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2101 Constitution Avenue　　Washington 25, D. C.

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Skid Prevention Research 1959

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1959
Washington, D. C.

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Resumé of First International Skid Prevention Conference

TILTON E. SHELBURNE, Director of Research
Virginia Council of Highway Investigation and Research

This report is a brief summary of the First International Skid Prevention Conference held at the University of Virginia in Charlottesville, September 8-12, 1958. It contains an explanation of the need for the conference, an account of the formation of the Steering Committee and subcommittees, together with an enumeration of the conference objectives. Information is also given concerning the type of sessions held and the conference program. The individual papers and discussions and the final subcommittee reports will be published in a conference Proceedings. Reports of the individual subcommittees present the status of existing knowledge of the subject, inventory deficiencies in present knowledge and practices, and enumerate areas in which additional research is needed. Several of the subcommittee reports also contain definite recommendations relating to ways and means of furthering the knowledge of the various aspects of the traction problem and of improving this particular phase of highway safety.

● THE PROBLEM of providing adequate traction between the vehicle tire and the pavement surface is a highly important one for only by adequate traction is it possible to start, steer and stop vehicles. The problem is accentuated by increased traffic and is important in the great road building program in which the nation is now engaged. The Interstate System is being designed to incorporate high geometric and structural design standards but the question may be raised as to whether adequate attention is being given to road surface properties which have such an important influence on the safety of the traveling public.

Engineers who have conducted tests find that in some instances pavements which are quite adequate structurally may, when subjected to a heavy volume of traffic for only a relatively few months, become dangerously slippery when wet. Also such tests often reveal a wide range in the coefficient of friction of pavements attributable to various construction materials and road surface textures. Some state highway departments have adopted the practice of performing skid tests or friction measurements on sections of pavement that appear to be accident prone or those on which skidding accidents resulting in fatalities occur. The problem of slipperiness is also encountered on airfield pavements, instances have been reported where pilots have had difficulty in stopping airplanes on wet pavements.

While some outstanding research has been performed on various phases of the problem, much more needs to be known, both quantitatively and qualitatively, about the frequency and nature of various kinds of skidding, causes, and the relationship of the various elements involved. Many of the studies conducted in this country have been reported only to groups interested in particular phases of the problem. Highway engineers, for example, are not intimately familiar with the role of the driver, the vehicle, the brake, or the tire in skidding accidents, nor are the specialists in these fields aware of all the problems the highway engineer must face. It was felt that much could be gained by an exchange of information between representatives from the various special fields, all of whom are working on certain phases of the skidding problem.

An examination of the many methods employed for measuring road surface friction lent emphasis to the need for such an exchange of information. It was found that at least a dozen such methods were in use in this country, and European agencies, working independently, had developed a number of others. In addition, very notable approaches had been made recently by some agencies in the developing of laboratory equipment to evaluate pavement surfaces and materials. Yet the full value of these various testing methods was not being realized because little effort had been made to correlate results obtained from them. It was necessary that the various independent groups exchange information on the many elements involved in measuring road slipperiness if the scope of needed research were to be narrowed and years of uncorrelated effort avoided.

When this reasoning was applied to the general problem of skidding it became apparent that rapid progress in skid prevention required that the various specialty fields would have to exchange information. Such an exchange would require a survey of what is now known and a clarification of what is not known. It was for the purpose of providing such an exchange that the First International Skid Prevention Conference was called.

FORMATION OF STEERING COMMITTEE AND SUBCOMMITTEES

Discussions of the need for the conference began early in 1957. While it was recognized that the skidding problem was of interest to a large number of various types of organizations, both here and in Europe, it was believed that the conference could best be planned by a few individuals who were active in the field. Subsequently, a Steering Committee was organized of individuals representing organizations vitally affected. This group was composed of some 20 individuals representing 17 organizations. The Steering Committee was responsible for the over-all planning of the conference, the establishment of the objectives, and decisions on numerous details concerning not only the conference itself, but the policies relating to publication of the Proceedings and many other items. An organizational meeting of the Steering Committee was held late in 1957 and four 1-day meetings were held during the past year. The author served as Co-Chairman of this group with Dr. W. H. Glanville, Director of the British Road Research Laboratory.

Early in the deliberations it became apparent that for planning and organizing the conference, each phase of the program could best be planned by a subcommittee. Five distinct areas of the problem were recognized and a subcommittee chairman was appointed from the Steering Committee to organize and plan each phase. The subcommittee chairmen were given considerable latitude as to the selection of membership, but it general, they selected men on the basis of qualifications, interest in the problem, and willingness to contribute.

Recognizing that the analysis of frictional forces necessary to accomplish accelerations, steering and stopping was important to the friction problem one subcommittee, headed by K. A. Stonex of the General Motors Proving Ground, was concerned with "The Relationship of Vehicle Dynamics to Skidding." Another important phase of the problem relates to the human element. This subcommittee operated under the chairmanship of Burton Marsh, Director, Traffic Engineering and Safety Department of the American Automobile Association. Paramount to the skidding problem are the tire and the pavement surface. John H. Cox of the Firestone Tire and Rubber Company, and Chairman of the Technical Committee of the Tire and Rim Association, was chairman of a subcommittee concerned with "The Relationship of Tire Design and Composition to Skidding." R. A. Moyer, Research Professor of the University of California, and A. T. Goldbeck, Engineering Consultant of the National Crushed Stone Association, were co-chairmen of a committee on "The Relationship of Road Surface Properties to Skidding." The fifth subcommittee was concerned with a "Review of the Laboratory and Field Methods of Measuring Road Surface Friction."

In addition to the above subcommittees, two others were organized to assist the Steering Committee in handling certain details. Carl Fritts, Vice-President of the Automotive Safety Foundation, was chairman of a Ways and Means Committee, which solicited organizations for financial support in carrying on the conference. A Public Information Committee handled news releases and advised on certain policies relating to the publication of the conference Proceedings.

OBJECTIVES

In addition to the formation of subcommittees for arranging the conference program, the Steering Committee also established the objectives of the conference for the guidance of the subcommittees. It was established that the International Skid Prevention Conference would have as its ultimate objective the reduction of skidding and skidding accidents to the fullest extent possible. To this end the immediate objectives of the conference were established as:

1. To exchange available information within each of the individual fields and between these fields relevant to the problem of adequate traction.
2. To inventory existing knowledge of the subject.
3. To inventory existing deficiencies in present knowledge and practices.
4. To develop a comprehensive program of research.
5. To demonstrate and correlate test results of existing equipment and methods for measuring skid resistance and initiate a program to develop standard testing procedures.

PROGRAM

The conference was sponsored by the University of Virginia in cooperation with 34 other agencies. It was held in Newcomb Hall, the new student activities building in Charlottesville, September 8-12, 1958. It should be mentioned that the program developed was a full one starting on Monday morning and lasting through until Friday noon. One session was devoted to opening ceremonies including a welcome by the President of the University of Virginia and a keynote address by Dr. Ned H. Dearborn, President of the National Safety Council. One-half day sessions of papers and discussions were scheduled by three of the subcommittees and full-day sessions from 8:15 to 5:00 p.m. were arranged by the other two. In addition, three subcommittees held informal open committee evening sessions.

The summary session on Friday morning was devoted to reports from the five subcommittees outlining the success of the committees in meeting the objectives established for the conference. Since in some instances these reports were of a tentative nature, further consideration was given them by the subcommittees and today the subcommittee chairmen are presenting final reports.

Exclusive of committee reports and discussions a total of 57 formal papers were presented to the group at eight sessions. Attendance at the conference was in the neighborhood of 200 individuals who came from 23 different states and three foreign countries. What is even more interesting is that these individuals represented a wide variety of backgrounds, interests, and organizations such as governmental agencies, research groups, automobile manufacturers, the tire industry, safety associations and universities.

PROCEEDINGS

The Steering Committee decided that one excellent contribution that could be made by the conference would be the publishing of all papers and discussions developed at the meeting. In addition to all papers and discussions the reports of the five subcommittees will be included in the Proceedings. These reports contain not only a summary of the status of present knowledge of the various phases of the skidding problem but also many of them inventory existing deficiencies in present knowledge and practices and contain recommendations as to possible approaches for further research in some of the areas where additional work is needed. Progress is being made on publishing the Proceedings and copies will be available some time after February 1st. Copies will be sent to all those who registered, contributed, or participated in the conference. Others desiring copies can obtain them from the University of Virginia by purchase. This publication is believed to be invaluable to all those interested in the subject.

CORRELATION STUDY

One of the objectives as established by the Steering Committee was the demonstration and correlation of test results of existing equipment and methods of measuring skid resistance. With the cooperation and assistance of several agencies and individuals such a study was conducted prior to the conference. Measurements were made with several test vehicles on Virginia pavements exhibiting a wide range of skid resistance. Some tentative results were given at the conference and a final report was included.

AN APPRAISAL

It seems appropriate to review the conference in retrospect attempting to appraise its accomplishments. There is perhaps little need to comment specifically at this time on the findings and recommendations of the five subcommittees as these will be presented by the individual chairmen.

The First International Skid Prevention Conference grew out of the need for an exchange of information among representatives of the several organizations concerned with the general problem of skid prevention. It is believed that this conference fulfilled successfully this need. The participants included capable men from all fields relevant to the skid problem and from them will come an imposing volume of information. These papers and discussions comprise an inventory of existing knowledge and pose particular problems for which solutions are needed.

In general, there seemed to be a good measure of agreement in most of the items raised at the conference. This is encouraging in that problems are being defined even if the best solution is not now apparent. Discussions at the conference did indicate areas in which future research may prove most fruitful.

For example, it developed that present data on skidding accidents was lacking and it was noted that benefit may be obtained from effective instruction in driving techniques. Another important point made at the conference was that many skidding accidents might be avoided if an anti-locking brake could be perfected. While improvements are being made in tire design and composition there appears to be a need for a better informed public in this respect. Undoubtedly one of the greatest improvements can come from the pavement surface itself. It is believed that this facet of the problem—the construction of surfaces having adequate skid resistance—deserves greater attention from highway engineers and administrators.

Finally, it is believed that the conference provided a valuable impetus to the work necessary for a drastic reduction in skidding and skidding accidents. If this impetus can be maintained and ways and means can be found for implementing the findings and recommendations of the subcommittees there can be no question that the conference successfully accomplished its objectives.

ACKNOWLEDGMENTS

The enthusiastic support given to the conference by all who attended and participated, and the financial assistance given by several organizations, are appreciated by the Steering Committee.

Accidents and the Human Element in Skidding

Final Report of Subcommittee B to the First International Skid Prevention Conference
University of Virginia, Charlottesville, Virginia, September 12, 1958

ACCIDENTS

●SKIDDING was reported as involved in four out of ten (41 percent) rural accidents in Virginia in 1957, according to reports reviewed in a study just completed, covering 34,139 accident reports.

In Great Britain in 1957, records indicate that one out of four (27 percent) personal injury accidents on wet road surfaces involved skidding—while on icy surfaces the proportion was four out of five (82 percent).

On the Pennsylvania Turnpike in 1952-1953, nearly one out of four accidents (22 percent) involved failure of the driver to cope with road conditions. Most of these accidents involved skidding.

These three analyses show what this subcommittee believes will be found wherever there is extensive motor vehicle traffic and adequate accident records:

Skidding is an important factor in highway accidents—indeed, far more serious a factor than is generally realized. And here we're not talking about icy conditions. Furthermore, many skids occur in which, because of circumstances, there is no accident.

Not only is the general public uninformed, but there is evidence that all too many highway administrators and engineers, other officials, and even traffic and safety specialists are inadequately informed.

One reason for this situation in the United States is that reliable skid accident data are unavailable in most states. Indeed, in major part because large-scale reliable skid accident data have not been produced by states, the National Safety Council has not included a summary on this subject in its annual Accident Facts booklet since the 1943 edition.

Furthermore, it is shocking but true that a standard form recommended by a national committee for police accident reporting doesn't even include a place for checking whether or not skidding took place. Consequently such information does not appear in the Standard Motor-Vehicle Traffic Accident Summaries for states or cities. Yet it is generally agreed that skidding is a factor in a large percentage of serious accidents—especially of course when road surfaces are wet or icy.

Moreover, the wet skid factor becomes more serious as speeds increase and the traction coefficient decreases—often sharply.

Increasing development of freeways and other high-type highways inevitably means higher speeds on such superior facilities. Furthermore, traffic volumes are increasing rapidly in many countries—and at the same speed it is clearly more dangerous to skid when there are more vehicles on the road.

Adequate and reliable accident data can be of great value in coping with skidding problems. Skid spot maps can identify bad skid zones. Such information can be used in public information; for enforcement as in apprehending persons driving at excessive speeds; in traffic engineering as in posting warning signs and installing center, lane and road-edge markings; in highway maintenance as in applying anti-skid surfacing materials. Skid accident information can also be of practical use in highway design as in reaching decisions as to sharpness of curves, intersection design, choice of road surfacing materials, methods, etc. Moreover, clearly the value of adequate accident data will increase as highway transportation develops.

Accident reports, based on investigations by trained police to the maximum extent feasible, should be made for all fatal and other personal injury accidents, and for at least the more serious accidents that involve property damage only.

Where feasible, even more thorough "case studies" of serious accidents on a limited sampling basis, can yield more technical, background information (as of basic reasons for driver trouble) when such studies are carried out by an engineer, physician and social scientist working together.

THE HUMAN ELEMENT

While improvements affecting skidding will be produced through physical developments in roads and control devices, tires, and vehicles, driver actions will remain a dominant factor in skidding. Hence, it is highly important that interest in such physical development be paralleled by adequate attention to human factors.

From analysis of driver-vehicle-and-highway factors in accidents and from other sources, it appears that many drivers are woefully uninformed about skidding. Matters often misunderstood or unknown include the following:

1. Friction between tires and road is often greatly reduced when the road surface is wet, increasing vehicle stopping distances very greatly. The effect of wetness on slipperiness varies greatly with different road surfaces, however.
2. Such friction for an emergency stop on most wet road surfaces is much lower in high speed stops. In a quite high-speed stop on a wet road, such friction is almost as low as that on ice.
3. Some road surfaces which are very non-skiddy when dry, become treacherously slippery when wet.
4. When a road surface is wet, its slipperiness cannot be judged at all by a motorist looking at it.
5. A shower after a dry speel on a heavily traveled highway may cause the highway, due to oil drippings and road film, to suddenly become very slippery until the rain cleans off the surface—even on the best of road surfaces.
6. Even the slightest swerve, brake application, or speed-up can "trigger" a skid on wet or icy road surfaces. The higher the speed, the more true this is.
7. Unevenly or badly worn tires may result in skidding and loss of control on wet roads the conditions of which are otherwise excellent.
8. Skidding is especially likely to occur at curves, near intersections, on steep hills, at traffic circles. One reason is greater pavement wear resulting in lowered friction coefficients. These are also places where drivers decelerate sharply, swerve or otherwise change course rapidly.
9. Many drivers have not developed patterns for action in skids—and understanding of what not to do. These are things which cannot be learned by reading alone—they must be experienced.

RECOMMENDATIONS

This subcommittee presents for Conference adoption the following recommendations:

<u>Recommendation 1—Accident Reports.</u> Each state in the United States, each country having substantial motor vehicle traffic, and each other agency which obtains accident reports is urged to give new and adequate attention to (1) having accident report forms which will produce specific information as to skidding (including information as to accidents in which skidding was a major or contributing factor, information as to the time of beginning of the skid in the accident action sequence, and distance skidded or length of skid marks); (2) assuring satisfactory accident reporting; (3) obtaining thorough skid accident analyses suited to needs of police, engineers, educators, etc., and (4) getting effective use of accident data in dealing with skidding. Skid information should be included in accident reports, whether or not skidding is considered the primary, main or direct cause of the accident.

<u>Recommendation 2—Status of Skid Knowledge.</u> Studies should be made to find out the extent of lack of knowledge and of misunderstanding about skidding among drivers and learners.

<u>Recommendation 3—Skid Instruction in Driver Education Courses, etc.</u> Specific instruction as to skid factors, forces and hazards should be included in high school driver and traffic education courses. Science teachers should be effective in educating and impressing students as to the various principles, factors and relationships involved

in skidding. Appropriate emphasis should also be given in such courses on how to drive under slippery conditions.

Similar knowledge should be imparted to the great majority of drivers who are past high school age. Research should be conducted as to how to accomplish this objective effectively.

Recommendation 4—Training in Sensing Impending Skids. Methods should be developed for training drivers in "sensing" and evaluating possible or impending skid situations in advance.

Recommendation 5—Training Through Induced Skids. Safe but effective techniques should be developed for training drivers, in advanced instruction or courses, in what to do in skids when they occur. Included should be actual experience in skidding to provide the "feel" of skidding, to overcome the natural tendency to panic, and to provide practice in recovery.

Recommendation 6—Driver Clues. To the maximum reasonable extent, drivers should be given helpful clues as to what is ahead, to help them avoid skids. Included should be: (a) realistic speed guide signs for sharp curves; (b) warning signs effective day and night for sharp curves, steep hills, dangerous intersections, traffic circles—these being likely skid locations; (c) reflectorized center, lane, and pavement edge lines, and reflectorized curve delineators; (d) signs warning of pavement which is especially slippery when wet, but only until prompt corrective measures are taken.

Recommendation 7—"Skid Zone" Programs. Each state highway department in the U.S.A. and each country having considerable motor vehicle traffic should carry on a continuing program of locating "skid zones" with unsatisfactorily low wet skid coefficients. In developing such programs, study should be given to the well-developed and effective program in England (through the Road Research Laboratory), to other European programs, and to developing programs and procedures in California, Kentucky, Michigan, Tennessee, and Virginia.

Such programs should be correlated with skid accident information, just as rapidly as reliable accident facts can be secured and analyzed.

However, such program can and should be put into operation even before accident data become available, based on wet skid coefficient surveys conducted on a priority basis, first on main highways at intersection zones, curves, traffic circles, on steep grades, and at locations ascertained from highway patrol officers, maintenance personnel, and motorists' complaints.

Such "skid zone" programs should include carrying out corrective measures, redetermining wet friction coefficients and keeping an appropriate map and tabulation as a "scoreboard" and "progress indicator" so that all highway department units and the general public may be kept informed. Repeat skid tests should be made at least annually.

Recommendation 9—Skid Resistance Standards. Highway authorities in all countries having considerable motor vehicle traffic should take steps as expeditiously as feasible to develop reasonable minimum standards of skidding resistance suitable for different highway speeds, times, locations, conditions, testing methods and devices to be used —but fundamentally providing adequate, reasonable anti-skid protection to motor vehicle drivers. Such minimum standards should apply both to existing and to new highways and should be developed expeditiously, especially since their advantages should apply to freeways and major highway systems (such as in the U.S.A. the National System of Interstate and Defense Highways) in the early stages of their development.

In the United States, it is suggested that development of such minimum skid resistance standards might well be a research project of the American Association of State Highway Officials, perhaps administered by the Highway Research Board.

COMMITTEE ON ACCIDENTS AND THE HUMAN ELEMENT IN SKIDDING

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O.K. Normann, Vice-Chairman
Richard O. Bennett
G.J. Fabian
Theodore W. Forbes
Roy Haeusler
W.A. McConnell
Daniel Reynolds
Harold S. Roberts
E.L. Smith

SUPPLEMENT—ADVANCE RESEARCH ON SKIDDING

Our subcommittee has been greatly impressed and encouraged by the many evidences of valuable research on skidding carried on by governmental and private agencies in a number of countries. Tire groups, motor vehicle manufacturers, road materials groups, governmental agencies—highway and other, universities and all other agencies which have done significant research relating to skidding are commended. Furthermore, the interchange of ideas which the Conference has made possible has produced many benefits.

During this Conference, our subcommittee has been greatly impressed by skid research progress in various European countries—notably, because of their participation through papers, in Holland, Germany and England. The dynamic quality of interest and activity in Europe challenges us. There are, no doubt, a number of reasons for such dynamic activity. Roads, weather, numbers of motor cycles and other factors presumably explain this in part.

However, in the case of England, another major reason seems clearly to be the existence of the Road Research Laboratory of the Department of Scientific and Industrial Research with permanent, suitably qualified staff and so organized, financed, and positioned that it is free to study any road or highway matter including safety—and apparently to devote reasonably adequate time and consideration to selected researches. Moreover, and most impressive, this English organization is clearly effective in cooperating with private-industry research and development, and in getting highway authorities and others to apply research findings, with outstanding results in the skid-research field. One reason for such laboratory effectiveness is that it is non-executive in function—it is solely a fact-finding, study and investigating agency.

Recommendation—Commendation of England's Road Research Laboratory, etc. It is recommended that this Conference commend this organization and operation in England for accomplishments in skid research—as well as all research units which have likewise presented valuable research reports at this Conference.

It is further recommended that this Conference group urge all countries having extensive highway systems and considerable motor vehicle traffic to give serious consideration to setting up some centralized research organization, with financing, staffing and operational policies which will be of similar service.

Relationship of Vehicle Dynamics to Skidding

Report of Subcommittee on Relationship of Vehicle Dynamics to Skidding to the First International Skid Prevention Conference, September 8-12, 1958

● THIS PORTION of the program consisted of the following papers:

"The Fundamentals of Braking—Heat Capacity and Control," J. George Oetzel, Vice President—Engineering Research, Warner Electric Brake and Clutch Company.

"Traction and Braking Characteristics of Vehicles," W. A. McConnell, Executive Technical Assistant—Vehicles Testing, Ford Motor Company—Engineering Staff.

"Vehicle Road Stability as Related to Suspension Geometry," R. T. Jarman, Project Engineer, Suspension Laboratory, Chrysler Corporation.

"The Dynamics of Vehicle Skid Deviation as Caused by Road Conditions," Dr. William Zuk, Highway Research Engineer, Virginia Council of Highway Investigation and Research and Associate Professor of Civil Engineering, University of Virginia.

"Experiments with a Device to Prevent Wheel Locking During Braking," R. D. Lister and R. N. Kemp, Vehicle Section, Traffic and Safety Division, British Road Research Laboratory.

INVENTORY OF WHAT WE KNOW

Brake Development

The fundamentals of brake systems are treated comprehensively and clearly in the paper "Fundamentals of Braking—Heat Capacity and Control," by J. George Oetzel. This paper lists the primary problems confronting the brake development engineer, and the paper and the appendices cover a great deal of engineering data on the braking problem and braking systems.

Included as a part of this report is an extensive bibliography on the general subject of vehicle braking which has been prepared by the subcommittee.

The student of the literature is well aware of the numerous problems which still confront the brake engineer in spite of the vast research over more than 50 years. While many problems still remain, it is to be noted that with proper maintenance the performance of modern braking systems on automotive vehicles is reliable and predictable.

Theory of Car Control and Stability

During the past five years, an extensive research project at the Cornell Aeronautical Laboratories[1] has resulted in a partial understanding, at least, of control and stability problems of the automobile. In essence, in the earliest stages, this work adapted the analysis of aircraft stability and control to the automotive problems, developed a tentative theory, and evaluated this theory by careful experimentation. Mr. Jarman summarized a part of this work in his paper. Progress is still continuing in this area.

Dr. Zuk contributed an application of dynamic theory to the treatment of certain perturbations.

Tire-Brake Behavior

Many of the problems of vehicle dynamics related to the skidding problem are associated with tire-brake behavior. For this reason, many aspects of tire behavior related to the dynamics of the tire-road system are studied by automotive engineers

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[1] "Research in Automobile Stability and Control and in Tire Performance." Five papers by W. F. Milliken and D. W. Whitcomb; Leonard Segel; W. Close and C. L. Muzzey; A. G. Fonda; D. W. Whitcomb and W. F. Milliken. Presented at a General Meeting of the Automobile Division, the Institution of Mechanical Engineers, in London, November 13, 1956.

so that the dynamics of the vehicle may be understood better. The paper by Mr. McConnell presented at this Conference, "Traction and Braking Characteristics of Vehicles," includes such data; significant is the demonstration that the static friction between the tires and the road surface is never reestablished on a rolling tire. From this, he concludes that the maximum benefit which can be derived from an anti-skid device is to regain most of the frictional reaction which is lost at high skidding speeds. Lister and Kemp, in their paper also presented at this Conference, "Experiments with a Device to Prevent Wheel Locking During Braking," give a very interesting study of experiments with such a device. The bibliographies of these papers, particularly McConnell's, include the significant references in this field.

GAPS IN OUR KNOWLEDGE

Tire Efficiencies

Tire efficiencies are reasonably well established under normal conditions in the transmission of braking, driving, and steering forces and combinations thereof, but little is known about efficiencies under extreme conditions of steering and braking. Since these are the conditions of particular interest to this Conference, the deficiency in knowledge must be regarded as a gap.

Effect of Unbalanced Braking on Skidding

There are data on the effect of unbalanced braking, front and rear, on skidding of a vehicle, but little data have been shown on the effect of unbalance in braking on the right and left sides.

Dynamic Behavior of Suspension Systems on Brake Balance

Little is known about the dynamic behavior of suspension systems with regard to changes in brake balance, and the resulting influence on skidding.

Differential Design

Little data are available on the influence of differential design on skidding. As an example, there are few quantitative measurements on record of the effect of the general class of locked differentials and on the variations of locking design.

METHODS OF FILLING THE GAP

Research

It is almost redundant to say that the only method of obtaining data which we do not now possess is through continued research.

1. The bibliographies associated with the papers presented on this program and prepared by the subcommittee are testimonial of the duration, scope, and depth of the research in this area. A reference to these bibliographies makes it clear that there are thousands of engineers and scientists engaged currently in such research, principally because of the pressures of industrial competition.

This research has been under way for some years. It is continuing with increasing emphasis, and it is inevitable that valuable results will be derived.

2. The Winter Driving Hazards Committee of the National Safety Council has a history of more than 20 years of significant achievement in evaluating and describing the hazards of operation on roads made slippery by snow and ice. During this period, they have made critical evaluations of innumerable traction devices with respect to standard equipment, and it is suggested that this unbiased group might make immediate studies to measure the effect of unbalanced right and left braking and of differential design on skidding.

Exchange of Information

It is recognized everywhere that the exchange of information through technical societies and through such conferences as the International Skid Prevention Conference add to the rate at which new knowledge is developed. We are confident that a most effective method of filling the gaps in our knowledge of this problem will be the interchange of information in scientific conferences. Here each of a group may add one of a series of related facts, so that when many of the pieces are in place, the remainder may be inferred.

Continued Development of Anti-Skid Devices

This Conference has seen some interesting results with anti-skid devices, and at least the elements of a discussion of their limitations.

We are led to believe, from the data presented by McConnell, that the ultimate in an anti-skid device would be to restore a reaction between the tire and the road, equivalent, for example, to a 5-mph sliding speed. It has been shown many times that the coefficient of friction decreases with sliding speed; according to this presentation, we might hope to reestablish as the ultimate the sliding coefficient prevailing at 5 mph sliding speed to the case of a vehicle going an actual speed of 60 mph, for example. It is also implied that of the total reaction between the tire and the road, part can be used for stopping and part for steering. In the experiment described by Lister and Kemp, we are given some quantitative measurements of relative stopping ability of a vehicle with an anti-skid device, and a demonstration, but not quantitative measurements, of the degree of steering control available simultaneously; it seems evident that continued development of these devices is essential to determine the practical maximum capabilities in simultaneous stopping and steering.

Control Systems

Vehicle control systems have developed through the years on a practical basis, and it is believed that they have evolved to the point where they are generally satisfactory to the majority of people. However, the effectiveness of control systems is determined currently by popular vote rather than by scientific evaluation. It is our hope that the application of the methods of experimental psychology will promote the development of control systems more effective with regard to both precision and driver response.

For the Subcommittee
by K. A. Stonex, Chairman

Appendix

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Relationship of Tire Design and Composition to Skidding

Report of the Subcommittee on Factors in Tires that Influence Skid Resistance to the First International Skid Prevention Conference, September 9, 1958

WHAT WE KNOW

● THE FUNCTION of a tire is complex, and the requirements may be diammetrically opposed. The total tire design must effect a compromise of control, stability, comfort, noise, skid resistance, and treadwear characteristics meeting the majority of driving requirements.

For example, a soft sponge-like tread composition with a highly slotted design might be best for skid resistance on some road surfaces, but would wear so fast that any advantage would be quickly lost.

The Effect of Tread Design

The tread design is one of the most effective features of the tire in influencing its resistance to skidding on most common road surfaces when they are wet. Note we are talking about "wet" pavement. The elements of an anti-skid design which contribute to its skidding resistance or increase the coefficient of friction on wet surfaces, are the following, which in effect, reduce the lubricating action of the fluid by removing it.

Grooves. These provide a venting or a void to which the fluid at the interface of the tire and the road can be displaced by the pressure between them. Circumferential grooves can improve the skid resistance from 20 to 100 percent on wet surfaces depending on its coefficient.

Edges. These provide a wiping action over wet road surfaces and more effectively remove the fluid between them and the tire. On extremely low coefficient road surfaces the effect of the wiping action of the edges made with molded slots and cut slits can improve skid resistance up to 100 percent. For most road surfaces in the range of coefficient 0.4 to 0.5 the improvement is 20 to 25 percent.

The extent to which the design features influence the resistance to skidding is summarized in Figures 1 and 2.

The tire industry has made a very marked improvement in skid resistance on wet pavements in recent years by the use of highly slotted anti-skid designs. This is made possible by tread compound improvements which increase the tear resistance and permit the same highly slotted tire to be driven at turnpike speeds for long periods of time without failure.

A comparison between the degree of slotting used in present designs and those of 12 to 15 years ago is given by Figure 3 and Figure 4 for highway-type tires. A similar comparison for mud and snow types is given by Figures 5 and 6.

It should be noted that while relatively large percentage improvements on very smooth low coefficient wet surfaces can be obtained by anti-skid designs or treatments, skidding distances are still very large and hazardous. For example, an improvement of 33 percent in changing the coefficient from 0.3 to 0.4 changes the skid distance at 30 mph only 25 ft from 100 to 75 ft. This is still a very long and hazardous slide, especially if the vehicle cannot be controlled.

The rapid loss of skid resistance on wet surfaces as the tire approaches a worn out condition emphasizes the hazards of operating on such smooth or bald tires.

Figure 7 shows the loss of skid resistance with decreasing anti-skid depth. On the extremely low coefficient surface of wet ice it is found that the edges provided by grooves, slots or slits are effective to approximately 20 or 25 percent.

Now consider dry pavement. On dry pavement the most effective tire is the one having the largest net contact area with the road, that is, the "bald" tire. Grooves or slots, in general, provide edges which tear or decompose with the high temperatures

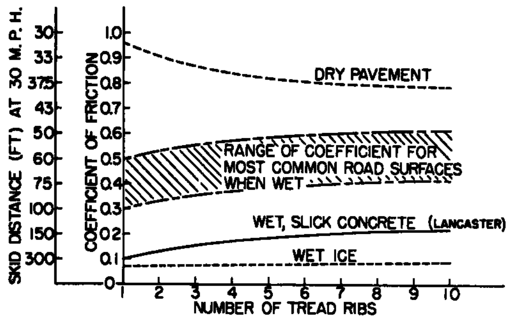

Figure 1. Coefficient vs number of tread ribs; highway-type passenger tires, comparisons at 30 mph.

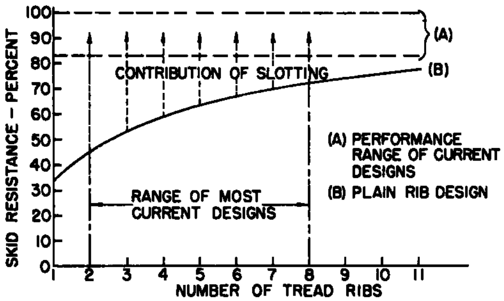

Figure 2. Skid resistance of passenger tires; effect of tread ribs combined with slotting, wet slick concrete (Lancaster test surface).

developed at the interface in dry skidding and this action diminishes the resistance to skidding.

The comparison between the coefficients of friction realized on dry pavements with and without tread ribs on the tire is shown in Figure 1.

Modern mud and snow tires provide an improvement of the order of 25 percent in skid resistance on winter surfaces over present conventional highway types of tires, utilizing the maximum edges, grooves and slots—but at a sacrifice at treadwear. The comparison between the performance of highway and snow type is shown in Figure 8.

Tread treatments of mud and snow tires such as "tractionizing" and the use of corn grit treads are effective in improving skid resistance on winter surfaces by approxi-

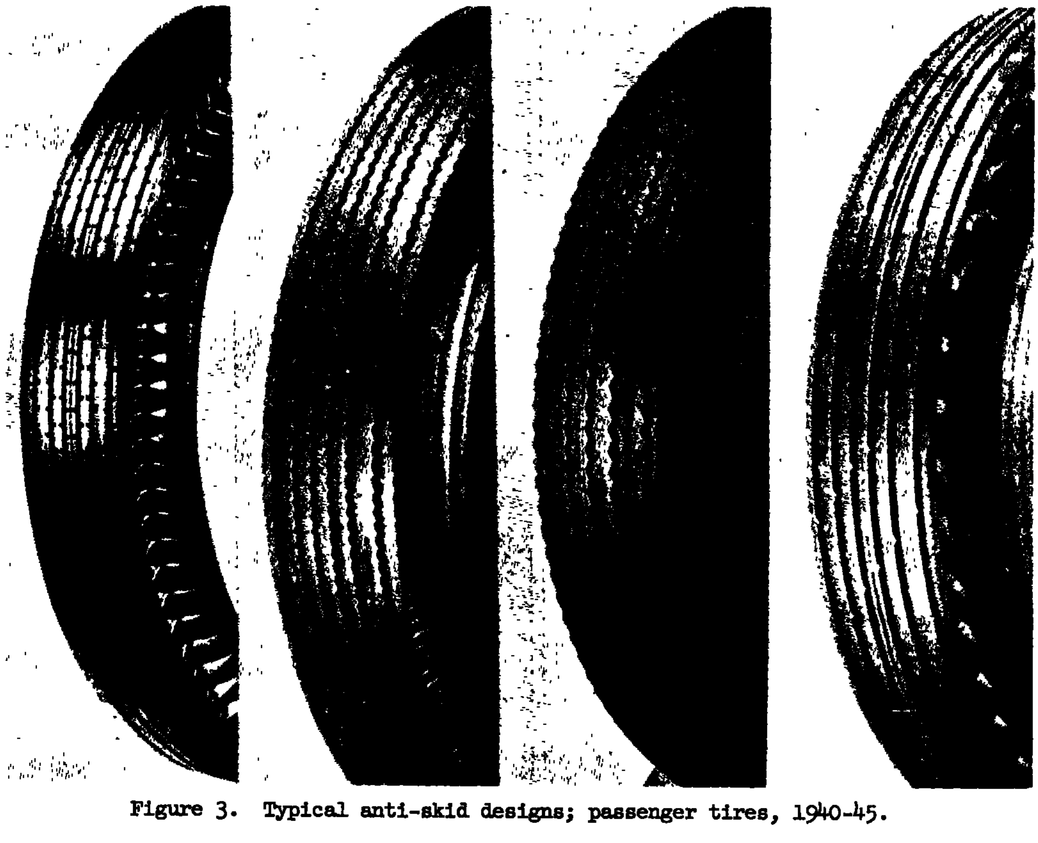

Figure 3. Typical anti-skid designs; passenger tires, 1940-45.

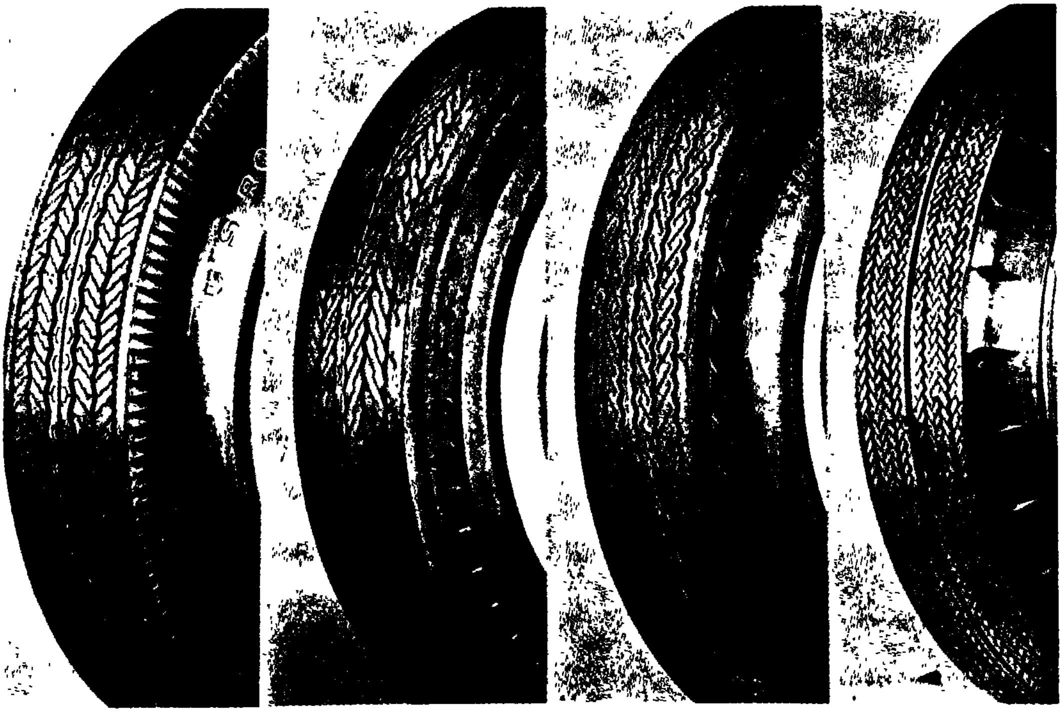

Figure 4. Typical anti-skid designs in passengers tires, 1957-58.

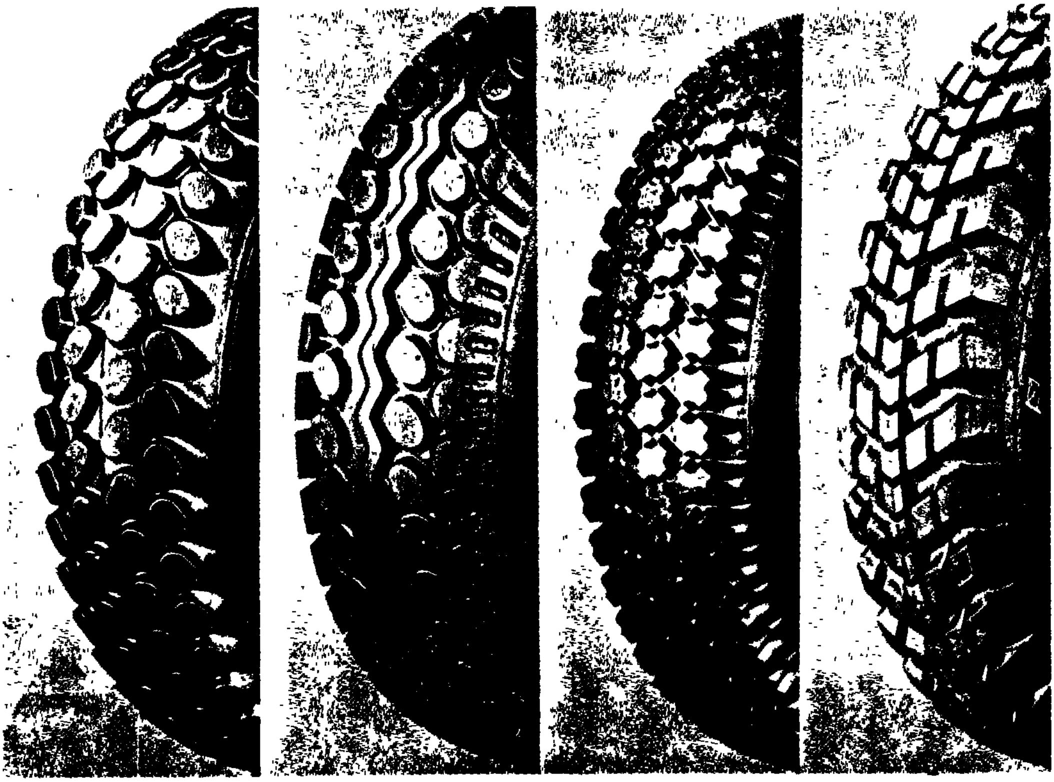

Figure 5. Representative mud and snow tires, 1948-49.

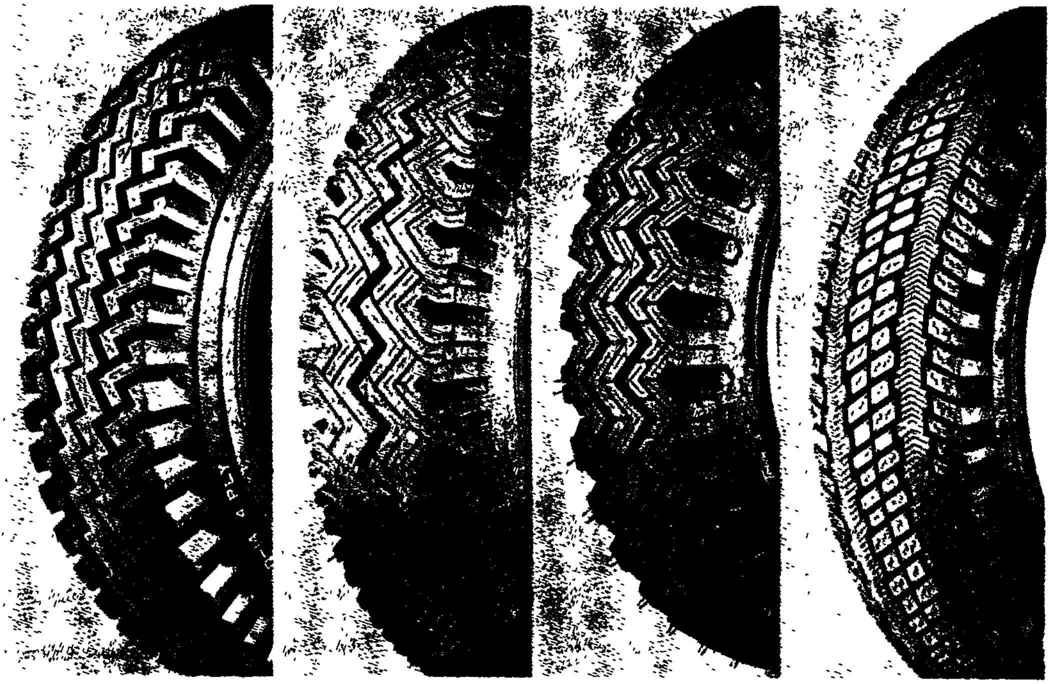

Figure 6. Representative mud and snow tires, 1956-57.

mately 10 percent. These treatments are limited because they can be done only to a degree that does not result in tread tearing and subsequent failure at present day driving speeds.

Typical examples of the tread treatments such as "tractionizing" and "corn grit treads" are shown in Figures 9 and 10.

May we emphasize that poor tire maintenance, causing excessive or uneven wear, such as underinflation and misalignment, can quickly destroy the skid resistance value of any design.

The Effect of Carcass Construction and Tire Size

The data shows the effect of carcass construction features such as cord angle, number of plies; also tire size, does not have a significant effect on skid resistance.

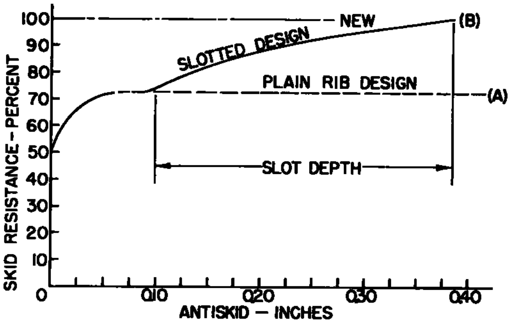

Figure 7. Skid resistance vs anti-skid depth; wet slick concrete (Lancaster test surface).

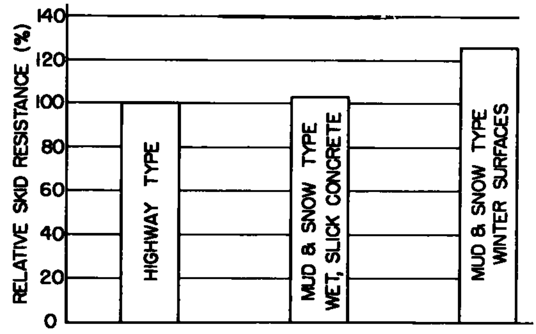

Figure 8. Relative skid resistance; mud and snow vs highway-type passenger tires.

Figure 9. "Tractionized" tread treatment.

The Effect of Tread Composition

The effect of tread composition on skid resistance is very important. However, of equal importance are wear resistance and weathering; ozone, deterioration, and cracking resistance; and low heat build-up, good ride, low noise, stability, etc. Almost without exception, compound alterations which improve one or more of the essential service characteristics adversely affect the others. Further, a compound giving the best skid resistance on dry pavement may not be satisfactory for wet surfaces on ice and snow.

The superior skid resistance of GRS synthetic rubber, which is now the standard in all USA passenger tread compounds, is well established—especially in high speed, locked wheel panic stops on dry surfaces. This is primarily due to the fact that GRS's initial melting point is about 100 deg higher than natural rubber.

Figure 10. Tread stock with corn grits.

Special winter tread rubber provides a substantial improvement in frictional coefficient on ice and snow, as has been pointed out, at an appreciable sacrifice in treadwear.

Effect of Load, Inflation, and Speed

The load and inflation affect the coefficient of friction, but the effect is relatively minor.

Speed and application of power, factors entirely under control of the driver, create forces of enormous magnitude.

Even under the best possible dry road conditions, the tire-road surface reaction may be insufficient for vehicle control.

Certainly on low friction surfaces the available tire-road forces can easily become entirely inadequate.

Under such conditions, there is no choice but for the driver to reduce speed and power factors into a range of safe vehicle control.

NEED

1. A standard skid test tire is necessary to develop and correlate road surface friction measurements.
2. Strictly controlled studies will have to be undertaken to assure that a given type of standard skid test tire will give reproducible measurements on each type of surface friction measuring device, and will produce accurate correlations.

METHODS OF FULFILLING THE NEED

1. Tire manufacturers have a vital interest in skid prevention, the experience, facilities, manpower, and the technology to push forward research in tire-road friction reaction.

   Competition has resulted in major progress as demonstrated by new mud-snow designs. This research will continue to produce results.
2. The Technical Advisory Committee of the Tire and Rim Association has authorized this committee to prepare a standard skid test tire specification subject to the approval of the Association. These tires may be manufactured by any member and offered for sale in limited sizes.

J.H. Cox, Chairman
Clarence Hofelt, Jr.
W.C. Johnson
Louis Marick
M.A. Reinhart

Relationship of Road Surface Properties To Skidding

Report of Subcommittee D to the First International Skid Prevention Conference
University of Virginia, Charlottesville, Virginia, September 8-12, 1958

● THIS REPORT is based on papers presented on September 11 before the First International Skid Prevention Conference. Nineteen papers were given at that Conference, together with a number of discussions. Obviously, I can only hope to give you the highlights which, in the main, have been agreed to by the Conference Subcommittee and later also by the Steering Committee.

Professor Moyer and I were co-chairmen of the Conference subcommittee, an arrangement necessitated in part by geographical location.

Highlights of Existing Knowledge Which Are of Outstanding Importance

The following statements are based on the various presentations given on the program of September 11. In some cases, these observations did not meet with universal agreement between all investigators and therefore should be subject to further research for verification.

1. Pavements of all types are much more slippery when wet than when dry. The skidding hazard is greatest during the first few minutes of rainfall following a period of dry weather, while after a continued downpour the slipperiness is greatly reduced.
2. Many road surface factors affect skid resistance, including surface condition, surface construction type, surface maintenance, type of aggregate, cement or binder, surface texture, road roughness, foreign material, and surface contamination, water, surface scouring, age, weathering and climatic effects, time effects, temperature, traffic, and highway design.
3. The effect of surface texture on flexible pavements was the subject of some disagreement. Although no one denied the hazard of a smooth texture caused by an excess of bitumen in contact with the tire, the relative merits of coarse and fine texture as related to aggregate size were still in debate. Several cited the advantage of a coarse, open texture on which surface water can drain away rapidly; this type of texture was described by some as "nobby." However, other data indicate that the highest coefficients of friction may be obtained on pavements constructed of very fine aggregate the greatest proportion of which may pass a No. 40 sieve. Even sheet asphalts with around 10 percent asphalt binder and 12 percent aggregate passing the No. 200 sieve have been reported to have very satisfactory skid resistance.
4. It is well recognized that rounded aggregates and the presence of an excess of asphalt are common causes of slipperiness. However, the polishing of certain types of aggregate used in surface construction is rather generally believed to be the principal cause of pavement slipperiness in most of the United States. Cases have been reported where even "nobby" textured surfaces built of such aggregates have become extremely slippery as a result of the polishing action of rubber tired traffic.
5. On multi-lane surfaces, the driving lane generally is appreciably more slippery than the passing lane. This is due to the polishing action of greater traffic, and in part to the greater accumulation of oil films.
6. Almost all aggregates will become polished under intense traffic, some, however, much sooner than others. Certain sandstones and gneisses are said not to polish in the laboratory. The softer stones generally polish sooner than the harder stones. However, in service, many roads built with the softer stones have not polished sufficiently to cause slipperiness; their skid resistance is adequate for the traffic conditions.
7. Work in Europe, both in England and the Netherlands, has indicated that the skid resistance depends partly on the deformations of the rubber due to projections in the surface. Apparently for the best results, individual particles in the road surface should have angles at their tips of 90 deg or less.

8. On ice, the most hazardous condition exists at temperatures near the freezing point. Thus, at -30 F, the bare tire skid distance is around 80 ft, but at +35 F it is 250 ft. It is found that tire chains are most beneficial under the severest conditions. Special tires are effective 85 to 90 percent of the winter period. But no matter what may be the tire equipment, speeds should be considerably reduced when driving on ice and snow. Snow tires and tire chains are apt to give a false sense of security. Reduction in speed is highly important.

9. The geometric design of pavements is dependent on the frictional resistance between the tires and the road surface. The friction coefficients suggested are as follows:

a. Maximum side friction factors[1] ranging from 0.16 at 30 mph to 0.12 at 70 mph are used with practical super-elevation slopes to determine minimum safe radii of horizontal curves for open highway conditions.

b. For intersection curves where design speeds are less than 50 mph maximum side friction factors ranging from 0.32 at 15 mph to 0.16 at 40 mph, similarly are used to determine minimum safe radii.

c. Straight-ahead or braking friction factors[2] for wet weather conditions ranging from 0.35 at 30 mph to 0.28 at 70 mph are used to determine safe stopping distances which establish minimum sight distances for provision throughout the highway.

d. Speed-change rates used to establish length of deceleration lanes are equivalent to straight-ahead or braking friction factors ranging from 0.18 to 0.28 for deceleration from initial speeds of 30 to 70 mph, respectively.

Although the above friction factors are not referred to any particular form of test, they necessarily represent values which correspond with those measured by braking a vehicle. They were determined as those to be nearly all-inclusive regarding variations in roadway types, vehicle and tire and weather conditions. Relatively uniform roadway surface characteristics necessarily are assumed. For other than completely adverse conditions the values used provide a substantial safety factor for the large majority of existing roadway surfaces.

The criteria used in geometric design made no allowance for unusually low frictional values resulting from ice, bleeding asphalt, oil slicks, or very highly polished aggregates on the pavement surface. It is assumed that these are temporary conditions which will be eliminated by maintenance.

Wet roadway surface friction factors used to determine design braking distances (9c) are logical check criteria for determination of roadway surfaces that require corrective measures to provide essential highway safety.

10. One prolific source of skidding accidents is the presence of ruts in the shoulders immediately adjacent to pavement surfaces. Such ruts are extremely hazardous and should be guarded against with vigilance.

11. Preventive and Corrective Measures. Methods reported to have been used to improve the skid resistance of bituminous pavements with no other deficiencies include seal coats with non-polishing aggregate cover, resurfacing with siliceous rock asphalt, resurfacing with fine sand mixes designed to simulate rock asphalt, coating with epoxy resins with abrasive cover, and coating with asphalt-rubber latex covered with non-polishing aggregates. The use of thin silica sand mortar overlays for resurfacing slippery concrete surfaces was also reported.

Deficiencies in Our Present Knowledge

There are deficiencies in our present knowledge, notwithstanding the tremendous amount of research which has been done in this country and in Europe. It is difficult to catalogue all of the subjects which might profitably be investigated. However, the following will indicate at least a few of the more prominent deficiencies.

1. Although some ingenious friction measuring devices have been built to determine coefficient of friction, it seems to be desirable that these methods be carefully reviewed

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[1] AASHO Policy on Geometric Design of Rural Highways, pp. 128-133 (1954).

[2] ibid., pp. 112-117.

with the idea of insuring that all of the forces involved be fully accounted for. Devices of a given type should give practically identical results and until that can be assured, such devices cannot safely be used in a national standard. This does not at all imply that such devices are not valuable for comparing different road surfaces. They are extremely useful for rating road surfaces for slipperiness. A simple device for comparing the various methods used in different states is much to be desired.

2. Of immediate importance is the development of methods for proportioning and building road surfaces which will have built-in non-skid properties.

a. Concrete Pavement. In the concrete pavement, possibly this can be done by the use of more sand in the mix with the idea of creating a thicker mortar surface than has been customary for many years. Air entrainment may possibly make this idea practicable. This is suggested as worthy of research.

In the building of concrete pavement surfaces there is the possibility of vibrating anti-skid aggregate into the surface during construction. This has been done successfully in the laboratory. It needs work in actual construction. Also, when necessary, two-course construction can be resorted to, using a mortar top course.

b. Asphaltic Pavements. In the asphalt type of pavement proper proportioning and the use of anti-stripping agents to prevent flushing of the asphalt to the surface are desirable. Research along this line should be profitable.

Also, in the asphalt type, more work on the minimum percentage of siliceous sand needed to provide anti-skid properties is necessary. Possibly also that proportioning of the mix which will result in the more rapid wear of the matrix than of the coarse aggregate may be beneficial. Possibly basic research on the asphaltic cement would be profitable.

3. The method of using a sand-asphalt, thin surface mixture as practiced in Virginia needs more widespread investigation throughout the country in order to determine if this relatively lean surface mixture will be sufficiently durable under all conditions. If this type of mix is not found to be sufficiently durable, then further research on the durability phase of this type of mixture will be needed. Also, the contention by some that in heavy downpours, such fine textured surfaces may lose their skid resistance, especially with regard to vehicles traveling at high speed, needs further investigation. The work of the NACA at Langley Field, showing the tendency of tires to "aquaplane" over heavy films of water at high speed, is cited.

4. Other economical methods of improving the skid resistance of pavements having no other deficiency should be investigated, both in the laboratory and on actual road surfaces.

5. Laboratory methods for studying pavement slipperiness and methods for overcoming it have been used with apparent success and they offer great promise of furnishing valuable preliminary data prior to proof of these methods under actual road conditions. The calibration of laboratory devices in terms of permissible degrees of actual road slipperiness would be useful.

6. Pavements, like all other structures, need maintenance for their adequate preservation. Intense traffic has brought about the necessity for a new type of maintenance, that for preserving the surface in a sufficiently non-skid condition. Without doubt, many more researches on the improvement of slippery road surfaces could be made with profit. The above are merely suggestions.

Statement of Methods Which Give Promise of Overcoming Slipperiness

At present, the most effective method of overcoming the slippery surface condition seems to be the use of the fine grained silica sand asphalt mix. This mixture resembles sheet-asphalt in texture, but contains less asphalt (around 8 percent) and fewer fines passing the No. 200 (not over 8 percent, often much lower). The purpose of the lower percent of asphalt is to produce a surface which will gradually wear and expose previously unexposed sand particles. Hydrated lime or certain heat stable chemical additives are usually added to the mix to prevent stripping of the asphalt in the presence of water. This type of mixture is laid hot by one of a number of commercially available spreading devices. The rate of application ranges from 12 to 50 lb per sq yd.

Other means of de-slicking pavement surfaces involve the use of ordinary bituminous surface treatments or seal coats with small size, durable, non-polishing cover aggregates. Such treatments are recognized as temporary and requiring renewal at intervals of several years. Immediately after application, this type of treatment must be protected from damage from heavy traffic, particularly in regions where rainstorms may be expected to occur without warning; otherwise the cover aggregate may be whipped off, leaving a "fat" surface which may become as slippery as the original surface. At best, surface treatments may not be expected to provide as uniform non-skid texture as the fine sand-asphalt plant mixes.

In extreme cases perhaps some of the new developments involving special resins with abrasive cover may be found desirable. At present, however, treatments of this type are too costly for general use.

RECOMMENDATIONS OF SUBCOMMITTEE D (ROAD SURFACE PROPERTIES AND THEIR RELATION TO SKIDDING)

The following recommendations were agreed to by the Skid Prevention Conference Committee:

1. That all states be encouraged to institute a program of rating highways with regard to slipperiness. This can be done initially on large portions of their systems by reference to skidding accident records, to the experience of local highway and police personnel, and by careful judgment, bearing in mind that appearance of the pavement may be misleading. Pavements with doubtful skid resistance should be subjected to some accepted type of skid test.
2. That every effort be made to develop a standard test method for measuring pavement slipperiness.
3. Further, that the AASHO be encouraged to adopt standards of road slipperiness in terms of minimum coefficients of friction. These standards should be proportioned to the potential skidding hazards created by geometric features such as curvature, grade, sight distance, width, intersections, and to the volume of traffic using the section. These geometric and traffic factors should govern a classification of the skidding hazard as slight, moderate, or critical, and separate road surface friction standards should be set up for each class. Such standards should serve as a basis for determining sections of road which need anti-skid treatment.
4. That all states be encouraged to develop methods of building surfaces having adequate skid resistance at the time of road construction. The findings of the skid resistance measurements on existing roads and of laboratory tests should be utilized to avoid the use of surfaces which are prone to become dangerously slippery in service.
5. That all states attempt to provide a reasonable similarity in the friction levels in contiguous projects through appropriate surface treatments (but with due regard to the friction levels suggested in Section 3).

CONCLUSION

In conclusion let me acknowledge the assistance and advice of the members of Subcommittee D on "Road Surface Properties and Their Relation to Skidding." This committee consisted of:

Ralph A. Moyer, Co-Chairman
Harold Allen
D.W. Loutzenheiser
F.P. Nichols, Jr.
K.B. Woods
A.T. Goldbeck, Co-Chairman

Comparison of Several Methods of Measuring Road Surface Friction

JACK H. DILLARD, Highway Research Engineer, Virginia Council of Highway Investigation and Research, Charlottesville, Virginia; and
TERRENCE M. ALLEN, Assistant Professor, Highway Traffic Safety Center, Michigan State University

●DURING THE PLANNING of the First International Skid Prevention Conference, September 8-12, 1958, at the University of Virginia, it was recognized that the lack of data on the relationship of the various machines that measure coefficient of friction was a serious handicap in attacking skid resistance problems. Therefore, the authors conceived an approach to a correlation of several machines and proposed an experiment. With the endorsement of Subcommittee E and the Steering Committee, planning of the experiment began and during the week of August 25-29, 1958, two weeks prior to the conference, the experiment was conducted.

The need for such a correlation had become apparent in recent years. Concurrent with recognition of the problem of pavement slipperiness in the 1920's and 1930's came the need to make measurements, a need resulting in development by many people of techniques and equipment for measuring road surface slipperiness. Because some engineers were seeking economy, some convenience, and some proximity to theoretical concepts, the equipment differs considerably. The total result of the innovations is that many beneficial ideas are represented in the several dozen machines used in the United States to measure road surface slipperiness, but also that the existing methods differ appreciably in their designs and the results they obtain. These differences make difficult the pooling of data collected by various agencies throughout the country and in general hamper progress toward safe, anti-skid roads.

PURPOSES OF STUDY

Specifically, the purposes of the correlation study were as follows:

1. To compare the test results obtained by the various machines equipped as they are normally used by the respective agencies (Series X).
2. To compare the test results when the tire variable was minimized by using the same kind of tire on each vehicle (Series Y).
3. To obtain information on as many other important aspects of measurement as could be worked into the experiment (Series Z). These include:
    (a) To compare the results from a stopping distance method and a decelerometer.
    (b) To compare the sliding, incipient, and sideway force coefficients.
    (c) To determine the influence of speed on the locked-wheel and incipient friction coefficients.
    (d) To compare a portable laboratory and field method with a stopping distance method.

DESIGN OF THE EXPERIMENT

The experiment was carefully designed so that a sound statistical analysis of results was possible. Insofar as possible all factors affecting results were controlled either experimentally or statistically.

Four test sites, each having a different level of friction, ranging from dangerously low to very high with two intermediate levels approximately uniformly spaced within this range, were selected. The designations of the levels, and their approximate coefficients of friction as obtained from the means of all measurements on the section were as follows: poor 0.25, fair 0.37, good 0.51, and excellent 0.62. These values were obtained at 40 mph when the pavements were wet.

In the main portion of the experiment (Series X and Series Y) each machine tested each pavement with its regular tires (those normally used on the equipment) and with the standard (specially prepared) tires. For adequate precision, more than one test run was required for each combination of machine, tires, and pavement. Available data indicated that successive measurements by the stopping distance method had a standard deviation of the order of 0.02. In order to be 95 percent confident of an ac-

TABLE 1

SUMMARY OF CHARACTERISTICS OF MACHINES PARTICIPATING IN STUDY

Machine No.	Agency	Type	Braking Conditions	Tire Size	Normal Static Load per Wheel (lb)	Force Measuring System
1	Bureau of Public Roads	1-wheel trailer	1 wheel locked	6.70-15	1,110	Drawbar force
2	Portland Cement Association	2-wheel trailer	2 wheels locked	6.70-15	925	Beam deflection
3	Cornell Aero Laboratory	1-wheel trailer	1 wheel locked	6.70-15	970	Brake torque
4	General Motors Proving Grounds	2-wheel trailer	2 wheels locked	7.60-15	967	Torque tube deflection
5	National Aeronautics and Space Administration, Langley Field	2-wheel trailer	2 wheels slipping	6.70-15	932	Gear box torque
6	Joint Highway Research Project, Purdue Univ.	Skid car	4 wheels locked	6.70-15	905 approx.	Length of skid
7	Tennessee Highway Research Project	2-wheel trailer	Inside wheel locked	6.70-15	871	Drawbar force
8	Virginia Council of Highway Investigation and Research, Univ. of Va.	Skid car	4 wheels locked	7.40-14	1,015	Length of skid
9	Virginia Council of Highway Investigation and Research, Univ. of Va.	Tapley decelerometer mounted in No. 8				
10	Bureau of Public Roads	An alteration of No. 1 to measure sideway force coefficient				
11	Cornell Aero Laboratory	An alteration of No. 3 to measure sideway force coefficient				
12	National Crushed Stone Association	Bicycle wheel apparatus				

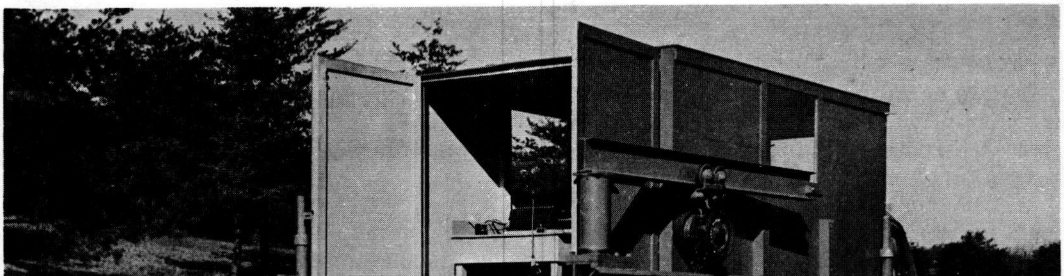

Figure 1. In the Bureau of Public Roads equipment the drawbar force is measured by electrical strain gages for locked-wheel conditions. The trailer can be converted to measure sideway force by fixing the wheel at a predetermined angle to the direction of travel (see Appendix).

curacy of ± 0.02, it was calculated that six repeat measurements would be sufficient. Each machine made six measurements on each of the four pavements for each set of tires, resulting in a total of 48 measurements for each machine.

All machines tested the same pavement with both sets of tires the same day, then moved to the next test site together. All factors such as water film thickness and surface condition were held as constant as possible. The experiment was designed so that all consistent differences between machines were due primarily to the machines themselves and not to uncontrolled factors.

EQUIPMENT PARTICIPATING

Test Machines

The equipment has been described in detail elsewhere (1, 2, 3, 4, 5, 6), therefore only brief descriptions are given here. For those machines not described in the literature (Portland Cement Association and Bureau of Public Roads machines) more detailed descriptions are given in the Appendix. Table 1 summarizes the characteristics of the equipment that participated in the correlation study. This equipment also is described briefly in Figures 1-9. As can be seen, the study encompassed most of the broad categories of road surface friction measuring machines.

Tire Pressure Controls

The tire pressures were controlled in the standard tires, but with the regular tires the equipment operated as it normally does. In the standard tires, pressures of 26 psi were maintained (measured when tire was cold) for the 15-in. wheels and 24 psi for the 14-in. wheels.

Description of Standard Tires

The standard tires (Fig. 10) were made from an oil-extended polymer styrene butadiene rubber (OEP-SBR). Specially prepared stock (experimental No. DZ 219A676) was used and care was exerted to minimize non-uniformity.

For wheels of 14-in. rim diameter the mold code is BSR-3 and for the 15-in. wheel it is BSR-2. Wade Johnson, Manager of the Tire Test Division, Goodyear Tire and Rubber Company, has indicated that tires of this tread design and composition can probably be made available for experimental purposes through 1962 or possibly longer.

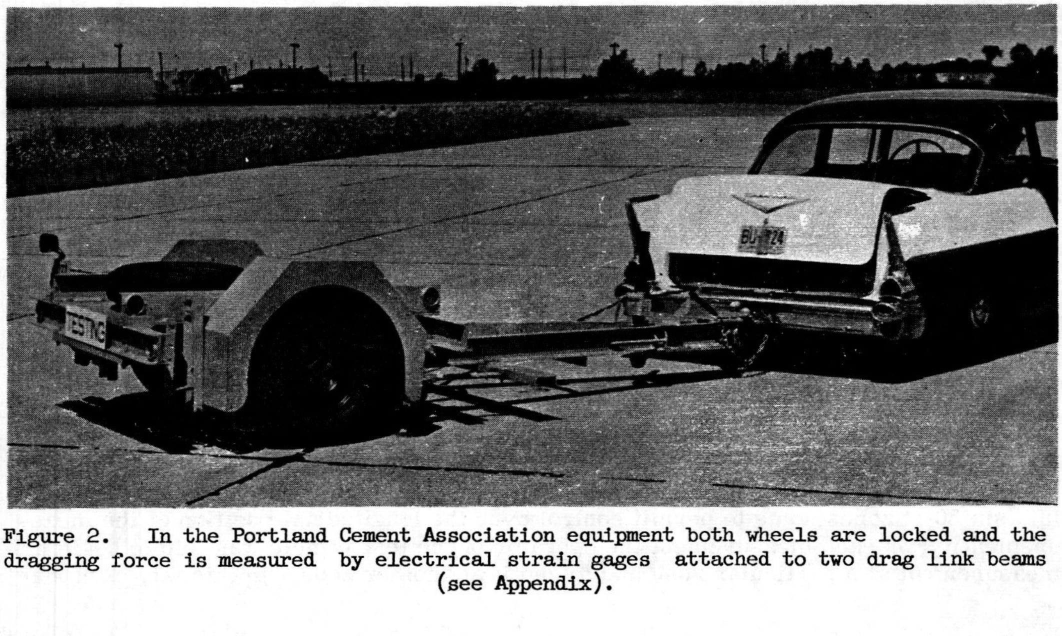

Figure 2. In the Portland Cement Association equipment both wheels are locked and the dragging force is measured by electrical strain gages attached to two drag link beams (see Appendix).

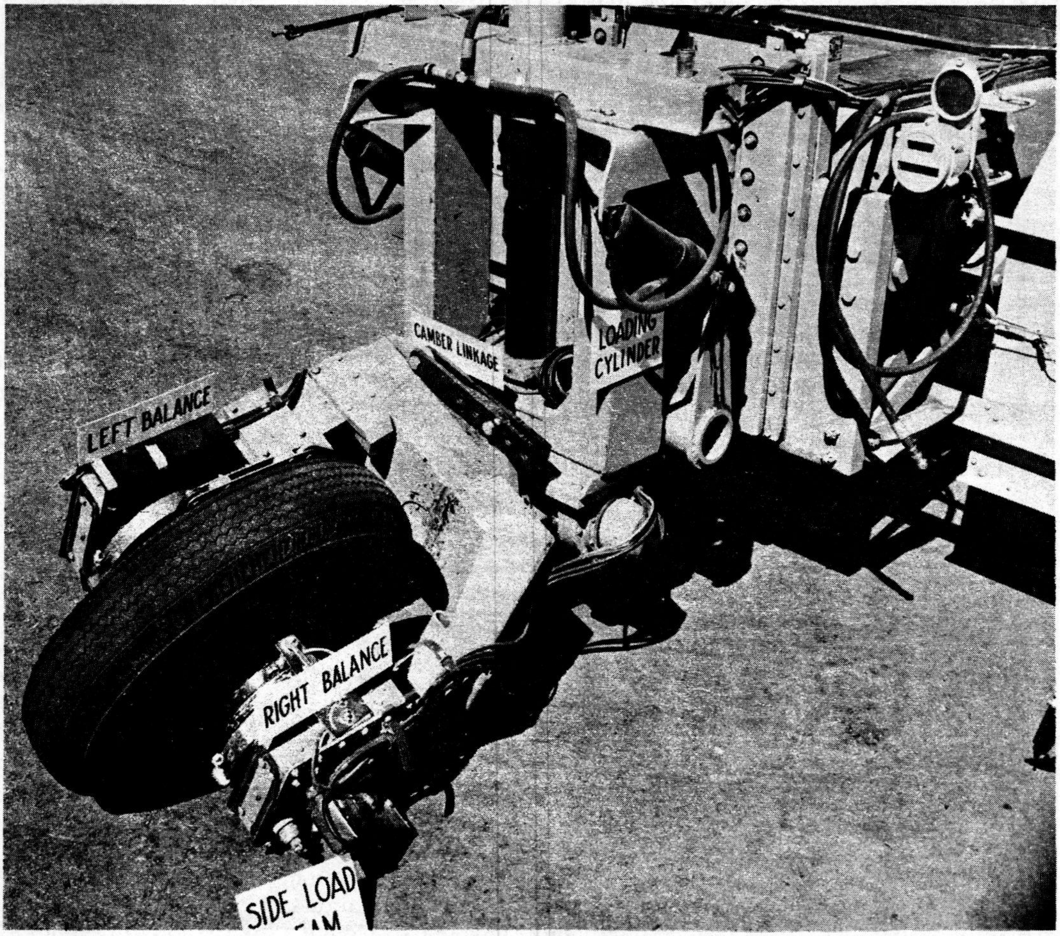

Figure 3. In the Cornell Aeronautical Laboratory equipment, in contrast to the other trailers, the wheel is loaded pneumatically. Electrical strain gages measure the forces from which the coefficient is computed. The machine is also capable of measuring the sideway force coefficient by measuring the forces generated as the wheel is rotated 30 deg from the direction of travel (1).

DESCRIPTION OF TESTS

Testing Procedure

The measurements on each level were made in a series of "runs." For the Series X (regular tire) and also for the Series Y (standard tire) each machine made one measurement during each run for six runs. In Series X and Y, the tests were made at 40 mph. The sequence was randomized within each run so as to avoid order effects. In Series Z the sequence of measurements was generally arranged for practical reasons and was systematic rather than random. The Series Z measurements were made after the Series X and Series Y tests were completed.

Test Site Descriptions

A typical test site layout is shown in Figure 11. Each 300-ft test site was marked into six 50-ft zones so as to permit control over the longitudinal position of the measurement. For each measurement the operator of the test vehicle was told to begin his measurement at a particular zone and to end it at another zone. In this way each ma-

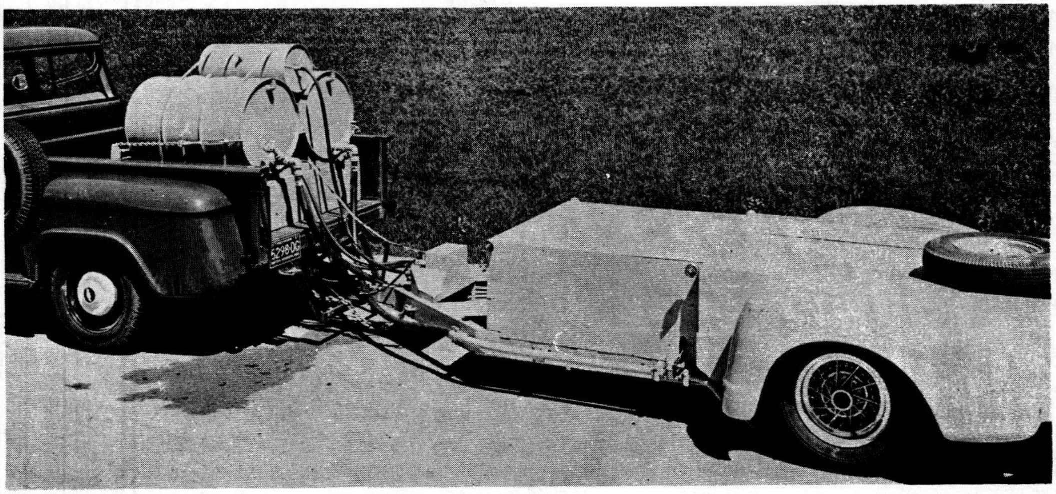

Figure 4. In the equipment used at the General Motors Proving Grounds both wheels are locked and the force measurements are obtained by measuring the bending in the torque tube by means of strain gages (2).

chine was making measurements throughout each of the zones.

It was decided at the outset that all machines should begin their measurements in the normal wheel paths, but this was not possible because of the differences in the design of the machines. The one-wheel trailers (Bureau of Public Roads, Cornell tire tester, and NASA) have their trailer carts mounted along the centerline of the towing vehicle. On some test sites (good and fair) it was necessary to place the soaker hoses along the boundary of the test lane and these vehicles could not maneuver close enough to the hoses to get the cart in the center of the left wheel path nor could they safely maneuver close enough to the shoulder to get the cart in the center of the right wheel path. The NASA cart was towed by a station wagon, however, so it was possible to come close to the center of the wheel paths. Only for the Bureau of Public Roads machine and the Cornell tire tester on the good and fair sites were the measurements taken in the outer edge of the wheel paths. The other vehicles attempted and generally succeeded in beginning the measurement in the wheel path.

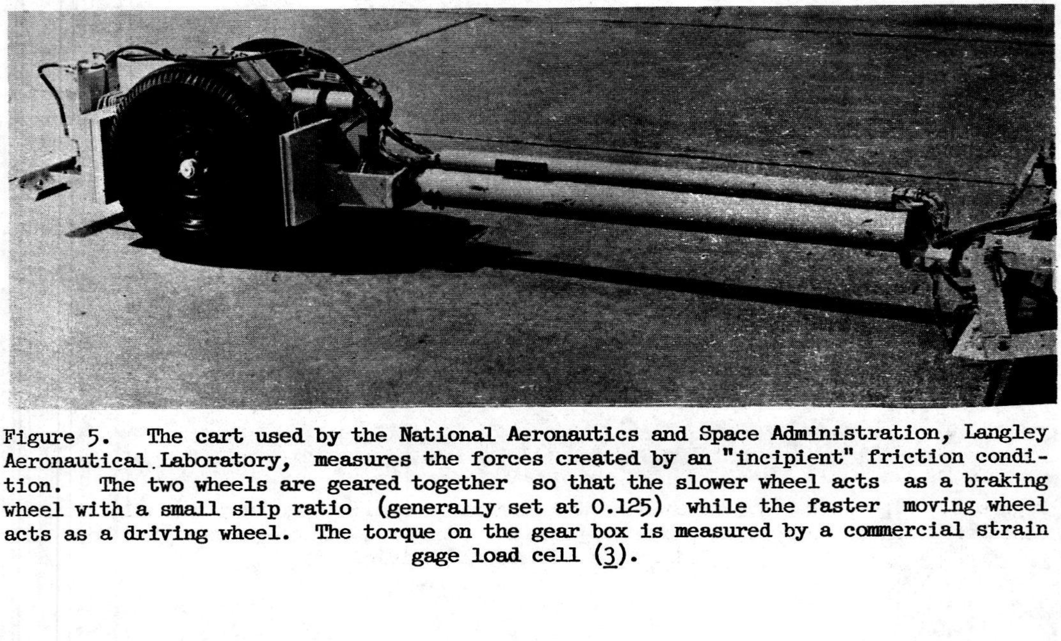

Figure 5. The cart used by the National Aeronautics and Space Administration, Langley Aeronautical Laboratory, measures the forces created by an "incipient" friction condition. The two wheels are geared together so that the slower wheel acts as a braking wheel with a small slip ratio (generally set at 0.125) while the faster moving wheel acts as a driving wheel. The torque on the gear box is measured by a commercial strain gage load cell (3).

Figure 6. The car used by the Purdue Joint Highway Research Project eliminates irregular foot braking by utilizing a special vacuum braking system activated by a hand microswitch (4).

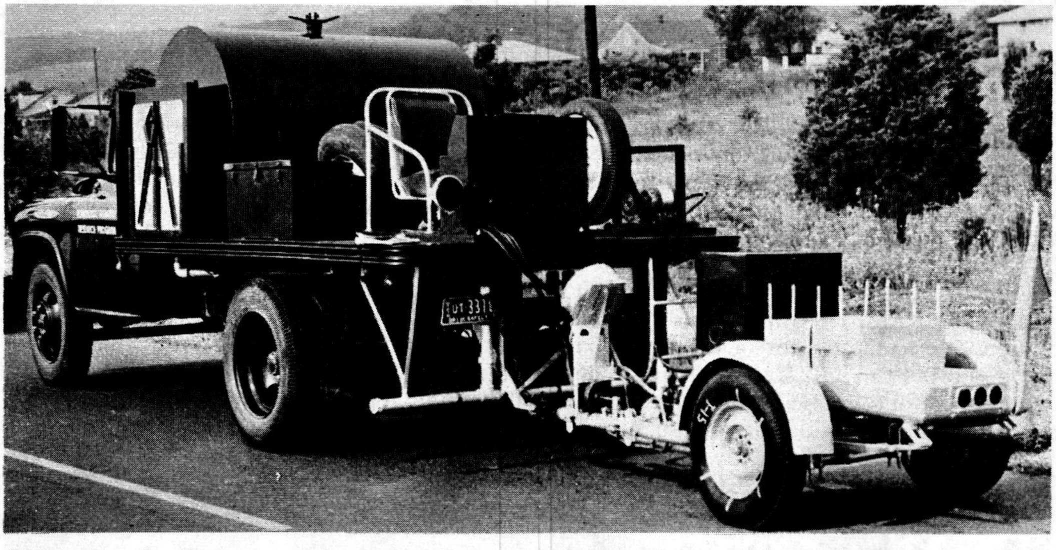

Figure 7. In the equipment of the Tennessee Highway Research Program only the inside wheel is locked and the drawbar force is measured by automatic recording equipment which operates from a fluid pressure device (5).

Figure 8. The skid test car used by the Virginia Council of Highway Investigation and Research utilizes no special braking equipment. Only recording equipment has been added to the commercial vehicle.

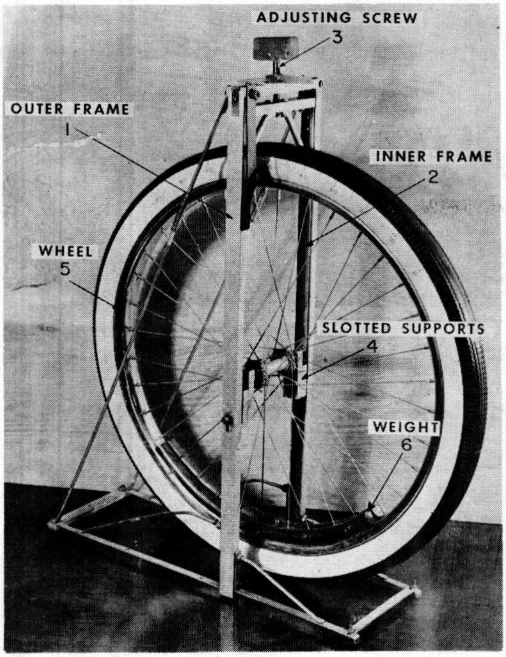

Figure 9. In the National Crushed Stone Association equipment the eccentric weight on the rim drives the wheel. The tread is removed in the portion of the wheel which precedes the zero reading and friction is created as the treaded portion comes in contact with the surface. The central angle through which the wheel passes is an empirical measure of slipperiness.

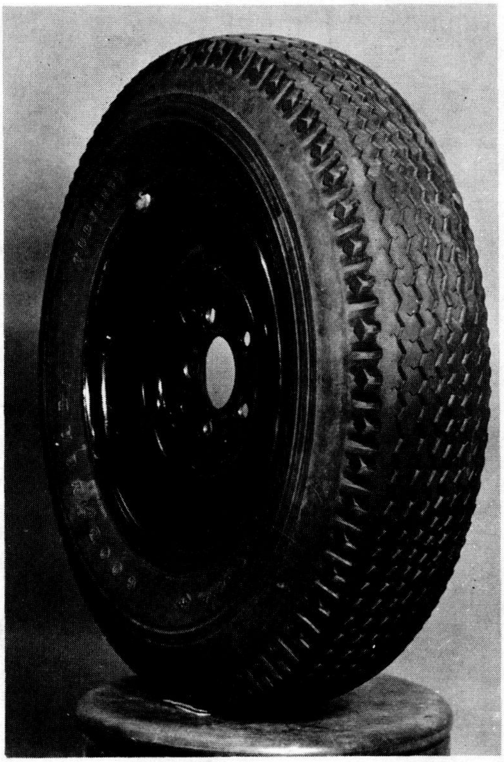

Figure 10. The Goodyear Tire and Rubber Company was designated by the Tire and Rim Association to supply the standard tires. Specially prepared stock was used and careful control exerted to minimize non-uniformity.

Water Control

Water control was considered a significant factor in the experiment. The watering system layout is shown in Figure 12. Eight 50-ft lengths of canvas garden soaker hose were used, each fed by a separate conduit hose. Tests conducted prior to the experiment showed that a uniform flow of water could not be expected from lengths longer than 50 ft, but a relatively uniform flow of water could be obtained throughout lengths

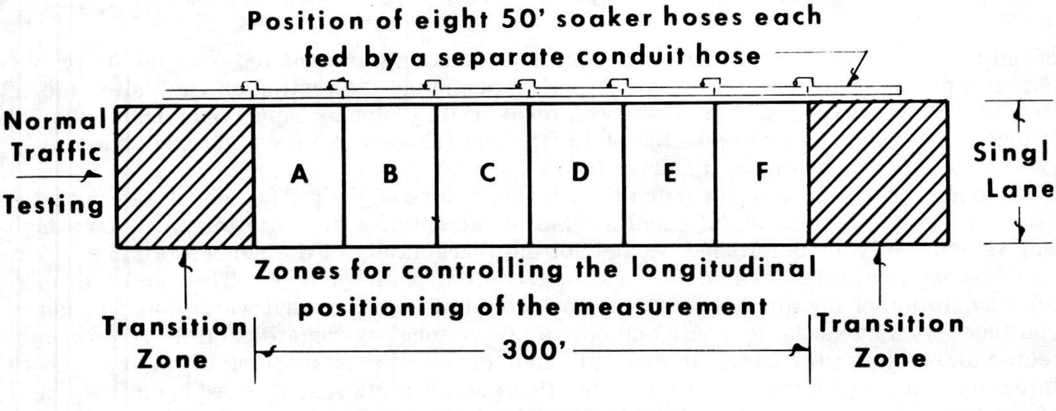

Figure 11. Test site layout.

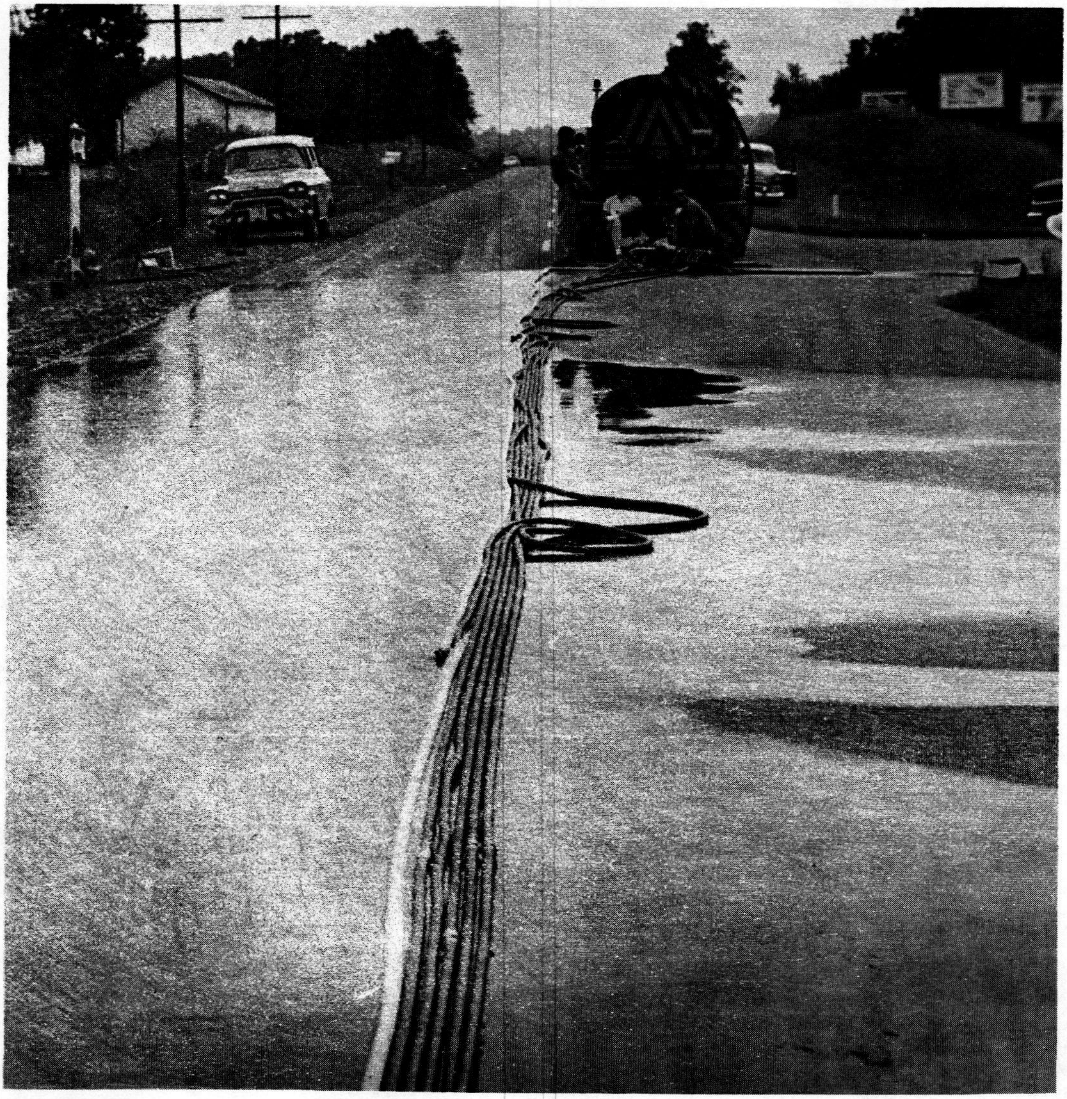

Figure 12. Each 50-ft length of soaker hose was fed by a separate conduit hose. The pressure at the entry of the soaker was checked and standardized on each test site.

of only 50 ft. A valve at the entry to each soaker hose was adjusted each day to provide uniform pressure at that point. Also, before beginning the testing on each site, the flow of water from the soaker hoses was measured by placing small pans under the 300-ft length at an approximate spacing of 13 ft. The valves were then adjusted again to compensate for appreciably different flows.

Attempts were made to measure the film thickness of the water, but it was not possible to obtain any meaningful results. Measurement of water film thickness on a highway is not easily accomplished because of the irregularity of the surface: there is, in fact, no one film thickness on a coarse aggregate asphalt surface. The most meaningful description of the amount of water used would probably be that water was flowing continuously across the test site and only an occasional aggregate particle could be detected above the water film. In general, control over the positioning of the tests, both laterally and longitudinally, and insuring that each vehicle tested over the entire length of the test site, would contribute substantially to minimizing the effect of water film variation.

Figure 13. "Poor" site; dense plant-made asphaltic concrete; limestone aggregate, maximum size $\frac{1}{2}$ in., Virginia grading I-3.

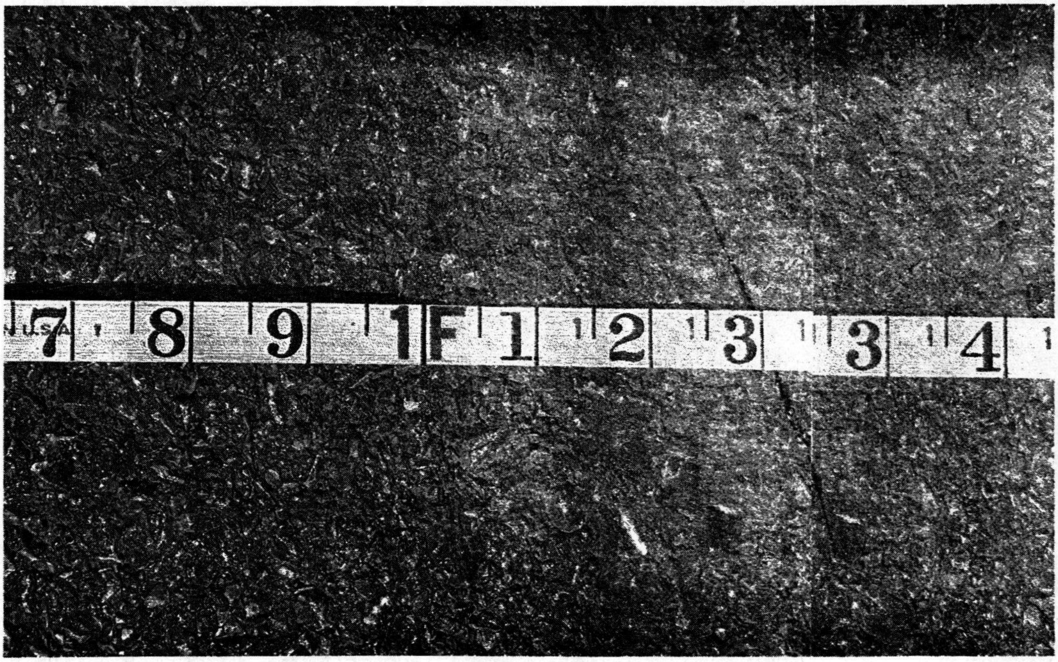

Figure 14. "Fair" site; dense plant-made asphaltic concrete; limestone aggregate, maximum size $\frac{1}{2}$ in., Virginia grading I-3.

Also to minimize the cleansing effects of the water flowing across the pavement as the test was in progress, the entire test section was cleaned of traffic film and dust by watering and brooming before the testing began.

Road Surface Condition

The types of surfaces tested are shown in Figures 13, 14, 15, and 16 which are stereo pairs provided for a three-dimensional view. However, the general texture can

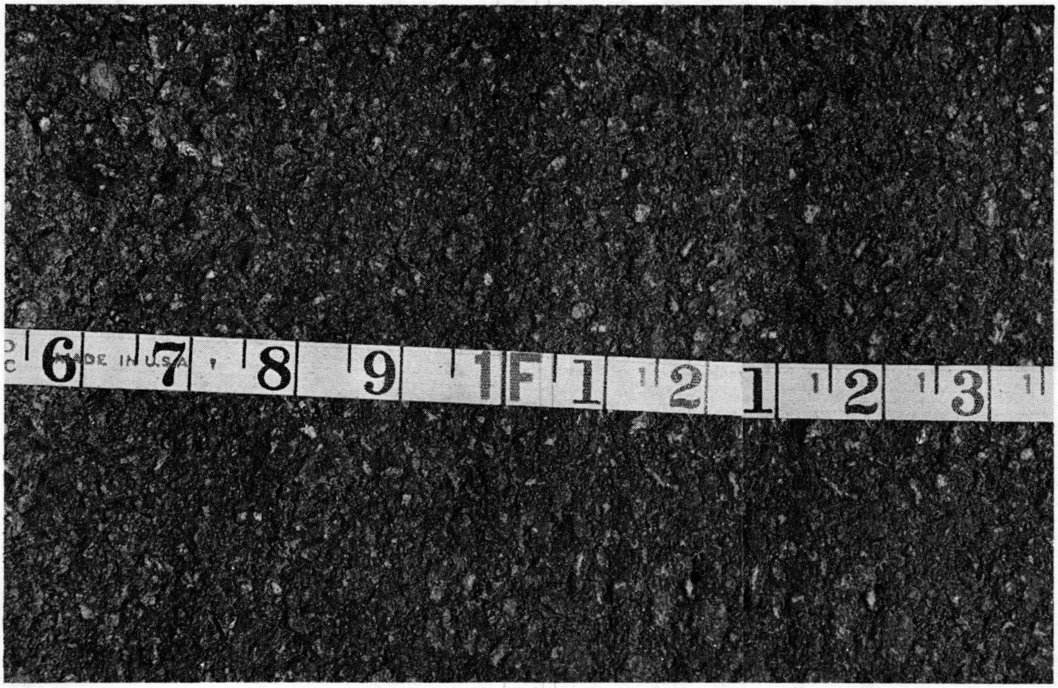

Figure 15. "Good" site; dense plant-made asphaltic concrete; granite aggregate, maximum size $\frac{1}{2}$ in., Virginia grading I-3.

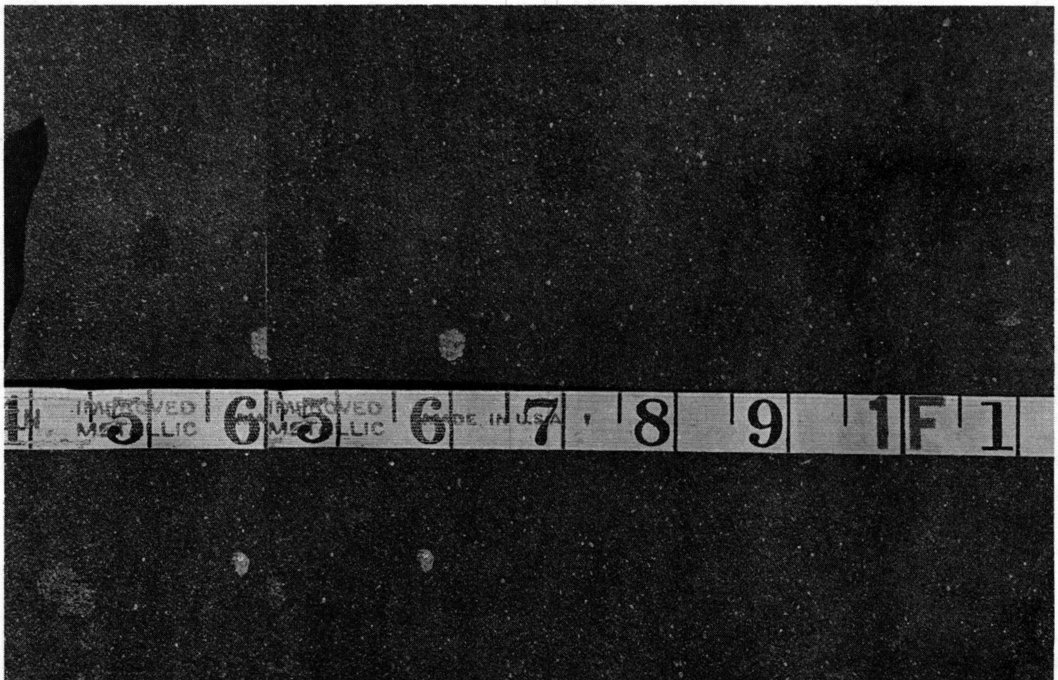

Figure 16. "Excellent" site; plant-made deslicking mix; silica sand aggregate, 100 percent passing No. 10 sieve, Virginia grading F-4.

also be observed with the unaided eye and a more complete description is given in the Appendix. Three of the surfaces were dense-graded $\frac{1}{2}$-in. top size asphaltic concrete and the fourth was a fine plant-made sand deslicking mix. There were some differences in the surfaces with regard to adherence to a true cross-section. No measurements of roughness were made, but the puddling of water or lack of it indicated the surface irregularities. The following evaluation might be applied to the surfaces:

Level	Condition
Poor	Some moderate undulation in the wheel tracks, hence some slight puddling of water (less than $\frac{1}{16}$ in.)
Fair	Some continuous rutting in wheel tracks, hence considerable puddling ($\frac{1}{8}$ to $\frac{1}{4}$ in.)
Good	Smooth, no visible puddling
Excellent	Smooth, no visible puddling

TEST RESULTS, SERIES X AND Y

The Series X measurements were made to provide a comparison between the various machines as they are normally used by the respective agencies. This would give an insight into the relationships of the data previously collected by the various agencies and permit a more meaningful exchange of existing data. But because some important variables (that is, type and tread patterns of tires) were operating, only a limited comparison could be made of the accuracy of the machines themselves. To gain a comparison between the abilities of the machines to measure friction it was necessary to eliminate or minimize the tire variable. This was done by equipping machines with a specially prepared standard tire, as has been previously discussed. The results of these two series are discussed in the following.

The test results for Series X and Series Y are summarized in Table 2. Machine No. 1 did not participate in Series X because it was not feasible to change tires in a short period of time. Because of a breakdown machine No. 2 secured measurements only on the fair and excellent levels.

The trends of the data are shown in Figure 17 for regular tires and in Figure 18 for standard tires. Each plotted point represents the mean of six measurements. It should be pointed out that the abscissa is not a quantitative scale, but (from Table 2) the interval between the grand means of each level is equal to 0.13, 0.13, and 0.11, therefore the plotted points can be considered to approximate a curve.

TABLE 2

SUMMARY OF DATA FOR SERIES X AND Y

Machine No		Mean and Standard Deviation[1]							
		Poor		Fair		Good		Excellent	
		X	Y	X	Y	X	Y	X	Y
1 (BPR)	Mean	-	0.12	-	0.25	-	0.37	-	0.45
	Sta. dev.	-	0.02	-	0.048	-	0.047	-	0.037
2 (PCA)	Mean	-	-	0.38	0.41	-	-	0.63	0.65
	Std. dev.	-	-	0.035	0.032	-	-	0.032	0.014
3 (Cornell)	Mean	0.23	0.22	0.34	0.32	0.56	0.57	0.60	0.62
	Std. dev.	0.01	0.012	0.018	0.009	0.031	0.020	0.031	0.022
4 (GM)	Mean	0.23	0.26	0.38	0.38	0.51	0.51	0.70	0.67
	Std. dev.	0.01	0.010	0.027	0.054	0.018	0.023	0.013	0.029
5 (NASA)	Mean	0.46	0.33	0.57	0.47	0.64	0.66	0.75	0.65
	Std. dev.	0.010	0.013	0.021	0.057	0.013	0.00	0.018	0.017
6 (Purdue)	Mean	0.26	0.29	0.40	0.44	0.48	0.52	0.61	0.63
	Std. dev.	0.045	0.013	0.015	0.008	0.016	0.013	0.015	0.013
7 (Tenn.)	Mean	0.07	0.18	0.18	0.26	0.36	0.40	0.42	0.52
	Std. dev.	0.023	0.012	0.020	0.047	0.033	0.045	0.060	0.031
8 (Va.)	Mean	0.28	0.33	0.41	0.47	0.51	0.57	0.66	0.69
	Std. dev.	0.010	0.016	0.022	0.009	0.014	0.013	0.019	0.014
Mean, all machines		0.25	0.25	0.38	0.37	0.51	0.51	0.62	0.61
Grand mean for each level		0.25		0.38		0.51		0.62	

[1] Six measurements per cell

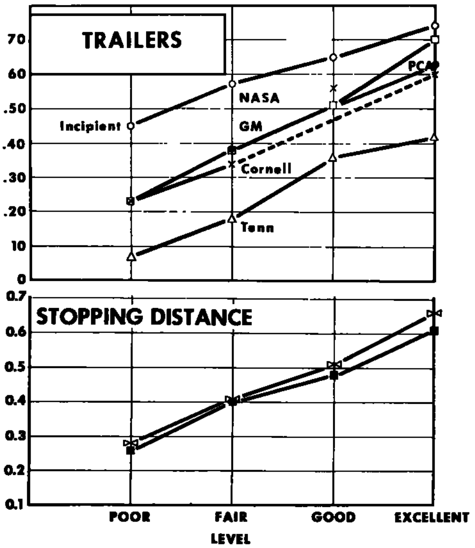

Figure 17. Measurements with regular tires (Series X).

With the regular tires (Fig. 17) the stopping distance methods (Purdue and Virginia) occupy a position similar to GM, PCA, and Cornell. The incipient friction coefficient is well above the others and the Tennessee machine (the only machine using a smooth tread tire) is well below the others.

The greatest divergence occurs on the excellent site, where the locked-wheel coefficients vary from 0.70 (GM) to 0.42 (Tenn.). Because the Tennessee machine used smooth tread tires, it is to be expected that lower values would be obtained.

Inasmuch as the machines utilized different types of tires it is to be expected that some differences would exist. However, even when the vehicles were equipped with the standard tire the divergences were substantial. As can be noted in Figure 18, the maximum difference between the locked-wheel machines is in the order of 0.20 to 0.25, the greatest divergence occurring on the excellent site, where GM obtained 0.67 and BPR 0.45. It is interesting to note that if, say, the fair site were being tested to determine whether it were below a minimum acceptable locked-wheel coefficient of friction of 0.4 (the standard currently used in Virginia), three machines (Purdue, Virginia, and PCA) would have "passed" the site and three would have "failed" it, with one machine (GM) a borderline case.

It should be pointed out that with the Cornell machine the mean of the measurements for the good site has been disregarded in connecting the point on the fair site to the excellent site. There was considerable evidence from visual observation that the test wheel was not locking and it was thought that rolling friction influenced the results. For this reason a straight line has been extended from the fair to the excellent site.

With standard tires the incipient (NASA) coefficient is well above the other trailers except on the excellent site. This is in contrast to the position of the plot on Series X, where the incipient coefficient remained well above the others over all sites. This rather unusual behavior is not readily explainable and will undoubtedly require some additional investigation.

Another point to be noted is that the stopping distance methods, Purdue especially, are not appreciably higher on the good and excellent sites than several of the trailers. It had been anticipated prior to the experiment that the stopping distance methods would yield results higher than the trailers. This is discussed in greater detail in a later section.

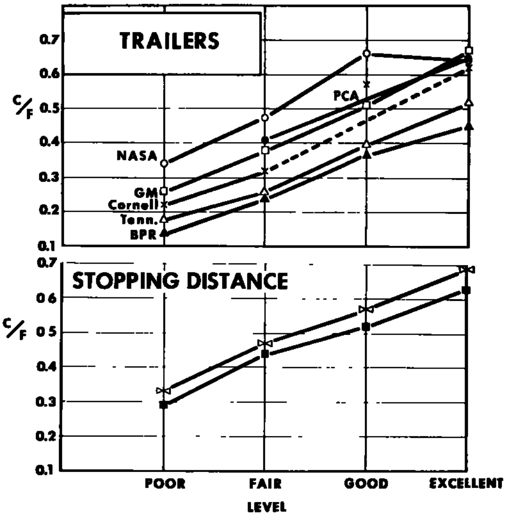

Figure 18. Measurements with standard tires (Series Y).

Statistical Interpretation

The preceding discussion was based on the means of six measurements, but does not take into account the dispersion of the individual measurements about the means. The question then arose as to whether the differences between the means were greater than could be expected from the error of measurement. That is, it is possible that the sample means might differ appreciably but that the dispersion of the individual measurements might be so great as to make imprudent the drawing of conclusions concerning the differences in the means. To take the error of measurement into account a statistical analysis was made. Only the findings of the analysis are presented in the text; the analysis itself is explained in the Appendix.

Results with Standard Tires. From the analysis it was concluded that the results from the trailers, considered as a group, are statistically different, as also are the stopping distance results. An analysis was then carried out to see if any two machines agreed with each other across all levels of friction. It was found that no machine agreed with any other machine (within the statistical error of measurement) at more than one level of friction.

Another pertinent question was whether or not some machines were merely consistently high or low, and agreement could be reached by a simple additive correction factor. The analysis showed that no simple additive factor could make the results for the different machines comparable. That differences in the shape of the "curves" made such equations impossible was verified by the analysis. The results from the two cars can be brought into fair agreement by a simple addition factor, but the trailers cannot be brought into agreement by constant additive factors. There are substantial differences in the design of the machines which may account for the differences in the shapes of the curves. Further research along this line could be very rewarding.

Effects of Tires

Comparisons of the results from Series X and Series Y provide an insight into the effects of tires on the measurement of friction. The interest here is not in the rating of tires with regard to their ability to develop high friction, but on the qualitative influence of tires on the friction measurement.

The analysis showed that for every machine except No. 3 (Cornell) and No. 4 (General Motors) the results were significantly different with the two sets of tires. A question of greater interest, however, is whether results with one set can be equated to those with the other by a simple correction factor. If so, control of the tire variable in future measurements would be much more feasible. Except for the NASA machine, which measured rolling friction, it was found that results for the different sets of tires could be equated by a simple additive correction factor. Although such a conclusion must be restricted to the conditions and tires (GRS) embodied in this experiment, this was true even for the Tennessee machine, which used smooth tread tires.

Variability of Measurements

Another question, in addition to the average coefficient of friction obtained, is how closely successive individual measurements of the same pavement agree with one another. The standard deviation is the measure of the scatter of successive measurements of the same pavement by the same machine. The smaller the standard deviation, the more reliable the measurement.

The data (Table 3) showed that there were substantial differences in variability between machines. The cars had consistently smaller standard deviations, with an overall average of 0.014. Trailers obtained average values from 0.021 to 0.039. Two machines (Nos. 4 and 5) had significantly higher variabilities in the Y Series, which used standard tires. The cause of this difference in variabilities is not clear, but examination of the data suggests that these machines were affected more by the water film variations on the fair site than the other machines. For this reason the average standard deviation for these machines (Table 3) shows two average variabilities, one including the variability from all sites and the other excluding the fair site variabilities.

From the standard deviations, it is possible to estimate the number of measurements required for a given degree of precision. To be 95 percent confident that the average of N measurements will be within a tolerance T, the number of measurements required

TABLE 3

AVERAGE[1] STANDARD DEVIATIONS

Machine No.	Series X[2]	Series Y[3]	Both Series	No. Measurements for Tolerance + 0.02
1 (BPR)	-	0.0397	0.0397	16
2 (PCA)	0.0297	0.0207	0.0256	7
3 (Cornell)	0.0243	0.0164	0.0208	5
4 (GM)	0.0185	0.0225[4] - 0.0332	0.0203[4] - 0.0269	5 or 8
5 (NASA)	0.0161	0.0121[4] - 0.0303	0.0145[4] - 0.0243	3 or 6
6 (Purdue)	0.0138	0.0121	0.0130	2
7 (Tenn.)	0.0378	0.0365	0.0371	14
8 (Va.)	0.0172	0.0134	0.0154	3

[1] Root mean square method.

[2] Regular tires.

[3] Standard tires

[4] Excluding measurements on fair site.

can be estimated from $N = \left(\frac{2SD}{T}\right)^2$ in which SD is the standard deviation. The number of measurements needed by the various machines to be within the tolerance of ±0.02 is also shown in Table 3. It should be noted that for the least variable machine (Purdue) the number of measurements required for a tolerance of ±0.02 is $\left(\frac{2 \times 0.013}{0.02}\right)^2 = 1.6 = 2$ measurements. For the most variable machine (BPR), $\left(\frac{2 \times 0.0397}{0.02}\right)^2 = 16$ measurements would be needed. In ordinary field work, somewhat higher standard deviations might be expected.

The machine of the Bureau of Public Roads was only in the development stage at the time of the test and this undoubtedly accounts for some of the variability. However it is important to note from Table 3 that the most variable machines were of the drawbar force type, and further that the least variable were those employing the stopping distance methods. The differences in the precision of the various methods appear to be related to their basic design or method of measurement. A more thorough study of the variability as related to method of obtaining the coefficient is warranted by these data.

The variability was also analyzed to see if the variability of measurements was different at different levels of friction. When the deviant sets of GM and NASA previously mentioned were excluded, it was found that no machine with either set of tires had consistently different precision of measurement for a high-friction pavement than for a low-friction one. Results also suggest that the common procedure of reporting precision of coefficients of friction in percent (that is, ±5 percent) is in error. Precision should be reported in units of the coefficient (that is, 1.3 ±0.05).

Comments on Series X and Y

The analysis has shown that the differences among various machines were statistically significant. Examination of Figures 17 and 18 shows that the differences are significant from a practical viewpoint as well, which can be easily seen when the problem of establishing a minimum coefficient is faced. The best interest of the traveling public demands that pavements that are slippery when wet be eliminated from the highway system and this means establishing a minimum acceptable coefficient of friction. As long as the differences in results obtained by the various methods are substantial this minimum can not have much meaning. To attempt to correlate all of the various machines with each other would be exhausting. Search for the causes of the differences in the results seems much more promising, and it is hoped that the data provided in this paper will serve as an impetus to this end.

TEST RESULTS, SERIES Z

As has been pointed out earlier, Series Z was a grouping of miscellaneous subexperiments. Although no less care was taken in securing the Z measurements, it is true that they were taken after Series X and Y were completed and the pavement had therefore been subjected to considerable wear. In some instances (for example, in Zb, where readings at 55-40-15 mph are compared) the 40-mph reading was taken during the Y Series several hours before the 55-mph and 15-mph readings and the analysis must take this into account. All measurements were taken on wet pavements at 40 mph (with exceptions noted) with the standard tires.

Za: Comparison of Coefficients of Friction Computed from Stopping Distance and Decelerometer

A decelerometer was rigidly mounted in the center of the space normally occupied by the back seat in the Virginia skid test car. A film recording was made of the decelerometer readings, a speedometer, and a stop meter for each of 48 measurements. Curves of six measurements for each site in the Y Series (Fig. 19) show the deceleration of the skid test car as the stopping distance test was being made. The plots exhibit typical deceleration-speed relationships of a fully braked vehicle. The deceleration of the vehicle increases rapidly as the driver jams on the brakes; the maximum impending coefficient is reached, then the brakes lock and the rate of deceleration is

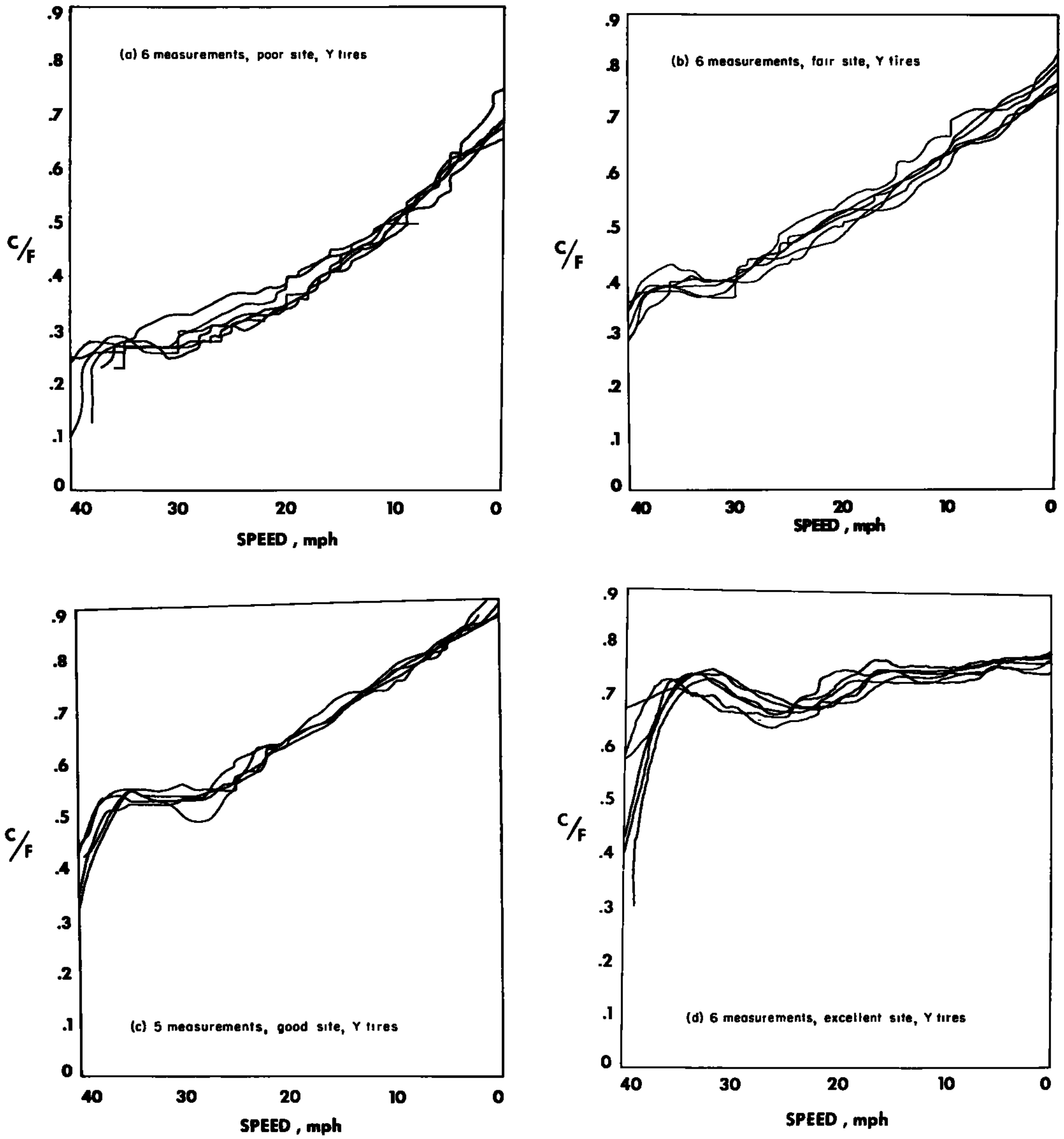

Figure 19. Coefficient of friction vs speed-decelerometer.

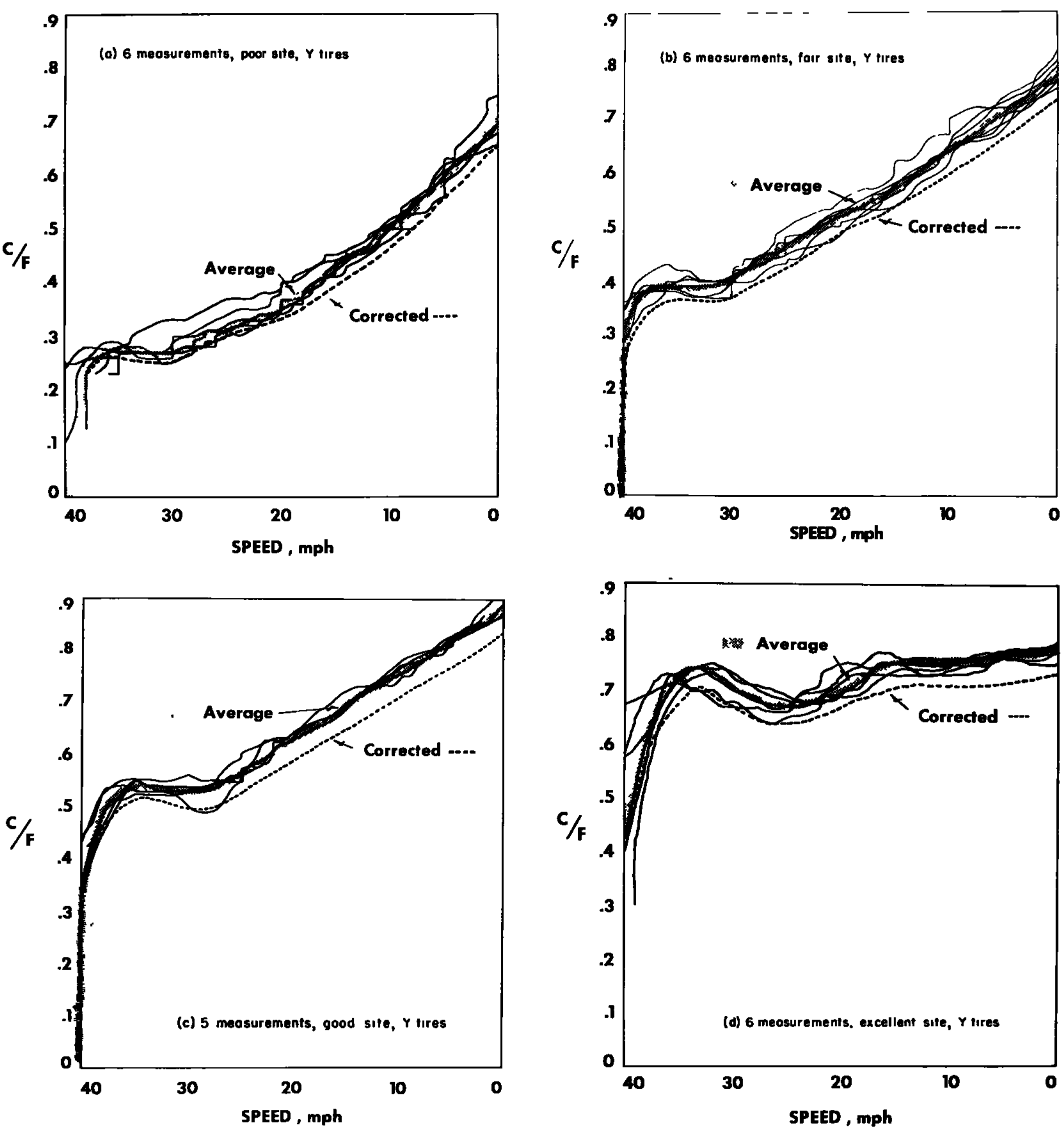

Figure 20. Coefficient of friction vs speed-decelerometer.

somewhat less. Once the brakes are locked the rate of deceleration increases as the speed of the skidding vehicle decreases. A plot of deceleration vs speed for a single wheel would exhibit a more pronounced incipient peak, but the four wheels did not lock at the same instant and the incipient peak and the minimum locked-wheel value are thereby obscured somewhat.

It is interesting to note the difference between the general shape of the plot on the excellent site (Fig. 19d) and those of the other three sites. On the excellent site a maximum deceleration is attained at about 20 mph and the deceleration levels off beyond this in contrast to a continued increase in deceleration on the other three sites. The significance here is that on the excellent site a different relationship is suggested, one in which the coefficient of friction is not influenced by speed as significantly as it is on some other surfaces. (This same conclusion is suggested by Figure 21.)

The average coefficient of friction for each site was computed by integrating the corrected average curve for each site (Fig. 20) by use of a planimeter. The correction

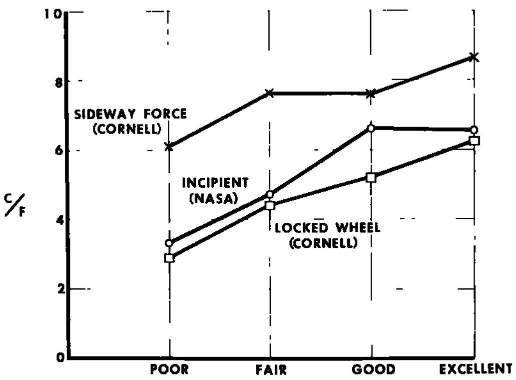

Figure 21. Comparison of the sideway force, incipient, and locked-wheel coefficients of friction.

is for the tilt of the skid test car. Displacement of the decelerometer pendulum is caused by a combination of the non-horizontal position of the car during skidding and the deceleration of the vehicle. The tilt correction was made as explained in the Appendix.

The results obtained from the decelerometer are compared with the stopping distance results in Table 4. For practical purposes the comparison is quite favorable with a maximum deviation of 0.04.

It was hoped that the deceleration curves would provide an insight into the coefficient of friction that would have been obtained if the Virginia skid test car had been towed at a constant speed of 40 mph. This was to be accomplished by extrapolating the locked-wheel portion of the deceleration-speed curve to 40 mph. Some problems have been encountered in doing this and in the interest of completing a version of the paper this phase of the analysis has not been completed. It is hoped that this topic may be the subject of a subsequent paper.

Zb: Comparison of Incipient, Locked-Wheel, and Sideway Force Coefficients

The sideway force coefficient has been used little in this country, but has been used extensively in Europe. Its adherents see many advantages in the method, the most significant here probably being that it is indicative of the action of a tire on an undriven wheel which has skidded because of too high a speed when rounding a curve.

The incipient coefficient is generally considered to be the maximum coefficient (see comments in Zc) that can be obtained when tire and wheel are traveling perpendicular to the axle of the wheel and generally occurs at slip ratios of about 0.10 to 0.15. In automobiles the incipient condition is attainable, but few drivers can adequately control the brake pressure to provide the proper slip without locking the wheels. For those in the highway transportation field the incipient coefficient is of interest primarily because it generally represents the maximum that can be developed in the road-tire-brake system at high speeds.

The most widely used coefficient in this country is the locked-wheel value, which realistically represents the conditions met by a vehicle locking its wheels in an emergency straight ahead skid.

Figure 21 provides a comparison between the three coefficients. The data show that the sideway force coefficient is considerably greater in magnitude than the other two, also that the numerical difference between the values on the poor and the excellent sites are less than the incipient or locked-wheel coefficients. The average slope of the curves is greatest for the locked-wheel coefficient, which could be interpreted as meaning that the locked-wheel coefficient is more sensitive to the differ-

TABLE 4

COMPARISON OF COEFFICIENT FROM STOPPING DISTANCE AND DECELERATION CURVES

Method	Poor		Fair		Good		Excellent	
	X	Y	X	Y	X	Y	X	Y
Stopping distance	0.28	0.33	0.41	0.47	0.51	0.57	0.66	0.69
Decelerometer	0.29	0.37	0.41	0.50	0.55	0.61	0.63	0.67

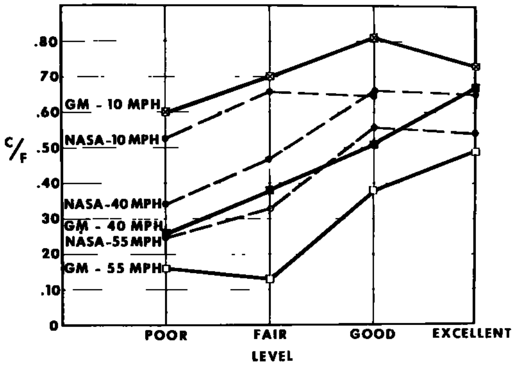

Figure 22. Influence of speed on locked wheel and incipient coefficient.

TABLE 5

INFLUENCE OF SPEED ON INCIPIENT AND LOCKED-WHEEL COEFFICIENTS (10-40-55 mph)

Machines Participating	Level											
	Poor			Fair			Good			Excellent[1]		
	10	40	55	10	40	55	10	40	55	10	40	55
GM (4)	0.60	0.26	0.16	0.70	0.38	0.13	0.81	0.51	0.38	0.73	0.67	0.49
NASA (5)	0.53	0.33	0.25	0.66	0.47	0.33	0.65	0.66	0 56	-	0.65	0 54

[1] Some noticeable erosion of surface as tests proceeded. Thus, results at 10 and 55 mph are considered as taken on a surface "different" from that on which the 40-mph measurements were taken.

ences that occur in the road surfaces. The standard patterned tires were used on the three vehicles.

The data illustrate, as has been done many times before, that the utilization of the incipient condition during an emergency stop from high speeds would appreciably contribute to safety. For instance, if in an emergency condition on a poor road surface an average coefficient of 0.34 could be attained instead of 0.22 (locked-wheel), the stopping distance would be reduced from 243 ft to 157 ft, a difference of 86 ft. At 50 mph the difference would be even greater, of the order of 170 ft.

Zc: Comparison of Effect of Speed on Incipient and Locked-Wheel Coefficients

The purpose in Series Zc was to compare the influences of speed on the two coefficients across the four levels of friction. The data are plotted in Figure 22.

It should be noted that at 10 mph the locked-wheel coefficients are greater than the incipient values across all levels. At 40 mph the incipient coefficient of friction is greater than the locked-wheel value. According to these data, there is a speed (which probably differs for each site) between 10 and 40 mph where the locked-wheel and the incipient values are equal.

Zd: Correlation of Bicycle Wheel with a Stopping Distance Method (Virginia)

The bicycle wheel machine of the National Crushed Stone Association secured measurements when the field testing equipment was not operating over the test site. A minimum of 100 readings were made over the 300-ft length of each test site.

The slipperiness readings are not expressible in terms of the coefficient of friction, but are an empirical indication of road surface slipperiness. The coefficient of friction and the stopping distances are plotted against slipperiness readings in Figure 23.

The bicycle wheel apparatus is an inexpensive device, costing less than $100 to build, and would be suitable for laboratory as well as field measurements. The National Crushed Stone Association uses the device to indicate slipperiness on a laboratory test track and has found it valuable. The method shows considerable promise for use in this way, as shown by Figure 23.

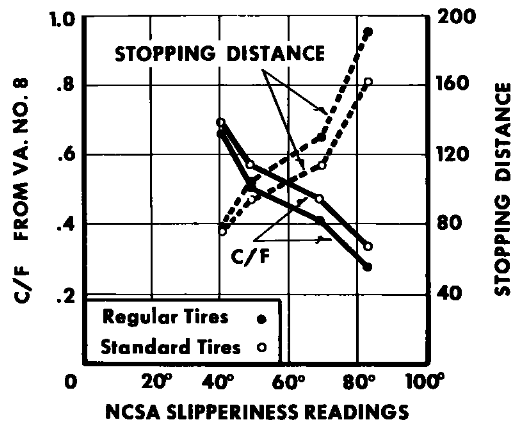

Figure 23. Coefficient of friction and stopping distance vs slipperiness.

The one outstanding question about devices of this nature is whether the textural influence of the surfaces might not differ inordinately on surfaces of various types, as the contact patch of the bicycle wheel is approximately a 1-in. square. It is possible that great variations might result if the device were used on very coarse mixes made from two aggregates with widely different slipperiness characteristics. The contact area might alternately be testing the individual aggregates in contrast to an automobile tire (with a contact patch approximately 4 in. by 6 in.), which would be influenced by both aggregates at the same time.

The mixes tested in the correlation study were mixes made from a single type of aggregate and were dense gradings with relatively fine textures. Because the bicycle wheel is an empirical measure of slipperiness, establishment of the relationship between it and a stopping distance method should include as broad a range of surfaces as found in practice. This condition was not met in this experiment.

Correlation study results obtained from the wheel are encouraging. If further comparisons on a variety of surfaces are as good, the wheel will provide a valuable link between laboratory and field measurements.

CONCLUSIONS

From the results of this study, the following general conclusions seem warranted:

1. The coefficients of pavement friction obtained by the different machines included in the study differed substantially, both statistically and from a practical standpoint. Qualitative differences in results made it impossible to make measurements of the different machines comparable to one another by the use of an additive factor.
2. Relationships between measurements made by trailers and measurements made by the stopping distance method were not clarified. Some trailer results were higher than expected, some lower, with respect to the stopping distance results. Further research is needed on this problem.
3. The locked-wheel coefficients obtained with different types of tires indicate that results from different tires can be correlated by an additive factor. Although this factor will differ from tire to tire, it appears to hold across the various levels of friction.
4. There were important differences between machines in terms of the variability of successive measurements of the same pavement. The data suggest that variability is related to design characteristics of the machines.
5. The variability of measurements was not influenced by level of friction. This indicates that the precision of measurement of coefficient of friction is about the same for high-friction pavements as for low-friction pavements.

There is no doubt whatsoever that the machines that participated in the study, and others as well, have been valuable tools for initially assessing the variables operative in the road-tire-vehicle system. Substantial improvements in road surfaces, brakes, and tires, have been brought about by the measurements from these machines. Further experiments with these machines will add even more enlightenment to this area. However, until the differences, which are both qualitative and quantitative, are accounted for there will be significant doubt about whether a particular variable would have been shown to be operating in the same way when measured by two different machines. As research activities in slipperiness prevention increase and probing goes deeper, confidence in the method of test is essential. Determination of the causes of differences in the coefficient of friction and the variability of the various machines would undoubtedly be a great step forward.

ACKNOWLEDGMENTS

The authors would like to thank the various agencies, and especially their representatives, who participated in the study. The interest demonstrated by these people in the study was encouraging and their patience during the testing was most gratifying.

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Appendix

BUREAU OF PUBLIC ROADS APPARATUS

Equipment developed by the Bureau of Public Roads for measuring the skid resistance characteristics of pavement surfaces is a single-wheel trailer designed to measure either straight-skid or side-skid forces. The trailer is towed by a 2-ton truck. A portable plywood shelter on the truck body houses the operator and the recording equipment. An intercom system, installed in the truck cab and the shelter, provides a means for two-way communication between the instrument operator and the truck driver.

The trailer has a single wheel formed by two rings, which clamp to a 4½- by 15-in. rim on which a 6.70- by 15-in. tire is mounted. A large 15- by 3-in. electric brake, bolted to the wheel, is used for the straight-skid locked-wheel tests. The hub of the wheel is mounted by tapered bearings to a 2-in. axle, which supports the trailer frame on a pair of standard automobile leaf springs. The trailer frame is rectangular and is made of heavy structural steel channel. A bridge over the wheel supports a mudguard, lights, and a sign.

Two structural steel channels bolted to the front corners of the rectangular frame converge and form a wye. A plate at the front end is supported by a tee with two side links to form a hitch at the center rear of the towing truck. This hitch is designed to carry all of the vertical load, to prevent overturning of the trailer, and to allow the trailer to follow around turns.

A dynamometer used to measure forces for the straight-skid locked-wheel condition forms a second hitch and connects the trailer axle to a standard trailer ball hitch on the truck. This dynamometer linkage begins as a yoke connected to bronze bearings on the axle. A round steel bar with threaded ends and a reduced central cross-section is screwed into tapped blocks bolted to the yoke at the rear. Two electrical resistance strain gages cemented to the reduced section and covered with waterproofing material are used to indicate strain in the steel bar. Four round bars held by square end blocks surround the ball hitch on the truck. The front end of the dynamometer is screwed into the rear end block.

Signals from the strain gages on the dynamometer are amplified and recorded by an oscillograph in the truck shelter. Wheel revolutions of the trailer are obtained from a microswitch mounted against a cam on the trailer wheel hub and recorded on the oscillograph. Wheel revolutions are also registered on an electromagnetic counter. Alternating current (110-v, 60-cycle) for the oscillograph is obtained from a 1,200-watt motor generator mounted on a platform under the right rear corner of the truck. A voltmeter on the instrument table indicates the voltage supplied by the motor generator. A standard manual control arm for operating the electric brake is mounted at the end of the instrument table.

PORTLAND CEMENT ASSOCIATION APPARATUS

The Portland Cement Association test apparatus consists of a two-wheel trailer and road watering system. The trailer is drawn by a Chevrolet 210 coach, which also contains the major components of the watering system.

The trailer was designed to provide a low center of gravity and a nominal 925-lb load on each tire. The axle and springs are from a 1949 Ford. The suspension is such that the vertical loads are taken by the vertical shackles at each end of the springs. These shackles are of sufficient length and adjusted to a geometric relation such that the residual horizontal component of the load due to their angularity is negligible. The horizontal drag load of each end of the axle is transmitted by links to the drag link beam secured to the cross beam under the tongue ahead of the axle. The reduced portions of these aluminum drag link beams carry the strain gages that indicate a drag load occurring at the tire-ground contact. The vertical shackles are supported by similar horizontal beams, which could be instrumented to indicate the load on the axle directly, if this becomes desirable. Aluminum strain gage beams have been used to take advantage of their lower modulus of elasticity and proportionately higher output from a strain gage system. The lateral loads on the axle are transmitted by horizontal arms of a Watts linkage to the center rocker, whose center bearing is on the trailer centerline just aft of the axle. This removes the lateral force inputs due to vertical motion of the axle with respect to the trailer, which occur with the simple sway bar arrangement, and is in part responsible for the lack of side sway experienced during operation.

The brakes are conventional Ford hydraulic brakes which came with the axle, but larger front brake actuating cylinders have been substituted. A Chevrolet master cylinder is installed at the hitch of the tongue to operate the brakes. The master cylinder, which is operated by a hydraulic brake booster, is actuated through a push-pull cable system in the car. Both wheels are locked during the test run.

GRADATIONS OF THE ASPHALTIC SURFACES TESTED

Specifications—Virginia Designation I-3[1]

U. S. Sieve	Percent Passing
½ in.	100
⅜ in.	80-100
No. 4	50-70
No. 10	35-50
No. 40	10-25
No. 80	3-15
No. 200	2-10

Asphalt content: 6.25 percent

Specifications—Deslicking Mix[1]
(Excellent Site)

U. S. Sieve	Percent Passing
No. 4	100
No. 10	100-95
No. 40	40-95
No. 80	12-30
No. 200	0-8

Asphalt centent: 7.5-9.5 percent

[1] Sand for these mixes must be 95 percent silicon dioxide.

STATISTICAL ANALYSIS

Statistical analysis of the data consisted of three main parts: analysis of variance of Series Y (standard tires); analysis of variance of Series X and Series Y combined; and analysis of the variability between individual measurements. Although the three parts are interrelated, and the actual chronological order of the analysis was quite different, the foregoing order was chosen for simplicity of presentation. Standard statistical procedures were used.

Series Y

Table 6 shows the analysis of variance for the seven machines for which there were complete data with standard tires. This was basically a 7 x 14 factorial with six measurements per cell. The variation between machines was subdivided into two parts—variation between types of machines (trailers vs cars), and within types (between trailers, and between cars). Because there were large differences in the error variance for the two types, separate error terms were used.

TABLE 6

ANALYSIS OF VARIANCE, Y SERIES ONLY

Source of Variation	df	SS	MS	F
Trailers vs cars	1	0 240482	0.2404822	302.1[1]
Between trailers	4	0 738900	0.1847250	177.6[1]
Between cars	1	0.024300	0 0243000	148.2[1]
Levels of friction	3	3 133590	1 0445309	1314.8[1]
Levels x trailers vs cars	3	0.034375	0 0114585	14 4[1]
Levels x trailers	12	0.100240	0 0083533	8.0[1]
Levels x cars	3	0.001933	0 0006444	3.9[2]
Error, trailers	100	0.104033	0.0010433	
Error, cars	39	0.006397	0.0001640	
Error, total	139	0.110430	0.0007945	
Total	166	4.384250		

[1] Significant beyond 0.01 level. [2] Significant beyond 0.05 level

All main effects are significant far beyond the 0.01 level. The significance of the Methods x Levels interaction indicates that the shape of the average curve for trailers was substantially different from that for the cars. The Trailers x Levels interaction indicates differences in the shape of curves for the different trailers. As was mentioned in the text, trailer No. 5, which measured rolling friction, seemed to obtain qualitatively different results. Even with this machine removed, however, this interaction was still highly significant. Examination of Figures 17 and 18 showed the differences in shape to be substantial. Therefore, no simple additive correction factor can make results comparable at all levels. The Cars x Levels interaction was significant only at the 0.05 level, and differences in curve shape are small enough that a simple additive correction factor can bring results for the two cars into fair agreement.

Individual cell means for different machines were compared to see if any one machine got substantial agreement with any other one machine. Each machine was compared to every other machine, at each level of friction. Because of heterogeneity of variance, the variance estimate for each comparison was based on the variabilities of the two cells involved. Only a few of the cell means were not significantly different. Only machines No. 5 (trailer measuring rolling friction) and No. 6 (a car) had means not significantly different at more than one level of friction. But since the results of these machines should differ on a theoretical basis, and differences between these machines at the other two levels were marked, these agreements can only be deemed fortuitous. The statistical analysis, then, bears out the conclusion suggested by examination of the data: No machine obtained friction measurements which were in agreement with those of any other machine.

Combined Series X and Y

The measurements made with the tires regularly used by each machine make possible comparisons with previous measurements with those tires. However, the only general information Series X can add concerns the effects of tires on the measurement of friction.

Table 7 shows the analysis of variance including both standard tires and regular tires. (This is not a factorial design, as the "regular" tires were different for each machine.) The individual comparisons listed under "tires within machines" show that for all machines except No. 3 and No. 4, the regular tires obtained measurements sig-

TABLE 7

ANALYSIS OF VARIANCE, COMBINED X AND Y SERIES

Source of Variation	df	SS	MS	F
Machines	5	1.744346	0.348869	589.53
Tires within machines:				
No. 3	1	0.000075	0.000075	0.17
No. 4	1	0.000002	0.000002	0.00
No. 5	1	0.079218	0.079218	134.75[1]
No. 6	1	0.012675	0.012675	75.74[1]
No. 7	1	0.080033	0.080033	58.03[1]
No. 8	1	0.031008	0.031008	130.11[1]
Levels	3	5.545736	1.848578	3125.24[1]
Levels x machines	15	0.185251	0.012350	20.88[1]
Levels x tires within machines:				
No. 3	3	0.003075	0.001025	2.38
No. 4	3	0.003899	0.001296	1.79
No. 5	3	0.033073	0.011024	18.75[1]
No. 6	3	0.000742	0.000247	1.48
No. 7	3	0.008050	0.002683	1.95
No. 8	3	0.001625	0.005417	2.27
Error:				
No. 3	40	0.017233	0.000431	
No. 4	40	0.028983	0.000725	
No. 5	40	0.023517	0.000588	
No. 6	38	0.006360	0.000167	
No. 7	40	0.055167	0.001379	
No. 8	40	0.009533	0.000238	
Total	238	0.140793	0.000592	
Total	285	7.869601		

[1] Significant beyond 0.01 level.

nificantly higher or lower than the standard tires. The "levels x tires within machines" is of particular importance. With the exception of machine No. 5, a simple additive correction can make results with regular tires in essential agreement with results with the standard tires.

TABLE 8

VALUES OF CHI-SQUARE FOR BARTLETT'S TEST FOR HOMOGENEITY OF VARIANCE BETWEEN LEVELS OF FRICTION

Machine	X Series	Y Series
No. 1	-	3.36
No. 3	6.17	4.76
No. 4	4.77	10.61[1]
No. 5	2.85	17.96[2]
No. 6	7.51	1.77
No. 7	7.13	7.42
No. 8	2.87	2.38

[1] Significant beyond 0.05 level

[2] Significant beyond 0.01 level.

Error Variance

The foregoing analysis was based on comparison of the average coefficients of friction. Of equal importance is the variability of measurement (that is, the differences between successive measurements of the same pavement by the same machine). The variance of each cell was computed, and comparisons were made using Bartlett's test.

The first question was whether or not variability of measurement was different at different levels of friction. If variability were related to coefficient of friction, a suitable transformation should be sought. For each machine and each series, the variabilities at each level of friction were compared using Bartlett's test. The values of chi-square are shown in Table 8. Since day-to-day changes in variability were expected, and since these changes were confounded with levels of friction, significant results would not necessarily indicate that variability was related to level of friction. Only for machines No. 4 and No. 5 with standard tires was the value of chi-square significant. These results seem to be due to the unusually large variances obtained by these machines at the fair site already referred to in the text.

A plot of cell means and cell standard deviations showed no evidence of any relationship between variability and level of friction. Therefore, it was concluded that the coefficient of friction was the appropriate variable to use for statistical analysis. A plot of coefficient of variation did show evidence of a relationship. The usual procedure of reporting variability of measurement of coefficients of friction (that is, ± 5 percent) assumes the coefficient of variation is constant. It is therefore suggested that this procedure should be changed in accordance with the foregoing results, and variability should be reported in terms of the coefficient (that is, ± 0.02).

CORRECTION FOR TILTING OF CAR DURING LOCKED-WHEEL TEST

The correction for tilt was made on the basis of data supplied by General Motors Proving Grounds, whose tests have shown that the maximum angle that the horizontal axis of a 1958 Chevrolet will develop with the road is about 2 deg 40 min at deceleration rate of 25 ft per sec per sec. This deceleration rate equals 0.78 g's, which corresponds to a coefficient of 0.78, neglecting wind resistance of the car. It was assumed that a linear relationship existed between tilt and rate of deceleration (g's), hence between tilt and the instantaneous coefficient of friction ($\alpha_x = K_2 R_t$). Now, since the influence of tilt on the decelerometer reading, which is in g's, can be determined ($R_c = K_1 \alpha_x$), the correction can be made as follows:

$R_t = R_a - R_c$ in which R_t = true deceleration;
R_a = apparent deceleration; and
R_c = reading due to tilt and not deceleration.

But $R_c = K_1 \alpha_x$ in which α_x is the angle of tilt, and $\alpha_x = K_2 R_t$.

K_1 and K_2 can be evaluated from the previous assumptions, and

$$R_t = R_a - K_1 K_2 R_t$$
$$R_t = R_a - K_3 R_t$$
$$R_t = \frac{R_a}{1 + K_3}$$

After evaluating the constant it was found that $R_t = 0.941\ R_a$

Discussion

W. A. MC CONNELL, Manager, Vehicles Testing Laboratories, Ford Motor Company—Preliminary results of this study show apparatus used by the Tennessee Highway Department and the Bureau of Public Roads to yield significantly lower values of friction coefficient than General Motors and Cornell equipment. Specifically, comparable average values for the various road samples checked are: Tennessee, 0.34; BPR, 0.38; Cornell, 0.43; and GM, 0.45. It is understood that these are revised values in which differences in weight transfer from the test tire to the pintle hook during braking, which arise from differences in trailer hitch height and length, have been allowed for.

Examination of the force measuring systems on the four machines show that the Tennessee machine measures the drawbar pull exerted by the braked trailer, a pull comprised of the tire-road reaction force less any decelerative forces on the trailer itself. Similarly, the measuring system of the BPR rig is sensitive to both friction force and inertial force for the entire trailer, although in this case much of the trailer weight is carried by the towing truck, and not on the test wheel. The weighing system of the Cornell trailer unit is connected to the axle, and will register friction force of the tire-toad contact less inertial force of the wheel and axle assembly only. The General Motors device weighs the torque reaction of the braked wheels. While the wheels decelerate the reading will be influenced both by friction force and polar moment of the wheels in an additive way. After the wheels lock, the reading should be a function of friction force only.

Although exact masses of the various units are not known, an estimate of these masses and the magnitude of the resulting inertial effects suggest that all four machines are observing identical tire-to-road friction forces. When appropriate corrections are made, all machines should show about the 0.45 value given by the General Motors trailer.

For example, the Tennessee trailer is estimated to weigh 1,700 lb with 835 lb on the test wheel. It is towed by what is estimated to be a 7,000-lb truck. When the trailer brake is applied and the weighing system indicates a 0.34 coefficient, approximately 0.34 x 835, or 285 lb, retarding force is applied to the towing truck. This force will produce a 0.04-g deceleration in the 7,000-lb truck, and, since they are connected, in the trailer. When a 1,700-lb trailer decelerates at a rate of 0.04 g, a 70-lb force is required. This 70 lb comes from the tire-road reaction, but will not be measured by the load cell between the trailer and the towing truck. Thus, the true road reaction is 285 + 70 lb, or 355 lb in this situation, and the true friction coefficient is 355/835, or 0.43.

It is understood that tests were conducted at an initial speed of 40 mph, over 150-ft distances, or a time interval of about 2.5 sec. The 0.04-g deceleration in this time interval would produce about a 2-mph change in speed, which would probably be imperceptible to the machine operator.

Similar estimates of the inertial effects on the BPR unit yield a corrected value of 0.43. The inertia of the wheel axle assembly on the Cornell tire tester is sufficiently light and the truck sufficiently heavy that their 0.43 value would not be materially increased.

The percent error introduced in the results will be equal to the mass behind the load cell divided by the mass ahead of the cell, and will be constant regardless of the magnitude of the deceleration produced by application of the trailer brakes. Thus, the Tennessee apparatus has a built-in error of 1,700/7,000 = 25 percent; the BPR equipment is in error by 1,360/11,000 ≒ 12.3 percent; the Cornell system by 100/17,000 = 0.6 percent. These errors will be somewhat variable as the water supply and weight of the towing truck varies.

It appears, therefore, that all units used in the correlation study are experiencing nearly identical tire-road friction coefficients; but careful evaluation must be made of the inertial effects as well as the geometry of each apparatus if the numbers presented by the various weighing arrangements are to be interpreted correctly. Even imperceptible decelerations and gradients of even a fraction of a percent cannot be ignored with the drawbar type weighing method.

It would seem possible to arrange the design of future testing machines so that no corrections are required. A parallel link suspension as used by the British Road Research Laboratory transfers the brake torque couple to the towing vehicle by tensile and compression loads in two horizontal arms, so that no change in normal pressure between the test tire and the road arises from the braking force, and no geometric corrections are needed. Likewise, measurement of torque, rather than thrust, obviates the need for inertial corrections.

E. A. WHITEHURST, Director, Tennessee Highway Research Program—Mr. McConnell's comments concerning the differences in coefficients of friction measured by the Tennessee, BPR, Cornell, and GM skid trailers are most interesting. It is suggested, however, that his analysis of the reason for such differences is not entirely in accord with the actual operation of some of the trailers, and that his contention that all should show numerical results in the order of the GM trailer is perhaps premature.

In the case of the Tennessee trailer, Mr. McConnell presupposes a deceleration during the skid test in the order of 2 mph. Although it is agreed that a driver may not be able to identify such a deceleration quantitatively, it is felt that he will recognize that deceleration is occurring. The driver of the Tennessee truck has been making skid tests of this nature for seven years. He is instructed to accelerate when the trailer wheel locks to offset just such deceleration.

Immediately prior to the correlation study, the Tennessee trailer was equipped with an electrical generating speedometer capable of measuring speed accurately and of detecting small differences in speed. The output from this speedometer was fed to a chart recorder and to a meter, both of which were activated just prior to each skid test. During these particular tests, an additional man was carried on the towing truck for the sole purpose of observing the speedometer output on the meter, and the recorded output on the chart was examined immediately after each test. No decelerations in the order of 2 mph were indicated either by the meter or by the chart record.

It seems appropriate at this time to look philosophically at the results of the test data collected by all vehicles, including the two stopping-distance automobiles. It is almost universally agree among those who have conducted studies of pavement slipperiness that on a wet pavement the coefficient of friction increases markedly as the speed decreases. Theoretically, an automobile sliding from some initial speed to zero should average all coefficients between that at the initial speed and that near zero speed. It follows that the coefficients of friction measured by the stopping-distance technique from an initial speed of 40 mph should be materially higher numerically than those measured by a sliding trailer at the speed of 40 mph.

In a paper presented at this Conference, Giles (6) states: "methods of tests which enable values of coefficient at different speeds to be directly determined have different advantages, and it is still not generally realized that where coefficients are deduced from skidding distance measurements using the relation $f = V^2 \div 2\,g\,S$, the resulting value of coefficient is in fact only that which would be obtained by direct measurement at a speed of $\frac{2}{3}$ V." He points out that this relationship was first discovered empirically from the results of skidding tests in Britain and includes with his paper an appendix which appears to mathematically justify his previous statement.

Examination of the correlation study results shows that on most occasions the numerical results of the GM trailer tests were nearly as great as those on the stopping-distance automobiles. If this is true and if Giles' analysis is correct, it must be assumed either that the GM trailer was used in tests at a speed of approximately 27 mph or that the stopping-distance tests were made from an initial speed of 60 mph. Those who took part in the correlation study are aware that every effort was exerted to have all tests performed at the control speed of 40 mph. Thus, it appears that some question may be raised as to the numerical accuracy of the results of the General Motors trailer.

It is agreed with Mr. McConnell that in all probability all units used in the correlation study did experience nearly identical tire-road friction coefficients. It also is agreed that careful evaluation must be made not only of the inertial effects and of the geometry of each apparatus, but also of the technique employed in each case for measuring some parameter which may then be interpreted in terms of coefficient of friction. It is suggested, however, that until much more is known about the several factors influencing the resistance between a sliding tire and the pavement surface on which it slides, and about the measurement of these factors, efforts to numerically equate the results of one apparatus with those of another be exercised with great caution.

Finally, the hope is expressed that extensive discussion of why one apparatus does not give results numerically identical to another will not cloud the highly significant and highly gratifying fact that so many pieces of equipment differing to a great degree in concept and design could test four pavements of previously unknown quality and rate them in an essentially identical manner.

RICHARD H. SAWYER, Langley Aeronautical Laboratory, National Aeronautics and Space Administration—After a careful analysis of the problem of the low friction coefficient values obtained in the correlation study by the vehicles using measurements of tow-bar force, the writer agrees with Mr. McConnell's analysis of the problem. For the assumed case of no change in driving power and a steady value of the skidding force, it is interesting to note that the following expression can be used to obtain the skidding force from the tow-bar force without the necessity of calculating the deceleration of the vehicles:

$$F_S = F_{TB} (1 + W_2/W_1)$$

in which

F_S = skidding force;
F_{TB} = tow-bar force;
W_2 = weight of trailer; and
W_1 = weight of towing vehicle.

Because the tow-bar method of measurement is also subject to error caused by accelerations produced by power changes as well as by the skidding force, the correlation study data should not be corrected by the foregoing, but calculations might be made as Mr. McConnell indicated to show that better agreement would result by such considerations. Inasmuch as the error due to neglecting effects of acceleration is so large, it appears that the tow-bar method of measurement is at considerable disadvantage with other methods, particularly since, even if attempts are made to correct the results by measurement of the acceleration, accurate measurements of such small values of acceleration in the presence of other transient accelerations caused by road unevenesses, etc., would appear to be extremely difficult.

C.G. GILES, Head, Road Surface Characteristics Branch, British Road Research Laboratory

NOTE:—Several weeks after completion of testing for the study, 4-in. cores were cut from the four test sites and offered to any group interested for laboratory testing. Two cores from each of the test sites were sent to Mr. Giles. After testing the cores in the laboratory's portable testing apparatus, as described briefly elsewhere (6), he sent the following data and comments by letter.

These samples are not really large enough to employ the British Road Research Laboratory's standard test conditions (3-in. wide slider and 5-in. sliding length), so a narrower slider and shorter sliding distance were required. However, the results so obtained are thought to be not too far from what would result if the normal conditions of test could be used.

Comparison of the results with the measurements obtained with the Virginia and Purdue skidding distance cars, which is probably the fairest comparison that can be made, seems to indicate quite reasonable correlation. The BRRL tester generally shows slightly higher values than the full-scale machines, but this is the usual finding when making comparisons of the two methods in Britain.

SUMMARY OF TEST RESULTS ON CORES FROM CORRELATION TEST SITES IN VIRGINIA

Sample	Classification	Coef. of Friction Brit. Rd. Res Lab.[1]			Full-Scale Machines[2]	
		A[2]	B[3]	Mean	Purdue	Virginia
P6	P	0.45	0.38	0.39	0.29	0.33
P8		0.38	0.35			
F10	F	0.50	0.43	0.51	0.44	0.47
F14		0.57	0.53			
G4	G	0.62	0.55	0.58	0.52	0.57
G11		0.60	0.56			
G14	E	0.63	0.66	0.65	0.63	0.69
G12		0.65	0.66			

[1] As measured by British Road Research Laboratory portable tester on samples cut from the test roads.

[2] Tests with 3-in. wide slider and 3-in. sliding length; may be some "edge" effects due to slider striking edge of block.

[3] Tests with 1¼-in. wide slider and 3¼-in. sliding length, no "edge" effects.

Quite apart from this, too, it has been found on previous occasions that however carefully a sample is cut from the road there is always a possibility that its surface condition may change before it is tested in the laboratory. In some cases the coefficient of friction on the cut sample has been found to be as much as 0.1 higher in the laboratory than the value measured in situ, before the sample was removed. Therefore, the results must be treated with some caution.

Review of Laboratory and Field Methods of Measuring Road Surface Friction

Report of Subcommittee E to the First International Skid Prevention Conference
Charlottesville, Virginia, September 8-12, 1958

● THIS CONSTITUTES the final report of Subcommittee E, Review of Laboratory and Field Methods of Measuring Road Surface Friction. The report is a result of the deliberations of the subcommittee prior to, during, and subsequent to the Conference. It was hoped originally that a subcommittee report could be compiled to represent an international viewpoint but since it was not practical for the European representative to attend the meetings of the subcommittee it was decided that the report could only refer specifically to the American situation. Mr. Giles, Head, Surface Characteristics Section, British Road Research Laboratory, is a member of Subcommittee E and was most helpful in the subcommittee activities prior to and during the Conference, but was unable to attend the subsequent session during which the ideas behind the present report were discussed.

The report is divided into five major sections in conformance with the following objectives of the conference:

1. To exchange available information within each of the individual fields and between these fields relevant to the problem of adequate traction.
2. To inventory existing knowledge of the subject.
3. To inventory existing deficiencies in present knowledge and practices.
4. To develop a comprehensive program of research.
5. To demonstrate and correlate test results of existing equipment and methods for measuring skid resistance, and initiate a program to develop standard testing procedures.

COMMENTS ON THE EXCHANGE OF INFORMATION AND INVENTORY OF EXISTING KNOWLEDGE

It was the subcommittee's responsibility to organize that portion of the Conference program relating to a review of laboratory and field methods of measuring skidding. The program was comprised of 17 papers, six of which were authored by Europeans. It is these papers that constitute the fulfillment of Objectives 1 and 2 of the Conference, and therefore, the contents of this report are concerned principally with Objectives 3, 4, and 5.

INVENTORY OF EXISTING DEFICIENCIES IN PRESENT KNOWLEDGE AND PRACTICES

In addition to the developing of a Conference program summarizing current information on methods of measuring road surface friction, one of the major aspirations of Subcommittee E was to encourage research in the area of laboratory and field testing. To encourage further research and channel it into the most fruitful areas, a list of some of the needed research is given below. It might be noted that most of the specific recommendations are concerned with field testing. This is so because field testing is far more advanced technically than laboratory testing and the problems more apparent. The subcommittee recognizes the excellent pioneer work that some organizations are doing in developing laboratory methods of evaluating pavement surfaces and materials. Laboratory tests are, however, only in the exploratory stage and the exact direction that the research should take is less clear.

The subcommittee would like to call attention to some of the areas needing further work. It is recommended:

1. That a survey or surveys be made in this country and abroad on:
   a. The design characteristics of existing field friction measuring machines.

b. The instrumentation used on the various field machines.

c. The calibration procedures used on the various field machines.

d. The methods suitable for measuring the dynamic normal forces active on the measuring wheel(s) of the various machines.

2. That basic research be undertaken on the phenomena during skidding at the interface of the tire, water film, and pavement.

3. That information be developed on the most suitable method and rate of application of water during field testing, and further that a universal expression of waterfilm thickness or rate of application be developed.

4. That the effect of temperature of tire, surface, and water on the coefficient of friction be determined.

5. That work on the laboratory methods of test be extended and especially the correlation of laboratory and field results.

DEVELOPMENT OF A COMPREHENSIVE PROGRAM OF RESEARCH

Subcommittee E feels very strongly that the work begun by the subcommittee should be continued by the formation of a group within some continuing and permanent organization such as the Highway Research Board. Unless this is done some of the interest generated by the subcommittee activities will be lost. The subcommittee is especially anxious that some continuing body encourage and coordinate research work on existing deficiencies of present testing methods. It is the committee's belief that only through the efforts of some continuing group can a dynamic approach to the solution of the testing phase of the slipperiness problem be expected.

The subcommittee was successful in interesting some of its own members in working on certain phases of the deficiencies listed above. It is possible that some of the agencies represented on the subcommittee will be working on each of the items above, depending upon how expeditiously the research can be worked into the programs of the various agencies. [1] This by no means should be thought to indicate that work by others should not be encouraged for the problems are complex and will need the combined efforts of many research agencies. It is hoped that others can be encouraged to participate in working on the needed research.

CORRELATION STUDY

Another activity in which Subcommittee E participated in an advisory capacity was the correlation study of various field methods of measuring road surface friction. The purpose of this study was to permit a comparison of several test methods currently in use in this country. Measurements were made prior to the conference on pavements exhibiting a wide range of road slipperiness conditions. Since this study is being reported separately it is mentioned here only to record the compliance of Subcommittee E in meeting the first part of Objective 5 of the Conference.

THE INITIATION OF A PROGRAM TO DEVELOP STANDARD TESTING PROCEDURES

It is important to point out again that the thoughts expressed by the subcommittee on standardization were being directed to the American scene and apply only to American conditions.

The standardization question was considered to have two facets: (1) the need for an

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[1] The following agencies represented on the subcommittee have expressed a desire to work on some phase of the needed research:

1. Tennessee Highway Research Program;
2. NACA, Langley Aeronautical Laboratory;
3. Virginia Council of Highway Investigation and Research;
4. Joint Highway Research Project, Purdue University; and
5. Cornell Aeronautical Laboratory, Inc.

immediate standard of reference, and (2) a permanent standard of reference. The thoughts of the subcommittee on these two facets are related below:

An Interim Standard. It was the belief of the subcommittee that the practical matter of providing pavements with adequate skid resistance could best be served by establishing a single standard of reference. Such a standard of reference must be capable of fulfilling the immediate need of the various highway agencies and it was thought imperative, therefore, that the interim standard be applicable almost immediately. After considerable discussion, it was decided that the stopping distance method would be the most expedient interim standard throughout the country. The subcommittee, therefore, would like to specifically recommend that the stopping distance method be adopted for this purpose. It should be emphasized that while the stopping distance method is being recommended as the standard of reference, any method in which an agency has confidence could be used by them for evaluating pavements and materials. The important point is that the results from a particular device be related to a stopping distance method and that any pavement standards that are to be established be expressed in terms of the stopping distance method.

The subcommittee would also like to point out that additional thought will have to be given to: (1) the instrumentation of the standard stopping distance method, (2) the selection of a standard tire and (3) the procedural aspects of conducting the tests. Those who take up and continue the work of Subcommittee E could handle this matter, but the subcommittee would like to emphasize that the need for these items is immediate and hopes that decisions regarding these items can be made prior to the summer of 1959.

The subcommittee felt that selection of an interim standard was based on practical considerations and that further work should be done in carefully selecting an eventual standard field testing method. Further, it is believed that ASTM and AASHO are the appropriate agencies for handling this matter but it is not known if committees of these organizations are presently available to carry out this work. Subcommittee E suggests, therefore, that the formation of such a subcommittee be discussed with the officials of ASTM and AASHO.

While the subcommittee did not believe themselves to be in a position to make recommendations about the specific details of a permanent standard test they did arrive at certain general recommendations. It was the belief of the group that the standard method should:

1. Measure the sliding coefficient since that condition is the one most frequently met in skidding accidents. The subcommittee would like to point out, however, that other coefficients, the sideway force and incipient, are valuable indices of slipperiness under other conditions.
2. Utilize realistic passenger car loadings and tire pressures.
3. Be capable of being reliably used over the speed range normally employed by passenger vehicles.
4. Be capable of reliably measuring any portion of a road surface. It should be capable of measuring the friction at any point laterally across the road, on grades, curves, and over fairly short sections of pavement.
5. Be usable in all types of traffic without hazard to anyone.
6. Provide a continuous and permanent record of the force measurements (and indirectly the coefficient) and the speed over the site being tested.
7. Be independent of operator variable.
8. Be designed so that weight shift vertically would not affect results significantly.
9. Utilize a standard tire that:
    a. can be made available over a long period of time.
    b. has a standard composition, carcass and tread design.

SUMMARY

In summary the subcommittee would like to reiterate the following recommendations:

1. That a group be formed within some permanent and continuing organization like

the Highway Research Board to perpetuate the work begun by Subcommittee E.

2. That the stopping distance method be used as an interim standard of reference and that decisions concerning instrumentation, standard tires, and procedures be made by an appropriate group prior to the summer of 1959.

3. That ASTM and AASHO initiate the necessary steps to begin work on standardizing a field testing machine, and further, that the recommendations of Subcommittee E as to the general nature of the testing machine be considered in their deliberations.

SUBCOMMITTEE E MEMBERSHIP

G.J. Fabian, Principal Engineer, Cornell Aeronautical Laboratory
C.G. Giles, Head, Surface Characteristics Section, British Road Research Laboratory
W.H. Goetz, Research Engineer, Purdue University
J.E. Gray, Engineering Director, National Crushed Stone Association
E.G. Wiles, Physical Research Engineer, Bureau of Public Roads
J.H. Dillard, Highway Research Engineer, Virginia Council of Highway Investigation and Research
J.M. Rice, Director, Natural Rubber Bureau, Road Research Laboratory
P.C. Skeels, Head, Experimental Engineering Section, General Motors Proving Grounds
R.H. Sawyer, Aeronautical Engineer, Langley Aeronautical Laboratory
E.A. Whitehurst, Director, Tennessee Highway Research Program
F.P. Nichols, Jr., Highway Research Engineer, Virginia Council of Highway Investigation and Research
Tilton E. Shelburne, Director of Research, Virginia Council of Highway Investigation and Research

A Laboratory Investigation of Pavement Slipperiness

J.W. SHUPE, Associate Professor, Applied Mechanics Department,
Kansas State College, Manhattan, Kansas; and
W.H. GOETZ, Professor, School of Civil Engineering,
Purdue University, Lafayette, Indiana

This report briefly describes the laboratory skid-test apparatus developed at Purdue University to evaluate the skid resistance of portland cement or bituminous specimens molded in the laboratory or cored from the pavement surface. A field correlation study was performed on 28 test sections, representing a large variation in surface textures. Passenger car stopping-distance tests were performed on each of the sections, after which cores were obtained and evaluated in the laboratory skid-test apparatus. In general, there was fairly good agreement between the two methods of evaluating slipperiness. Accelerated wear and polish procedures for both portland cement and bituminous specimens, intended to simulate the polishing action of traffic, are also described.

A summary is presented of the initial phase of the investigation in which the polishing characteristics of bituminous mixtures composed of 22 different mineral aggregates were determined. Also summarized are a comparison of the polishing characteristics of aggregates in portland cement and bituminous mixtures, a consideration of the effect of surface texture on the skid resistance of bituminous mixtures, and an evaluation of the effect of initial aggregate shape on the anti-skid characteristics of bituminous mixtures.

A discussion, based on laboratory test results, is presented as to the effect of blending a polish-resistant material with a polish-susceptible aggregate in both portland cement and bituminous mixtures. The blending materials included in the study were natural sands, harsh silica sands, slag, and sandstone. For the slag sandstone both coarse- and fine-aggregate replacement were investigated.

The anti-skid characteristics of a number of fine-grained surfaces were also evaluated. Included in these surfaces were sand-asphalt mixtures composed of a dozen natural sands of dissimilar characteristics and some of the non-skid surface treatments, such as Kentucky rock asphalt, silica sand, proprietary mixtures and resinous binders supporting different varieties of abrasives. By contrast, skid resistance values are also presented for some of the slickest surfaces likely to be encountered by traffic.

In summarizing the results of this study, general recommendations are made with regard to design and construction practices which tend to minimize pavement slipperiness.

● EXPERIENCE indicates that highways which are constructed to conform to current design standards may become dangerously slippery when wet after a relatively short period of wear. As the polishing effect of traffic continues to become more intensified, the incidence of slippery sections of pavement will tend to increase. In order to minimize the occurrence of these skidding hazards, the highway engineer must include permanency of skid resistance as a design parameter in selecting a suitable paving mixture.

A laboratory testing procedure was developed at Purdue University to investigate the slipperiness potential of different highway materials, and to predict the resistance of paving mixtures to the polishing effect of simulated traffic. The laboratory testing method, a field correlation study, and an accelerated wear and polish procedure are summarized in this report, along with the results of the initial phases of the research which have been reported upon previously (7). Included in this summary are (1) a report of the polishing characteristics of aggregates in both portland cement and bituminous mixtures and (2) a study of the effect of surface texture, or degree of openness, and initial aggregate shape on the skid resistance of bituminous mixtures. A more complete discussion is presented of subsequent research in which the effect of blending a polish-resistant material with a polish-susceptible aggregate in both portland cement and bituminous mixtures was determined, and of a study in which the anti-skid characteristics of fine-grained surface treatments were investigated. A final summary is presented which includes the authors' recommendations with regard to design and construction practices that tend to minimize pavement slipperiness.

LABORATORY SKID-TEST APPARATUS

The laboratory test procedure was developed to evaluate the skid resistance of portland cement or bituminous specimens molded in the laboratory or cored from the pavement surface. The laboratory skid-test apparatus spins a 6-in. diameter test specimen at a constant speed of 2,500 rpm and measures the skid resistance by forcing a rubber testing shoe against the surface of the test specimen with a unit pressure of 28 psi. The amount of torque developed in the shaft supporting the testing shoe, due to the skidding action of the shoe on the test specimen, is automatically recorded as a measure of the skid resistance of the specimen. All tests were performed with the surface in the wet condition.

The skid resistance of each specimen was expressed as a relative resistance value (RRV), with Kentucky rock asphalt, which from field studies (1, 2) has consistently exhibited excellent resistance to skidding, selected as the reference non-skid material. The skid-test apparatus was adjusted so that a Kentucky rock asphalt specimen cored from the highway surface gave an RRV of 1.00; and the relative skid resistance of the other surface types, based on an RRV of unity for Kentucky rock asphalt, was determined to the nearest 0.01. A complete discussion of the laboratory skid-test apparatus is presented in reference (5).

A field correlation study was performed on 17 bituminous and 9 portland cement concrete test sections, all evaluated with the surface in a wet condition. Three stopping-distance tests were made on each of the sections by locking the wheels of the test vehicle at a speed of approximately 34 mph and measuring the distance required to skid to a complete stop. The average coefficient of friction was calculated by substituting in the standard stopping-distance equation:

$$s = \frac{V^2}{30f}$$

where:

s = total stopping distance in feet,
V = initial speed of vehicle in mph,
f = average coefficient of friction over entire speed range of from V to 0 mph.

Three 6-in. diameter cores also were taken from each test section and evaluated in the laboratory skid-test apparatus. The results of a comparison of the field

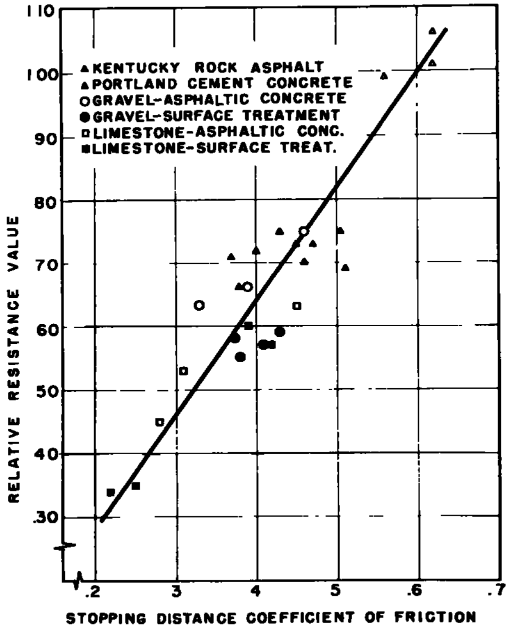


Figure 1. Comparison between field and laboratory skid-test measurements.

and laboratory methods of evaluating skid resistance are summarized in Figure 1. Each plotted point represents the average coefficient of friction computed from the stopping distances of three lock-wheel tests performed on the highway, and the average RRV for three cores obtained from the test area and evaluated in the laboratory skid-test apparatus.

There was fairly good agreement between the field and laboratory methods of evaluating skid resistance, as shown in Figure 1. It was felt that a towed-vehicle type of field test (3, 8) which, like the laboratory test apparatus, measures skid resistance at constant speed would have resulted in a better correlation than the stopping-distance method. Unfortunately, such a unit was not available for this study. A detailed discussion of factors contributing to the variation in results between the field and laboratory methods of evaluating slipperiness is presented in reference (5). A consideration of these factors led to the conclusion that such discrepancies as exist tend to favor the laboratory method as giving a more realistic evaluation of slipperiness of wet surfaces than the stopping-distance method for speeds of 30 mph and upward.

TABLE 1

AGGREGATE GRADATION FOR STANDARD LABORATORY SPECIMENS

Passing Sieve	Retained on Sieve	Asphaltic Concrete	Portland Cement Concrete
½ in.	⅜ in.	12	25
⅜ in.	No. 4	36	25
No. 4	No. 8	10	7
No. 8	No. 16	11	12
No. 16	No. 30	12	12
No. 30	No. 50	11	13
No. 50	No. 100	3	6
No. 100	No. 200	2	0
No. 200	Pan	3	0
		100	100

ACCELERATED WEAR AND POLISH PROCEDURE

The primary criterion in selecting a standard laboratory specimen and in developing an accelerated wear and polish procedure was to simulate the surface characteristics that a similar mix would exhibit after an appreciable amount of highway service under the action of heavy traffic. The aggregate gradations for the standard laboratory specimens are listed in Table 1. For the standard asphaltic concrete test specimen the asphalt content was kept intentionally low to emphasize the effect of the aggregate. The standard portland cement concrete specimen was designed with a high cement factor and sufficient water to result in a slump of approximately 1 to 2 in. To facilitate a comparison of the polishing characteristics of the various aggregates, each portland cement and bituminous test specimen was composed entirely of one aggregate, except for that phase of the study in which blending of aggregates was investigated.

The bituminous specimens were vibrated to accomplish initial compaction, rolled with conical rollers to simulate the surface aggregate orientation that occurs on the highway, subjected to a coarse-wear cycle in which crushed quartz was used as the abrasive, given a fine-polish cycle with limestone mineral filler as the abrasive, and rolled again to coat the surface aggregate with a light film of asphalt. The variation in skid resistance of three typical bituminous mixtures due to this wear and polish procedure is illustrated in Figure 2. The relative resistance values are plotted as the ordinate with the position in the wearing cycle indicated along the abscissa. The initial RRV's were determined after the specimens had been vibrated, and the other four points correspond to values determined immediately following (1) initial rolling, (2) coarse polish, (3) fine polish, and (4) final rolling.

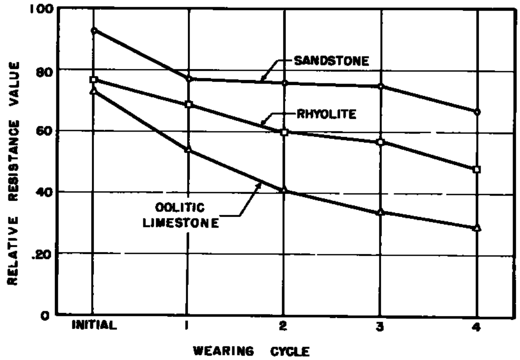


Figure 2. Variation in skid resistance of bituminous mixtures with wear.

These three curves illustrate the excellent resistance to polishing of bituminous mixtures containing sandstone, as compared to specimens composed of rhyolite, which exhibit fair polishing resistance, or to mixtures made with oolitic

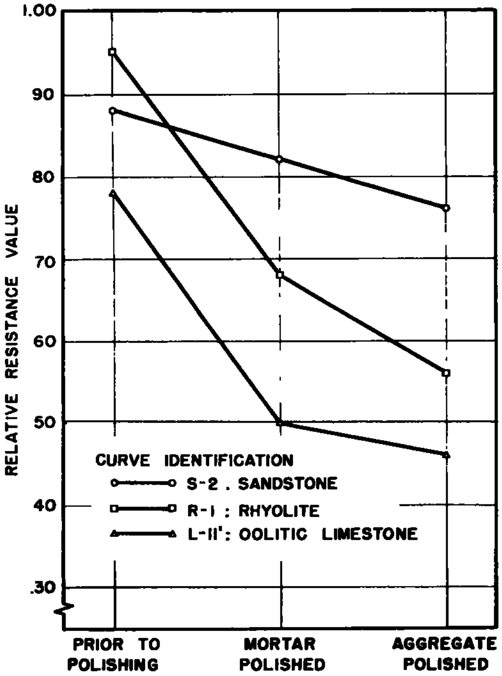


Figure 3. Polishing characteristics of portland cement concrete.

limestone, which polished quite readily. In comparing the characteristics of the different specimens, the results determined at the completion of the fine-polish cycle (wear cycle No. 3 of Fig. 2) are probably the most significant. At this point in the wearing procedure the test specimen possesses a clean surface with a texture similar to that of a well-worn bituminous pavement. The subsequent rolling operation was intended to indicate the susceptibility of the mixture to the loss in skid resistance which occurs due to the road film that accumulates on some highways during certain seasons of the year.

The portland cement test specimens were subjected to a somewhat different procedure. During the finishing operation, the surface of each portland cement specimen was lightly brushed with a whisk broom, to give a "sandpaper" texture. After curing for 7 days, each specimen was tested for skid resistance in this condition, which is identified as the "prior to polishing" condition. Subjecting a portland cement concrete specimen to the entire wear and polish procedure used for bituminous mixtures only resulted in a slight amount of wear of the mortar, and failed to expose an appreciable quantity of coarse aggregate. Concrete specimens which were subjected to a wearing procedure similar to, but slightly more severe than, that given to the bituminous mixtures are described as being in the "mortar polished" condition. Each specimen was tested in the skid-test apparatus in this condition.

Next, the top ¼ in. of each portland cement specimen was removed by a masonry saw equipped with a diamond blade, and the freshly-sawed face was subjected to the same wearing procedure that had been given initially to the mortar surface. The specimen was again tested for skid resistance, this time in what is described as the "aggregate polished" condition. Figure 3 indicates the variation in skid resistance of three typical portland cement specimens, with RRV's listed for each of the three points in wearing procedure. The specimens, upon which the results illustrated in Figure 3 were based, were composed of the same three aggregates used in the bituminous mixtures on which the RRV's plotted in Figure 2 were obtained.

SUMMARY OF THE INITIAL PHASES OF THE RESEARCH

A brief summary is presented of the results from the initial phases of the research on skid resistance at Purdue University. These data are given since this information is closely related to the blending study which follows, and the recommendations submitted in the final section for minimizing pavement slipperiness also refer to the findings of the early program of research. A complete treatment of this initial work is given in reference (7).

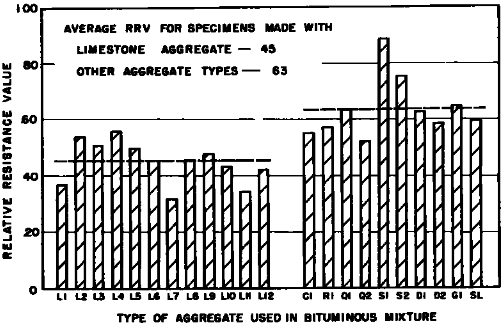


Figure 4. Skidding resistance of bituminous mixtures at the completion of the fine polish cycle.

Polishing Characteristics of Mineral Aggregates

The results of the resistance to polishing of bituminous-concrete mixtures composed of 22 different aggregates are summarized in Figure 4. Relative resistance values at the completion of the fine-polish cycle are plotted as the ordinate with the type of aggregate used in each of the mixtures indicated along the abscissa. Twelve limestones (L-1 through L-12) were included in the study, and the values obtained for these aggregates are plotted to the left in Figure 4. Results for the other ten aggregates which, reading from left to right, include a chert, a rhyolite, two high-quartz gravels, two sandstones, two diabases, a granite, and a blast-furnace slag, are plotted to the right in Figure 4.

TABLE 2

MIXTURE COMPOSITION OF FINE-TEXTURED SPECIMENS

Passing Sieve	Retained Sieve	Gradation No. 5	Silica Sand	Carborundum	Kentucky Rock Asphalt
No. 4	No. 8	19.2	0	0	0
No. 8	No. 16	15.1	0	0	1.7
No. 16	No. 30	14.0	0.5	88.1	4.3
No. 30	No. 50	13.3	38.4	11.7	43.3
No. 50	No. 100	15.1	56.7	0.1	37.2
No. 100	No. 200	13.7	4.0	0.1	6.8
No. 200	Pan	9.6	0.4	0	6.7
		100.0	100.0	100.0	100.0

Gradation No. 5 Specimens

L-4, L-11, and SL-1	5.7 percent asphalt
All other aggregates	5.4 percent asphalt

Silica Sand Specimen

1,700 g of silica sand; 40 g hydrated lime; and 6.2 percent asphalt.

Carborundum Specimen

900 g of silica sand; 900 g carborundum; 40 g hydrated lime; and 5.7 percent asphalt.

Kentucky Rock Asphalt Specimen

1,800 g of the total natural material, of which 8.03 percent was asphalt, as determined by extraction.

An examination of these results leads to three conclusions with regard to bituminous-concrete mixtures, which apply primarily to the aggregate types included in this study:

1. Limestones, as a group, do not exhibit as good resistance to polishing as other aggregate types. The average RRV for mixes containing the 12 limestones was 0.45 while mixes composed of the other aggregates had an average RRV of 0.63.
2. There is appreciable variability in the resistance to polishing of the various limestones. Mixes in which the limestone consisted almost entirely of calcium carbonate polished quite readily and produced RRV's in the low 0.30's. Mixes containing highly-dolomitic limestone exhibited somewhat better resistance to polishing with RRV's in the middle 0.50's.
3. Sandstones possess by far the best resistance to polishing of any of the aggregates evaluated in this study.

In order to compare the polishing characteristics of aggregates in portland cement and bituminous mixtures, six aggregates were selected for study. Portland cement and bituminous specimens were made with each of the six aggregates, subjected to their respective wear and polish procedures, and evaluated for skid resistance in the laboratory testing equipment. The results of this study are summarized in Figure 5, and indicate that if appreciable exposure of the coarse aggregate occurs in specimens composed entirely of one aggregate type, the skid resistances of portland cement and bituminous mixtures will be similar.

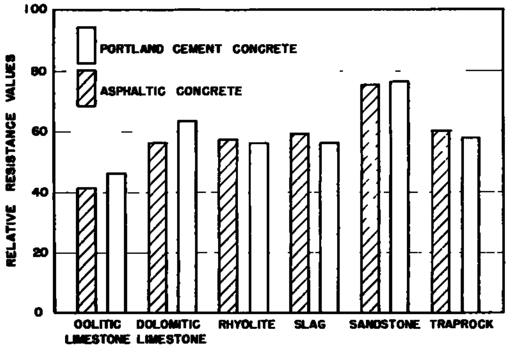


Figure 5. Skid resistance of portland cement and asphaltic concrete test specimens.

Effect of Surface Texture and Initial Aggregate Shape

The bituminous mixtures for the aggregate-evaluation study were composed entirely of crushed aggregate conforming to a standard gradation. To investigate the effect of specimen surface texture, as determined primarily by gradation, and initial aggregate shape on the skid-resistance of bituminous mixtures, four representative aggregates were selected for additional study. Two of these aggregates were limestone; one, a highly-dolomitic limestone (L-4) that had exhibited good resistance to polishing; and the other, an oolitic limestone (L-11) which had polished quite readily. The other two aggregates were a rhyolite (R-1) and a sandstone (S-2).

For the surface-texture investigation bituminous mixtures conforming to five different gradations were molded, subjected to the wear and polish procedure, and evaluated for skid resistance. Gradation No. 1 was very open-graded, with the mixtures becoming progressively more dense-graded as the gradation number increased. Gradation No. 5 is listed in Table 2, and the other gradations are given in reference (7). Mixtures conforming to gradation No. 1 were so open-graded that they exhibited very little surface durability and disintegrated during the wearing procedure.

The test data of the surface-texture investigation are summarized in Figure 6 by presenting results for two of the gradations. This figure shows the RRV's obtained with each of the four aggregates at the completion of the fine-polish cycle, both for specimens conforming to gradation No. 5, the most dense-graded mixture, and gradation No. 2, the most open-graded mixture which satisfactorily completed the wear and polish procedure. Although the texture effect was not as significant as the difference in aggregate types, in all four cases the dense-graded specimens exhibited better skid resistance than the corresponding open-graded specimens.

To provide a basis for determining the effect of initial aggregate shape, a sample of each of the four selected aggregates was placed in a Los Angeles abrasion machine and revolved for four hours. No steel balls were used, and the wearing action of aggregate on aggregate and against the shell of the machine caused the individual pieces of aggregate to become quite rounded. The resulting material was then sieved, batched, and mixed in accordance with the standard procedure. The finished specimen was identical to the corresponding standard bituminous-concrete specimen used in the aggregate-evaluation study, except that the standard specimen contained aggregate which was freshly crushed while the modified specimen consisted entirely of artificially-rounded aggregate.

The relative resistance values following initial rolling, coarse polish, and fine polish are plotted in Figure 7 for the two types of specimens and for each of the four aggregates. The initial skid resistances of the specimens containing the angular aggregates were appreciably higher than for the corresponding rounded-aggregate specimens, which was to be expected. At the completion of the fine-polish cycle, however, for a given aggregate there was no significant difference between the skid resistances of the angular- and rounded-aggregate specimens.

THE SKID RESISTANCE OF SELECTED FINE-TEXTURED SURFACES

The term "fine-textured" is used in this section to describe the degree of openness of surfaces and is dependent upon the magnitude of the individual surface voids. The

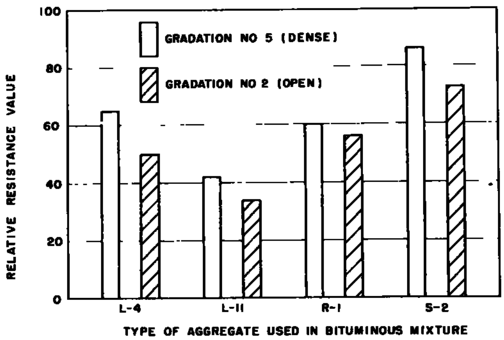


Figure 6. Compariosn of the resistance to polishing of dense and open graded bitiminous mixtures.

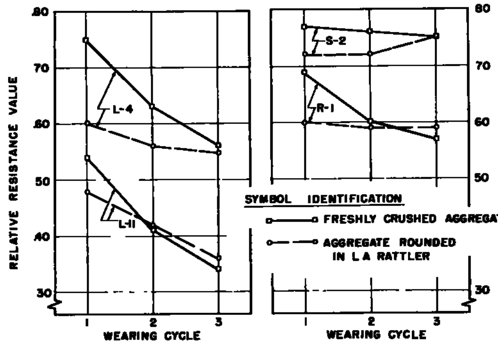
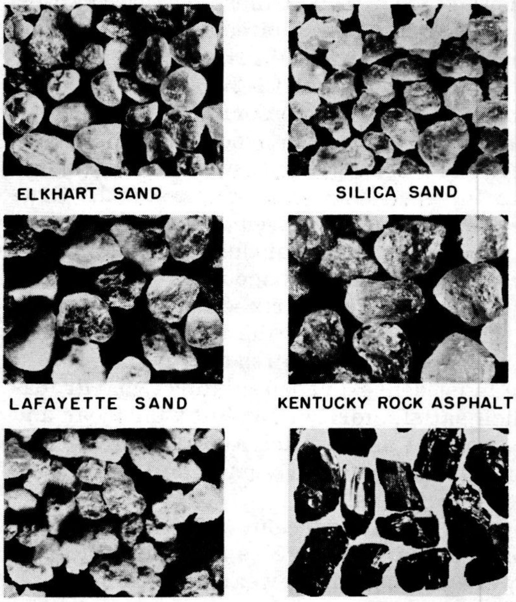


Figure 7. Effect of aggregate shape on the polishing characteristics of bituminous mixtures.



ELKHART SAND

SILICA SAND

LAFAYETTE SAND

KENTUCKY ROCK ASPHALT

VIRGINIA SAND

CARBORUNDUM

Figure 8. Particle shape of materials used for fine-textured specimens.

most dense-graded bituminous mixtures used in the surface-texture study, as well as the fine-grained, open-graded Kentucky rock asphalt and silica-sand surface treatments, all result in surfaces in which the size of each of the individual voids is small. These surfaces are identified as "fine-textured." By contrast, a "coarse-textured" surface is typified by a bituminous surface treatment consisting of one-size coarse aggregate in which the size of each surface void is large.

Initial Laboratory Investigation

The investigation of the effect of surface texture on the skid resistance of bituminous mixtures led to the conclusion that reasonably dense-graded mixes possess greater skid resistance than open-graded mixes of similar materials. Similarly, results of field studies (1, 2) indicate that fine-grained surfaces, containing hard angular particles, exhibit excellent resistance to skidding. In order to investigate this relationship more fully, and also in order to study various materials as potential blending ingredients for improving the anti-skid characteristics of polish-susceptible aggregates, 12 different fine-textured specimens were made and tested in the laboratory equipment.

The composition of the various mixtures is listed in Table 2. Three of the specimens were individually graded, but nine of the specimens conformed to gradation No. 5, the most dense-graded mixture of those used for the surface-texture investigation. In addition to the four aggregates used in the surface-texture and initial-shape studies, that is, oolitic and dolomitic limestone, rhyolite, and sandstone, two slags and three natural sands were included. SL-1 was a typical gray blast-furnace slag with a high degree of porosity, while SL-2 was a black, glassy non-porous boiler slag.

The particle shapes of the three natural sands are shown in the left column of Figure 8. These enlarged photographs were made of material passing the No. 30 and retained on the No. 50 sieve. The Elkhart sand, appearing at the top of the column, is the most rounded of the three; the Lafayette sand is somewhat more angular than the Elkhart sand; and the Virginia sand is harsher than the Lafayette sand.

The other three materials shown in Figure 8 also were used in making fine-textured specimens. The very harsh silica sand, illustrated by the top figure in the right-hand column, was obtained from Virginia. The silica-sand mixture listed in Table 2 is representative of a type of non-skid treatment which has been used very successfully in that state.

The enlarged photograph of particles contained in Kentucky rock asphalt was made after the asphalt has been extracted from the specimen. These hard quartz particles are somewhat less angular than the grains of the Virginia silica sand.

The remaining print in Figure 8 is of

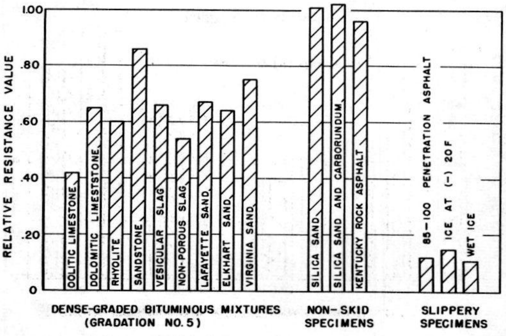


Figure 9. The skidding resistance of selected fine-textured specimens.

a sample of carborundum. While it may not be practical to use this material as a highway aggregate, it was felt that a comparison of an artificial abrasive with some of the common highway aggregates would be of interest. The degree of harshness of carborundum approaches that of the Virginia silica sand. In selecting a suitable mixture for a fine-textured specimen, carborundum and silica sand were combined in equal parts by weight, as indicated in Table 2.

Two other specimens included in the fine-textured category were a surface which consisted entirely of 85-100 penetration asphalt cement and a specimen of solid ice. The asphalt-cement specimen was tested in the wet condition only, and the ice in both the dry and wet conditions. These surfaces were included to indicate the relative resistance values for the most slippery conditions likely to be encountered on a highway surface.

In the initial investigation of fine-textured surfaces, fourteen specimens were tested in the laboratory skid-test apparatus in the conventional manner. The relative resistance values of the nine dense-graded bituminous mixtures at the completion of the total wear and polish procedure are shown to the left of Figure 9. Results for the three non-skid specimens are plotted adjacent to them, and for the three slippery specimens at the right of the figure.

The four aggregates which had been included in the aggregate-evaluation study using an open-graded mixture, that is, oolitic and dolomitic limestone, rhyolite, and sandstone, indicated about the same relative degree of effectiveness in developing skid resistance that was found in the previous study. Bituminous mixtures containing dolomitic limestone and rhyolite exhibited appreciably better skidding resistance than those made with oolitic limestone, while sandstone bituminous mixtures gave by far the best anti-skid characteristics. The vesicular blast-furnace slag gave results, which were comparable to those of the dolomitic limestone, and appreciably higher than for the glassy, non-porous boiler slag.

The three graded natural sands all exhibited good anti-skid characteristics. Bituminous mixtures containing Elkhart, Lafayette, and Virginia sand gave relative resistance values of 0.64, 0.67, and 0.75, respectively. As indicated by Figure 8, and mentioned previously, the Elkhart sand was the most rounded and the Virginia sand the most angular of the three. Consequently, it would appear that the skidding resistance of the fine-textured bituminous mixtures is dependent to some degree on the angularity of the aggregate particles.

TABLE 3

SKID RESISTANCE OF INDIANA SANDS

	Relative Resistance Value		
Indiana Specifications No. 14 sand, 6 percent asphalt	After Initial Rolling	After Coarse Wear	After Fine Polish
1.	0.69	0.72	0.70
2.	0.66	0.70	0.63
3.	0.64	0.72	0.64
4.	0.65	0.73	0.63
5.	0.63	0.67	0.67
6.	0.60	0.66	0.68
7.	0.60	0.65	0.66
8.	0.60	0.64	0.64
9.	0.54	0.66	0.61
10.	0.65	0.67	0.65
11.	0.56	0.65	0.60
12.	0.66	0.70	0.65
13.	0.65	0.70	0.63
14.	0.62	0.65	0.65
15.	0.52	0.64	0.57
16.	0.66	0.68	0.62
17.	0.60	0.70	0.62
18.	0.73	0.70	0.68
19.	0.70	0.71	0.68
20.	0.55	0.67	0.66
Indiana High-Silica Sand 6.5 percent asphalt			
1.	0.85	0.78	0.98
2.	0.64	0.70	0.69
Indiana Dune Sand 7 percent asphalt			
1.	0.80	Surface failed during testing.	

The three "non-skid" surface types all exhibited excellent anti-skid characteristics. The laboratory Kentucky rock asphalt specimen had an RRV of 0.96, which was slightly less than the value obtained on a Kentucky rock asphalt specimen cored from the pavement surface. This was probably due to the fact that the texture of the laboratory specimen was more uniform than that of the field specimen, in which some of the particles were dislodged from the surface, resulting in a slightly roughened texture.

The silica-sand and the combination silica-sand and carborundum specimens gave essentially equal results. They both exhibited somewhat better anti-skid properties than the laboratory Kentucky rock asphalt specimen, probably due to greater angularity of the individual particles.

Values for the three slippery sections were plotted to provide a better appreciation of the significance of a low RRV. Wet ice, with an RRV of 0.11, was the most slippery of any of the specimens tested, while a wet pure asphalt surface was only slightly higher at 0.12.

Indiana Natural Sands

The excellent skid resistance exhibited by some of the fine-textured surfaces encouraged a more thorough investigation of the characteristics of the sands available in Indiana as possible sources for a relatively inexpensive non-skid surface treatment. Twenty natural sands, conforming to Indiana Specifications for No. 14 sand (9), were obtained from commercial sources distributed throughout the state. Sieve analysis on these sands indicated that essentially all of the material passed the No. 4 sieve, the majority of the sand was fairly well-graded between the No. 8 and No. 50 sieves, and from 1 to 4 percent of the material passed the No. 100 sieve.

Two sources of sand with a high silica content were included in the study, as well as one dune sand. The majority of the particles for the silica sands were in the No. 30 to No. 50 range, while the dune sand was somewhat finer.

Laboratory specimens were formed with each of these materials as received. An asphalt content of 6 percent, based on the total weight of the mixture, was used with the No. 14 sands; 6.5 percent with the silica sands; and 7 percent with the dune sand. Relative resistance values corresponding to three points in the wear and polish procedure are listed in Table 3 for mixtures made from each of the 23 sands.

The 20 sands from commercial sources exhibited fairly uniform skid resistances which, although not as high as for some of the non-skid surface treatments previously discussed, indicated that the use of these sands could produce surfaces possessing reasonably good anti-skid characteristics. After initial rolling the 20 sands gave an average RRV of 0.62, with a range in values from 0.52 to 0.73. Following the coarse-polish cycle, during which the asphalt was scoured from the surface aggregate and some of the larger naturally-rounded particles may have been roughened somewhat, the average RRV increased to 0.68, with a range from 0.64 to 0.72. The fine-polish cycle caused a decrease in skid resistance for most of the sands so that the final average RRV was 0.64, with a range from 0.57 to 0.70.

One of the silica sands exhibited excellent skid resistance and gave results comparable to that of the Virginia silica sand. The second silica sand, although of similar gradation, contained particles which were not as harsh and angular as the first aggregate. In addition there appeared to be a dusty coating on the larger particles, and the skid resistance measurements with this sand were appreciably lower than with the harsh silica sand. The specimen made with dune sand exhibited good initial skid resistance, but did not possess sufficient durability to resist disintegration during the wearing and testing procedure.

Proprietary Mixes

To round out the picture on fine-textured surfaces, some of the proprietary mixes, which are currently being advocated as non-skid treatments, were investigated. One such mixture was a crushed diabase traprock to which had been added a powdered asphalt and an asphalt flux oil. The anti-skid characteristics of this treatment were good, but the initial stability of the mixture was low so that a specimen made of this material had to be cured some little time before testing in the laboratory apparatus.

Laboratory skid tests were also performed on resinous surface treatments containing emery, crushed quartz, and aluminum oxide. In forming these specimens the resin binder was placed on a prepared concrete disc in a liquid state and the grit was distributed over the surface. As the resin set chemically to form a tough plastic binder, the abrasive was rigidly held in place. Initially, resin specimens containing each of the three abrasives exhibited excellent skid resistances, with RRV's of over 1.00. After an appreciable amount of wear, however, the values decreased somewhat, with the quartz specimen showing a greater drop in skid resistance than the specimens containing the relatively harder abrasives. There is little particle-by-particle wear with surfaces of this nature, and the anti-skid characteristics are determined primarily by the initial shape and the resistance to polishing of the abrasive.

AGGREGATE BLENDING INVESTIGATION

In many areas of the United States the primary aggregate used in highway construction is limestone, and economic considerations, as well as the many desirable qualities of limestone for use in paving mixtures, require maximum utilization of this material. As illustrated by the aggregate-evaluation and field-correlation studies, some limestones polish quite readily when exposed to traffic. The purpose of the blending phase of the research was to investigate the effect of combining polish-resistant materials with a polish-susceptible limestone in an effort to obtain adequate skid resistance in the resulting paving mixture.

The limestone selected as the polish-susceptible aggregate was L-11, an oolitic limestone available in quantity, and one which had exhibited very little resistance to polishing. The aggregate was used for the entire study in both portland cement and bituminous specimens.

Asphaltic Concrete

The blending materials included in the bituminous study were calcareous sandstone (S-2), vesicular (blast-furnace) slag (SL-1), non-porous (boiler) slag (SL-2), Lafayette sand, silica sand, and carborundum. Blending of both fine and coarse aggregate was accomplished, for the most part, without deviating from the gradation of the standard specimen used in the aggregate-evaluation study. A portion of the oolitic limestone was replaced by an equal amount of the blending ingredient, with the gradation of the substitute and replaced materials being identical. With silica sand and carborundum, which were essentially one-size materials, it was not feasible to maintain the

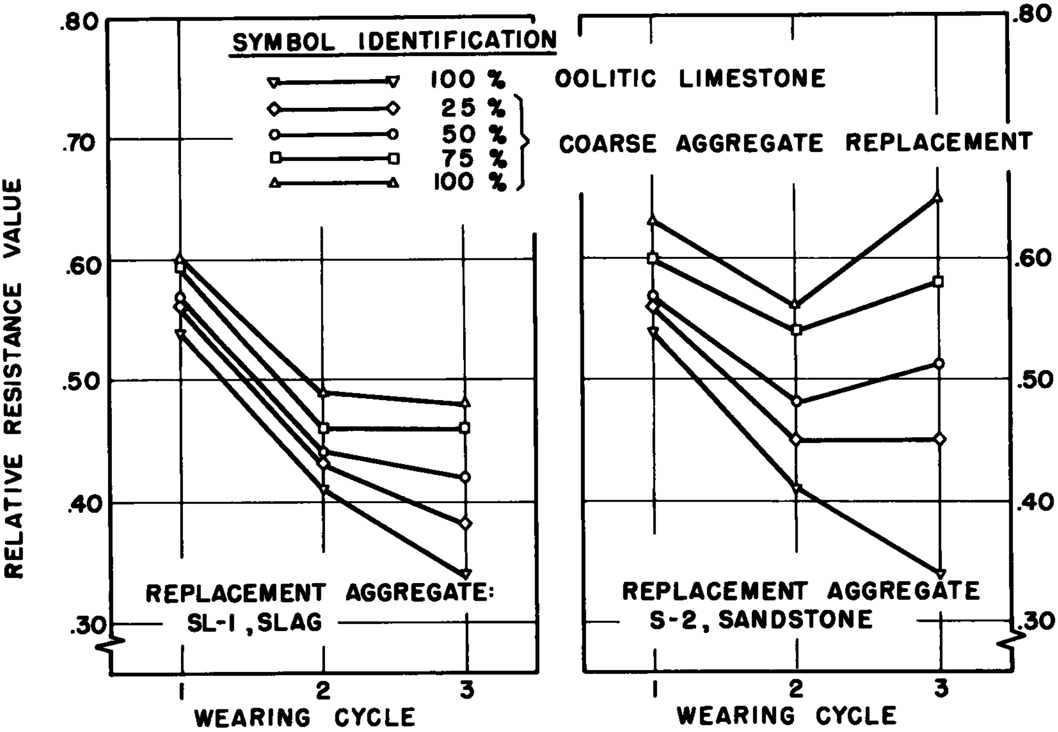


Figure 10. Effect of replacing the coarse aggregate fraction with a polish resistant material in asphaltic concrete.

exact gradation of the standard specimen, and the blended mixture contained a higher percentage of fine material than the standard specimen.

Coarse-Aggregate Substitution. The two coarse aggregates which were studied as replacement materials were the sandstone (S-2) and the vesicular (blast-furnace) slag (SL-1). The fraction of the limestone on which the substitution was made was that portion retained on a No. 4 sieve. This constituted 48 percent of the total aggregate. The amount of replacement material for each of five mixes was as follows:

Mixture Identification	1	2	3	4	5
Percent Substitution Based on Coarse Aggregate	0	25	50	75	100
Percent Substitution Based on Total Aggregate	0	12	24	36	48

Since 48 percent of the total mix was coarse aggregate, 100 percent replacement of the coarse aggregate corresponded to 48 percent of the total aggregate.

The specimens were subjected to the conventional testing and polishing procedure, and the results are shown graphically in Figure 10. The five curves drawn for each type of replacement material represent the results for a bituminous mixture in which the aggregate consisted entirely of oolitic limestone, and for mixtures containing, respectively, 25, 50, 75, and 100 percent coarse-aggregate replacement.

For the initial testing cycle, replacing a part of the coarse-aggregate fraction resulted in a slight improvement in skidding resistance, with the degree of effectiveness increasing with the percent of substitution. This advantage became more significant as wear and polish progressed. The sandstone was much more effective in improving the anti-skid characteristics of the mixtures than the blast-furnace slag. As evaluated at the completion of the fine-polish cycle, a 50 percent substitution of the coarse limestone with sandstone accomplished a greater increase in skid resistance than a 100 percent coarse slag replacement.

An interesting aspect of the sandstone-replacement specimens was the fact that their skid resistance actually improved during the fine-polish cycle. Although there was an appreciable decrease in the skidding resistance of the specimens during the coarse-wear procedure, in which the angularity of the aggregate was reduced, subsequent polishing served to wear and erode away the softer limestone and asphalt matrix, and provided greater exposure of the skid-resistant sandstone. The specimen, in which the limestone coarse aggregate was entirely replaced by sandstone, exhibited better skid resistance at the completion of the fine-polish cycle than it had shown initially.

Fine-Aggregate Substitution. The specimens for evaluating fine-aggregate substitution also conformed to the standard laboratory specimen in gradation and asphalt content. The fraction of the material replaced was that passing the No. 4 sieve and retained on the No. 100 sieve. Forty-seven percent of the total aggregate fell within this range. The amount of replacement material for each of the five mixes was as follows:

Mixture Identification	1	2	3	4	5
Percent Substitution Based on Fine Aggregate	0	25	50	75	100
Percent Substitution Based on Total Aggregate	0	11.8	23.5	35.3	47.0

Four fine-aggregate replacement materials were investigated. In addition to the vesicular (blast furnace) slag and calcareous sandstone, used in the coarse-aggregate substitution study, a glassy, non-porous (boiler) slag (SL-2) and a natural sand from Lafayette, Indiana, also were included.

The test specimens were subjected to the conventional testing and polishing procedure, and the results are shown graphically in Figure 11. As with the coarse-aggregate substitution, the lowest curve of the five represents the results for a bituminous mixture made entirely with oolitic limestone with the other four curves representing

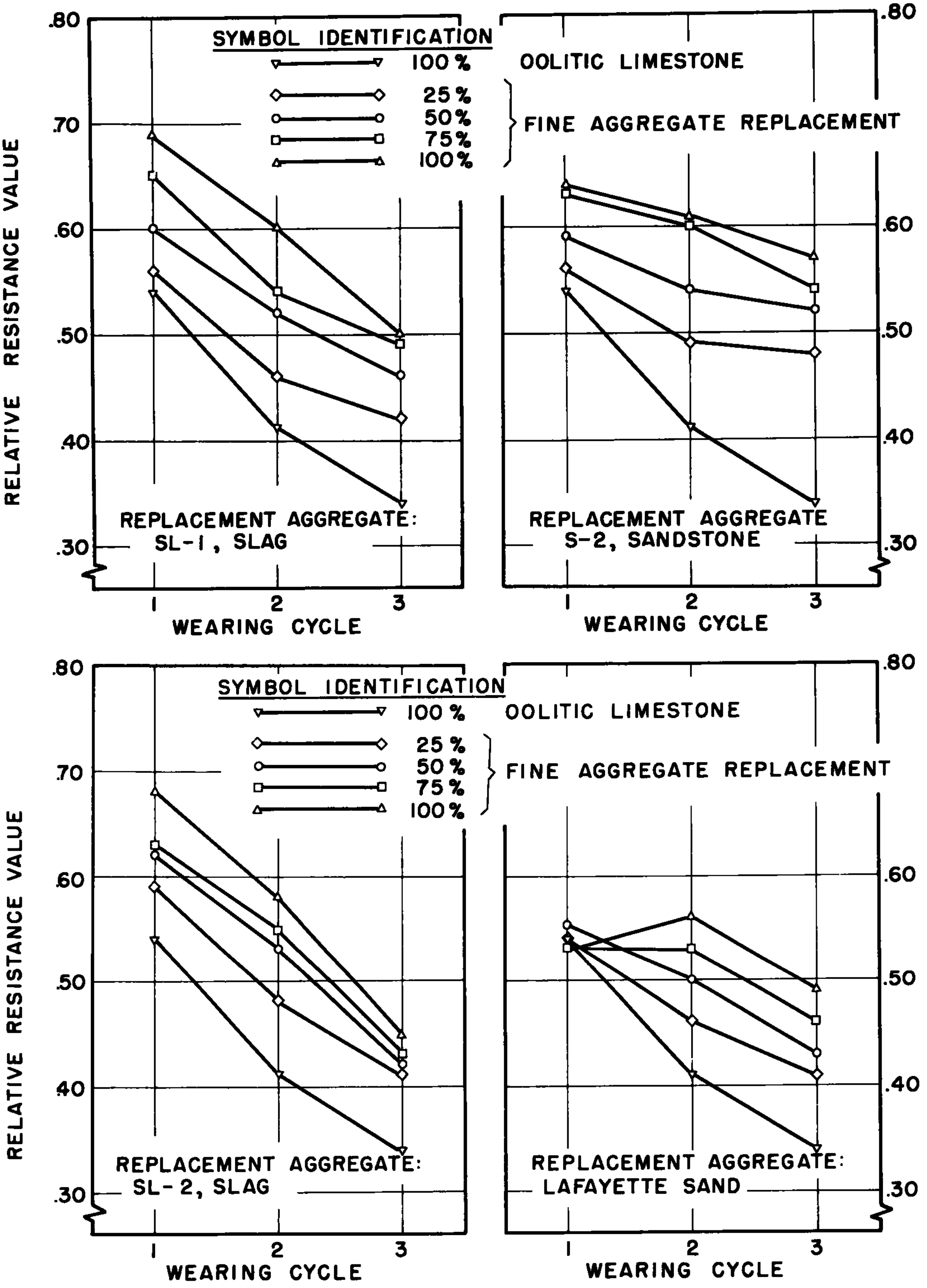


Figure 11. Effect of replacing the fine aggregate fraction with a harder material in asphaltic concrete.

mixtures which contain, respectively, 25, 50, 75, and 100 percent fine-aggregate replacement.

In comparing the effectiveness of the four different replacement materials at the beginning of the wearing cycle, it is noted that both of the slags provided an appreciable improvement in the skidding resistance; the sandstone was somewhat less effective; and the Lafayette sand caused no significant change from the RRV determined for the 100 percent limestone specimen. The Lafayette sand was more rounded than the crushed limestone that it replaced, so even though it was an appreciably harder material, the two effects compensated in the initial condition, and the skidding resistance was unaffected by the substitution.

After an appreciable amount of wear, as indicated by the results at the completion of the fine-polish cycle, the relative effectiveness of the four materials was different from that of the initial condition. The sandstone was the most effective, in that it resulted in an increase in the RRV from 0.34 to 0.57 for a 100 percent fine aggregate replacement; the vesicular (blast-furnace) slag and Lafayette sand resulted in RRV's of 0.50 and 0.49, respectively, for 100 percent fine aggregate replacement; and the non-porous (boiler) slag was the least effective of the four materials, with a total fine aggregate substitution giving an RRV of only 0.45.

Fine-Aggregate Combination. The silica sand and carborundum used in this phase of the blending study were not sufficiently well-graded to be used as substitute materials. Instead of replacing a certain fraction of the oolitic limestone, as in the two related phases of this study, the blending material was combined with a quantity of limestone which conformed to the standard gradation. This resulted in a test specimen with a finer surface texture than that of the standard bituminous specimen, with the texture becoming increasingly fine as the percentage of combination was raised.

For the silica-sand specimens, sufficient material was combined with the standard limestone mix to result in specimens with 10, 20, 30, and 40 percent of silica sand, respectively, based on the total weight of the aggregate. Smaller amounts of carborundum were used, with the mixes containing 5, 10, 15, and 20 percent, respectively, also based on the total aggregate weight.

These specimens were subjected to the standard testing and wearing procedure, and the results are shown graphically in Figure 12. The combination of these non-skid materials with the oolitic limestone resulted in a significant increase in the anti-skid properties of the mixtures for all degrees of wear. There was probably a slight increase in skidding resistance due to the finer surface texture, but most of the improvement was attributable to the nature of the harsh, polish-resistant particles which were added.

A 20 percent addition of silica sand increased the RRV of an oolitic limestone specimen at the completion of the fine-polish cycle from 0.34 to 0.54, while a 40 percent addition doubled the RRV to 0.68. The addition of carborundum gave slightly higher anti-skid properties to the mixtures than did an equal percentage of silica sand in the early phases of the wearing procedure, but at the completion of the fine-polish cycle the difference was negligible.

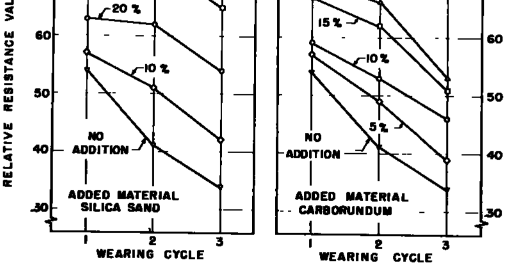


Figure 12. Effect of combining a non-skid material with a polish-susceptible aggregate in asphaltic concrete.

Comparison of the Blending Treatments. A graphical comparison of the relative effectiveness of the various blending treatments is presented in Figure 13. This figure shows the relative resistance values at the completion of the fine-polish cycle, both for a specimen in which the aggregate consisted entirely of oolitic limestone and for specimens representing each of the blending treatments. Mixes selected for comparison contained the blending ingredient in a proportion of approximately one part to two parts of oolitic limestone. The coarse- and fine-aggregate substitu-

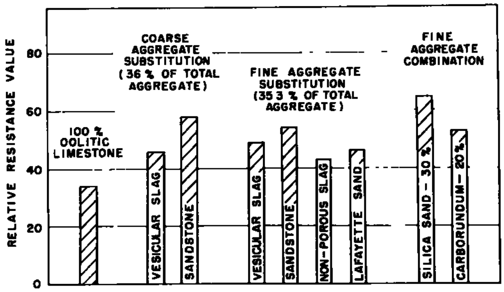


Figure 13. The effect of blending various materials with a polish-susceptible oolitic limestone in asphaltic concrete.

tion specimens had a higher amount of blending material, that is, 36 and 35.3 percent, than the fine-aggregate combination specimens, which contained 30 percent silica sand and 20 percent carborundum, respectively.

Even though the percentage of blending material was slightly less than for the coarse- and fine-aggregate replacement treatments, combining silica sand with the oolitic limestone was the most effective method of improving the anti-skid characteristics of the test specimens. As previously indicated, the improved skidding resistance may have been due in part to the finer texture, resulting from the addition of a fine material to the standard gradation, but was probably primarily dependent upon the harsh abrasive nature of the silica sand. In addition to the high resistance presented by the individual silica-sand particles, there also is evidence to indicate that the presence of the sand prevented the large limestone pieces from becoming too highly polished. One series of laboratory tests (7) indicated that grinding with coarse silica sand on a test specimen composed of limestone, after it has been polished to its most slippery condition using limestone mineral filler as an abrasive, improved the skid resistance of the polished surface.

The addition of carborundum had essentially the same effect as an equal amount of silica sand. Since it is a great deal more expensive than silica sand, the use of this material for the purpose of improving the skid resistance of paving mixtures is not discussed further.

The next most effective substitution material was S-2, the calcareous sandstone. As illustrated in Figure 13, in both the coarse- and fine-aggregate replacement specimens, the mixtures containing sandstone exhibited the highest skid resistance of all specimens included in the respective type of treatment. The vesicular blast-furnace slag showed somewhat better blending characteristics than the Lafayette sand, while the glassy, non-porous slag had the least effect of any of the materials in improving the anti-skid properties. A 75 percent fine-aggregate replacement of the non-porous slag (SL-2) caused an increase in RRV of from 0.34 to only 0.43. Although the individual non-porous boiler slag particles were hard and had sharp corners, they also possessed flat glassy faces which, under the kneading action of the rolling procedure, were oriented parallel to the surface and developed very little skid resistance during testing.

Portland Cement Concrete

The aggregate blending investigation with portland-cement concrete was much more limited in scope than for the bituminous study. Calcareous sandstone was used as a blending ingredient in both coarse- and fine-aggregate replacement; Lafayette sand was also used for fine-aggregate replacement; and silica sand was used in combination with the polish-susceptible limestone. Coarse-aggregate replacement was based upon the material retained on the No. 4 sieve, which constituted 50 percent of the total aggregate, while fine-aggregate replacement was based upon the 50 percent of the aggregate which passed the No. 4 sieve.

For the coarse- and fine-aggregate replacement studies, three mixtures, which conformed to a standard gradation, were used for each test series. For one specimen the aggregate consisted entirely of oolitic limestone; in the second, 50 percent of either the coarse or fine aggregate was replaced with a blending material; and for the third, total substitution of either the coarse or fine fraction was made. Since the mixture was composed of equal parts of coarse and fine aggregate, a complete replacement of either of the fractions was equivalent to a 50 percent substitution based on the total aggregate.

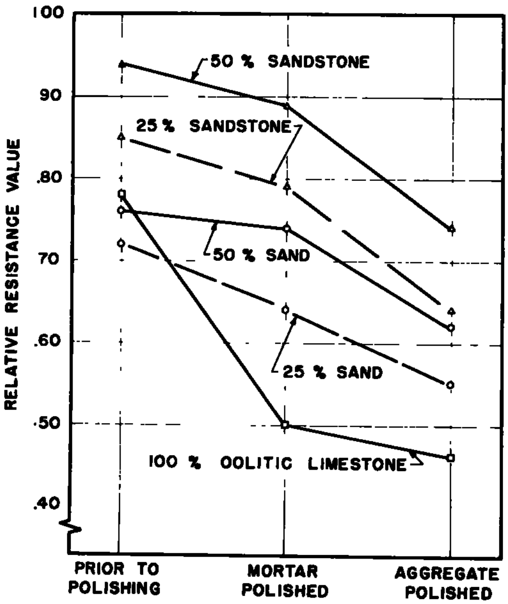


Figure 14. Fine aggregate replacement in portland cement concrete.

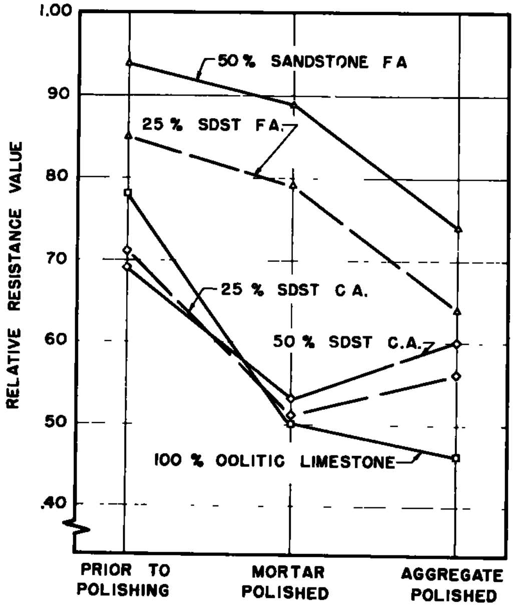


Figure 15. Blending sandstone with oolitic limestone in portland cement concrete.

The results of the substitution studies with portland-cement concrete are presented in Figures 14 and 15. Relative resistance values are plotted for each of the specimens on tests made initially, when the surface was in a lightly-brushed "sandpaper" condition; after the mortar-polished cycle; and after the surface was sawed and subjected to the aggregate-polished cycle.

A comparison of the effectiveness of crushed sandstone and natural sand as fine-aggregate replacement material is shown in Figure 14. Initially the sandstone caused an appreciable increase in the skid resistance of the blended specimen, while the rounded natural sand particles resulted in lower RRV's than were measured for the specimen made entirely of oolitic limestone. After some wear, the use of both materials provided an improvement in skid resistance, with the sandstone accomplishing by far a more significant increase. A 25 percent replacement with sandstone, based on the total weight of the aggregate, was somewhat more effective in improving skid resistance than a 50 percent natural-sand substitution.

Figure 15 illustrates the relative effectiveness of substituting an equal amount of coarse or fine sandstone in a concrete specimen containing a polish-susceptible aggregate. The addition of the sandstone coarse aggregate caused a decrease in the initial skid resistance of the blended specimen, as compared to the 100 percent limestone specimen. After the mortar-polish cycle, in which very little of the coarse aggregate was exposed, the coarse sandstone caused a negligible increase in skid resistance, while an equal weight of fine sandstone caused a tremendous improvement in the anti-skid properties of the blended specimens.

Even after the top ¼ in. of each specimen had been sawed off, resulting in maximum exposure of the coarse aggregate, fine-aggregate replacement with sandstone was much more effective in improving the skid resistance than was coarse-aggregate replacement. At the completion of the aggregate-polish cycle, a 25 percent replacement with sandstone fine aggregate increased the RRV of a 100 percent oolitic limestone specimen from 0.46 to 0.64, while a 50 percent sandstone coarse-aggregate substitution resulted in an RRV of only 0.60.

The use of silica sand as a blending material in portland-cement concrete was investigated by combining a given amount of the sand with a quantity of limestone conforming to the standard gradation. This material was quite effective in improving the anti-skid properties of specimens made from the limestone. A 20 percent silica-sand combination, based on the total weight of the aggregate, effected almost the identical results that a 25 percent fine sandstone replacement accomplished for all three points in the wearing cycle. Similarly, a 40 percent silica-sand combination caused an increase in skid resistance approximately the same as that experienced with a 50 percent fine-sandstone substitution. Since the results for the two blending materials were nearly identical, a plot of the variation in skid resistance due to the addition of silica sand is not included with this report.

RECOMMENDATIONS FOR MINIMIZING PAVEMENT SLIPPERINESS

A summary of the results of this investigation is presented in this section, along with suggestions as to design and construction practices which tend to minimize pavement slipperiness. Some of these recommendations are rather obvious, or currently are fairly well recognized, while others have been submitted previously in conjunction with the initial phase of this study (7); but all are included for the sake of completeness in summarizing the total findings of the research program to date. This was a laboratory investigation, restricted in scope to the materials and testing procedures previously enumerated, and the extension of this knowledge to predict the performance of pavement surfaces may not be completely objective. However, the following discussion is intended to be an unbiased evaluation of the program of research, and includes a very general application of the major findings of this study to highway construction practices which will lessen the occurrence of pavement surfaces which are "Slippery When Wet."

1. If an excess of asphalt does not occur at the surface, dense-graded bituminous mixtures will exhibit somewhat better anti-skid characteristics than open-graded mixtures composed of identical aggregate. Dense-graded mixtures exhibit a greater tendency toward "bleeding," due to the additional compaction of traffic, than open-graded mixtures; but if this contingency is adequately considered in the design of the mixture, the dense-graded surfaces, by furnishing a greater uniformity of friction transfer over the entire contact area between the tire and surface, provide somewhat greater skid resistance than pavements containing surface voids of appreciable individual size. In addition, an open-graded surface exposes the aggregate to greater envelopment by the tire and to a higher polishing effort than a dense-graded surface.
2. Since surfaces containing crushed aggregate possess better initial skid-resistance than pavements made from rounded aggregates of the same composition, there is some justification, based on skid resistance alone, for requiring that any naturally-rounded coarse aggregate be entirely crushed if it is to be used in the pavement surface. After an appreciable period of wear, however, the skid resistance of the two surfaces will be nearly identical.
3. The polishing characteristics of aggregates will be similar both in portland cement and in bituminous mixtures which are composed entirely of one aggregate type. However, it will usually require a greater wearing effort to polish the aggregate and to arrive at the ultimate slippery condition with portland cement concrete as compared to bituminous surfaces.
4. There are certain limestones which should not constitute the total surface aggregate in bituminous pavements. Results of the initial laboratory study indicate that uniform fine-grained or oolitic limestones, consisting essentially of pure calcium carbonate, fall in this category. Surfaces of this nature possess only fair skid resistance when new, and may become dangerously slippery after a moderate amount of traffic.
5. Other types of limestones, such as the highly-dolomitic Indiana limestone, may be entirely satisfactory as the total surface aggregate for bituminous pavements if severe traffic conditions are not anticipated. Surfaces composed of these more-resistant limestones may ultimately polish; and, if traffic is extreme, can do so in a relatively short period. However, this same observation also can be made for pavements constructed with such aggregates as the fine-grained basalts, chert, and high-quartz gravel. These relatively polish-resistant aggregates may retain a certain degree of

their initial angularity for an appreciable period, but due to the uniform nature of wear of the fine-grained structure, can ultimately polish excessively.

6. In order for a pavement surface, constructed either with portland cement or bituminous materials, to retain a non-skid surface under prolonged action of heavy traffic, some type of differential wear of the surface components is essential, since a uniformly-polished surface will be dangerously slippery when wet. For portland cement concrete, this differential wear may occur due to the variation in resistance to wear of the cement paste and the fine and coarse aggregate. For both portland cement and bituminous surfaces an aggregate, such as sandstone or some varieties of granite for which a coarse particle-by-particle type of wear occurs, may contribute to excellent skid resistance. Similarly the differential wear that takes place with Kentucky rock asphalt or a silica-sand surface treatment, due to ejection of aggregate particles from the pavement surface by traffic, results in a "non-skid" pavement.

7. Blending of a polish-resistant fine aggregate to improve the anti-skid characteristics of a polish-susceptible limestone is, at best, only moderately successful with bituminous mixtures. The laboratory investigation indicated that an appreciable quantity of a harsh material, such as silica sand, was required to increase the skid resistance to a reasonable value. This quantity of silica sand probably could be used much more effectively as a non-skid surface treatment. Frequently the nature of wear of a bituminous highway surface is such that the fine-aggregate and asphalt matrix erodes away, and the area of contact between the tire and pavement consists almost entirely of coarse aggregate. For such a condition, the blending of skid-resistant fine material results in little improvement in the anti-skid characteristics of the mixture.

8. Blending of a polish-resistant fine aggregate to improve the anti-skid characteristics of a polish-susceptible limestone in portland cement concrete is much more effective than with bituminous mixtures. The fine-aggregate mortar makes an important contribution to the skid resistance developed by portland cement concrete, even after wear has progressed to the point where appreciable amounts of coarse aggregate are exposed. Laboratory results indicate that the use of a harsh, resistant fine aggregate with a polish-susceptible limestone coarse-aggregate will usually result in good skid resistance of the mixture, while even a naturally-rounded sand will promote sufficient differential wear to develop adequate skid resistance.

9. Limestone should not be used as the total aggregate in portland cement concrete pavements. If the cement paste, the fine-aggregate of the mortar, and the coarse aggregate all possess essentially the same resistance to wear, a uniformly-polished surface may result that is dangerously slippery when wet.

10. From the skid-resistance standpoint, the majority of natural Indiana sands can be used in satisfactory bituminous surface treatments, and this would probably be generally true on a national basis. There is some variability of results depending upon the roundness and degree of polish of the individual particles, and the resulting treatment may not be as skid resistant as those composed of harsh silica sand or crushed sandstone; but consideration should be directed toward natural sand deposits as potential sources of material capable of producing surfaces with adequate skid resistance.

11. A non-skid silica-sand surface treatment, such as that developed by Virginia (4), probably holds the best promise of being generally accepted as an effective means of combating pavement slipperiness. The continuous rejuvenation of the surface, which accompanies the particle-by-particle type of wear, results in excellent anti-skid characteristics during the entire life of the treatment. Such non-skid surface treatments, when placed on existing slippery pavements that are structurally adequate or used as a preventive measure in new construction with polish-susceptible aggregates, can make a significant contribution to driving safety.

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