extensively used in Britain and France, and is also being applied elsewhere in Europe. It has been rarely used in the United States.

Portable and Laboratory Instruments—A number of devices have been developed either to measure the frictional properties of pavement specimens in the laboratory or to serve as a link between field and laboratory investigations by being adaptable to testing conditions in both environments. Among them are the pendulum-type devices, the single-wheel-type devices, and the skid-cart testers.

These are specialized instruments, used normally for special purposes, such as the laboratory testing of potential paving mixes, or taking spot-checks at a busy intersection. It is always open to question how well such devices simulate the actual interaction of vehicle tires with the road surface; at best they can only indicate the skid resistance for a very limited range of operating conditions.

Skid Resistance Parameters

The main goal of all the research effort utilizing this large variety of equipment has been to discover and evaluate the parameters that significantly contribute to the skid resistance of pavement surfaces. While quantitative expressions are not yet available, a reasonably good understanding of the problem has been achieved in qualitative terms.

The skid resistance offered by a pavement surface to a vehicle tire is determined by three groups of parameters: (a) those associated with the pavement surface, (b) those associated with the vehicle, and (c) those associated with operating conditions.

Within each group, there are primary (important) and secondary (not so important) parameters. The primary parameters are: (a) aggregate characteristics and surface texture in the first group, (b) rubber properties and tread pattern in the second group, and (c) temperature and vehicle speed in the third group.

In very general terms, skid resistance will be high if effective instantaneous drainage can take place in the contact region (high adhesion term) and high hysteresis losses are provoked in the tire rubber (high deformation term). Each of the primary parameters has a decisive influence on either one or both of these basic factors of skid resistance.

Aggregate Characteristics—To be able to puncture thin "squeeze-film" between the tire and the pavement, and to cause appreciable grooving of the tire rubber, the aggregates in a paving mix should be angular, hard, and polish-resistant under wear. Opinions differ on particle size and gradation characteristics.

Numerous experiments have proved the importance of particle shape. Using the same aggregate type, skid resistance is normally higher on bituminous mixes with angular aggregates than on mixes with rounded aggregates.

It is not sufficient for the aggregates to be sharp and angular initially; they should also retain these characteristics in service. Experience shows that considerable reductions in skid resistance may be caused by traffic wear—as much as 50 percent of the initial skid resistance is lost on some pavements during the first two years of service. Much of this is caused by the polishing of the individual aggregate particles in the mix. The rate of deterioration is considerably slower in the later stages of service, and polishing practically levels out once the "ultimate state of polish" is reached. Heavy and fast vehicles cause more rapid reduction of skid resistance than light and slow ones; under heavy traffic the ultimate state of polish may be reached as early as two years after construction. (It may be noted that a number of accelerated wear machines and procedures have been developed to simulate the effect of traffic wear on laboratory pavement specimens.) Polishing always requires the presence of some abrasive material, such as the clay, silt, and sand-sized dirt and dust usually covering road surfaces.

In order to resist polishing, the individual aggregate particles should be hard. Calcite, with a Mohs hardness of 3, is susceptible to polishing by just about any ingredient of the road scum; quartz has a Mohs hardness of 7, and the only mineral abundantly present in the road scum that would be hard enough to cause it to polish is quartz itself.

It is therefore not surprising that limestones are often the main cause of slipperiness on both flexible and rigid pavements. (Certain limestones, it must be added, particularly the highly dolomitic formations and those having a relatively high acid-insoluble sand-size content, have given entirely satisfactory performance.) Sandstones and slags are usually regarded as good anti-skid aggregates. Sandstones give a good example of differential wear, which is a desirable kind of wear. Due to the difference in hardness between the hard crystals and the friable matrix, traffic wear actually contributes to a rough, uneven surface texture on sandstone aggregates.

Surface Texture—A sharp, gritty, "deep" surface texture, with adequate channels and escape paths among the asperities, facilitates the escape of the lubricating water from the contact patch, and is therefore an important factor in providing good skid resistance.

The large-scale texture (roughness) of a pavement surface may be important in breaking up the contact patch into smaller areas that drain faster. This effect is definitely significant for smooth tires; with patterned tires, however, the roughness of the surface may become a secondary factor since the tire pattern itself can adequately subdivide the contact area. What is always important is the small-scale texture of the surface, i.e., the sharpness of the very small-scale projections and ridges (harshness). Experience has shown that road surfaces with "sandpaper texture" usually exhibit high skid resistance.

The possible role of differential wear in retaining a harsh or rough surface texture has been mentioned before. Another similarly beneficial type of wear is that observed with Kentucky rock-asphalt and silica-sand surface treatments. The individual aggregate particles are dislodged from the surface before they get excessively polished, and other, unpolished particles become exposed.

Pavement surface textures have been recorded by photographic and ink-printing techniques, and the sand-patch method has been used to determine texture depth.

Other Pavement Factors—Pavement type is not regarded as a critical factor; good skid resistance may be achieved with any modern pavement structure. Skid resistance appears to vary over a wider range on bituminous pavements than on portland cement concrete pavements, probably because of the more effective polishing of the aggregates. An advantage of bituminous pavement construction is that polishing aggregates may safely be used in lower layers, and wear-resistant aggregates need only be used in a thin surface course. With portland cement concrete pavements, surface finish is of considerable importance. Broom or burlap-drag finishing usually provides good initial skid resistance, although it may be necessary to provide deeper texture on high-speed roads.

Mix proportions and the properties of the binder may also be of some significance. In bituminous pavements excessive asphalt content and improper aggregate gradation may lead to bleeding; bleeding bituminous surfaces are always slippery, with friction coefficients as low as 0.10 to 0.20. On portland cement concrete pavements, surface slipperiness may be due to excess sand or water in the mix, or to a finishing carried out with excess cement paste.

Surface contamination (loose dust and grit on the pavement) is of limited consequence on wet roads, but it may reduce the skid resistance of dry pavements by as much as 50 percent. The presence of the so-called "traffic film" (an accumulation of oil, worn rubber, and dust) is usually regarded as a sign of increased slipperiness. Ice or snow cover naturally reduces skid resistance; typical measurements may be 0.05 to 0.20 on ice-covered roads, and 0.15 to 0.35 on packed snow.

Due to intensive polishing action, curves, roundabouts, bus stops, steep slopes, etc., are usually associated with slippery conditions.

Rubber Properties—It has only been a relatively recent development in the history of skid resistance research to focus attention on the properties of the tire rubber, most notably on its hysteresis characteristics. It has been concluded that the deformation component of skid resistance is due to hysteresis (internal friction) losses within the tire rubber as the deformations caused by the surface asperities are being recovered. High hysteresis (low resilience) rubber tires will therefore provoke higher frictional resistance, particularly on rough surfaces where the deformation term is especially significant. Modern "dead-rubber" (high hysteresis) tires provide about 20 percent improvement in skid resistance on rough surfaces. In order to avoid the overheating of the tire, a duplex structure may be used, with the tire tread built of high-hysteresis rubber and the rest of the tire of low-hysteresis rubber.

The hardness of the tread rubber may also have some bearing on skid resistance, especially on ice and other very smooth surfaces. The harder the tread rubber the smaller the contact area, resulting in higher localized pressures, better drainage, and increased frictional resistance.

Tread Pattern—It has been pointed out by several investigators that the friction coefficients measured with smooth and patterned tires differ considerably, possibly by as much as 50 percent. A tire with a good tread design, i.e., with circumferential ribs and transverse slots, will normally give higher skid resistance than a smooth tire, especially on polished wet surfaces.

The significance of a good tread pattern is derived from its effect on drainage conditions, and is therefore restricted to wet pavements. The elements of the tread pattern effectively break up the contact patch between the tire and the pavement surface into a number of small contact spots, making it possible for the lubricating liquid to more readily escape from the contact area. The edges in the pattern also provide a wiping action, tending to remove the lubricating film. Naturally, such improvements in drainage conditions are more effective on smooth surfaces than on rough surfaces. Similarly, patterned tires are more effective in improving skid resistance at high speeds than at low speeds, since at high speeds drainage is a more critical factor.

The role of tire characteristics in providing adequate skid resistance has been recognized by the tire industry. During the past decade, improvements in tire composition and design have led to a gradual improvement in average wet-road skid resistance on passenger-car tires.

Other Vehicle Factors—Laboratory tests have shown that the coefficient of friction is independent of the shape or size of the contact area but is inversely related to the contact pressure. Since with increasing wheel load or increasing inflation pressure the contact pressure also increases, it is not surprising that several investigators have observed a trend for skid resistance to be reduced at higher wheel loads and/or inflation pressures. In normal passenger car operation, however, these effects are of little significance.

The size of the wheel may also be of some interest. Test wheels of very small diameter may give rise to reductions in measured skid resistance.

Finally, skidding and skid resistance measurements are also influenced by the method of braking. The vehicle will tend to keep its straight course if all its wheels are locked simultaneously or if only the front wheels are locked, but will tend to go into a spin if only the rear wheels are locked.

Temperature—Among the parameters associated with operating (traveling or testing) conditions, temperature and vehicle speed have the most profound bearing on skid resistance.

It has been widely observed and reported that skid resistance tends to decrease with increasing temperatures (ambient, pavement, and tire temperatures). A typical reduction in skid resistance might be 0.02 for a 10 F rise in air temperature. This phenomenon has been recently traced back to the hysteresis characteristics of the tire rubber: with increasing temperatures the hysteresis losses in the rubber are reduced, resulting in lower frictional resistance. On very smooth surfaces (such as a glass plate), where the effect of hysteresis losses is negligible, the temperature effect is also negligible. Also, since rubber hysteresis changes more rapidly at lower temperatures, skid resistance measurements are more sensitive to temperature changes at lower temperatures.

Temperature changes also have an effect on the viscosity of both the lubricating liquid and the asphalt binder. On dry pavements, tread-surface temperatures as high as 1000 F may develop during skidding, leading to rubber melting. The melted rubber effectively lubricates the road surface, reducing its frictional resistance.

It is also a matter of general experience that the skid resistance of a pavement tends to be higher in the winter than in the summer. Typical differences may be of the order of 0.10. These seasonal variations in skid resistance are believed to be partially due to temperature changes and partially to seasonal changes in the fine-scale texture (micro-roughness) of the road surface.

Skid resistance is also related to a number of other climatic factors. As an example a heavy rainfall following a dry spell may significantly improve road friction.

Vehicle Speed—The frictional resistance of wet pavements is profoundly influenced by the speed of the vehicle; with increasing speed, skid resistance is reduced, often by a considerable amount. This is especially unpleasant in view of the fact that the skid resistance requirements for a vehicle to stop within a certain distance increase as the square of the vehicle speed.

The primary factor in this context is probably surface drainage again. At higher speeds the lubricating liquid simply has less time to escape from the contact region. (The contact time is about 0.06 sec for an automobile at 60 mph.) It is thus not surprising that the speed effect is much more significant on smooth pavements (where drainage is more critical) than on rough ones, more significant with smooth tires than with patterned ones, and negligible on dry roads.

Standard skid resistance tests are usually run at 40 mph or at 60 kmph.

Under certain conditions on water- or slush-covered pavements, when the speed of the vehicle exceeds a certain critical value, a water layer will gradually build up under the tire, detaching it completely from the pavement surface. The tire will then merely skim over this water layer, practically unable to develop any braking or maneuvering forces. This is the phenomenon of hydroplaning, now well documented and demonstrated both by laboratory and field (aircraft and automobile) experiments.

Under hydroplaning conditions the weight of the vehicle is believed to be balanced by an upward hydrodynamic thrust. Formulas have been derived to calculate the approximate critical speed (hydroplaning speed) at which the hydrodynamic lift becomes equal to the weight of the vehicle.

According to a simplified but experimentally substantiated formula, the hydroplaning speed (V_h, mph) can be expressed as $V_h = K\sqrt{p}$, where p is the inflation pressure in psi and K is an empirical constant with an approximate value of 10. The implication of this formula is that a 25-psi automobile tire may be subject to hydroplaning at speeds around 50 mph, while an 80-psi truck or bus tire is safe even at speeds slightly exceeding 80 mph.

A number of parameters, in addition to vehicle speed, have a bearing on the phenomenon of hydroplaning. The danger of hydroplaning may be diminished or eliminated by reducing the thickness of the water layer below a certain critical value (0.10-0.40 in., depending on surface texture) by using tires with good tread patterns, by increasing inflation pressure (if practical), and by constructing rough, open-textured pavements.

Other Operating Conditions—A number of other traveling and testing conditions may also influence skid resistance measurements, such as the amount of water on the surface, operator habits, and instrumentation features.

The first factor mentioned deserves further amplification. It is normally found that the first traces of the water on the pavement (e.g., merely wiping the surface over with a moderately wet cloth) will achieve much (80 to 90 percent) of the total skid resistance reduction upon wetting; the addition of more water will lead to further slight reductions until a water depth of 0.5 to 1.0 mm (depending on surface texture) is reached. The addition of more water will result in a slight gradual increase in skid resistance, at least at higher vehicle speeds.

PRESENT TRENDS

An attempt is made in this section of the paper to outline the current trends in skid resistance research, both in North America and in Europe. While the picture presented is certainly not a comprehensive one, it is intended to be representative as far as the main avenues of progress are concerned. Some new developments, some recent arguments in areas of dispute, and some specific current research projects are mentioned.

For the sake of uniformity in organization, the material is presented under the same headings as in the preceding section: nature of skid resistance, measurement of skid resistance, and skid resistance parameters. A fourth heading is added to cover the utilization of research findings in measures taken to prevent skidding accidents.

Nature of Skid Resistance

Research is continuing on the basic theoretical concepts of tire-pavement friction, with particular reference to the distinction between the adhesion component and the deformation component of the frictional force. It is being emphasized (20, 21, 25) that the relative magnitude of these components depends not only on the conditions of lubrication but also, and to a great extent, on the properties of the pavement surface. There are "adhesion-producing" surfaces with very many and extremely fine asperities, and "hysteresis-producing" surfaces with much fewer, large, and rounded asperities. The adhesion term has been found (20) to be very much material-dependent and directly related to the damping properties of the tire rubber.

There is a laboratory study under way (36) concerning the thickness of liquid films trapped between rubber and a hard surface during sliding. While this is not specifically a skid resistance investigation, it is part of a broader attack on friction and lubrication. The immediate goal is to discover under what conditions lubrication effectively cancels the adhesion component of the frictional force.

A long-overdue new development is the current drive to create a standard terminology to cover the study of tire-pavement friction. It is hard to think of another field of engineering activities where the basic terms are so poorly defined, and so recklessly used, as in skid resistance research. A sampling of overlapping terms in the conventional terminology in the field includes skid resistance and skidding resistance, braking traction and braking friction, road friction and tire friction, sliding friction and locked-wheel friction, incipient friction and impending friction, gripping coefficient and break-away coefficient, braking-force coefficient and sideway-force coefficient, critical coefficient and peak coefficient. The establishment of uniform terminology would lead to discipline of language and clarity of concepts.

The main elements of a recently suggested (21) system of terminology are the following. "Skid" or "skidding" is defined as an uncontrolled motion of a vehicle and also, in accordance with general practice, the sliding or locked-wheel mode of operation of skid testers. The corresponding frictional resistance is referred to as "skid resistance." The expression "skid number" is introduced and defined as the ratio of skid resistance to wheel load, times 100. A tire is said to be "slipping" when its angular velocity is between that of a rolling tire and zero. ("Slip" is defined as the ratio of the difference between the angular velocities of the rolling and slipping tires to the angular velocity of the rolling tire, times 100.) In analogy to skid resistance and skid number the terms "slip resistance" and "slip number" are introduced. To identify the mode of slip more precisely, distinction is made between "brake-slip resistance," "cornering-slip resistance," and "drive-slip resistance."

Measurement of Skid Resistance

Correlation Studies—In order to derive common benefits from the individual research efforts, there has been a pressing need in recent years to correlate, if possible, the test results obtained with the different skid resistance testers.

In the United States, the first large-scale and well-organized comparison study was conducted in Virginia, just prior to the First International Skid Prevention Conference, in 1958 (8). Ten skid-test devices were compared, including six braking force trailers, two stopping distance test cars, a test car with a decelerometer, and a portable single-wheel type apparatus. The tests were performed on wet pavements at four test sites ranging from very slippery to good. The scatter of results obtained with the different devices was highly significant, varying from 0.20 to 0.40. Reproducibility appeared to be best for the stopping distance tests, worst for the drawbar-force type trailers.

Following this test series a considerable amount of development work was devoted to improving the skid trailers, particularly the calibration techniques and the force-measuring systems. The benefits became apparent during the second, more comprehensive Virginia correlation study conducted at Tappahannock, Virginia, in 1962.

This study (9) involved eight skid trailers, eight stopping distance test vehicles, and fourteen portable testers. The tests were performed on five specially prepared wet pavement surfaces, ranging in skid resistance from extremely low to relatively high. This time the locked-wheel trailers were found to give reliable and closely similar measurements, even the machines with different force-measuring systems. However, the scatter of the results obtained with the different trailers was still significant, and was apparently affected by both testing speed and surface characteristics. Very satisfactory correlation was established between the trailer test and stopping distance test results. Considering the test vehicles and the portable testers, the differences were large, especially at low friction values.

In Europe, a good example of such studies is the test series conducted in Paris (6) that compares the trailer method, the sideway force method, and the decelerometer technique. The three sets of test results appeared to be in good agreement. Less satisfactory results were obtained in a test series in Germany (27, 35, 39), which involved three of the most popular European test vehicles.

Several current research projects in Europe are aimed at establishing a meaningful relationship between the full-scale test vehicles and the portable testers (23).

Trends of Standardization—One direct result of the various correlation studies has been the full realization that the results of skid resistance tests are always performance (and not absolute) values, referring to a specific testing equipment and a specific set of testing conditions. This, in turn, has led to a growing desire on the part of all interested parties to establish a standardized testing technique.

In the United States, the locked-wheel skid trailer is on its way to becoming the standard equipment for routine field testing. This apparatus is simple and straightforward. It duplicates the first phase of the majority of skidding accidents, i.e., a locked-wheel skid. The interaction of a large number of factors in pavement-tire friction being as complicated as it is, it appears logical to use a method of measurement which eliminates extrapolation for such factors as speed, wheel load, tire size, and tread composition. Naturally, it is implied that the test trailer is constructed to closely simulate actual passenger car operation in all these respects.

It is expected that the standard skid resistance test will call for a locked-wheel skid trailer, sliding on wet pavement at a speed of 40 mph, mounting an ASTM standard skid test tire with a wheel load of 1085 lb (at rest). The ASTM standard tire (1) has an oil-extended SBR tread, its physical properties are closely specified, and it has a plain ribbed tread design. A tentative ASTM standard has been published (2) containing guidelines for constructing skid trailers.

The standardization process has been somewhat slower in Europe. The significant exception is Germany, where for some years now a locked-wheel trailer (Stuttgart-trailer) has been accepted as the standard testing apparatus (5, 27, 41). A trend has been noted in Europe (27) toward favoring smooth tires instead of patterned tires for skid resistance tests. The reason for this trend is that large and unpredictable variations in test results have been attributed to tread damage during locked-wheel tests and during continuous measurement of sideway-force or impending coefficients. Patterned tires are more susceptible to uneven wear and tread damage than smooth tires.

Other Developments—The requirements of modern road traffic as well as those of airplane operating conditions have led to the development of specialized test vehicles.

A skid trailer developed by the General Motors Corporation can perform skid tests at speeds around 90 mph. A trailer is being developed in Germany (5) to be used at testing speeds over 120 kmph. In Britain, a special test vehicle with a weight of 11 tons is being used on the Crowthorne research track of the Road Research Laboratory (14, 15) to investigate the effect of heavy wheel loads (up to 4.5 tons) and high inflation pressures (up to 300 psi). The variation of tire frictional forces with the amount of longitudinal and transverse slip is also being studied, by means of a vehicle carrying a test wheel whose longitudinal slip and slip angle are controllable. The skid trailer of the U. S. National Aeronautics and Space Administration (8) has been built to measure impending friction, which is the operative value with aircraft due to the elimination of wheel locking by automatic braking devices. Percentage slip may be varied from 0 to 50 percent on a very well instrumented Swedish test vehicle (17). A trailer-type device is being developed by the U. S. Federal Aviation Agency (37) which will measure friction coefficients on airfields under simulated landing conditions.

Skid Resistance Parameters

Pavement Parameters—Research concerning the effect of aggregate characteristics on the frictional properties of pavements is continuing along two main routes: full-scale tests on experimental road sections, and closely controlled laboratory tests.

The experimental road sections are laid by varying aggregate type, mix composition, and construction methods according to a predetermined pattern in segments along the test road. Traffic conditions are either controlled or closely observed, and periodic skid resistance measurements are taken. These studies normally take several years to complete but yield valuable data on a variety of pavement parameters and on the role of traffic and weathering. Such studies are either under way or are being planned in Tennessee, Texas, Florida, and New York. A study of this type was part of the AASHO Road Test (22), and similar investigations have been reported from Britain (14, 15), and Germany (5, 41).

Typical of current laboratory investigations are projects at the Swedish Road Research Institute (23), the National Crushed Stone Association, and the Portland Cement Association; these studies are aimed at determining the relationship between the petrographic characteristics of aggregates and their polishing susceptibility. The advantage of laboratory environment is that the interaction of the various skid resistance parameters can be simplified, or even the effect of one particular parameter can be isolated. However, the difficulty of simulating traffic wear and polishing must be faced. Several new accelerated-wear techniques are under development (23, 39).

Work is also continuing in connection with the other main pavement parameter, surface texture. The immediate task appears to be to express the texture of a pavement in quantitative terms, replacing the usual and somewhat ambiguous descriptors such as coarse, rough, and harsh. Present work by the National Aeronautics and Space Administration involves measuring the area over which a known volume of grease can be spread to just fill all surface depressions. A simple apparatus called the Outflow Meter, which provides quantitative measurements of the drainage capacity of pavement surfaces, has recently been constructed at the Pennsylvania State University (25). At the Crowthorne research track of the British Road Research Laboratory, measurements of surface texture are being made by a new stereoscopic method (15). Some preliminary work has been carried out (31) to establish the possible correlation between light-reflecting properties of a pavement and its frictional properties.

An extensive testing program is being conducted in Sweden (30) regarding skid resistance on ice- and snow-covered roads.

Vehicle Parameters—Considerable attention is being devoted to the role of rubber properties in tire friction, both in Europe (27, 36) and the United States (20). Recent developments include the significant finding (20) that high damping rubbers develop high adhesion as well as high hysteresis losses.

A study is in progress at the Crowthorne research station in Britain (14, 15) to evaluate the effect of the individual tread pattern elements, such as number of ribs, rib width, and rib separation. The behavior of different tires under different conditions of rolling and sliding is being investigated by photographing the contact patches under tires through an optical system built into the track. Significant reductions in skid resistance have been attributed to tire wear (10).

A relatively new area of research is concerned with the significance of studded tires in skid resistance and pavement wear. The use of studded tires on ice- or snow-covered pavements originated in the Scandinavian countries and has now spread to other countries in Europe and North America. There are now over 200 million studs manufactured in the United States per year (4). According to a recent test series (28), studded tires give about 40 percent higher effective skid resistance on ice than standard tires; the improvement is about 9 percent on packed snow, but is negligible on bare pavements. The studs appear to cause pressure spots, scratches, and grooves on the pavement surface, eventually leading to rutting (40).

Operating Conditions—The variation of skid resistance with temperature, seasons, and climatic conditions is also being further studied (23, 32). According to recent research (20), an increase in temperature leads to higher adhesion and lower hysteresis losses. The relationship between temperature and skid resistance can therefore be expected to depend on the relative significance of adhesion and hysteresis. It is a direct relationship on "adhesion-producing" surfaces, and an inverse relationship on "hysteresis-producing" surfaces.

Investigations are under way concerning frictional resistance at high vehicle speeds. It has recently been reported (14, 37) that coarse-textured surfaces are not only retaining a greater portion of their skid resistance at high speeds than the fine-textured surfaces, but they also exhibit a sharp recovery of skid resistance at speeds around 100 mph. The explanation has been offered (20) that the frequency required for maximum hysteresis loss on these surfaces is reached only at such high speeds.

The variation of skid resistance with speed is being examined in the light of surface texture parameters (18). The effect of the thickness of the water layer on the pavement and the hydraulics of run-off from road surfaces is also being studied (15, 23, 38).

Utilization of Research Results

Skid Resistance Standards—A common goal of many investigations, involving the consideration of stopping distances and the correlation of skidding accident data with skid resistance measurements, has been the establishment of minimum acceptable levels, or practical standards, of skid resistance. While most highway agencies now have such empirical standards, these are normally regarded as general guidelines only and not as legally binding standards.

The following standards have been suggested in Britain (13), in terms of sideway force coefficients measured at 30 mph: a minimum value of 0.60 for "difficult sites" (such as roundabouts, sharp curves, and steep gradients), minimum 0.50 for "general conditions," and minimum 0.40 for "easy sites" (straight and level sections without intersections). These values are based on measurements obtained with smooth tires. The possibility is now being explored (15) that measurements obtained with modern passenger-car tires may yield more reliable criteria.

For bituminous pavements in the city of Paris, a minimum sideway force coefficient of 0.50 is specified, measured one year after construction, at a speed of 30 kmph (30). In Belgium (30) a minimum sideway force coefficient of 0.50, as measured at 50 kmph, is required up to two years after construction. German specifications (5) call for a minimum sliding coefficient (skid-trailer) of 0.45 at 60 kmph.

Suggested minimum standards in the United States include 0.40 (26) or 0.50 (11) with locked-wheel trailers at 40 mph, 0.40 with the stopping distance method at 40 mph (29), and 0.40 with the decelerometer technique at 40 mph (24).

Anti-Skid Roads—In the final analysis the total research effort that has been discussed in this paper has just one single purpose: to develop ways and means of avoiding skidding accidents. One aspect of the problem is to make the roads safe by constructing surfaces which offer high frictional resistance throughout their service life. Failing in this high ideal, appropriate measures must be taken to correct existing slippery conditions.

In general terms, the requirements of adequate skid resistance call for angular and non-polishing aggregates, a harsh surface texture permitting fast drainage, and proper mix design (e.g., bitumen content) and construction methods (e.g., surface finish of portland cement concrete pavements). The best experiences in non-skid road construction (3, 33) have been obtained with silica-sand mixes, Kentucky rock asphalt, and slag mixes on the bituminous side, and with similar non-polishing aggregates and broom or burlap finish on the portland cement concrete side.

Slippery stretches of road are normally resurfaced using some non-skid mix. Special techniques include the application of resinous surface treatments (27), the removal of excess asphalt by burning, the dissolution of excess cement by acid treatment, and the mechanical roughening of portland cement concrete pavements.

Other Anti-Skid Measures—The other main aspect of providing adequate skid resistance on the roads is to increase the anti-skid characteristics of the vehicle itself. The two main possibilities are (a) improving the frictional properties of the tires and (b) controlling the braking action.

Tire friction can be improved by synthetic rubber tread compounds exhibiting high hysteresis losses and by bold tread patterns. Studded tires or tire chains may be needed on icy surfaces.

In order to utilize the maximum frictional resistance of pavements (impending friction or maximum slip resistance) devices are being developed (14, 16) which prevent wheel-locking during braking. Experimental versions of such devices have led to skid resistance improvements on the order of 10 to 30 percent.

Finally, the driver himself must, of course, be alerted to the dangers of skidding. He, too, can take anti-skid measures by adjusting his speed to road and weather conditions, and by using the "pumping" braking technique on wet or icy pavements.

FUTURE NEEDS

There is a definite need for continued research in many aspects of tire friction. Past results will have to be checked in the light of new developments and by means of the improved testing methods. Better understanding will have to be sought in areas of uncertainty or dispute. Some of the major research needs are summarized in this section of the paper.

A uniform terminology must be established so that the basic concepts of tire friction can be uniformly interpreted. It is strongly recommended that the HRB Subcommittee on Surface Slipperiness adopt such a standard, and insist on its use in any future reports.

In developing a better understanding of the basic mechanics of tire-pavement friction, a topic of high priority is the relative importance of the adhesion and deformation terms under different pavement, tire, and environmental conditions. Any further progress on this topic will automatically become the epicenter of new developments in the whole problem area.

The time is appropriate for international standards on measuring tire friction. Such a development would greatly enhance the benefits of individual research efforts; discussions and potentially fruitful arguments would not become bogged down on the relatively trivial point of how to measure the property in question. There would exist a common denominator to which points of common interest could be referred. Perhaps even more significantly, all routine tests could be performed by means of the standard method, the results of which would be easy to interpret in light of the widespread experience behind it.

The ASTM Committee on Skid Resistance is currently developing a standard method of measuring tire friction. It is the consensus of the membership of that committee that a skid-trailer would best satisfy the requirements for such a test method. At the same time, it is recognized that efforts should be made to further improve the trailer technique, particularly in the areas of trace evaluation, calibration procedures, speed recording, and brake control (19).

While the establishment of a standard approach is an immediate necessity, the use of nonstandard devices is not to be discouraged. On the contrary, there must remain a variety of measuring techniques in use, corresponding to the variety of goals of specific research projects. For example, further attention should be devoted to the relationship between tire friction and percentage slip; there are indications that on some pavements at high speeds tire friction increases with decreasing rotational speed, attaining a maximum at 100 percent slip (locked-wheel condition). It should also be possible to establish a meaningful correlation between locked-wheel coefficients and sideway force coefficients.

Of course, interest must be maintained with regard to new techniques of measuring the frictional resistance of pavements, such as the light reflectivity technique. It should be possible to evaluate the frictional behavior of a road surface in terms of its physical properties without a mandatory reference to a tire or some other rubber object actually sliding over it. Conversely, it should be possible to evaluate the frictional behavior of a tire in terms of its physical properties without actually dragging it over a pavement.

There is continuing need for laboratory investigations and for the reliable accelerated simulation of wear and performance under traffic. Nevertheless, such tests can never replace "real-life" testing programs. There is a definite need for laying full-scale test sections with both established and experimental design and construction methods, and for studying the performance of these sections under modern traffic conditions. Such projects may be unique in duration and perhaps in cost, but they are also unique in benefits.

In routine road construction, improved geometric design and better engineered traffic control systems should reduce the need for the critical vehicle maneuvers of cornering and braking (18).

Among the parameters associated with the pavement surface, quantitative characteristics of aggregates and of surface texture should be correlated with frictional resistance. A variety of ways are available for testing aggregates; the task is to decide which ones, or the combination of which ones, are relevant. Satisfactory and widely accepted techniques of quantitatively expressing surface texture should be developed. The effect of temperature, climatic factors, and traffic wear should be evaluated in terms of pavement type. It should be possible to predict with reasonable accuracy the future "skid resistance behavior" of a pavement at the time of construction, based on pavement and traffic parameters.

Among the parameters associated with the vehicle, basic rubber properties, tread pattern, tread depth, tire wear, wheel load, and suspension characteristics certainly require continued attention. The effect of vehicle speed should be expressed in quantitative terms. With regard to hydroplaning, it appears to be equally important to further explore the problem and to disseminate the knowledge presently available.

There is a pressing need for the establishment of realistic minimum acceptable values of frictional resistance in terms of pavement type, layout features, and traffic conditions (18). Such a scale can then be used to judge the adequacy, with respect to frictional resistance, of individual road sections. Similarly, criteria must be developed by which the adequacy of vehicle tires and braking systems may be judged, because all the present and future know-how on tire friction will have to be translated into eliminating skidding accidents by building safe roads and operating safe vehicles.

To realize these objectives, the public must be made fully aware of the implications of vehicle skidding, highway designers and contractors must appreciate the fundamental facts of tire friction, highway agencies must put into effect long-range research programs, and the individual research efforts must all be parts of an organized attack on the problem. It is the task of the HRB Subcommittee on Surface Slipperiness, the ASTM Committee on Skid Resistance, and the PIARC Technical Committee on Slipperiness to spearhead and to organize efficiently these developments.

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