HIGHWAY RESEARCH RECORD

Number 28

Roadway Surface Properties

3 Reports

Presented at the
42nd ANNUAL MEETING
January 7-11, 1963

HIGHWAY RESEARCH BOARD
of the
Division of Engineering and Industrial Research
National Academy of Sciences—
National Research Council
Washington, D. C.
1963

Department of Design

T. E. Shelburne, Chairman
Director of Research, Virginia Department of Highways
Charlottesville

COMMITTEE ON ROAD SURFACE PROPERTIES RELATED TO VEHICLE PERFORMANCE

Ralph A. Moyer, Chairman
Research Engineer
Institute of Transportation & Traffic Engineering
University of California, Berkeley

W. F. R. Briscoe, Manager, Operations Department, Product Development, United States Rubber Company, Detroit, Michigan

A. Y. Casanova, III, Highway Research Engineer, U. S. Bureau of Public Roads, Washington, D. C.

W. E. Chastain, Sr., Assistant Engineer of Research and Planning, Research Branch, Illinois Division of Highways, Springfield

John H. Cox, Manager, Mileage Tire Development, Firestone Tire and Rubber Company, Akron, Ohio

L. E. Gregg, L. E. Gregg and Associates, Consulting Engineers, Lexington, Kentucky

David C. Mahone, Highway Research Engineer, Virginia Council of Highway Investigation & Research, Charlottesville, Virginia

E. A. Whitehurst, Director, Tennessee Highway Research Program, University of Tennessee, Knoxville

Ross G. Wilcox, Highway Engineer, Portland Cement Association, Chicago, Illinois

Dillard D. Woodson, The Asphalt Institute, University of Maryland, College Park

Contents

The Penn State Road Friction Tester as Adapted to Routine Measurement of Pavement Skid Resistance

HARTWIG W. KUMMER and WOLFGANG E. MEYER, respectively, Research Assistant and Professor, Department of Mechanical Engineering, The Pennsylvania State University

The skid resistance problem is restated and the need for modern and efficient skid testing equipment for routine field tests is derived. The design and operation requirements for a routine tester are defined in terms of precision, ruggedness, compactness, traffic interference, and cost of operation. The design concept of the Penn State road friction tester is shown to fulfill these requirements. The trailer and towing vehicle, instrumentation and controls, the calibration equipment and method of calibration are described. Dimensions and specifications of the road friction tester, performance data and selected results of recent tests are given.

Also described is the prototype of a new portable tester developed especially for field use to supplement the large unit. The need for further work on the overall skid resistance problem is outlined and specific problems are shown to demand early solutions.

• SLIPPERY ROADS have been a problem for several decades (1) but only recently have they become more fully recognized as a serious menace to highway transportation. Modern techniques of investigating and evaluating traffic accidents identify skidding as a primary cause in 35 to 41 percent of all accidents on wet pavements (2). Although the seriousness of the skid problem is now generally accepted, the factors that control it are much less widely recognized.

In the last decade the average travel speed of vehicles has steadily climbed, reflecting both an increase of the legal speed limits and the tendency of drivers to exceed these limits by increasing margins.

The average travel speed of passenger cars on primary rural highways (3) has increased from 48.5 mph in 1950 to 53.8 mph in 1960 (Table 1), representing an increase of approximately 1 percent per year in terms of the 1950 speed (Fig. 1a). The speed increase in itself is perhaps not alarming, but becomes so when considered in terms of the required increase in the effectiveness of the frictional coupling between tire and road. For equal skid resistance, the coefficient of sliding must increase with the square of the speed. Thus, although the vehicle speed has gone up by approximately 11 percent, the frictional demand has increased by 23 percent over the last 10 years.

Traffic density is another factor that has a direct bearing on the skid resistance problem. For the years 1950 to 1960, Table 2 gives the total highway mileage in any one year, the annual total vehicle mileage, and the miles traveled annually per mile of highway (4-6). It is significant that the frequency of passes to which a given section of pavement is exposed has increased from 138,000 in 1950 to 205,000 in 1960.

Expressed in percent (Fig. 1b), the vehicle miles traveled have increased by 57.1 percent, whereas the total miles of highway have grown by only 5.66 percent, resulting in a 48.5 percent increase in the number of miles traveled on one mile of highway per year. This represents a like increase in the rate at which traffic polishes the pavement surface. Inasmuch as aggregate polish is one of the main causes of pavement

---

Paper sponsored by Committee on Road Surface Properties Related to Vehicle Performance.

TABLE 1

AVERAGE PASSENGER CAR SPEEDS ON PRIMARY RURAL HIGHWAYS

Year	Avg. Speed[a] (mph)	Cumulative Increase in Speed (%)	Required Increase in Coef. (%)
1950	48.5	0	0
1951	50	2.06	6.4
1952	51	5.16	10.5
1953	51.5	6.19	12.6
1954	51.5	6.19	12.6
1955	52	7.22	15.1
1956	52	7.22	15.1
1957	52.2	7.63	16.0
1958	52.8	8.87	18.5
1959	53.2	9.70	20.0
1960	53.8	10.92	23.0

[a] From reference (3).

slipperiness, any increase of traffic density is cause for concern even though the skid resistance of a pavement does not decrease linearly with the frequency of passes.

Figure 1c summarizes the effects of vehicle speed and aggregate polish on the sliding coefficient of friction. Whereas the magnitude of the sliding coefficient at any given speed is dependent on a large number of factors, the slope of the coefficient versus speed curve under wet conditions is dictated mainly by the geometric texture or "openness" of the pavement (7) and, to a lesser degree, by the tread design of a particular tire. Speed tests with various combinations of tires and pavements indicate that a coefficient drop of 0.5 to 3 percent per mph (based on the sliding coefficient at 35 mph) must be expected.

The coefficient is measurably lower in fall than in spring (8), and in any given season, lower than in the preceding year, the degree of decay being dependent mainly on the aggregate-binder combination, average vehicle speed and traffic density.

The increase in travel speed (and in the resulting frictional demand) and the frequency of the polishing action of passing vehicles, coupled with the decrease of the coefficient with speed and with polish, are the principal causes for the magnitude of the current skid resistance problem. That skidding accidents are courted by those who drive on excessively worn tires and the existence of several other factors, does not distract from the importance of these basic facts.

To control the skid resistance problem it must be possible to:

1. Accurately and economically measure the skid resistance or, what is very nearly the same, the coefficient of friction between a slipping or sliding tire or rubber specimen and the road surface;
2. Derive meaningful standards for the frictional demand that the majority of traffic situations make on specific road sections (the frictional demand varies with road layout, vehicle design, actual travel speeds and such difficult to define intangibles as driver judgment, skill and temper); and
3. Develop improved antiskid carpets that retain their surface properties for many years and find better ways of restoring the skid resistance of surfaces that have become polished or otherwise altered by traffic.

This report attempts to make a contribution to mastery of the measurement phase of the skid resistance problem by outlining the requirements which should be satisfied by skid resistance testers, and by describing two new tester designs: a trailer type and a portable device.

The highway engineer concerned with the skid resistance of a pavement is interested in the property of a surface as a physical characteristic, much as he would be interested in hardness or specific weight in other cases.

At present, however, it is not possible to describe the skid resistance property of a surface quantitatively. In a qualitative way, the skid resistance of a pavement may be characterized by the number of aggregate particles per unit area, their size and shape, by the molecular properties of aggregate and binder, etc., but a means of conveniently measuring these and other characteristics is lacking. For the time being one must depend on sliding a rubber specimen or tire over the surface to relay the desired information indirectly. Since the properties of the rubber as well as operational factors enter the picture in this method, the resulting coefficients are actually performance values

TABLE 2

TOTAL VEHICLE MILES AND MILES TRAVELED PER MILE OF ROAD[a]

Year	Total Miles of Roads (10^6)	Annual Total Miles Traveled (10^6)	Annual Miles Traveled per Mile of Road (10^3)	Cumulative Increase Since 1950 (%)		
				Miles of Roads	Miles Traveled	Miles Traveled per Mile of Road
1950	3.322	458,250	138	0	0	0
1951	3.327	491,090	148	0.135	7.17	7.25
1952	3.343	513,580	153	0.633	12.06	10.86
1953	3.366	544,430	162	1.32	18.80	17.40
1954	3.395	560,860	165	2.20	22.4	19.55
1955	3.418	603,430	176	2.99	31.7	27.50
1956	3.430	627,840	183	3.25	37.0	32.60
1957	3.453	642,580	186	3.94	40.2	34.80
1960	3.510	720,000	205	5.66	57.1	48.50

[a] From references (4, 5, 6).

and only implicitly contain the antiskid properties of the surface. Until it is possible to define and measure skid resistance of a pavement as a property, distinction between the meaning of the term skid resistance and coefficient is a matter of semantics. However, if both terms are used interchangeably, skid resistance loses its absolute meaning and becomes a relative term.

In this report, "skid resistance" will be used whenever reference is made to the friction potential of a tire-pavement combination in a general way. The term "coefficient" (in combination with an adjective, such as incipient, sliding, and steady state) will be reserved for situations which require more precise terminology.

SKID RESISTANCE MEASURING EQUIPMENT

Fundamental Requirements for Routine Testers

The equipment for routinely measuring skid resistance as part of highway maintenance programs is discussed herein. Through systematic gathering, mapping and evaluating of skid resistance data, slippery pavements can be identified and corrective measures taken before slipperiness becomes a direct accident cause. The specifications of such a tester will differ from those of a tester intended for research work or specific experimental programs.

There are 10 requirements that are regarded as fundamental to the design of a routine tester. They are not necessarily complete nor are the requirements listed in order of their importance, but included are the following:

1. Meaningful measurements;
2. Precision of test data;
3. Minimum data processing;
4. Balanced coverage and test cycle frequency;
5. Adequate range of operation;
6. High degree of mobility and maneuverability;
7. Minimum traffic interference;
8. Ruggedness;
9. Economy of operation; and
10. Comfort and safety of crew.

Meaningful Measurements.—The requirement to obtain meaningful data from a tester seems to be trivial and self-evident at first sight, but closer study indicates that this is not so. Since coefficients are performance values which can be altered at will by changing the test tire or an operational variable, a tester may fulfill all other requirements

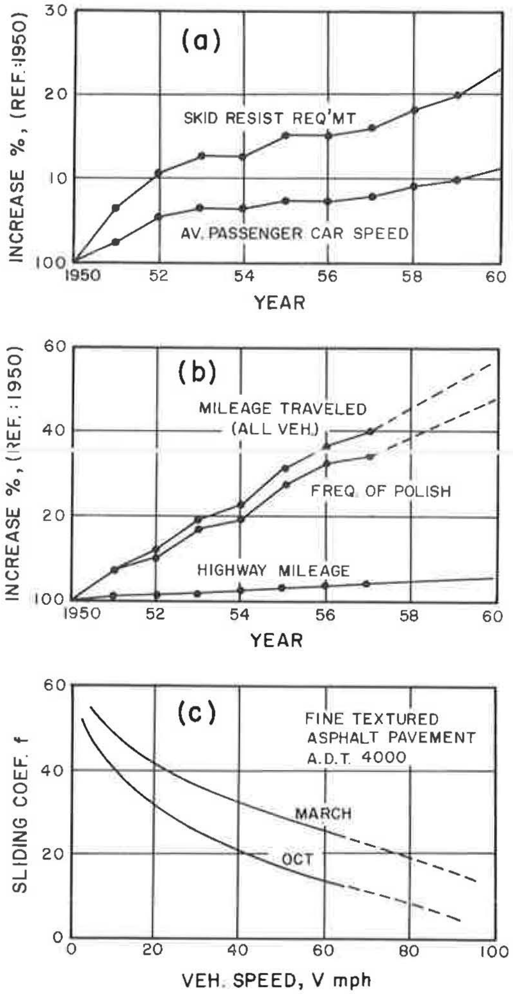


Figure 1. The skid resistance problem: (a) average passenger car speeds on primary rural highways; (b) total vehicle miles traveled per mile of highway; and (c) skid resistance as function of speed and aggregate polish.

but will not furnish data that have a direct bearing on the slipping and sliding coefficients experienced by traffic, and in extreme cases, the data may defy correlation. This requirement thus influences the selection of the mode of tire operation, the test speed (which also has a bearing on minimum traffic interference) and the method and rate of applying water to the pavement. Other factors are the normal load acting on the tire elements, rubber composition, etc. To testers that employ a rubber specimen instead of a tire, the same basic factors apply.

Precision of Test Data.—To enable the highway engineer to compare test results from pavement to pavement or performance of a given pavement from year to year, the test equipment must record with little error what the tire or rubber heel "feels" when it is dragged over the pavement surface. What degree of precision should be built into a tester? Precision is influenced by tester design, the type of instrumentation employed, and the degree to which such operational factors as wheel load, inflation pressure, test speed, temperature and water film thickness can be controlled or monitored.

Errors that change in magnitude as well as direction must be prevented especially. Constant errors can be predicted or calibrated as to magnitude and direction. A tester subject to an error of the latter type produces data that can be used for valid year-to-year comparisons. Correlation of data with that of other testers with which side-by-side comparisons cannot be made would be possible if magnitude and direction of the errors of both machines were known under all conditions, but this is virtually impossible to accomplish. Therefore, even constant errors must be kept small. An overall tester accuracy of ± 2 percent can be obtained without undue effort. Such accuracy allows no compromises in design and function, and the transmission of the force or torque signal to the recorder must be drift free with respect to time and temperature and low in hysteresis. In addition, good calibrating equipment and a suitable calibrating procedure must be used to check out the entire system from tire or rubber slider to recorder or indicator. It is self-evident that the precision of the calibrating equipment must be higher than that of the tester. Calibration to an accuracy of the order of ± 1 percent is desirable and obtainable.

Minimum Data Processing.—In routine operations, a great bulk of data must be processed and this should be possible with minimum effort and little chance of error. These requirements dictate that the instruments should not record or display numbers which must be converted to coefficients, but that coefficients are displayed or recorded directly through suitable selection of dials, recorded charts, and instrument gains. It is also desirable to have other pertinent information such as test speed, test location, pavement type and condition, noted or coded on the charts. Speed should be recorded as a continuous trace rather than from the distance between event marks.

Currently, analog recording equipment appears to be the most practical. Advances in digital instrumentation, however, will make digital printout of the coefficient feasible within the next few years. With data storage and comparison as part of the data processing system, the digital method has definite merit, particularly where year-to-year comparisons for a highway system are to be made.

Balanced Coverage and Test Cycle Frequency.—To detect slippery sections with any degree of certainty, the tester should measure a large percentage of the total distance traveled, and perform many test cycles within the total distance traveled.

To express the coverage of a tester numerically, the coverage factor is introduced.

$$C_c = D_m/1{,}000 \tag{1}$$

in which D_m is the distance in feet over which the tester measures skid resistance while traveling 1,000 ft.

For certain manual testers C_c may equal 1, but generally D_m is less than 1,000 ft. For instance, in the case of trailer-type testers, tire wear and/or temperature damage to the tread set an upper limit to D_m. There is also a lower limit because a certain distance must be traversed with the test wheel locked if the steady state coefficient is to be obtained. It takes a certain amount of time until temperature equilibrium in the contact area is attained. Experiments have shown that for all practical purposes, at 35 mph the coefficient has stabilized after sliding 50 ft.

The coverage factor does not discriminate, however, between a tester that locks the tire once for 200 ft in 1,000 ft of travel and another that locks twice for 100 ft in the same travel distance. To distinguish between these testers the test frequency was introduced.

$$C_f = 1{,}000/D_c \tag{2}$$

in which D_c is the distance required for one complete test cycle.

Combining Eqs. 1 and 2,

$$C_f = \frac{D_m}{C_c D_c} \tag{3}$$

Although it is desirable to have C_f as well as C_c large, Eq. 3 shows that a compromise must be made.

Adequate Range of Operation.—The tester should be capable of executing a large number of cycles without the necessity of refilling the water tank. Because a meaningful coefficient requires a minimum water flow rate and sliding distance, the tester range between water stops can be increased only by careful timing and coordination of the braking and water cycles and by increased capacity of the water tank. The useful maximum capacity depends on the average distance between convenient water points and whether tests are conducted along a continuous route or if individual sites are to be reached from an operational base.

High Degree of Mobility and Maneuverability.—Mobility and maneuverability requirements can be satisfied by a good weight-to-horsepower ratio (80 lb/hp or less), by suitably selected transmission and rear axle ratios, by short overall length of the towing vehicle-trailer combination, good all around vision and provisions for facilitating transportation of the tester between test sites.

Minimum Traffic Interference.—Even with present-day traffic densities, routine measurements should not require keeping traffic off the test site. It is not practical to measure at peak traffic speeds, because this also necessitates traffic control during a test. However, it is necessary that all tests on a particular type of highway be made at one speed in order to make comparisons possible. In a survey of the Pennsylvania highway system in 1962, it was found that the most satisfactory test speeds are 35 mph on primary and secondary roads and 60 mph on limited-access highways.

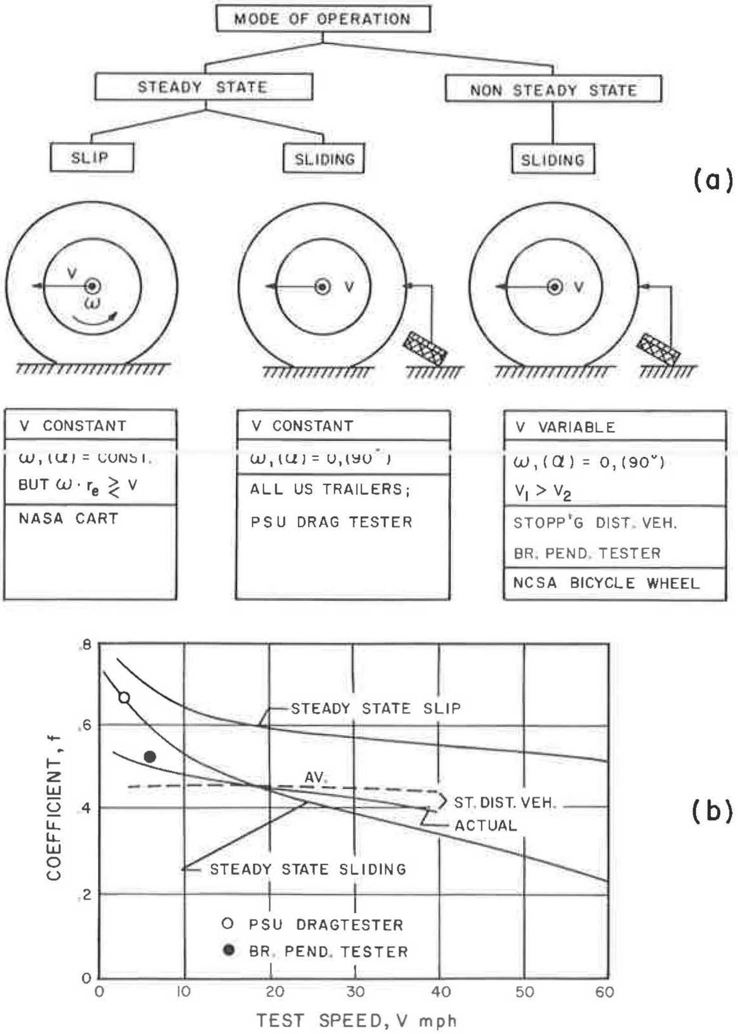


Figure 2. Classification of testers: (a) modes of operation; (b) corresponding sliding coefficients.

Ruggedness.—Routine testers accumulate mileage fast and have to travel and measure rough or damaged roads. Moreover, preventive maintenance, although highly desirable, cannot be counted on heavily in the case of a tester operated for prolonged periods away from its home base by nonspecialized personnel. The tester may have to travel continuously during the fall (which appears to be the best season for meaningful routine skid resistance measurements). Breakdowns of equipment and instrumentation can prevent completion of the test program before the onset of winter. Sound design, easily exchangeable instrument components (modular design), shock mountings, and use of standard components wherever feasible will do much to reduce breakdowns and the need for specialized maintenance.

Economy of Operation.—It is essential that operation of a routine tester be low in cost. The criterion is not so much the first cost of the equipment as the cost per test. The latter can be held down if the number of tests that can be made in a day is high, if the man-hours for operation and data analysis are low, if little maintenance and repair are needed, and if life expectancy of the tester is high.

Comfort and Safety of Crew.—Comfort and safety of the crew are considerations which cannot be ignored. In routine testing the crew may spend 6 to 8 hr per day in the vehicle. They may be called upon to perform certain functions again and again. Complete or partial automation of the various operations is therefore desirable and practical. Adequate space in the cab of the vehicle and space for personal luggage and for essential spare parts must be provided.

To insure the safety of the crew and other road users, good visibility is essential. Safety belts and warning lights, as well as effective safety colors and patterns on the tester, should be provided.

Classification of Testers

A classification of test equipment according to its mode of operation was suggested elsewhere (9). Figure 2 shows the three modes of operation and the resulting coefficients.

The steady-state slip mode of operation has not been used for skid resistance measurements in this country with the sole exception of the NASA friction cart. Under this mode, the tire is operated under constant slip, either in braking, driving or cornering, with the vehicle or tester speed kept constant. This type measures the highest (incipient) coefficient on any given pavement.

Most American and European trailers operate at the steady-state sliding mode by locking the test wheel and dragging it over the surface at constant speed. Since a locked wheel can be represented by a single tread element, a rubber slider may be used instead. Among the portable testers, the Penn State drag tester (described later) and the circular tester developed at the University of Wisconsin operate according to this mode. The resulting (sliding) coefficient is lower and decays more rapidly than the steady-state slip coefficient (10).

Stopping distance vehicles and the British pendulum tester represent applications of the nonsteady-state sliding mode. In these testers, a fixed amount of kinetic or potential energy available to the tester is dissipated completely or in part by the tire or rubber slider thereby causing a decrease of the sliding speed. Due to this speed decrease, the temperature pattern in the contact area differs from that prevailing under steady-state conditions resulting in differing coefficients at any given speed. The nonsteady-state coefficient is higher at higher speeds and lower at lower speeds (Fig. 2b). Air resistance effects may increase this trend. As a rule, the stopping distance vehicle is not capable of measuring the coefficient directly; it produces an average value (dashed line in Fig. 2b, representing the integration of the solid curve). Due to transients in slider load and temperature, the British pendulum tester plots below the steady-state sliding curve, whereas the Penn State drag tester, being a steady-state sliding device, produces results which fall on the corresponding curve obtained by locked-wheel trailer tests.

Figure 2b shows that there is no such thing as "the" coefficient for any given surface. However, the various coefficients produced by the three modes are relatable.

Presently Used Trailer Types

The mode selected for a tester was shown to have a profound effect on the magnitude of the skid resistance measured. Likewise, the designs of testers utilizing the same operating mode can vary widely and the differences may influence the results. The best criterion of a successful design is the simplicity of the equation linking the friction force measured by a force transducer or torque cell to the force in the contact area felt by the tire of rubber slider. The fewer terms the equation contains the better.

The governing equations for trailers that measure hitch forces or the forces in a link restraining the brake backing plate and for parallelogram trailers were developed earlier (9). Trailers measuring hitch forces have proved unsatisfactory.

Figure 3 shows schematically three presently used trailer types. Trailers in Figure 3a measure the bending moment M at the location shown; those in Figure 3b measure a force F_1 in a restraining link that serves as anchor for the brake backing plate which is otherwise free to rotate. Parallelogram trailers (Fig. 3c) measure a force F_2 in a link connecting the backing plate (that is also free to rotate) to the hitch of the towing vehicle.

The following three equations relate M, F_1, and F_2, respectively, to F and illustrate the different effect that the three designs have on the complexity of the individual equations. The notation employs the symbols of Figure 3.

When the wheel is locked, the friction force F distorts the contact area of the tire and thereby moves the center of the footprint rearward with respect to the wheel axis. This effect is neglected in the equations, but is discussed subsequently.

For trailers in Figure 3a:

$$f = \frac{M/L - i - [(h - r)(d/g) - (i - e)]\, a/(a - e)}{r + [(h - r)(d/g) - (i - e)]\, [a/(a - e)]\, b/a} \qquad (4)$$

in which

f = F/L sliding coefficient;
L = actual wheel load (which in the present case is different from the static wheel load L_o); and
d/g = horizontal deceleration expressed as fraction of the gravitational acceleration.

Eq. 4 indicates that f is by no means directly proportional to the measured moment M and that it is affected by the location of the center of gravity (cg), by deceleration or acceleration effects and, among others, by the geometric ratio b/a. Since fluctuations in speed cannot be avoided ($d/g \neq 0$) Eq. 4 can be simplified only by letting h approach r.

For trailers in Figure 3b:

$$f = \frac{(c/r)\,(F_1/L_o)}{1 - [(h - b)/(a - e)]\,(d/g) - (b/a)\, f_o} \qquad (5)$$

in which

f_o = F/L_o

As in the preceding case, the coefficient is affected by the location of the center of gravity, by d/g and by the geometric ratio b/a. Inasmuch as $d/g \neq 0$, Eq. 5 can be simplified only when h is made to approach b.

A linear relationship between F_1 and f would be obtained if $b/a = 0$. This is impossible to achieve, but can be approached by making b small and a large. Ideally the center of gravity is at the same elevation as the hitch (h - b), but again this cannot be attained, only approached. In the case of trailers in Figure 3a where the bending moment in the towbar is measured, the center of gravity does not have to be below the wheel center.

For trailers in Figure 3c:

$$f = (c/r)\,(F_2/L_o) \qquad (6)$$

The coefficient is directly proportional to F_2 (the force experienced by the transducer) and is not affected by speed fluctuations or dimension a of the trailer.

Suitability of Testers for Routine Use

Table 3 compares the various types of testers as to their suitability for routine surveys on the basis of criteria developed earlier.

To determine the cost per site, estimates had to be made with respect to life expectancy, maintenance and direct cost. It was assumed that tests were conducted only during 6 months of the year, and semiskilled personnel receiving $4,200 per year were employed.

A site is defined as a pavement section of 12 × 150 ft. To survey such a section, stopping distance vehicles and trailers need execute only one test, whereas 5 or more tests at different locations must be performed with portable testers to appraise the average skid resistance of the site correctly.

The assumed life expectancies may appear conservative, but day-to-day use wears

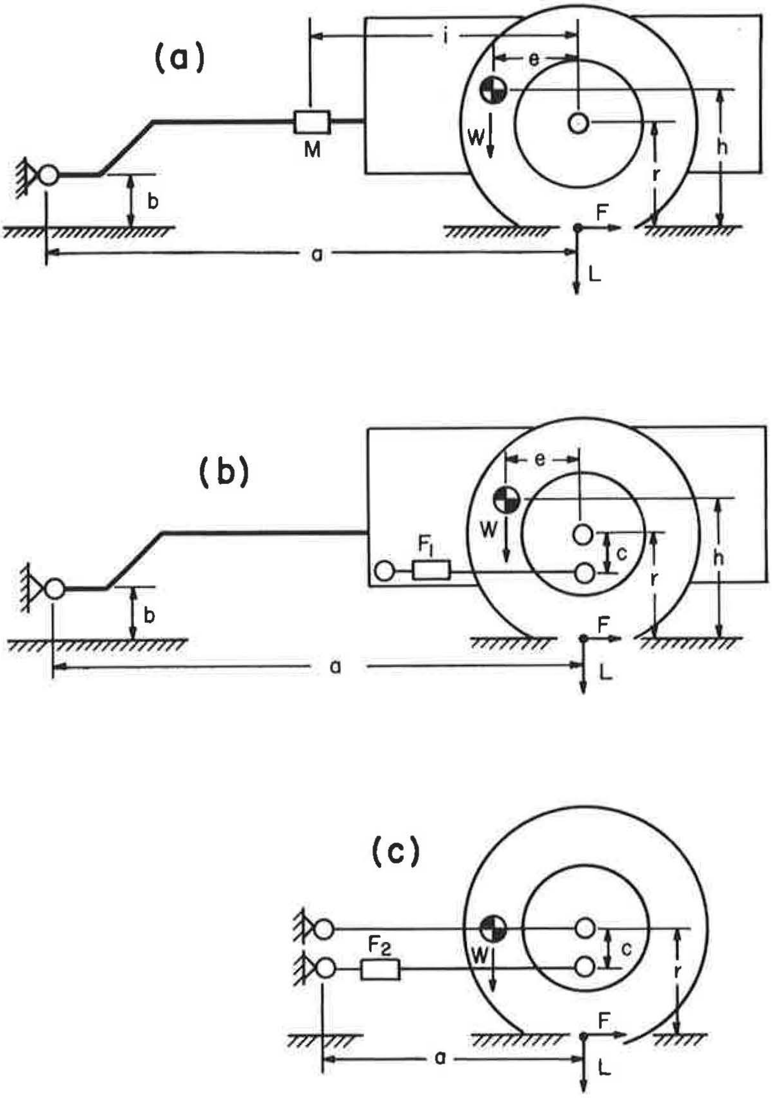


Figure 3. Trailer types: (a) trailers measuring bending moment; (b) trailers restraining brake backing plate against trailer structure; and (c) parallelogram-type trailer.

out any tester, and equipment should be phased out before major troubles develop.

The stopping distance method requires the largest crew because a water truck is needed to wet the test sections. The wages of the water truck crew and the cost of operation, maintenance, and depreciation were included in calculating the cost of the stopping distance method.

The figures for the costs per site are by necessity approximate ones, but they indicate orders of magnitude and provide a valid comparison.

PENN STATE ROAD FRICTION TESTER

Design Concept

The Penn State road friction tester was developed in two stages. The trailer was designed and built in 1958 and was used behind various towing vehicles. In 1961-62 it was integrated into a complete unit. Although the trailer was originally intended for research not only on pavement skid resistance, but also on tires and brakes, the design proved to be well suited to routine skid tests.

Trailer type testers are superior to the other types on all counts with the possible exceptions of data display and hazard to test crew. Although the initial cost of trailer testers are highest, the cost per test site is roughly 90 percent lower than for the two other tester types. Thus little doubt should exist that for any long-term skid resistance control program the trailer type is the only choice.

Having decided on a trailer type tester, the various trailer principles were analyzed for their compatibility with requirements 1, 2, 6 and 8 (Table 3). Comparison of the trailer types (Fig. 3) on the basis of Eqs. 4 through 6 clearly indicates the superiority of the parallelogram design.

Perhaps the most important feature of this design is that its wheel load is independent of the friction force F. Therefore dimension a can be made small (provided this does not interfere with the suspension dynamics) permitting the trailer to be quite "stubby." A compact trailer is regarded as a prerequisite for achieving good mobility and maneuverability.

Next a decision had to be made on whether to incorporate the parallelogram concept into a single- or two-wheel trailer. The second wheel of a two-wheel trailer can serve three purposes: (a) stabilizing the trailer with respect to motions around the roll axis, (b) preventing trailer yaw when only one wheel is locked, and (c) permitting alternate testing in the left- and right-wheel tracks.

Roll stabilization of the trailer by a second wheel is required only when the wheel load is applied by weights carried on the trailer platform resulting in a high center of gravity. When the wheel load can be applied by other means, the stabilizing role of the second wheel is not required.

To insure favorable suspension dynamics and a low weight-to-horsepower ratio, a pneumatic load cylinder indirectly suspended on the towing vehicle was selected to use part of the weight of the truck for loading the trailer wheel; thus, no extra mass must be added for this purpose. Use of a pneumatic loading element has other advantages. It permits changing the wheel load during operation by changing the air-pressure. Moreover, it permits automatic and close control of a fixed-wheel load by a precision regulator. Because of the low trailer weight, it is possible to use a Coulomb damper (rather than second wheel) mounted between trailer and towing vehicle for controlling the small yaw moments that develop on occasion. The pneumatic loading system also allows provision to be made for raising the trailer wheel off the road for transportation between test sites.

The capability of measuring skid resistance in either the left- or right-wheel track is of advantage in specialized experiments, but it is of little value for highway surveys. Tests showed the sliding coefficient to be the same in both wheel tracks of "no passing" lanes, whereas the left-wheel track exhibited lower readings where passing is permitted or where two lanes serve traffic going in the same direction. The difference between the skid resistance values of the two wheel tracks is due to different degrees of polish. Since highway engineers are generally interested in the lowest skid resistance of a section of pavement, it was decided to mount the single-wheel trailer so that it would normally run in the left-wheel track.

Pennsylvania is mountainous terrain and requires a weight-to-horsepower ratio of less than 80 lb/hp if the tester is to maintain the assigned test speed during skid measurements on upgrades and travel at average traffic speed to and from test locations.

A tester was desired whose suspension dynamics (of the truck-trailer combination) would permit testing on pavements with a fair degree of roughness and would remain unchanged over several years. These requirements were satisfied by selecting a Chevrolet C25, $\frac{3}{4}$-ton truck chassis (GVW rating of 7,500 lb) as the towing vehicle. The front and rear suspensions are virtually free of Coulomb damping and consequently do not lead to alteration of the natural frequency of the unit during its service life. Space in the cab and under the hood is ample and permits installation of all required accessories, controls, and instrumentation.

The truck is equipped with a 160-hp V-8 engine, a two-speed automatic transmission

TABLE 3

SUITABILITY OF TESTER TYPES FOR ROUTINE FIELD TESTS

Requirement	Portable Testers	Stopping Distance Vehicles	Trailers
Meaningful measurement	Poor to good	Good	Good to excellent
Precision of test data	Good	Poor to good	Good to excellent
Data display	Direct readout	Indirect	Indirect and direct readout
Coverage factor and test frequency	Poor	Poor	Good to excellent
Operating range	—	Poor to good	Good to excellent
Mobility and maneuverability	—	Excellent	Poor to excellent
Traffic interference	Very high	High	Low
Ruggedness	Good	Poor	Good to excellent
Hazard to test crew	High	High	Low
Required test crew	1-2	3-4	1-2
Operating cost:			
Initial cost, $	500	3,500	10,000-25,000
Sites tested/day	8-12	15-25	100-400
Life expectancy (yr)	6	2	5
Maintenance and direct cost/year, $	50	1,250	1,250
Total wages/year, $	4,200	8,400	4,200
Cost/site tested, $	3.34	4.70	0.32

and a limited-slip differential. The latter increases the margin of safety with respect to breakaway of the driving axle when measuring very slippery road surfaces.

The rear end of the truck was shortened by cutting 18 in. off the frame extension and modified to accommodate a 250-gal water tank, a ½-hp centrifugal pump, a 9-gal air storage tank (serving as capacitor for the trailer air spring), two batteries (one for the normal vehicle requirements, the other for powering the instruments), and the trailer hitch. Although the trailer normally runs in the left-wheel track, the hitch can be moved laterally to allow the wheel to run behind the center of the truck or in the right-wheel track.

In the cab is a large instrument panel which contains, suitably grouped gages, control equipment and instrumentation, a DC-AC convertor supplying the power for the recorder and an automatic cycle timer. An automatic speed control, auxiliary electric generator, air compressor, air storage tank and a distance switch are among the accessories mounted in the engine compartment.

Off-the-shelf components were used wherever possible to reduce maintenance and replacement problems and to hold down the construction cost of the tester.

Description of Trailer

The trailer consists of the main arm (1) and rod (2) that restrains the brake backing plate which is otherwise free to rotate (Fig. 4a). These two elements form the long sides of the parallelogram. The design incorporates a Chevrolet passenger car brake (3) and wheel assembly (4) which accepts the 7.50 × 14 ASTM Standard pavement test tire.

Supported by cantilever (5), is a Buick passenger car air suspension unit (6) subsequently referred to as the load cylinder that applies a controlled force to main arm and through it to wheel. The diaphragm area of the load cylinder remains constant within the normal range of travel, thus making the wheel load directly proportional to the air pressure within the load cylinder.

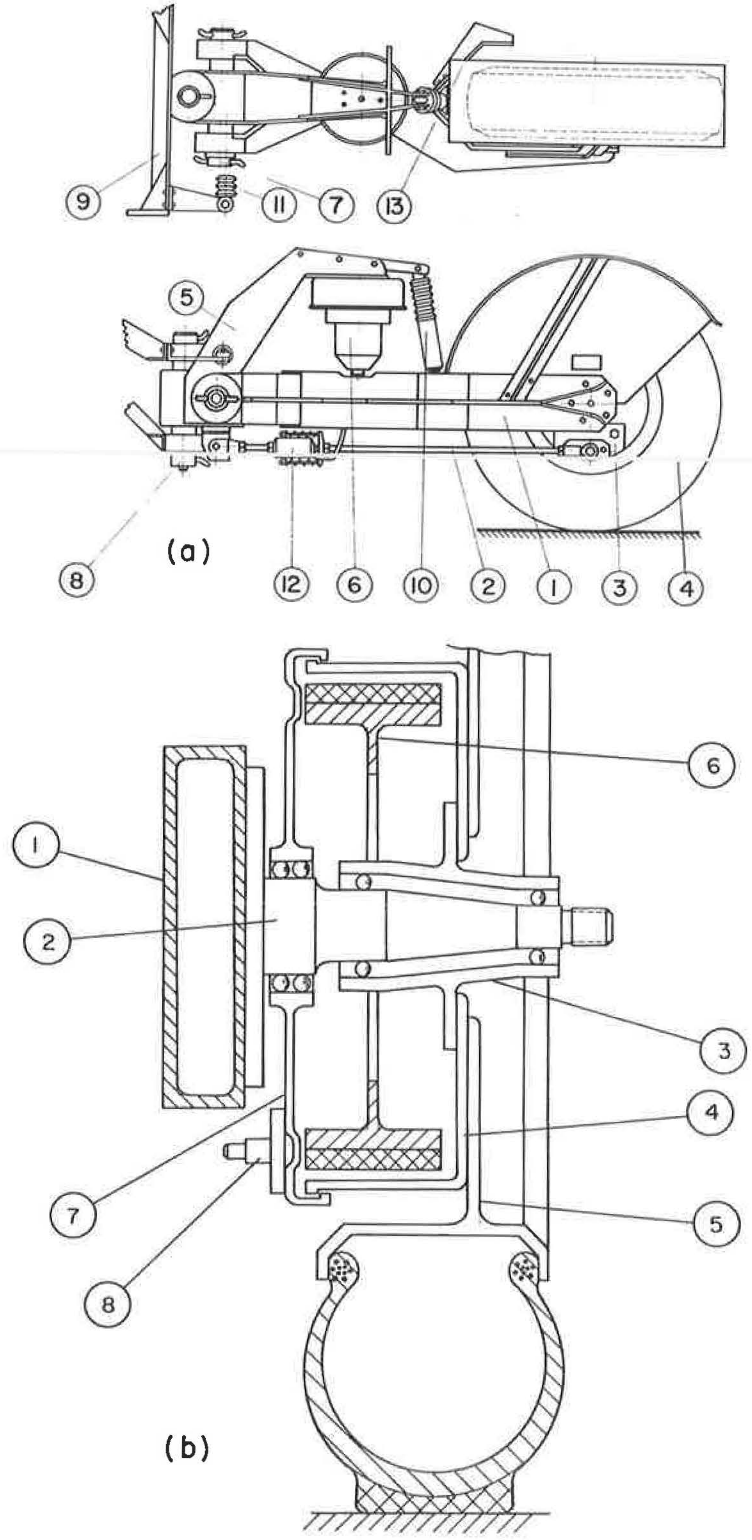


Figure 4. Penn State single-wheel parallelogram-type trailer: (a) design drawing; (b) wheel assembly.

Main arm is connected to the lower end of cantilever by pitch pivot (7) and the entire trailer is connected via yaw pivot (8) to hitch (9) of the towing vehicle. Both pivots are generously dimensioned pins supported on two sealed, self-aligning, double-row ball bearings. The main arm and cantilever are of welded construction with cross-sections of generous stiffness in bending and torsion. Trailer motion about the pitch axis is damped by a hydraulic shock absorber (10), that about the yaw axis is by a Coulomb damper (11) which also stabilizes the trailer when the test wheel is locked. Force transducer (12) is inserted in the foreward section of restraining rod. Carrier (13) is used to mount additional equipment or instrumentation and is detachable.

Figure 4b shows a cross-section of the trailer wheel assembly. Bolted to the end of trailer main arm (1) is spindle (2) supporting hub (3) via two ball bearings. Connected to the hub are brake drum (4) and wheel (5). Brake shoes (6) are attached to the reinforced backing plate (7). Supported by a heavy duty, double-row ball bearing, the backing plate is rotatable around the spindle, but is restrained by rod (Item 2 in Fig. 4a), attached to anchor (8) via a self-aligning bushing.

Support System

The trailer functions are supported by the electrical (Fig. 5a), the pneumatic (Fig. 5b) and the water system (Fig. 5c). The block diagram of the electrical system shows the two separate electrical circuits, one for the basic services and the other for program control and instrumentation. Each circuit has its own generator, fuse box and battery. The separation of the instrumentation circuit from the service circuit has the advantage that the voltage of the former can be controlled more closely and is not affected by load fluctuations caused by switching heavy loads, such as the water pump and the solenoid valves.

The service circuit is powered by a 60-w heavy duty Delco generator with diode rectification and transistorized regulator. It supplies power to the towing vehicle, the road speed governor, four solenoid operated air valves, the water pump, and the safety lighting equipment. In the instrumentation circuit a 35-w Delco DC generator supplies power to the instruments, a 20-w Carter DC-AC convertor for the potentiometer recorder, and a Cramer 6-cam cycle timer. All electrical connections to the trailer pass through a single connector.

The cycle timer controls the test cycle by actuating the brake, the water pump, the water valve and the coefficient recorder in the correct sequence, at appropriate intervals, and for the necessary duration. The timer may be triggered automatically either at fixed time intervals (tests can be repeated every 12, 15 or 20 sec) or at fixed distance intervals. In the latter case, a distance switch driven by the right-front wheel of the towing vehicle triggers the timer at intervals of either 600 or 1,200 ft.

The pneumatic system (Fig. 5b) maintains and controls wheel load and inflation pressure of the test wheel, operates the brake and water valves, three-auxiliary cylinders and accessories. A two-cylinder, single-stage Kelsey-Hayes air compressor (C) driven by the truck engine delivers 0.85 cfm of air at 135 psig.

Air passes from the compressor through one-way flow control valve (CV) and automatic drain filter (F) into storage tank (T_1). Regulator (R_1) reduces the pressure to a suitable working level (approximately 100 psig) that is monitored by gage (G_1). This regulated pressure may be applied to auxiliary cylinders ($AC_{1,2,3}$) via solenoid operated valve (SV_2). Cylinder (AC_3) raises the main arm of the trailer into the transport position after the air has been discharged from the load cylinder (LC). Cylinders ($AC_{1,2}$) are in parallel pneumatically with (AC_3) and mechanically with the rear coil springs of the towing vehicle. With air admitted, they elevate the rear end of the truck and thereby the trailer hitch. This gives the trailer wheel an 8-in. clearance above ground, adequate for fast travel on rough roads and in maneuvering. Solenoid valve (SV_2) is mounted on the trailer. It could be moved into the cab of the towing vehicle without difficulty and the trailer wheel could be raised from test to transport position without stopping the vehicle.

The regulated pressure is also applied, via solenoid actuated valve (SV_4), to air cylinder (AC_4) which opens and closes the water valve. Solenoid valve (SV_3) controls the air actuated, hydraulic brake master cylinder (BC); it also admits air via regulator

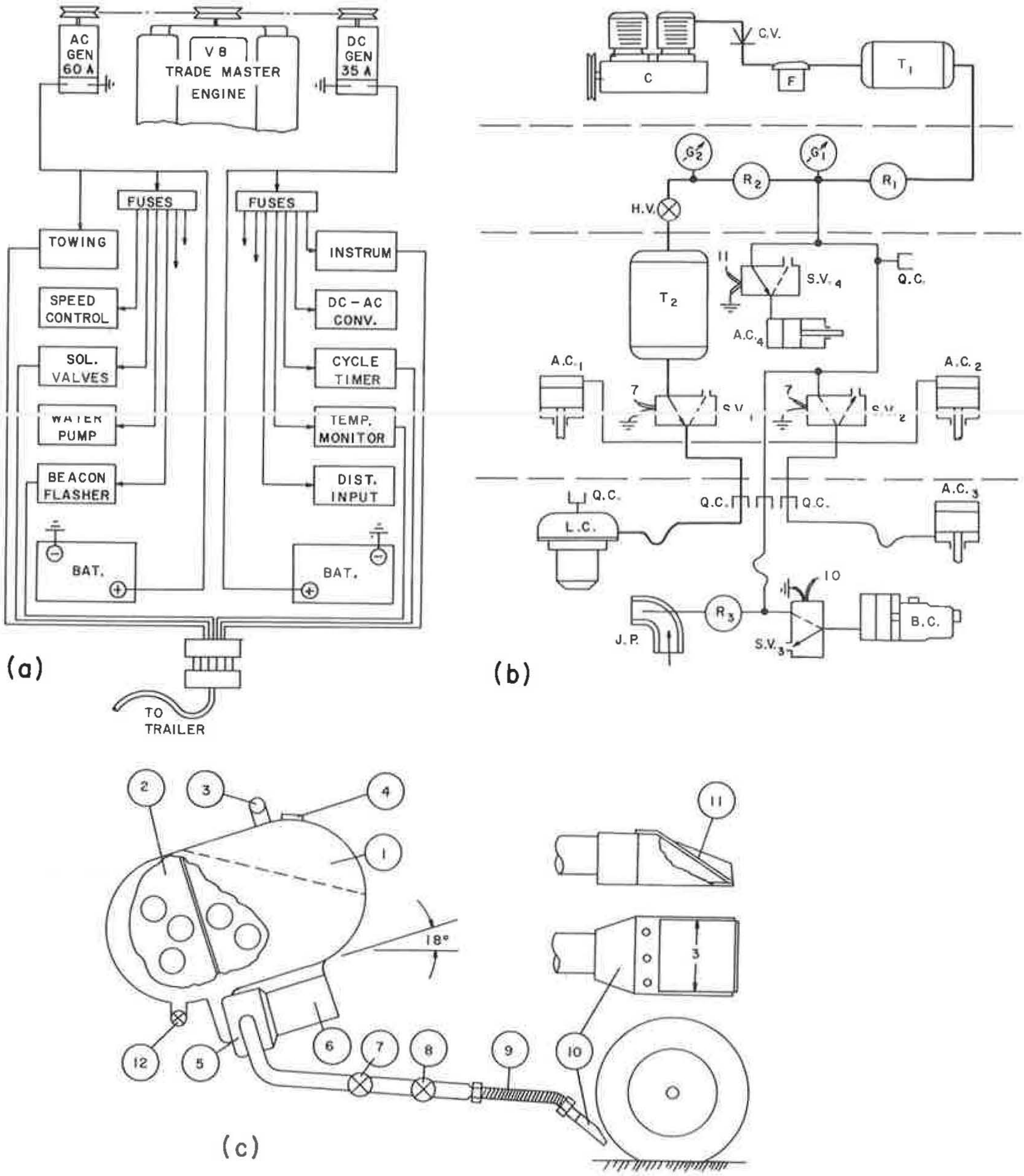


Figure 5. Support system: (a) electrical system; (b) pneumatic system; and (c) water system.

(R_3) to jet pump (JP). This pump sits on the fender of the trailer wheel and pulls air warmed by the trailer tire over a thermistor, thereby obtaining a temperature signal that is representative of the test temperature.

Precision regulator (R_2) reduces the pressure due to (R_1) to a value given by the desired wheel load. A one psi pressure change corresponds to a wheel load change of approximately 10 lb. Air flows from pressure regulator (R_2) through hand valve (HV), expansion tank (T_2), and solenoid valve (SV_1) to load cylinder (LC) of the trailer. The load cylinder solenoid valve (SV_1) is wired to solenoid (SV_2) so that the load cylinder is emptied when air is admitted to auxiliary cylinders ($AC_{1,2,3}$) and vice versa. The precision regulator holds any set load cylinder pressure within ± 0.05 psig, thereby keeping the test wheel load within ± 0.05 lb or 0.05 percent of the design wheel load. Since gage (G_2) for monitoring the load cylinder pressure has a resolution of only 0.25 psi, the difference between desired and obtained wheel load may be as much as ± 2.5 or 0.25 percent.

Whereas the precision regulator (R_2) maintains the static pressure in the load cylinder within the indicated limits, the regulator cannot respond quickly enough to temporary pressure increases that result from changes in the length of the load cylinder caused by the pitching motion of trailer and/or towing vehicle. To deal with this problem, storage tank (T_2) was added. To augment the volume of the compression chamber of the load cylinder and act as a capacitor, thereby keeping the pressure, and consequently the wheel load changes, small.

The water system (Fig. 5c) is laid out to hold sufficient water for approximately 150 tests and to produce a controlled flow rate that is not affected by the head in the water tank (1). The latter is a 12-gage, 275-gal fuel oil tank modified to hold 250 gal of water. Cross- and length-wise baffles (2) were installed to prevent sloshing of the water when the tank is only partly full. A 15-ft rubberized fire hose with a 1½-in. diameter is connected to filler elbow (3) with a Fyrefiter universal adapter on the other end that fits most fire hydrants (a hydrant wrench is carried in the truck). Opening (4) is closed by a rubber valve that serves as an air vent and prevents over-pressure on the tank when the hydrant is not closed in time. The tank can be filled from a hydrant in 3 min, whereas 15 to 25 min are needed if a garden hose must be used.

The water passes through a Brown & Sharpe centrifugal pump with a capacity of 1 gal/sec against a 15-ft head. The pump is driven by a ½-hp, 12-v General Electric DC shunt motor controlled by the cycle timer through a power relay. The manually adjusted ball valve (7) controls the flow rate, while ball valve (8), operated pneumatically and synchronized by the cycle timer with the brake cycle, starts and stops the water flow. With valve open, water passes through flexible hose (9) and discharges through variable orifice nozzle (10). The nozzle is 3-in. wide and deposits a splash-free stream of water directly ahead of the test wheel at all flow rates. The smooth flow is brought about by flexible element (11) that adjusts the nozzle opening automatically to the flow rate and seals off the line as soon as valve closes, thereby conserving water.

Recording System

A detailed study of available force transducers and recorders showed the Dillon load cell and remote indicator, in combination with the CEC-DeVar 301 recorder (Fig. 6a), best met the requirements for precision, minimum data processing and ruggedness.

1. The Dillon remote indicator operates on dry cell batteries and is therefore independent of the tester's electrical system. Because the maximum drain is only 18 ma, the dry cells permit continuous operation for 3 to 6 months.
2. The indicator is available with dual-range features which makes good resolution available at very low coefficients. (Although for routine work this is not too important, it can be of great value in research work.)
3. The load cell is of the differential transformer type, and as such, compact, rugged and electrically stable.
4. The load cell is available with a second output winding that can be matched to the input requirements of a recorder, thus permitting alternate or simultaneous use of an indicator and recorder.
5. The CEC-DeVar 301 recorder is transistorized, of modular design that permits quick exchange of components, has sufficient sensitivity to accept signals on the order of millivolts, and is electrically stable.
6. The recorder is available with three channels, thus permitting simultaneous recording of the coefficient, speed, and a third pertinent variable such as temperature.
7. The 4-in. chart of the recorder provides good resolution and has a graduation that permits coefficient and speed to be read directly.

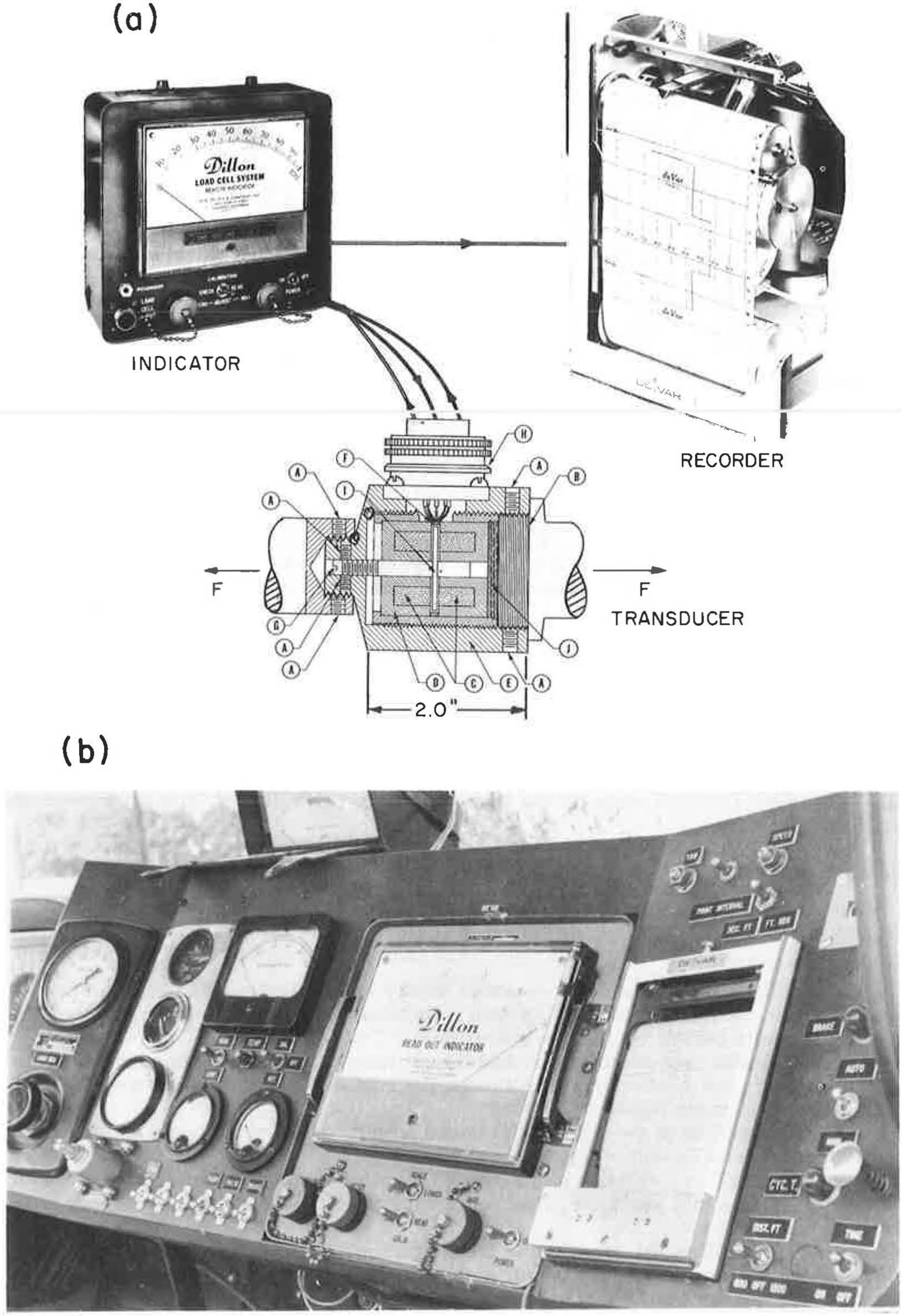


Figure 6. Instrumentation and control: (a) recording system; (b) instrument panel.

Figure 7. Penn State road friction tester: (a) trailer in test position; and (b) trailer in transport position.

The Dillon load cell (Fig. 6a) consists of an alloy steel case (E), with a threaded stud at one end and internal threads (B) at the opposite end. The construction embodies two transformers (C), each with its own primary and low impedance secondary windings enclosed in ceramic iron cup cores. Spaced between is a ferrous gap disc (I), the shaft of which is attached to one end of the load cell case at (G). In operation, the case elongates, thereby displacing the disc in relation to the transformers. This movement produces an electrical output exactly proportional to the displacement. The displacement is 0.005 in. at the maximum permissible load of 2,000 lb. The transformer windings are baked into the ceramic cores with moisture-proof epoxy resin. The entire assembly is sealed into the case by plug (J).

The instrument panel (Fig. 6b) contains, from left to right, the precision regulator for the wheel load control, the main regulator of the pneumatic system, the temperature monitor, the DC and AC voltmeters of the instrument and recorder circuits, respectively, the Dillon remote indicator and the CEC-DeVar 301 recorder. At the extreme right are the switches for selecting manual or automatic operation of the tester and for setting the desired time or distance intervals between cycles.

Figure 7a shows the Penn State road friction tester with the trailer wheel in test position. The water tank had to be opened to permit the installation of baffles. In closing it, the depression was left in the center to give increased view to the rear for backing up. On the water tank, a spare test wheel is carried. The truck spare wheel is mounted so that it extends past the hitch, thereby protecting it when the trailer is disconnected. The water pump and control mechanism, the pneumatic cylinders at the rear springs, and the batteries are accessible after removal of the truck spare wheel.

Figure 7b shows the trailer in transport position. The speed-measuring wheel is also raised. The temperature monitor is on the trailer fender, and the hose is carried in a pocket on the water tank.

Calibration Equipment

Availability of proper calibration equipment is a prerequisite for obtaining precise data from any tester. The calibration stand (Fig. 8a) was developed to increase the speed and precision of calibrating the Penn State trailer. The calibration stand is compact, can be carried by one man, and may be used with any trailer-type tester.

The stand consists of a base (1) which supports platform (2) via two ladder bearings (3). To insure alignment of platform and base, spacers (4) are inserted when positioning the test wheel on the stand, but are removed during calibration. The platform is attached to an air cylinder (7) which is pressurized by air supply (5). A precision gage indicates the pressure in the cylinder with a resolution of 0.1 psi which is equivalent to a force increment of 0.5 lb. (Because of the high sensitivity, the calibration stand may also be used to determine the static spring constant of tires in longitudinal direction. For this purpose a scale with a resolution of $^1/_{32}$ in. is provided.)

Calibration Procedure

The test wheel is placed on the platform of the calibration stand and locked by applying the brake (Fig. 8b). Wheel load and inflation pressure are checked or adjusted to the desired values and the recording system is switched on. The horizontal friction force F is simulated by increasing the pressure in the air cylinder by suitable steps. The friction force transmitted to the tire increases by corresponding increments to about 700 lb. Higher forces cannot be transmitted due to creep of the tire on the platform.

A tire with infinite longitudinal stiffness would make the force F_2 acting on the restraining rod directly proportional to F. On a tire of finite stiffness, the friction force F moves the center of the contact area and with it the vector of the wheel load L to the rear, thereby producing a moment, $L \times e$, which tends to turn the wheel in the same direction as the friction force F. Hence, F_2 is not directly proportional to F but increases more rapidly (Fig. 8c). The deviation from the straight line is determined by the ratio e/r of the deformation and the static radius. The relation between F and F_2 deviates progressively from linearity as the stiffness F/e of the tire decreases. Since new tires are stiffer than used ones, the calibration should be carried out only after the tire has been run 200 to 300 mi.

Erroneous results will be obtained if the calibration is attempted by applying a known torque to the test wheel. Such a procedure would provide a strictly linear, and therefore misleading, relation between friction force F and recorder deflection. For correct calibration the simulated friction force F must be transmitted through the tire used in the tests. Two tires having the same static radius r at identical wheel loads and inflation pressures do not necessarily have identical calibration curves.

Although e is usually small (0.3 to 0.5 in. for passenger car tires at a coefficient of 0.5) at a wheel load of 1,000 lb, a force of around 40 lb is added to the friction force F at a coefficient of 0.5. For routine surveys it is convenient to assume either a linear

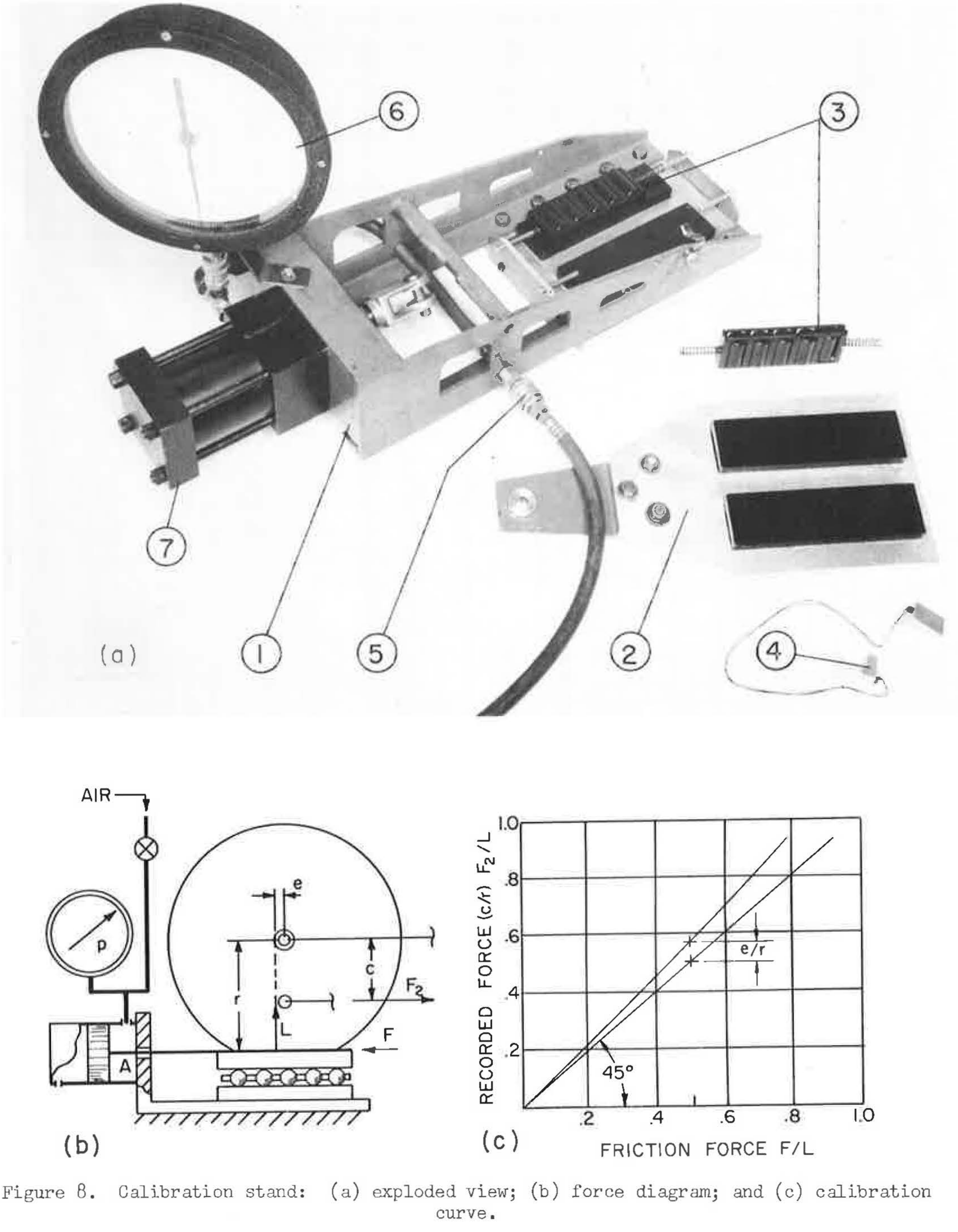


Figure 8. Calibration stand: (a) exploded view; (b) force diagram; and (c) calibration curve.

relationship (which exists at low coefficients) or slightly decrease the instrument gain to make the two curves (Fig. 8c) coincide better within the needed range. Slightly lower than the true values will then be read at low coefficients, but this may be considered to be on the safe side.

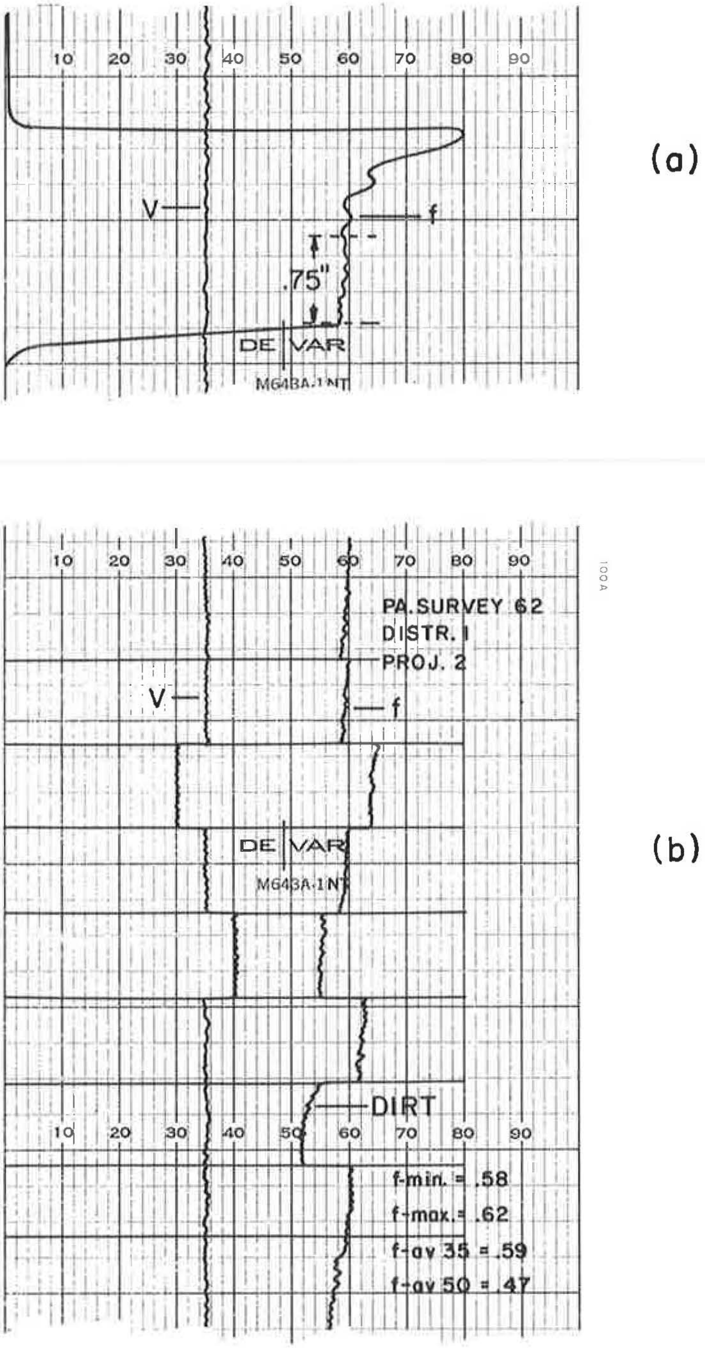


Figure 9. Typical records: (a) manually controlled test cycle; (b) series of automatically-controlled test cycles.

Record Evaluation

In addition to recording errors caused by tester design and instrumentation, errors can be introduced in evaluating the skid resistance trace of the recorder charts.

Figure 9a is a reproduction of a completely recorded cycle typical for testers shown in Figure 3b and 3c. The chart is read from the top. Due to the rapid deceleration of the wheel when the brake is first applied, the force transducer measuring F_1 or F_2 experiences a much larger force than does the tire. Hence the overshoot of the coefficient trace does not represent the skid resistance of the pavement. After the wheel has locked (at the point at which the trace first intersects the "60" chart line), the trace indicates the true coefficient. The temperature increase in the tire contact area is responsible for the tendency of the trace to drop further (Fig. 9b), but this drop may generally be ignored, provided the trace is always evaluated in the same manner.

In Figure 9a, a 0.75-in. section of trace f is averaged between the dashed lines and tabulated as a sliding coefficient of 0.59 at 35 mph (the speed is read from trace V). Since the initial portion of the trace is of no interest, it may be suppressed in routine surveys, partly to conserve paper and partly to eliminate the temptation of overrating the skid resistance of a pavement.

Figure 9b is a typical record from the 1962 survey of the Pennsylvania highway system. The chart section contains 9 individual tests with a sliding distance of 150 ft. The first two 35-mph tests (reading from top) show that the pavement has a very uniform friction level. The third test was run at 30 mph, the fourth again at 35 mph and the fifth at 40 mph. The last three provide information on the change of the sliding coefficient with speed. Test 6, again at 35 mph, reads higher than tests 1, 2 and 4, indicating a change in pavement texture. Test 7 is abnormally low. Since loose dirt was observed on the road during this test, measurement was ignored.

To describe the skid resistance of a particular highway section, the observed minimum and maximum coefficients and the average coefficient at 35 mph are reported. (The average coefficient is not necessarily the mean.) With the average coefficient at 35 mph and the slope obtained from the tests at 30 and 40 mph, the coefficient may be extrapolated to higher speeds.

In situations where traffic interference does not permit testing at or near the maximum traffic speed, it is convenient to make tests at different speeds in order to determine the coefficient vs speed slope of the pavement (7). The ability to change speed quickly between test cycles is a necessity for such a procedure. It can be employed only if the tester has an adequate weight-to-horsepower ratio and is readily maneuverable in traffic.

Sample Application

Any coefficient (slipping or sliding) is a performance value that is valid only for the particular set of conditions under which it was obtained. Since routine tests as a rule are conducted with a particular type of tire, it is of more than marginal interest to compare performance with tires typically used on automobiles.

Figure 10 compares the performance of the ASTM Standard tire with that of a relatively new and absolutely smooth Firestone Champion tire at three wheel loads, but constant inflation pressure. Although the data are valid only for the particular pavement on which the tests were made, they show certain trends which apply also to other conditions.

The curves have a common rapid drop of the sliding coefficients with speed. This pronounced drop is characteristic of all fine textured pavements, especially those with aggregates that do not polish readily and produce very high readings at low speeds. It is also typical that the smooth tire produces a lower coefficient (at speeds above 10 or 15 mph) that diverges progressively more from the coefficients of the treaded tires as the speed increases.

The ASTM Standard and the treaded Firestone Champion tire perform similarly. Their coefficients agree numerically at a point that shifts towards higher speeds as the wheel load is increased (arrows in Fig. 10). This shift in performance is brought about mainly by the two factors, contact length and wiping. At reduced wheel loads the Firestone tire provides higher coefficients than the ASTM tire due to the wiping action of the tread (the ASTM tire has only longitudinal ribs). As the wheel load increases, the contact length of both tires increases and gives the rubber elements more time to squeeze through the water film. The data show that the contact length has a larger influence than wiping as evidenced by the increase in the speed range in which the ASTM tire is superior.

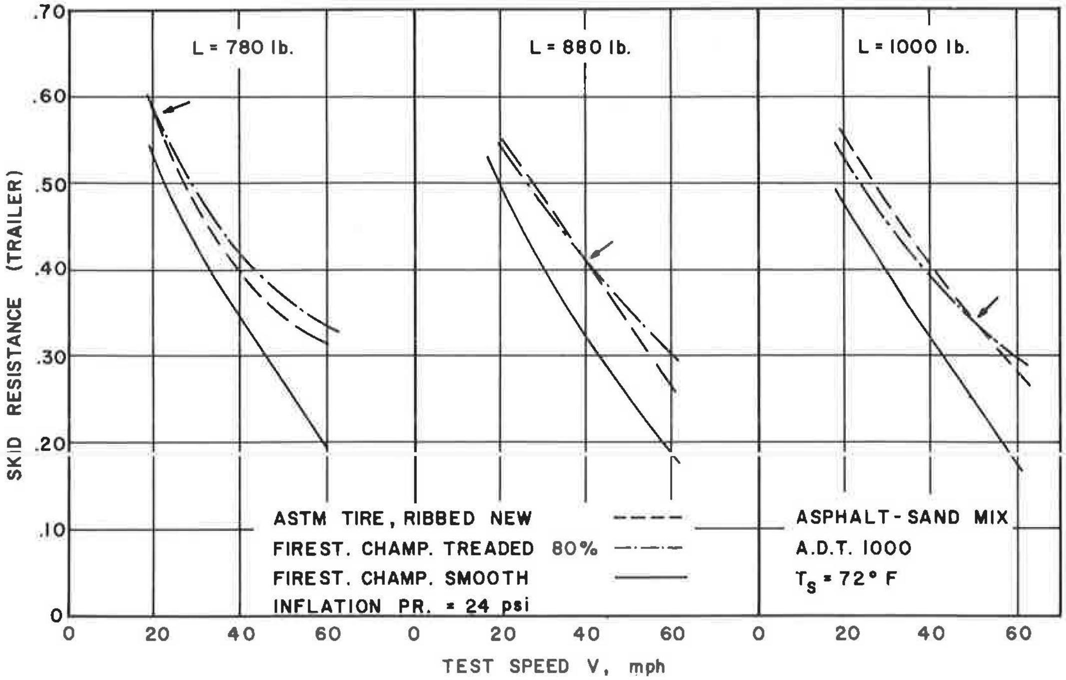


Figure 10. Effect of the tire tread design on skid resistance at different wheel loads.

The efficiency of the Penn State road friction tester is illustrated by the fact that the data were obtained by making four tests for each combination of tire tread, wheel load and speed, requiring a total of 108 test cycles. The entire 108 tests were completed in a little less than one hour, including the time for changing wheels and refilling the water tank.

PENN STATE DRAG TESTER

Design Concept

Under certain conditions trailer-type testers are not the best devices for measuring the skid resistance of pavements. This applies to rough primary roads, secondary and rural roads, and to intersection approaches. In stop and go traffic a full-scale tester loses its inherent advantages. A manual tester can be a useful substitute.

One of the objectives of the Penn State program was to evaluate existing portable testers with respect to their suitability for field tests. None of the designs seemed to satisfy all the requirements that are reasonably imposed on such a tester.

Since it must be anticipated that relatively untrained personnel will operate the tester simplicity of design and ease of operation must be combined with adequate accuracy. It would also be desirable for the tester to be able to measure rapidly a fairly large pavement section, thereby reducing the possibility that the skid resistance of a site is misjudged. Rapid data accession has the further advantage of reducing the exposure time of the operator to traffic. Finally a straightforward calibration procedure and a simple method for checking the accuracy of the instrument in the field were deemed necessary.

Because none of the existing portable testers fulfilled these requirements, a new type of tester was developed that meets the desired requirements. Because of its mode of operation it is referred to as a drag tester. Data obtained during the 1962 HRB-ASTM Correlation Study and at Penn State indicate that the drag tester correlates well with trailer-type testers on most pavements.

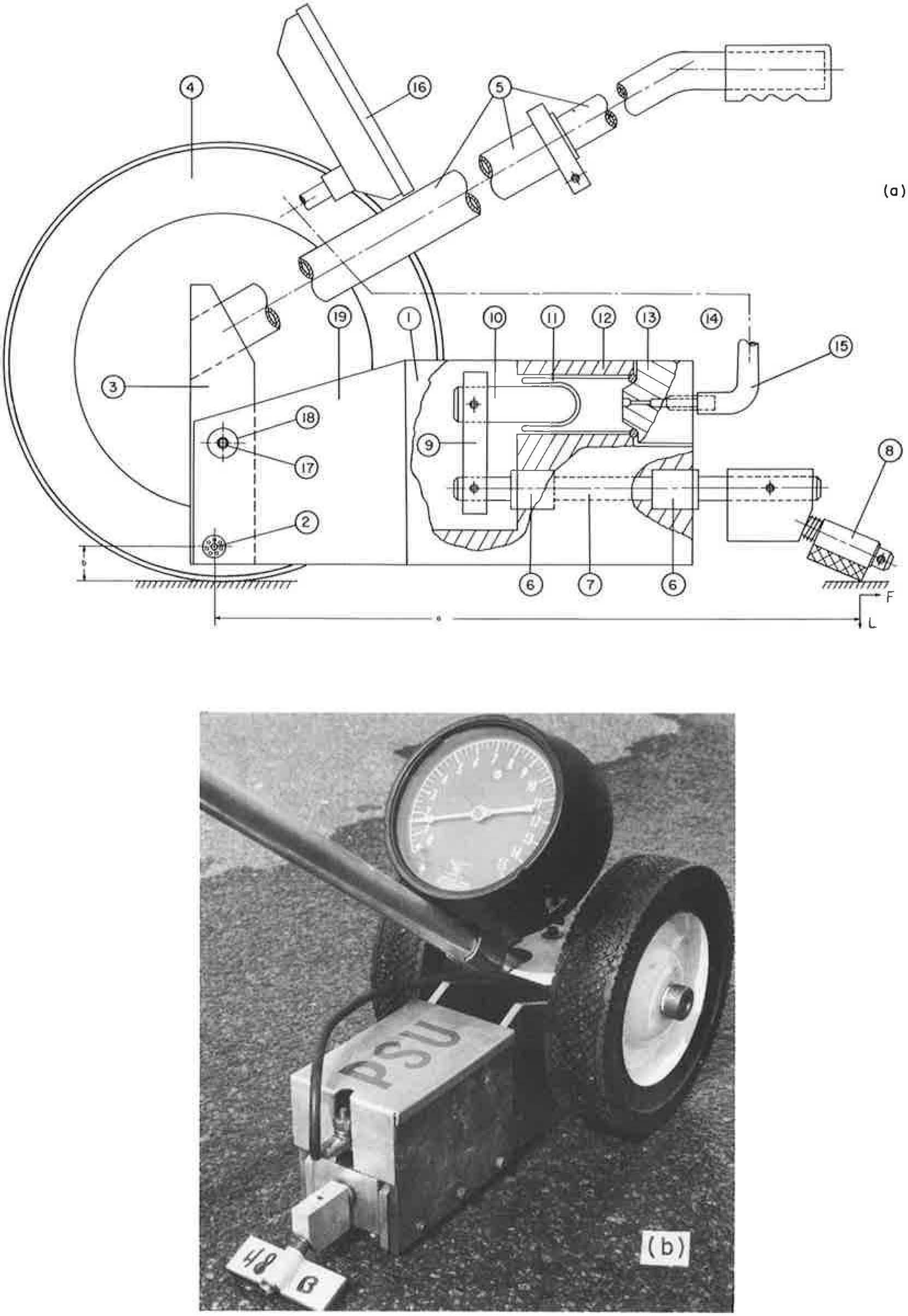


Figure 11. Penn State drag tester: (a) design drawing; (b) tester in use.

All testers operating at speeds below 10 or 20 mph have a disadvantage in that extrapolation of the skid resistance to higher speeds is unreliable when the geometric characteristics of the pavement surface is unknown. With the onset of hydrodynamic wedge formation under tire or rubber slider, the sliding coefficient decays more rapidly with speed on dense or fine textured pavements than on open or coarse pavements. To permit the extrapolation of the data of slow-speed testers, including those of the Penn State drag tester, a study is under way at Penn State that promises to provide a "drainage number" that is related to the pavement texture and thereby to the slope of the skid resistance vs speed curve.

Description

The drag tester is essentially a two-wheeled cart to be pushed by an operator over a wetted pavement at uniform walking speed (Fig. 11a).

The cart consists of housing (1) connected, via ball bearings (2), to block (3) to which are attached two wheels (4), and handle (5). The housing contains two ball bushings (6) which support hardened steel shaft (7). Attached to the latter is the rubber heeled slider (8) and connector (9) which rigidly connects the shaft with the transducer plunger (10).

The latter displaces the rolling rubber diaphragm (11) that seals the liquid-filled transducer cylinder (12). The diaphragm lip is retained by cover (13) and the cylinder is connected via restriction (14) and hose (15) to pressure gage (16). Because only low pressures can be generated in the system, the gage is of the bellow type. Since shaft is supported by ball bushings and because diaphragm simply rolls along as the plunger moves, the internal friction of the device is small compared to the friction forces measured and can be neglected. The travel of handle is restricted by stop (17) and hole (18) in the housing extension (19), but is sufficient to permit the operator adequate handle movement without altering the slider load.

Theory of Operation

The cart is placed in position on the wetted pavement and pushed along at uniform speed. The normal load L, due to the weight of housing, presses the edge of the rubber slider onto the pavement. The resulting friction force F attempts to displace slider, shaft, connector, and plunger. The resulting displacement of the liquid increases the pressure in the hydraulic system and causes gage to indicate a pressure proportional to the friction force F.

By definition, a coefficient of skid resistance or friction is

$$f = F/L \tag{7}$$

and

$$F = Ap \tag{8}$$

in which A is the effective area of the transducer and p is the pressure in the hydraulic system.

Thus,

$$f = (A/L)\,p \tag{9}$$

or the coefficient is proportional to the pressure p. To keep the unloading effect of the moment $F \times b$ on the slider load L_0 small, the ratio b/a is kept small (1/20). This keeps the error (made by assuming L to be equal to the static value L_0) below 3 percent up to coefficients of 0.6. The pressure gage has a face that indicates the coefficient multiplied by 10.

Calibrating Procedure

Since the slider load L is provided by the weight of the housing, the initial calibration and any recalibration are very simple. The procedure consists of two steps: finding the exact relation between the (horizontal) friction force F and the pressure dis-

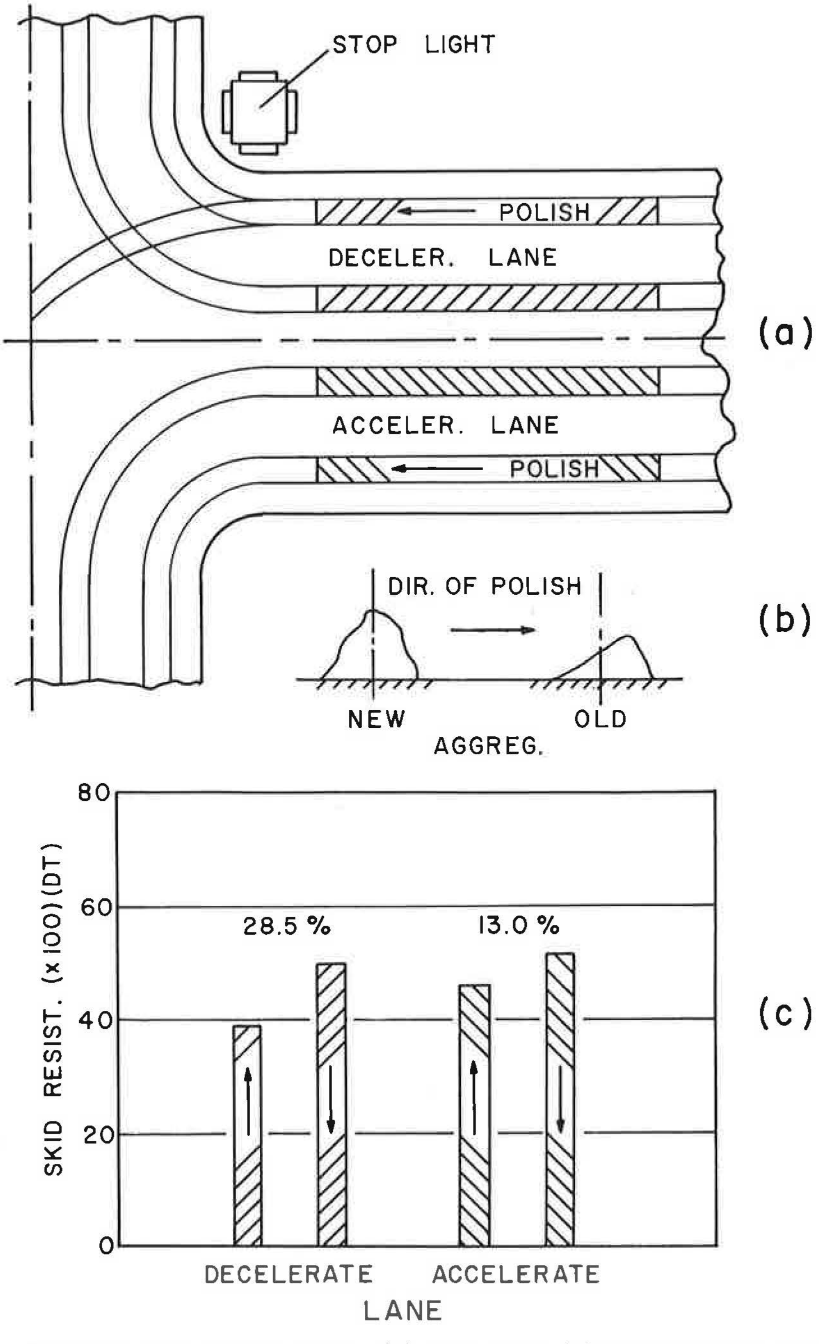


Figure 12. Pavement heel and toe wear: (a) test site; (b) unsymmetrical wear of aggregate; and (c) coefficients of test site.

played on the gage, and adjusting the slider load L to a value that insures correct indication of the coefficient by the pressure gage.

First, the tester is placed on a table and housing (Fig. 11a) is supported in such a manner that it and shaft are in a horizontal position with the slider edge clearing the surface. The pin holding the slider in place is removed and a 10-lb test nylon line is threaded through the pin hole. A small pulley supported on lightly oiled precision ball bearings is fastened to the edge of the table so that the fastened end line is horizontal and in line with shaft. A tray for carrying the calibration weights is attached to the free end of the line.

The no-load reading of the pressure gage must be adjusted before the actual calibration is made. This reading is about 0.5 on the gage scale because of the hydraulic head between plunger and the gage bellows.

With the housing restrained to resist the pull applied by the line, weights are placed on tray in 0.5-lb increments until a maximum load of 5.5 lb is reached. The corresponding numbers are read from the dial of the pressure gage. A plot of the dial readings against the force applied must give a straight line passing through the origin. The effective diaphragm area A was so chosen, that a 4.0-lb load should give a gage reading of approximately 10 (which is equal to a coefficient of 1.0).

Second, for the pressure gage to display the skid resistance f directly, the slider load must be made exactly equal to the horizontal force which causes the pressure gage to read 10.

With the slider reinstalled the slider edge is placed on the platform of a 10-lb capacity weighing scale. The wheels of the cart are supported to secure a horizontal position of the housing and the handle is supported in a position within the limits provided by stop and hole.

If the weighing scale shows a deviation of the slider load from the required slider load as previously determined, adjustment is made by adding or removing material from the housing end plate.

The drag tester is now calibrated to display the skid resistance directly.

To facilitate a check on the calibration in the field, stop is removed and the housing turned 90° to a vertical position with the slider end down. The combined weight of the slider, shaft, connector, and plunger causes the gage to indicate a pressure or corresponding skid resistance. This is a simple way of applying a fixed load to the hydraulic system. The gage reading is recorded and can be easily checked.

Sample Application

Determining the skid resistance on or near city intersections is an example of an application for which a portable tester is particularly suited, provided the data can be obtained quickly so that natural gaps in the traffic flow can be used. Figure 12a shows an intersection controlled by a traffic light. The Penn State drag tester was employed not so much for measuring the skid resistance in the lanes leading in and out of the intersection, but to demonstrate the existence of "heel" and "toe" wear of the pavement aggregate.

The development of heel and toe wear on the elements of the tire tread and the significant influence of this wear on the sliding coefficient were first reported by Gough et al., in 1956 (11). Because aggregate polish is brought about by the motion of the tread elements relative to the pavement surface and this motion is strongly directional when large driving or braking forces are transmitted to the ground, heel and toe wear of the aggregate is likely to occur in the manner illustrated by Figure 12b. It was expected that skid resistance measurements made in the direction of polish would yield lower values than measurements made in the opposite direction. It was further expected that the difference in skid resistance would be higher in the decelerating lane because traffic decelerates more rapidly than it accelerates.

A 20-ft test section was measured off in both the decelerating and accelerating lanes, and eight tests were made with the drag tester in the right-wheel track of each lane. Four measurements were made in the direction of the polishing action and four in the opposite direction. The mean values obtained in these tests are plotted in Figure 12c.

The results illustrate the existence of definite heel and toe wear in both lanes. There is a difference of 28.5 percent in the decelerating lane against 13.0 percent in the accelerating lane. This shows that under certain conditions the directional character of the polishing action must be taken into account if the data are to tell the full story.

The important result is that the 16 measurements were made in less than 10 min and only 12 to 14 sec were required per test. Thus, the operator could utilize natural gaps in the traffic flow without hazard. Since the drag tester is used by the operator while walking, a large number of tests can be performed in a day without undue strain. Furthermore, if there is not more than 300 ft between sites, the tester may be rolled by raising the handle to lift the slider off the pavement. The tester can easily be carried over longer distances because it weighs only 20 lb.

OUTLOOK

Vehicle speeds and the number of passes per mile of highway will continue to increase during the next decades. By 1970 the average vehicle speed will have increased by approximately 22 percent over the 1950 speed, requiring a 50 percent higher skid resistance. The number of passes will be double the 1950 figures. Highway engineers will not only have to provide more road mileage that is skid resistant by present-day standards, but the highways will have to have a higher skid resistance and retain it 5 to 10 years. If these goals are not reached, additional accidents attributable to skidding will occur at friction levels currently regarded as adequate.

Although it may be assumed that advances will be made by the automobile and tire industries to help meet the increased frictional demand, it is quite likely that the main burden of improvement will fall upon the highway agencies. High-speed tests on wet pavements and advances in the understanding of the squeeze film or drainage problem indicate that factors such as tire geometry, tread design, rubber composition and operational variables such as wheel load and inflation pressure do have an important bearing on friction. However, the "openness" of the pavement, the microscopic shape and molecular properties of aggregate and binder determine the skid resistance of a given pavement-tire combination more than anything else. Whereas openness governs the sinkage rate or time it takes the bulk of water to be squeezed out of the foreward zone of the tire contact area, the microroughness of the aggregate, the resulting micropressure distribution and molecular properties determine what magnitude of friction develops once contact has been made by a tire element with the surface.

The skid resistance problem has been described elsewhere (9) as a control problem consisting of the three phases: skid resistance measurement, comparison of the measured values against a standard of adequacy, and if necessary, upgrading the skid resistance of the pavement. To apply this approach successfully, the methods of measurement must be improved and uniform test procedures established. With such procedures, testers employing the same mode of operation will read identical coefficients on the same surface. For the British pendulum tester, this state has been reached with the development of a standard operating procedure by the ASTM Committee E17 on Skid Resistance in 1962. The development of a similar standard procedure for trailer-type testers is much more urgent because they, and not portable testers, will provide the bulk of skid resistance data during the coming years.

The 1962 HRB-ASTM Correlation Study has shown that significant progress has been made in the design and refinement of trailer-type testers since the 1958 Correlation Study, and the close agreement in the performance of these testers warrants the development of a trailer test procedure. This does not mean, however, that improvement of these testers should not continue. Still greater precision, dependability and efficiency would not be amiss. Because a large body of experience has been acquired by various agencies, the time may be at hand to agree upon one trailer design that could be produced in quantities to provide every highway department in the United States with a tester.

Meanwhile, the search for better methods of skid resistance measuring methods which might eventually eliminate the need for dragging tires or rubber sliders over the pavement should continue.

Also, realistic figures for minimum permissible skid resistance values must be developed to judge the adequacy of the surveyed pavements. Because it is not likely to be economically feasible to make all highways equally skid resistant, the standards must be flexible. Different standards of minimum skid resistance may apply to different highway types, straight stretches, curves, approaches to intersections, and grades.

Highway agencies must develop and put into practice long-range programs for continuous improvement of the skid resistance potential of pavements. Skid and polish resistance of aggregates must be considered important properties of pavements, just as are those defined by the Marshall test. It is not sufficient that a highway department know how to build skid resistance into a pavement, it also must see to it that the contractors do. The factors that control skid resistance are as vital in specifications as a are asphalt content, aggregate size, and temperature of the mix.

Although basic research will provide generally valid information, the variability of the materials used as aggregates makes it mandatory that experimental highway sections be constructed of economically attractive aggregates, upgraded with skid resistance improving additives where needed. Careful traffic counts and other pertinent observations should be made during the entire life of the experimental pavements. Since it takes years to fully appraise the performance of a pavement, these experimental sections should be placed now.

Other aspects of the skid resistance problem involve better road layouts and better engineered traffic control systems that reduce the number of situations in which motorists are suddenly confronted with the necessity of executing maneuvers that require friction levels in excess of those available. The motoring public must become more aware of the factors that lead to skidding and learn how to cope with them. States that have or will introduce compulsory vehicle inspection should include tires in the inspection procedure. Tires should carry knobs or ribs indicating a safe operating level. Such easily recognizable safety marks would enable all enforcement agencies to keep unsafe tires off the roads.

The skid resistance problem is too diverse and complex to be solved in a few years by a few agencies and research laboratories. A problem of this magnitude requires cooperation, leadership and long-range planning.

ACKNOWLEDGMENTS

The development of the road friction tester and the research involved in this development are a part of the activities of the Automotive Safety Research Program of the Department of Mechanical Engineering of the Pennsylvania State University.

The drag tester is being developed under the Joint Road Friction Project of the Pennsylvania Department of Highways and the University. The Department's permission to include certain data and information obtained in the course of this project is acknowledged.

REFERENCES

1. Moyer, R. A., "Skidding Characteristics of Automobile Tires on Road Surfaces and Their Relation to Highway Safety." Iowa Eng. Exp. Sta., Bull. 120 (1934).
2. Mills, J. P., and Shelton, W. B., "Virginia Accident Information Relating to Skidding." Proc. First Internat. Skid Prevention Conf., Va. Council of Highway Investigation and Research, Univ. of Va., Part I, p. 12 (1958).
3. "Highway Statistics." U. S. Department of Commerce, Bureau of Public Roads, p. 79 (1960).
4. "Automobile Facts and Figures." Automobile Manufacturers Assn., p. 40 and 48 (1958).
5. "The Highway Transportation Story." National Highway Users Conference, p. 35 and 37 (1961).
6. "Highway Statistics." Tables M-2, M-3 (1945-57).
7. Schulze, K. H., and Beckmann, L., "Friction Properties of Pavements at Different Speeds and Their Changes by Traffic." Paper No. 87C, ASTM Annual Meeting, New York (1962).
8. Giles, C. G., and Sabey, B. E., "A Note on the Problem of Seasonal Variations in Skidding Resistance." Proc. First International Skid Prevention Conf., Va. Council of Highway Investigation and Research, Univ. of Va., Part II, p. 563-568 (1958).
9. Kummer, H. W., and Meyer, W. E., "Measurement of Skid Resistance." Paper No. 87A, ASTM Annual Meeting, New York (1962).
10. Meyer, W. E., and Kummer, H. W., "Mechanism of Force Transmission Between Tire and Road." SAE Paper 490A (1962).

11. Gough, V. E., Hardman, J. H., and Maclaren, J. R., "Abraded Tire Treads." Trans. of the Institution of the Rubber Industry, Vol. 32, p. 46 (1956).

Appendix

PENN STATE ROAD FRICTION TESTER

Performance Record

The trailer has been used for approximately 12,000 tests since 1958. After the completion of the road friction tester (summer 1962), the unit participated in the HRB-ASTM Correlation Study at Tappahannock, Va. in which 1,200 test cycles were performed. Then, a survey of the Pennsylvania highway system was carried out for the Pennsylvania Department of Highways. Approximately 5,200 skid resistance measurements were made while traveling 4,000 mi. The survey was completed in 35 working days, so that on an average day, 150 tests were made and 115 mi traveled.

During the survey, the average fuel consumption was 12.1 mpg in travel between test sites and 8.9 mpg during testing. With water tank full (or 48 lb GVW/HP), the road friction tester was capable of testing grades up to 10 percent at the assigned speeds. With the tank empty (or 36 lb/HP), the tester easily maintained average passenger car speeds during travel from site to site. The maneuverability of the tester proved excellent due to good all-around vision and the ability to raise the test wheel for backing and turning on narrow roads. The unit handled well. The suspension dynamics were very satisfactory with full as well as empty water tank. Only very minor failures were encountered in the 10,000 tests conducted since June 1962.

Operating Procedure

The following procedure was employed in the 1962 skid resistance survey of the Pennsylvania highway system:

Transportation.—Lift test and speed control wheels and secure. Set primary air pressure regulator to 100 psi to insure adequate road clearance of the trailer. For longer trips, empty water tank. Switch on trailer tail light.

Preparation.—Lower test and speed control wheels. Check pressures in load cylinder, test tire and control wheel tire. Fill water tank from hydrant after flushing hydrant. Check calibration of force transducer by locking test wheel, and with automatic transmission in low, apply engine power until recorder displays a coefficient of 0.50. Compare with reading on remote indicator. Set water flow rate to provide a theoretical water film thickness of 0.5 mm at the proposed test speed. Reset cycle counter to zero and perform one cycle to check out electric, pneumatic and water system.

Testing.—Test at 35 mph on primary, secondary and rural roads, and 60 mph on limited-access highways and turnpike. Traffic permitting, conduct one test each at 30 and 40 mph on each pavement section of primary, secondary and rural roads, and at 40 and 50 mph on limited-access highways and turnpike. Test in the left-wheel track of the traffic lane. In special situations, test in the track that appears most polished. Use flashers and beacon sparingly, but as demanded by traffic. Record data, site identification, type of pavement, texture, surface condition, tire temperature and any unusual observations.

Specifications

Gross weight (water tank filled)	7,760 lb
Dry weight	5,760 lb
Overall length	235 in.
Overall width	70 in.
Overall height	70 in.
Maximum travel speed	70 mph
Maximum test speed	70 mph
Design test speed	35 to 60 mph

Cycle duration	10, 15 or 20 sec
Tests per mile	10, 7.5 or 5
Theoretical waterfilm at speeds up to 70 mph	0.5 mm
Capacity of water tank	250 gal
Time for filling (at 100 psig water pressure)	3 min
No. of cycles at 35 mph without refill	150
Coverage factor C_c	0.3 to 0.5
Test frequency C_f	2

Towing Vehicle

Make	Chevrolet
Type	C25 (chassis with cab)
Engine	160 hp
Transmission	2-speed Powerglide
Differential	Limited slip type
Tires	8 × 17.5, 8 ply

Trailer

Overall length	60 in.
Overall width	15 in.
Height	32 in.
Wheel axis to pitch axis	40.00 in.
Wheel axis to yaw axis	43.75 in.
Travel of trailer main arm:	
Around pitch axis	± 8°
Around yaw axis	± 45°
Total trailer weight	300 lb
Dead weight on wheel	150 lb
Wheel load range	150 to 1,000 lb
Test wheel, passenger car rim and tire	7.50 × 14

PENN STATE DRAG TESTER

Operating Procedure

The following procedure was employed in 1962 HRB-ASTM Correlation Study at Tappahannock, Va.

General.—When transporting tester, push upper portion of handle all the way in. For operation, adjust handle extension to most confortable position and firmly lock clamp. Do not let tester rest on rubber slider for prolonged periods of time. When testing, make sure that vertical movement of handle remains within limits given by the stops. To determine these limits, move handle up and down several times with tester at rest. Walk at uniform and brisk pace, but do not run.

Preparation for Test.—Check slider for wear. Use new slider when edge is worn more than ¼ in. as measured with a rule laid flat across the width of the slider. Select path for test. Remove loose particles and dust by thoroughly flushing surface. When testing on highways, select most heavily polished sections (usually the left-wheel track of the right traffic lane) and test in the direction of polish to obtain lowest possible readings.

Testing.—Push tester along selected and wetted path for approximately 15 ft and observe gage pointer. When steady state conditions are attained, note gage reading and lift off slider by raising handle. Proceed several feet along test path with slider raised, then re-establish contact between slider and pavement by lowering handle for second reading. Make three observations during one run and record average reading. Measure and record temperature of wetted pavement. Determine whether surface texture is fine (⅛ in. average surface dimension of aggregate), medium (¼ in.), or coarse (½ in. or larger).

Specifications

Total weight (dry)	20 lb
Load on slider	4.0 lb
Normal pressure on slider[1]	10 psi
Overall height, handle extended	35 ± 5 in.
Overall length, handle extended	48 in.
Height, handle retracted	20 in.
Length, handle retracted	35 in.
Overall width	8 in.
Wheel diameter	7.75 in.
Approximate speed during testing	3 mph
Slider dimensions (same as for British pendulum tester)	3 × 1 × 1/4
Drag length for average test	15 ft
Area surveyed per test	4 ft^2
Number of tests per slider edge[2]	100
Capacity of water container	2 qt
Number of tests per fill	3

---

[1] With wear of 1/8 in. as measured with a rule laid flat across the width of the slider.

[2] Tests on a uniform, fine sand, textured asphalt pavement have shown that a slider edge can be used for a total drag distance of 1,500 ft or more without objectionable wear or detectable change in the sliding coefficient.

California Skid Tests with Butyl Rubber Tires and Report of Visit to Road Research Laboratories in Europe Engaged in Skid Prevention Research

RALPH A. MOYER, Professor of Transportation Engineering and Research Engineer, Institute of Transportation and Traffic Engineering, University of California, Berkeley

•AN EXTENSIVE California program of skid resistance tests conducted in 1961 was reported in HRB Bull. 348 (1962). The 1961 tests yielded significant results primarily because of the use of a new torque meter device to measure the friction forces. The tests were run with four different types of tires including one tire with the recently developed butyl rubber tread which provided high hysteresis or energy losses and high coefficients of friction on wet pavements.

In view of the improved accuracy obtained with the new torque meter, and the high friction values obtained in the exploratory tests with the butyl rubber tire, a program of tests was carried out in 1962. Skid resistance measurements were made on a wide variety of pavement surfaces with two different brands of butyl rubber tires, and also with the 1958 and 1961 pavement test standard tires.

Before 1961, it was generally assumed that the only way to obtain significant improvement in the skid resistance of wet pavements was by the selection of aggregate types and pavement construction methods and controls, and/or by de-slicking treatments which had been established by laboratory and field tests. Studies were conducted by California in 1961, by the British Road Research Laboratory, and by Dr. Tabor of Cambridge University, England. They indicated that a new approach might be more effective in reducing the skidding hazard on wet pavements. It consisted of changing the properties of the rubber used in making tire treads and improving the tread patterns. In the 1961 California tests, the coefficients of friction measured on the same pavement at the same speed were as much as 40 percent greater for the good tread butyl tire than for the older type GRS tire with a smooth or poor tread pattern. Although it is recognized that the hazards cannot be entirely eliminated on every mile of pavement in the United States, the recent developments in changing the properties of tread rubber and improving the tread patterns for more skid resistance are most encouraging.

During the Summer of 1962, 10 road research laboratories in Europe were visited where research in skid resistance of pavements is being pursued. It is significant that traffic accident records in Europe have indicated that the incidence of skidding accidents on wet pavements is two to three times greater than in the United States. Also, traffic volumes in many countries of Europe are increasing at about twice the American rate. Vehicle speeds on major rural highways in Europe are also increasing, especially on the rapidly expanding mileage of motorways, expressways, autobahns and autostradas. For these reasons, it is not surprising that research on the prevention of skidding accidents is receiving far greater attention in Europe.

Paper sponsored by Committee on Road Surface Properties Related to Vehicle Performance.

1962 CALIFORNIA SKID TESTS

A major objective in conducting the 1962 California tests was to measure the coefficients of friction on 18 representative pavements with widely different surface characteristics for two different butyl rubber tires and for two standard tires used in the 1961 tests. The tests were conducted in the Spring after heavy rainstorms during February and March had thoroughly cleansed the pavement surfaces, removing oil slick, grease, rubber, and other deposits. In addition, the scouring action of traffic on the wet pavements developed a coarser-grained surface texture than is normally obtained due to the polishing wear effect of traffic during long periods of dry weather.

All of these factors contributed to an abnormal increase in the coefficients of friction on practically all pavements on which tests were run. In fact, the coefficients of friction measured on several pavements were the highest coefficients under wet pavement conditions on record in more than 12 years of study.

Normally skid tests are run only under wet pavement conditions because accident records show that skidding is a factor in less than one percent of the accidents occurring on dry pavements, and the coefficients of friction on all types of dry pavements are well above 0.50 and are usually considerably higher than on wet pavements. Furthermore, dry skid tests cause damaging tire wear, especially in the locked-wheel braking tests where considerable rubber is removed, creating flat spots. However, in view of the high coefficients of friction measured on certain wet pavements (in excess of 0.90), it was decided at the close of the program to run a series of dry tests to determine if an increase in the coefficients of friction was also obtained.

Description of Test Tires

Four different tires were used: Tire A, 1961 pavement test standard tire; Tire B, 1958 pavement test standard tire; Tire D, butyl rubber tire; and Tire E, butyl rubber tire. Figure 1 shows the type of tread pattern for each tire. (HRB Bull. 348.) For all tire types in the tests, a 25-psi inflation pressure was adopted to be maintained at all times. A break-in of at least 200 mi under 50 mph was adopted to wear off rubber with variable friction properties developed in the mold during the vulcanizing process.

Tire A.—Tire A was manufactured to meet the specifications of a Committee of the Tire and Rim Association for a standard tire to be used in pavement skid tests. The size was 7.50-14. The quality was that specified for new cars as a first-line tire. The tread was a plain rib design with five ribs equally spaced and with grooves of equal depth. No special groove pattern, cuts, or siping was provided. The tread compound was an oil-extended styrene butadiene rubber. The tire had a durometer hardness of 58. It was designed for operation at a load of 1,085 lb per tire and 24-psi inflation pressure.

Tire B.—Tire B was selected because it was used as the standard tire for the Virginia skid correlation tests in 1958. It was a typical first-line tire with a rib tread pattern consisting of seven ribs with saw-tooth edges, cuts and siping of the type widely used by manufacturers in 1958 to provide high skid resistance on wet pavements. The size was 6.70-15, and except for the change in size and tread pattern, it was similar to Tire A. The tread compound was an oil-extended styrene butadiene rubber.

Tire D.—Tire D was a butyl rubber tire recently developed by the tire industry to take advantage of the high hysteresis losses provided by butyl rubber. British tests have shown that rubber with the greatest hysteresis or energy losses gave the highest coefficients of friction on wet surfaces. The results of the 1961 California exploratory tests with a butyl rubber tire confirmed these results.

Tire D was purchased from a local retail store and is typical of the butyl tires sold in 1962. The size was 6.70-15. It was a premium quality tire made of rayon and nylon fabric. The tread consisted of 5 ribs with cuts and siping and a saw-tooth edge pattern. The durometer hardness was 54.

Tire E.—Tire E was a butyl rubber tire differing from Tire D primarily in the design of the tread pattern and in the 7.50-14 size. It was also purchased from a local retail store as a premium quality tire. The tread consisted of three ribs with a wide center rib made with a series of closely-spaced diagonal cuts and siping of various lengths.

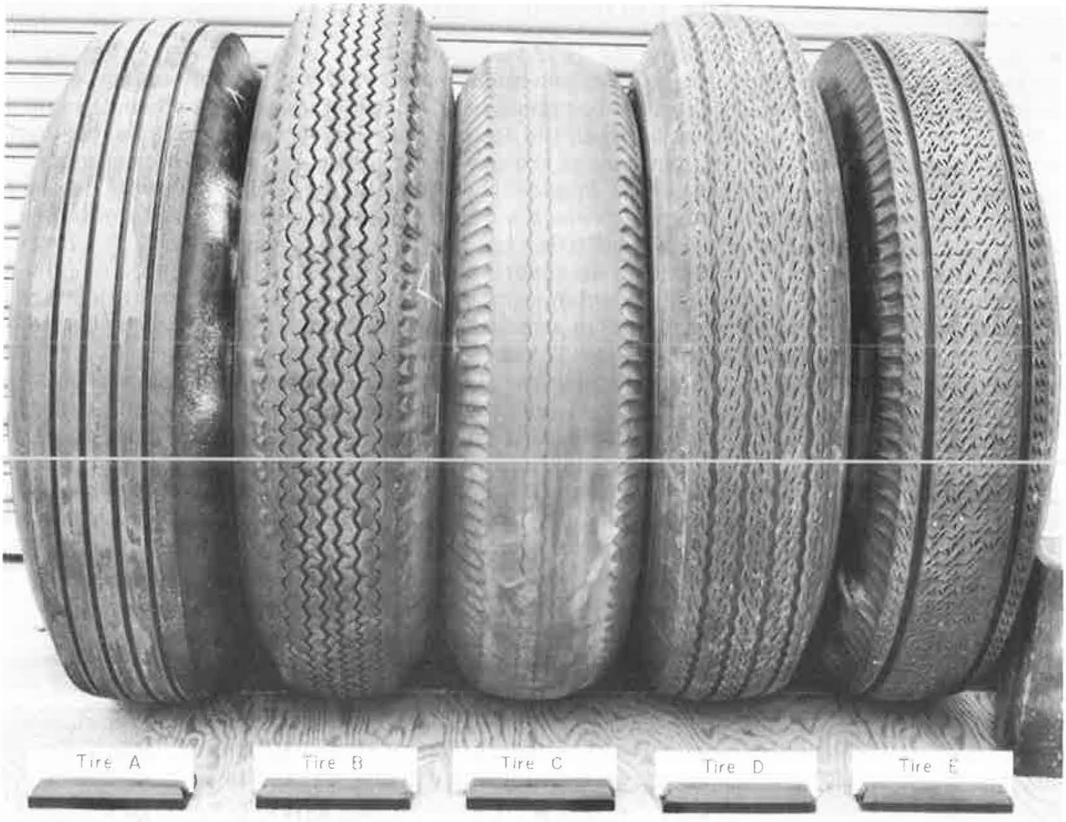


Figure 1. Tires used in 1961-1962 skid tests.

The edges of the ribs along the two main grooves of the tread were straight and plain. The width of each of the two grooves was 0.28 in. The tire had a durometer hardness of 50. The fabric was Super II Tyrex.

1962 TEST PAVEMENTS

Skid tests were conducted on 18 typical pavement surfaces representative of portland cement concrete and asphaltic concrete pavements. Such factors as surface texture, type of aggregates used, traffic volumes, age, accumulation of oil slick, grease and rubber, and the variable amount of aggregate polishing caused by traffic were considered as factors contributing to wide variations in coefficients of friction measured on wet pavements. Out of the total, 12 pavements were selected from the 21 in the 1961 program.

The pavements selected for the 1962 tests were classified in four groups: (a) portland cement concrete, (b) dense-graded asphaltic concrete, (c) open-graded asphaltic concrete, and (d) seal coats. Location, traffic volume, construction date, etc., are given in Figures 2 through 11 and Table 1.

The portland cement pavement surfaces were built with a Johnson float finisher equipped with a burlap drag. If properly used in a delayed finish before the initial set of the concrete, a burlap drag of two or three layers will produce a surface with a roughened sandy texture and excellent non-skid properties (Fig. 8). As mentioned, the heavy rains in February and March and the scouring effect of traffic had a remarkable cleansing and de-slicking effect on the surface texture. The change in the appearance of the Woodland Bypass concrete pavement between Fall 1961 and Spring 1962 is evident in Figure 8.

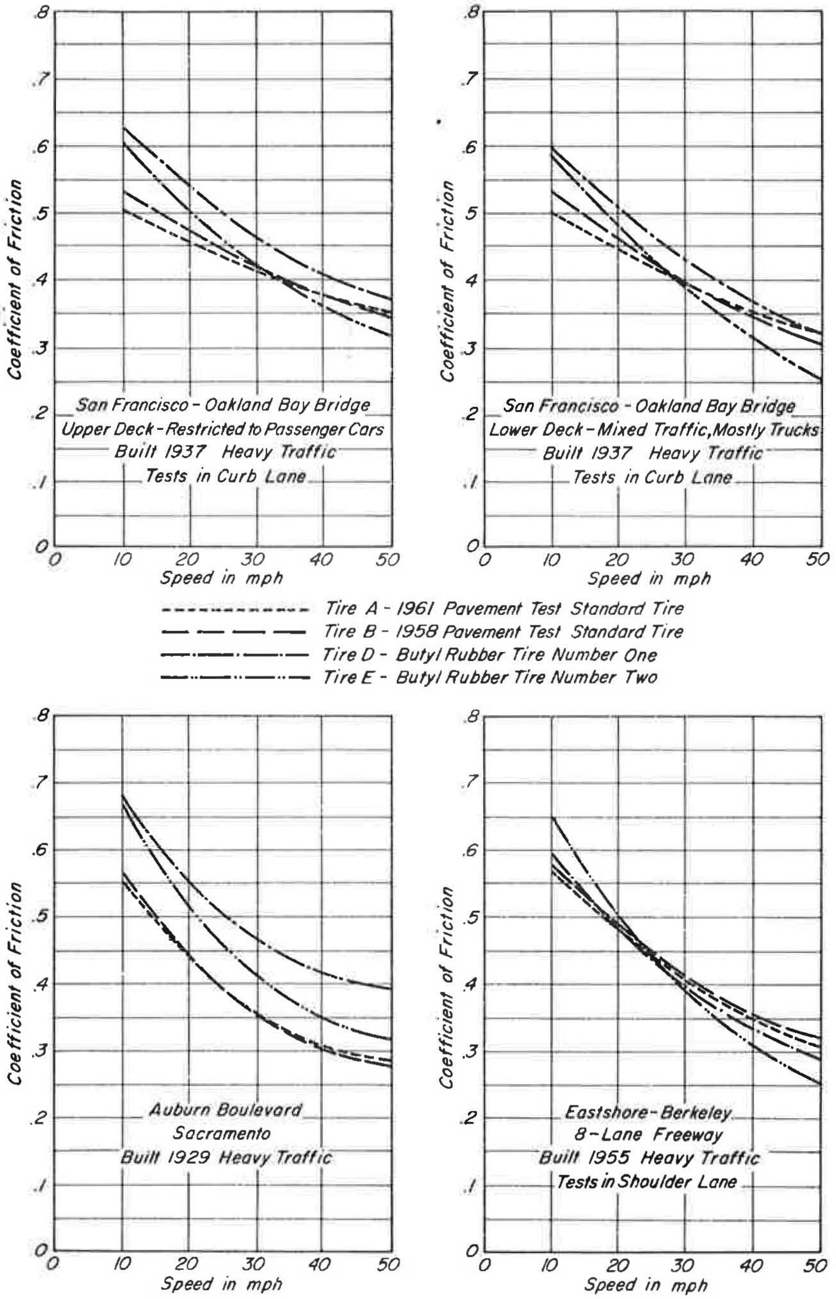


Figure 2. Test results on sections of wet portland cement concrete pavements for two types of butyl rubber tires and two other types.

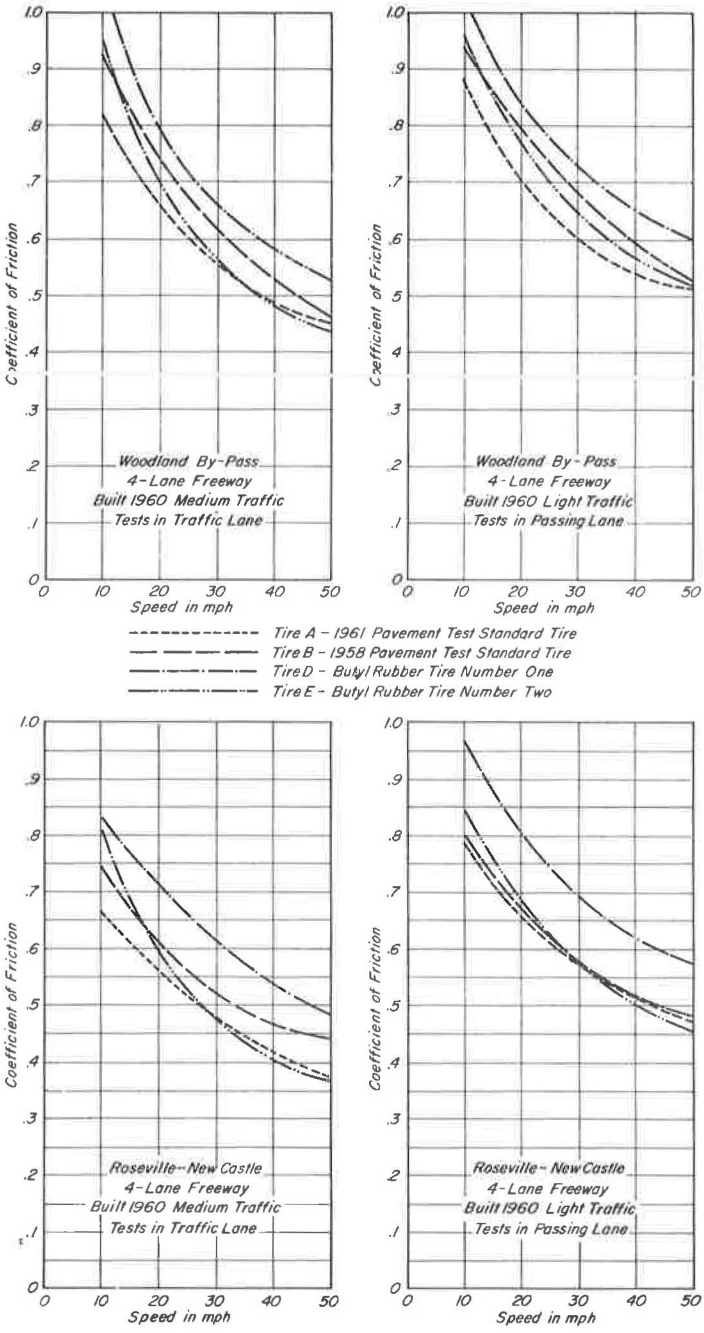


Figure 3. Test results on sections of wet portland cement concrete pavements for two types of butyl rubber tires and two other types.

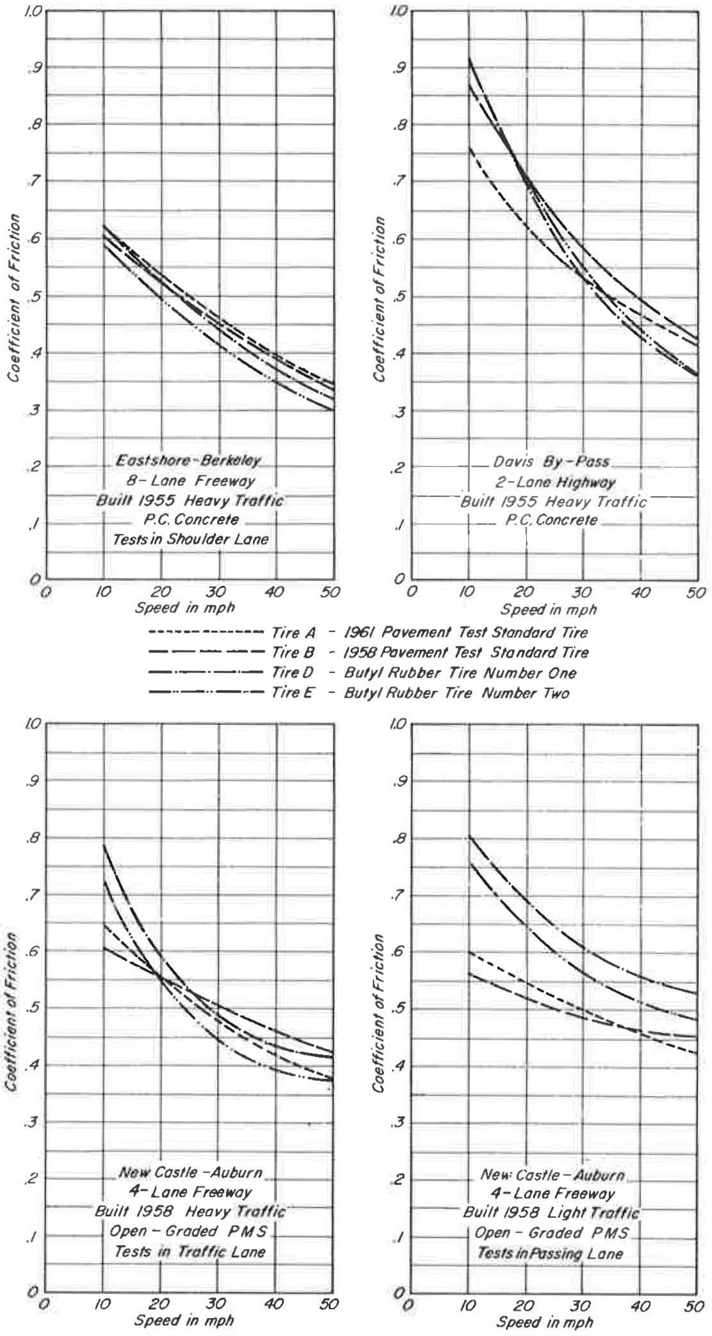


Figure 4. Test results on sections of wet open-graded asphalt plant mixes and wet portland cement concrete pavements for two types of butyl rubber tires and two other types.

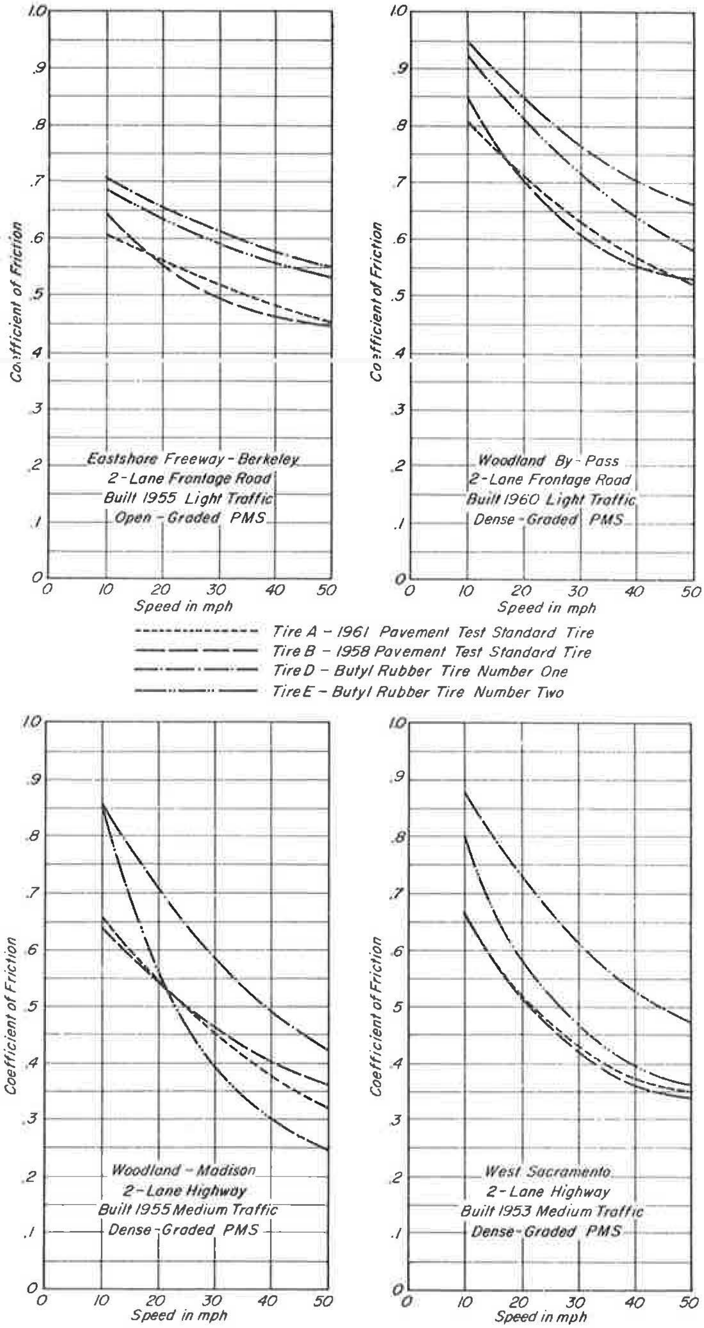


Figure 5. Test results on sections of wet dense-graded and open-graded asphalt plant mix surfaces for two types of butyl rubber tires and two other types.

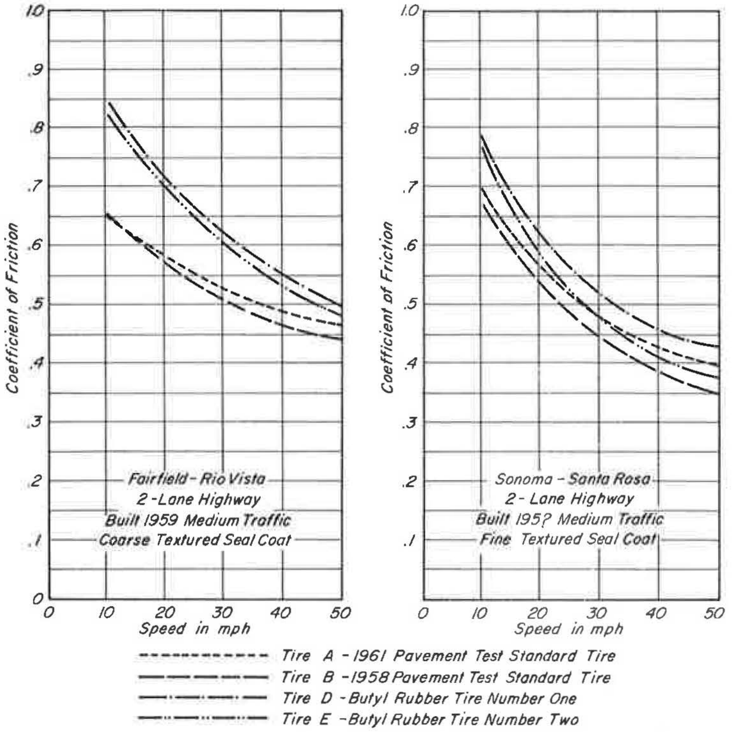


Figure 6. Test results on sections of wet coarse-textured and fine-textured asphalt seal coat surface for two types of butyl rubber tires and two other types.

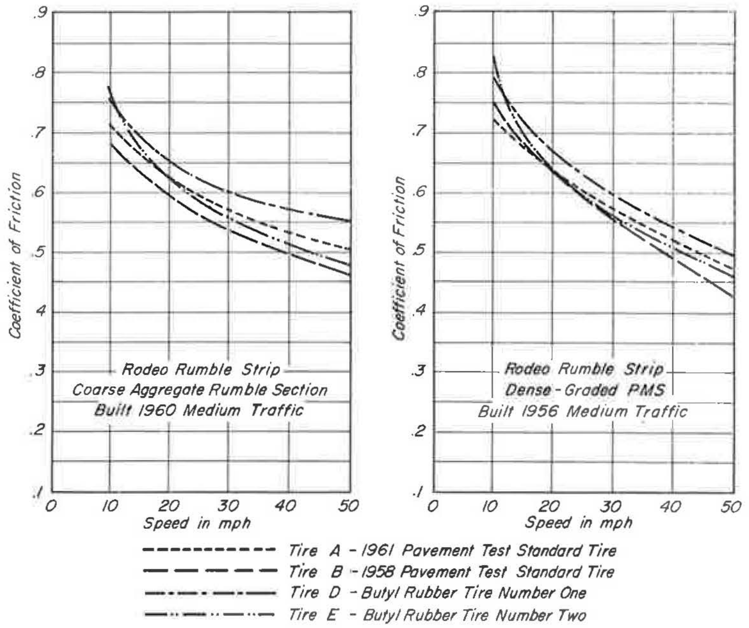
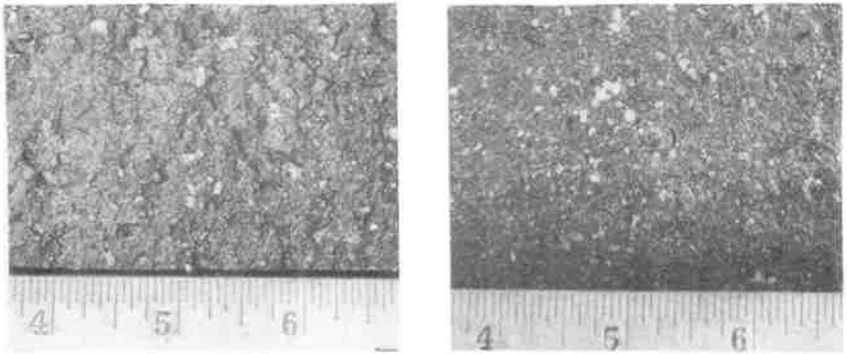
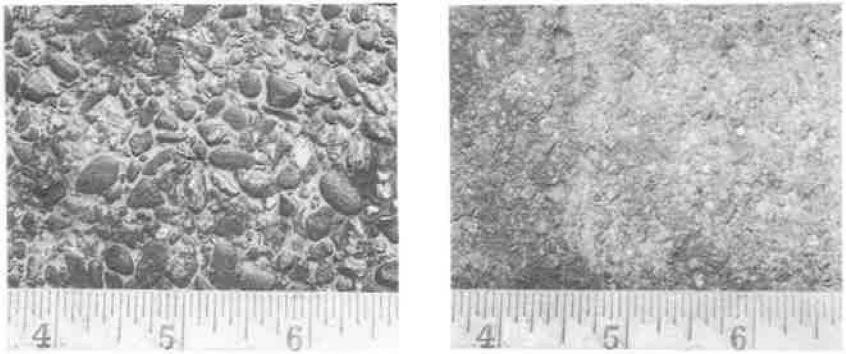


Figure 7. Test results on sections of wet rumble strip for two types of butyl rubber tires and two other types.



a - San Francisco-Oakland Bay Bridge, upper deck, built in 1937, lightweight p. c. concrete; heavy passenger car traffic.

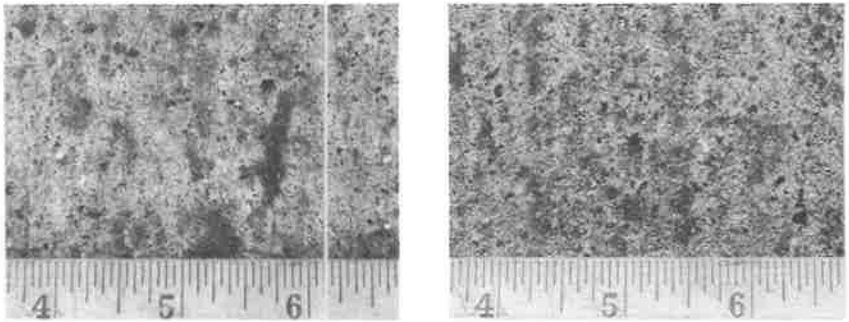
b - San Francisco-Oakland Bay Bridge, lower deck, built 1937, p. c. concrete; heavy truck traffic.



c - Fairfield-Rio Vista, coarse-textured seal coat, built 1959; medium traffic.

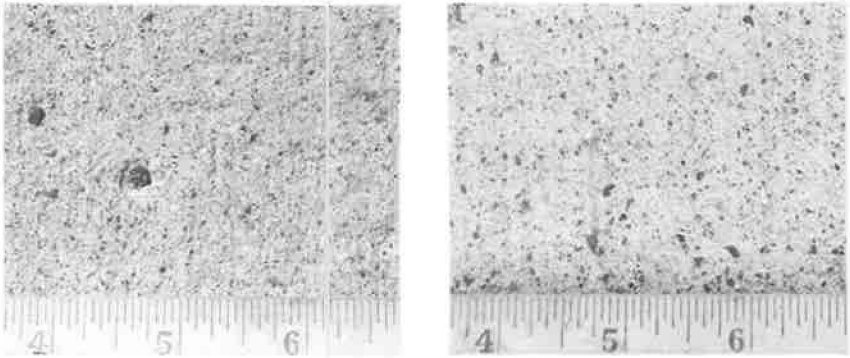
d - Sonoma-Santa Rosa, fine-textured slurry seal coat, built 1953; medium traffic.

Figure 8. Portland cement concrete pavements with burlap drag finish.



a - Woodland By-Pass, built 1960; medium traffic. Picture taken spring, 1962, following heavy rains.

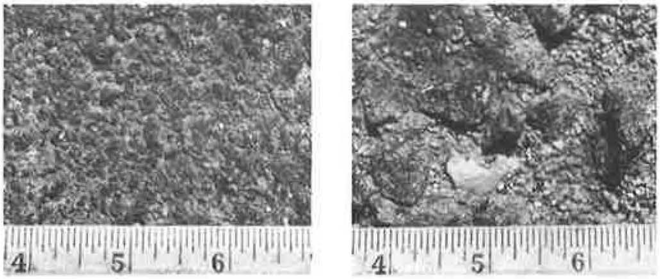
b - Woodland By-Pass, built 1960; medium traffic. Picture taken fall, 1961.



c - Woodland By-Pass, built 1960; light traffic. This section seldom used by traffic. Picture taken spring, 1962.

d - Woodland By-Pass, built 1960; light traffic. Picture taken spring, 1962.

Figure 9. Portland cement concrete pavements and coarse- and fine-textured asphalt seal coats.



a - Rodeo, rumble strip, dense-graded asphalt plant mix surface; medium traffic.

b - Rodeo, rumble strip, coarse aggregate rumble section, built 1960; medium traffic.

c - General view of rumble strip. Note the alternate dense-graded asphalt plant mix and coarse aggregate rumble sections.

Figure 10. Rumble strip.

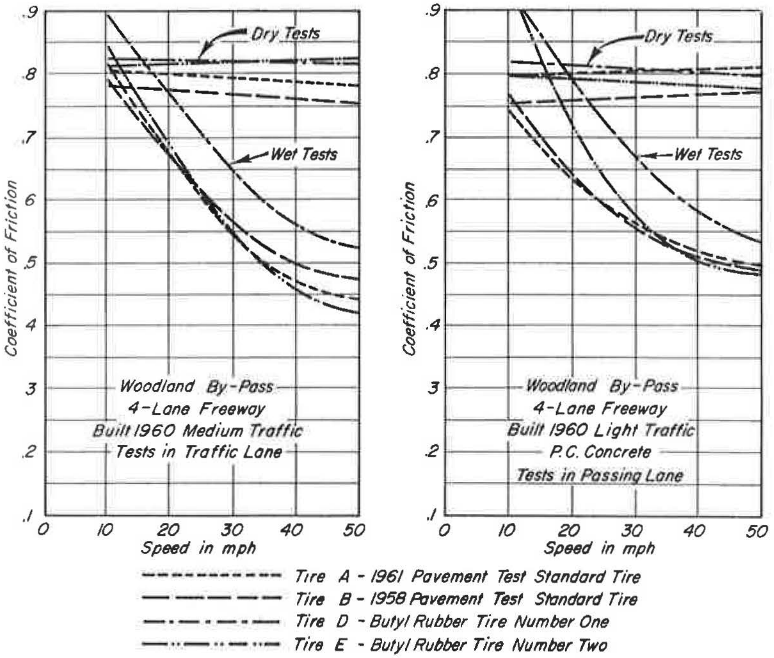


Figure 11. Test results on sections of dry and wet portland cement concrete pavements for two types of butyl rubber tires and two other types.

TABLE 1

COEFFICIENT OF FRICTION OF THREE P.C. CONCRETE AND THREE ASPHALTIC CONCRETE PAVEMENTS IN FALL 1961 AND SPRING 1962 USING FOUR TYPES OF TIRES[1]

Description of Pavement	Nominal Test Speed mph	Coefficients of Friction					
		Fall 1961 Tests		Spring 1962 Tests			
						Butyl Rubber	
		Tire A	Tire B	Tire A	Tire B	Tire D	Tire E
Davis By-Pass 2-Lane Highway Built 1954 P.C. Concrete Heavy Traffic	10	0.55	0.58	0.76	0.87	0.93	0.93
	20	0.45	0.51	0.63	0.72	0.71	0.71
	30	0.36	0.36	0.53	0.59	0.53	0.55
	40	0.30	0.37	0.47	0.50	0.44	0.44
	50	0.28	0.34	0.42	0.44	0.37	0.37
Ambient Air Temperature		80°F		58°F			
Woodland By-Pass 4-Lane Freeway Built 1960 P.C. Concrete Light Traffic Tests in Passing Lane	10	0.66	0.76	0.90	0.94	1.05	0.97
	20	0.59	0.69	0.72	0.80	0.85	0.78
	30	0.51	0.61	0.61	0.68	0.74	0.66
	40	0.44	0.53	0.55	0.60	0.66	0.58
	50	0.41	0.48	0.52	0.53	0.61	0.53
Ambient Air Temperature		94°F		58°F			
Berkeley Eastshore Freeway 8-Lane Freeway Built 1955 Heavy Traffic Tests in Shoulder Lane	10	0.57	0.63	0.57	0.58	0.60	0.65
	20	0.46	0.51	0.49	0.49	0.49	0.50
	30	0.36	0.40	0.41	0.42	0.40	0.40
	40	0.30	0.33	0.35	0.36	0.33	0.31
	50	0.26	0.28	0.31	0.32	0.29	0.26
Ambient Air Temperature		44°F		60°F			
Berkeley Eastshore Freeway 2-Lane Frontage Road Built 1955 Light Traffic Open Graded PMS	10	0.63	0.67	0.60	0.65	0.70	0.68
	20	0.56	0.60	0.56	0.55	0.67	0.63
	30	0.51	0.55	0.52	0.50	0.62	0.59
	40	0.48	0.51	0.48	0.47	0.58	0.56
	50	0.45	0.48	0.45	0.45	0.55	0.53
Ambient Air Temperature		44°F		60°F			
Fairfield-Rio Vista 2-Lane Highway Built 1959 Medium Traffic Coarse Textured Seal Coat	10	0.52	0.53	0.65	0.65	0.84	0.82
	20	0.46	0.46	0.58	0.57	0.71	0.70
	30	0.41	0.41	0.53	0.56	0.62	0.60
	40	0.37	0.37	0.49	0.46	0.55	0.53
	50	0.35	0.35	0.47	0.44	0.50	0.48
Ambient Air Temperature		74°F		64°F			
West Sacramento 2-Lane Highway Built 1953 Medium Traffic Dense Graded PMS	10	0.53	0.54	0.66	0.67	0.88	0.80
	20	0.40	0.45	0.52	0.51	0.74	0.59
	30	0.33	0.38	0.43	0.42	0.62	0.48
	40	0.28	0.31	0.38	0.37	0.53	0.40
	50	0.24	0.26	0.35	0.34	0.48	0.37
Ambient Air Temperature		80°F		60°F			

[1] Tire A, 1961 pavement test standard tire; Tire B, 1958 pavement test standard tire; Tire D, butyl rubber tire; and Tire E, butyl rubber tire.

The upper deck of the San Francisco-Oakland Bay Bridge (Fig. 9) has carried high volumes of passenger car traffic for the past 25 years while the lower deck has been used almost exclusively for heavy truck traffic. Figure 9 indicates that the heavy truck traffic has caused far more polishing wear on the aggregate and surface of the lower deck than the upper deck, which was used by the more than 80 million passenger cars per lane since 1937. As the data will show, this change in surface texture caused by traffic contributed to a significant change in skid resistance of the two surfaces.

Although there was still some evidence of bleeding in the Woodland-Madison dense-graded plant mix surface, the heavy rains and the scouring effect had a significant deslicking effect (Fig. 8).

In Figure 11, the Fairfield-Rio Vista seal coat provided a coarse, open-graded type surface with many coarse, rounded gravel particles exposed to the action of traffic (Fig. 9). The Sonoma-Santa Rosa surface is a fine-textured slurry seal coat built in 1953. The slurry seal is widely used in California to rejuvenate old asphalt pavements which are badly cracked. It consists of a mixture of asphalt emulsion, coarse, sharp sand and water, and is applied with a special spreader-box squeegee device to provide a surface coating or thickness of about 1/8 to 1/4 in. Since no tests had previously been run on the slurry seal type of asphalt surfacing, it was decided to include this section of pavement.

The rumble strip (Fig. 10) was used to create a distinctive type of tire noise as a warning to drivers of an unusual traffic hazard directly ahead—in this instance, a dangerous intersection requiring traffic to stop. To create the noise, large aggregate, 3/4 to 1 in. maximum, was used as cover in a seal coat type construction which provided a coarse, knobby type of asphaltic surface. The rumble sections were 25 ft long and were placed as alternate strips across dense-graded plant mix sections where there was practically no tire noise. The dense-graded asphalt plant mix sections were 100 ft long, but for the last 300 ft preceding the stop sign, the length was reduced to 50 ft.

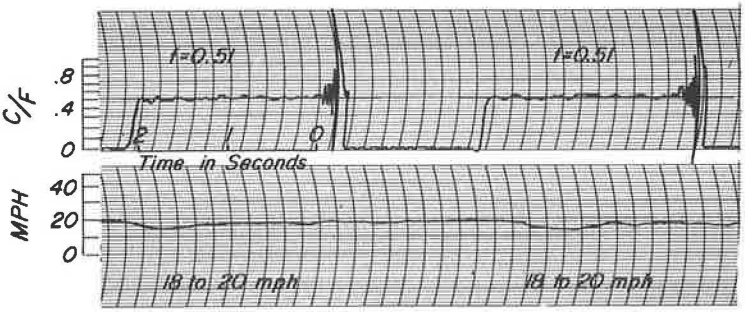
TEST RESULTS

The results of skid tests on three portland cement concrete pavements and three asphaltic pavements are given in Table 1 and shown in Figures 2 to 6. Results on other surfaces are shown in Figures 7 and 11.

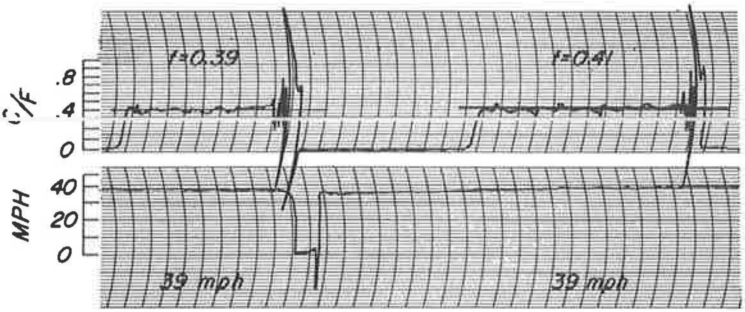
Resistance forces were measured with the California truck-trailer skid test equipment (Fig. 12). A typical oscillograph record obtained in the wet surface tests on the Davis Bypass is shown in Figure 13. An accurate indication of the speed in miles per hour and the coefficient of friction are shown on the oscillograph record for each test.

A significant feature of the oscillograph records is the large initial force which is developed within the first 0.2 sec after the brakes are applied. This instantaneous braking force applied at one wheel was found to be as large as 3,200 lb or about eight times greater than the uniform locked-wheel braking force of 400 lb. When it is realized

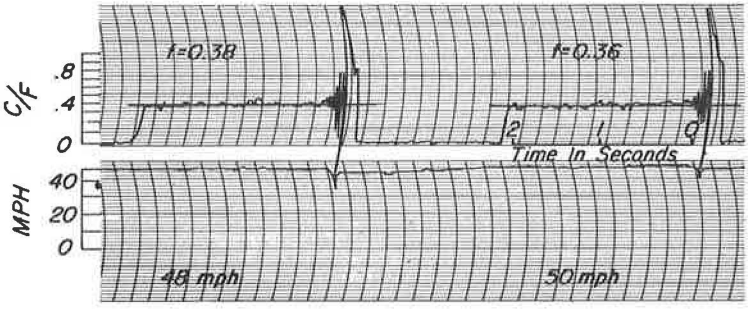
Figure 12. California truck-trailer skid test equipment.



(a) 1961 Pavement Test Standard Tire



(b) 1958 Pavement Test Standard Tire



(c) 1958 Pavement Test Standard Tire

Figure 13. Oscillograph records for wet surface tests, Davis Bypass.

that a braking force of 400 lb in the locked-wheel tests corresponds to a coefficient of friction of 0.43, it does not appear possible that a braking force of 3,200 lb can be developed. However, one of the pins holding the tension link in place in the torque meter failed, despite the fact that it had been designed with a factor of safety of about 6. Also, observations on the behavior of the trailer with the sudden application of the brakes have indicated that a very sharp impact force is developed when the brakes are applied. Although this large instantaneous braking force apparently does not greatly reduce stopping distances, it does account in part for the higher average coefficients of friction which are normally obtained in stopping distance tests as compared with the coefficients measured with dynamometers in constant-speed trailer braking tests. This observation also emphasizes the importance of using a large factor of safety in designing the various parts in motor vehicle braking systems to prevent failure in emergency or panic stops.

The coefficients for all of the data in Table 1 and Figures 2 to 7 are for wet pavements. The coefficients for the three portland cement concrete pavements and the three asphaltic pavements given are all quite high except for the Eastshore Freeway where the coefficients at 50 mph drop to about 0.30 for all tires as compared to coefficients of 0.40 to 0.50 at 50 mph for the other surfaces. The traffic volumes on the Eastshore Freeway are very high, with an average ADT in 1961 of about 90,000 vehicles, including about 12 percent trucks. The highest traffic flow, and especially the heavy truck traffic, is concentrated in the shoulder lane on which the tests were run. The result was that this heavy traffic caused a polishing wear effect and a coating of oil and grease to accumulate, two major factors responsible for the low friction values.

The ambient air temperatures were from 10 F to 36 F higher in the Fall 1961 tests than in the Spring 1962 tests on all surfaces except the two in Berkeley where the temperatures were 16 F higher in the Spring than in the Fall (Table 1). In previous studies, the coefficients of friction decrease approximately 0.02 for each 10 F rise in air temperature. The coefficients for all surfaces except Berkeley were from 0.10 to 0.30 higher in the Spring tests than in the Fall tests. This large increase in the friction values for the majority of the surfaces was due in part to the lower temperatures at which tests were run in Spring 1962, but primarily it was due to a change in the surface condition of the pavements caused by the heavy rains. For the Eastshore Freeway shoulder lane and frontage road, the increase in the friction values due to the heavy rains was partly offset by the decrease in running the tests at higher temperature. This accounts for the small change in friction values for the Spring and Fall tests for this surface.

The greatest increase in the coefficients brought about by the rains was observed in the tests on the Davis and Woodland portland cement concrete pavements with an average increase of 0.20 at speeds of 10 and 20 mph and of 0.10 at speeds of 40 and 50 mph. The friction values measured in the spring on these two pavements were the highest wet pavement friction values measured in all the studies in California over a period of 12 years. It is believed that the three reasons for the high friction values were (a) the pavements were built in 1960 with a gritty sandy surface texture and traffic had not as yet caused a polishing wear effect, (b) the heavy rains cleansed the surfaces thoroughly and removed the coatings of oil, grease and rubber which accumulate during the dry season from May to October, and (c) the scouring action of traffic during the rains in which sand on the pavements serves as an abrasive causing a coarse-grind traffic wear effect and improves the surface texture by creating conditions required to obtain high friction values. In dry weather, the fine dust particles on the pavement and the buffing action of the tires, cause a polishing traffic wear effect which results in low coefficients of friction in wet pavement tests on surfaces built with a fine-grained aggregate of uniform hardness.

In practically all tests at all speeds for the surfaces in Table 1, the butyl rubber tires developed the highest coefficients of friction. Coefficients for Tire D were from 0.1 to 0.2 higher than for Tire A which developed the lowest coefficients of these tests. On four surfaces, the coefficients for Tire D were about the same as for Tire E. On the other two surfaces, the coefficients for Tire D were from 0.05 to 0.10 higher than for Tire E.

The high hysteresis losses for the butyl tires, no doubt, were responsible for the higher friction values. Tires D and E developed greater plastic deformation than Tires A and B. Thus, the butyl rubber provided greater enveloping or interlocking effect of the rubber with the aggregate particles on the surface and this resulted in higher friction values. In other words, practically all the energy required to deform the tire was converted into braking energy and higher coefficients of friction.

The tread pattern for Tire D was an important factor contributing to the higher friction values measured with Tire D than Tire E. The results on surfaces built with fine-grained aggregate and on slippery dense-graded type surfaces have repeatedly shown that tires with a good tread pattern most effective in squeezing and squeegeeing the water off the surface will provide the highest friction values.

The coefficients of friction on the upper deck of the Bay Bridge used by passenger cars only were about 0.05 higher than on the lower deck which carries heavy truck traffic, and that the coefficients on the lower deck were almost the same as on the shoulder lane of the Eastshore Freeway (Fig. 2). This indicates that heavy truck traffic causes a greater amount of polishing on concrete pavements than high-volume passenger car traffic and that the coefficients of friction on concrete pavements carrying heavy truck traffic appear to reach about the same limiting friction values. Although the data in Figure 2 showed that Tire D developed the highest coefficients on the four traffic-worn, dense, fine-grained concrete pavements, the results were not consistent. For this type of surface, butyl showed no marked advantage in skid resistance. In fact, Tire E showed the lowest friction values of the four tires tested at 40 and 50 mph, except on the old Auburn Boulevard concrete pavement. The tread pattern design for Tire E appeared to be the major reason for the low friction values.

The test results in Figure 3 indicated that Tire D showed a marked superiority in skid resistance for all four surfaces. Tire E showed no advantage over Tires A and B. The friction values for all of the tires were high, and indicated the upper limit in friction values which may be obtained on wet portland cement concrete pavements under the most favorable conditions. The effect of speed is quite marked on all concrete pavements, with coefficients at 50 mph reduced to approximately one-half the values measured at 10 mph. Thus, on new concrete pavements with friction values averaging 0.90 at 10 mph, the coefficients were reduced to 0.45 at 50 mph, and on old concrete pavements with coefficients averaging 0.60 at 10 mph, they were reduced to 0.30 at 50 mph.

On the open-graded and dense-graded asphalt plant mix surfaces (Figs. 4 and 5), the butyl tires showed a marked superiority in friction values, except for the two surfaces where tests were conducted in the traffic lane of a four-lane freeway or on the dense-graded plant mix section where there were patches of excess asphalt. The reduction in friction values with an increase in speed is only about one-half as large with the open-graded asphalt plant mix surfaces as with the dense-graded plant mix surfaces and the portland cement concrete pavements. Also, a greater reduction in friction values with an increase in speed was obtained with butyl tires than with Tires A and B. This suggests that while the plastic deformation and the energy losses are higher for butyl, these energy losses decrease at the higher speeds of 40 and 50 mph primarily because the plastic deformation developed by the butyl rubber tires is not as effective in providing high skid resistance at high speeds as at low speeds.

The friction values for the coarse and fine seal coat surfaces (Fig. 6) follow the same general pattern as for the open-graded and dense-graded asphalt plant mix surfaces. It is significant that the fine-textured slurry seal coat on the Sonoma-Santa Rosa highway, built in 1953, provided fairly high friction values. This asphalt emulsion treatment has performed quite well under traffic. There was no indication of excess asphalt and the surface appeared to have retained its coarse-grained, sandy, non-skid texture for more than 8 years.

The results of the tests on the Rodeo rumble strip (Fig. 7) indicated that the coarse aggregate provided friction values similar to open-graded asphalt plant mix surfaces. The friction values at 10 mph were lower, and at 50 mph higher on the rumble sections. Tire D developed the highest friction values, while butyl Tire E developed about the same friction values as Tires A and B.

A significant feature of the dry pavement test results on the Woodland Bypass concrete pavements (Fig. 11) was that higher skid resistance values were measured at 10 mph in the wet tests than in the dry tests for the butyl tires, but for Tires A and B, the friction values at 10 mph were about the same in both tests. As in previous dry tests, very little change in the friction values was observed at speeds up to 50 mph, but on wet pavement, there was the usual large reduction in the coefficients of friction as the speed was increased.

The tire wear in the dry pavement, locked-wheel braking tests with butyl tires was so severe that the tread pattern was completely worn off in six to eight tests in the portion that was sliding on the pavement, even though the brakes were applied for only one second for each test. In the locked-wheel braking tests on the very abrasive dry portland cement concrete pavement with a coarse, sandy surface texture, the butyl rubber was worn off very fast in the form of a large visible spray of powdered rubber particles trailing the tire. Butyl tires did not develop the heavy black skid marks on the pavement which are normally obtained in dry pavement locked-wheel braking tests with tires such as Tires A and B. Also there was no loud tire squeal noise in the locked-wheel braking tests with butyl. It is evident that in these respects the butyl rubber has radically different properties from the usual synthetic rubber tires.

CONCLUSIONS

The following general conclusions were reached after a careful study:

1. The highest coefficients of friction on wet pavements were measured in tests using the butyl rubber Tire D with a well-designed fine-rib tread pattern.
2. The coefficients of friction measured with butyl rubber Tire E varied considerably from the highest to the lowest when compared with the coefficients measured with Tires A, B and D. The tread design for Tire E was not as effective in developing high skid resistance on all surfaces as the tread design for Tire D.
3. The high hysteresis losses developed by Tires D and E were more pronounced on wet pavements at 10 mph than at 50 mph, as indicated by the high friction values at 10 mph and the greatly reduced friction values at 50 mph.
4. A very high rate of tire wear was observed in the locked-wheel braking tests with Tires D and E on a highly abrasive type of concrete pavement. This extreme rate of wear was not observed in similar tests with Tires A and B.
5. No tire squeal or other noises were observed with Tires D and E.
6. The results were not conclusive in regard to overall advantages which can be provided by butyl or similar types of rubber polymers. Marked improvement in skid resistance and reduction of tire noise can be obtained with butyl rubber, but considerable improvement should be made in reducing tire wear to obtain high tire mileage and highest overall standards of tire performance.
7. The effect of heavy rains in raising the coefficients of wet pavements by 0.10 to 0.20 suggests the need for a new type of cleansing and scouring treatment of slippery pavements.

The following is a list of the European road research laboratories which were visited in 1962. Included are names of the directors and/or engineers and a brief listing of the major research activity in skid prevention at each laboratory:

1. British Road Research Laboratory in three locations: (a) headquarters office and materials research laboratory at Harmondsworth; (b) highway safety, skid prevention and traffic research at Langley; (c) research track, vehicle guidance and skid prevention research at Crowthorne. Sir William Glanville, Director, and Mr. C. G. Giles, in charge of skid prevention research.
2. University of Cambridge, Research Laboratory for the Physics and Chemistry of Solids, Cavendish Laboratory, basic research in friction of solids and liquids (including friction of rubber tires on wet surfaces). Dr. David Tabor.
3. Dunlop Research Center, Dunlop Tyre and Rubber Company, Fort Dunlop, Birmingham, England. Tire research, friction of rubber, skid prevention, cornering, riding quality and related characteristics of tires. Mr. V. E. Gough.
4. Permanent International Association of Road Congresses, Committee on Slipperiness, Mr. G. Mathieu, Chairman; Office of Director General of Technical Services for the City of Paris, France—Research on skid resistance. Mr. H. Crouzat, Chief Engineer, Bureau of the Voirie (Thoroughfares) of Paris, Secretary, PIARC Committee on Slipperiness.
5. Laboratorio del Transporte y Mecanica del Suelo (Laboratory of Transportation and Soil Mechanics), University of Madrid, Madrid, Spain. Research in road materials and skid resistance of pavements. Professor J. L. Escario, Director of Laboratory.
6. Instituto Sperimentale Stradale (Road Research Institute). Road materials research, testing laboratory and research in skid resistance. Italian Touring Club, Dr. R. Ariano, Director, Milan, Italy.
7. Institut fur Strassen und Verkehrswesen, Bauhof fur den Winterdienst (Highway and Traffic Engineering Institute, Laboratory for Winter Highway Services). Research on skid resistance. Laboratory studies in the design of snow and ice removal equipment, especially in the design of rotary snow plows. Inzell, Bavaria, Germany. Dr. Ing. R. Croce, Director.

8. Ministere des Travaux Publics (Ministry of Public Works). Skid resistance research. Mr. A. Doyen, Chief Engineer of Roads and Bridges, Brussels, Belgium.

9. Rijkswaterstaat Rijkswegenbouwlaboratorium (State Road Laboratory), The Hague, Netherlands. Road Materials research and skid resistance of pavements. Dr. A. Van der Burgh, Director.

10. Statens Vaginstitute (National Road Research Institute), Stockholm, Sweden. Skid resistance research; snow, ice and winter driving research. Mr. G. Kullberg.

Although the research on skid prevention and on the measurement of skid resistance of pavements conducted by each laboratory is carried out on a free and independent basis, the research is coordinated on a voluntary basis by the Permanent International Association of Road Congresses Committee on Road Slipperiness of which Mr. G. Matheiu has been chairman since 1955. Practically all of the countries have designed and built their own testing equipment to measure the skid resistance of pavements, although in France, Belgium, Denmark and Norway, the French Stradographe, manufactured by the firm of Albert Collet on behalf of the Syndicate for the Manufacture of Asphalt Road Emulsions, has been used for many years. The Committee on Slipperiness includes in its membership representatives from each country that is actively engaged in a program of measuring the skid resistance of pavements. Meetings of the Committee are held each year and papers are presented and discussed. An important activity has been to promote comparative measurements of skid resistance of roads in various parts of Europe with the different types of apparatus used by the various countries. These tests are made for the purpose of correlating the results and standardizing the various methods of measuring road slipperiness. A brief summary of the results of a recent program of comparative measurements using the French Stradographe (owned and operated by the Danish Road Research Laboratory) and the Swedish and German skid test vehicles will be given.

Many of the countries, especially in northern Europe, are much more active in research on skid prevention than the Unites States because skidding is a far more serious accident hazard in Europe. Giles reported that in England about one-sixth of all traffic accidents are a result of skidding, and that one-half of the accidents on wet pavements are skidding accidents. On snow and ice about 90 percent of the accidents have been reported as skidding accidents. The British Road Research Laboratory has recognized the importance of conducting research and has been engaged in this type for more than 30 years. It is apparent that the British Road Research Laboratory has developed the most comprehensive program and is the world's leading authority is skid prevention research.

The National Road Research Institute in Stockholm has a large full-time staff engaged in research dealing with the measurement of skid resistance not only on all types of road surfaces but also on snow and ice. Skidding accidents and inadequate traction on snow and ice have given rise to many problems requiring special study, not only in their effect on the safe operation of vehicles, but also in the operation of jet planes on airport runways. The Swedish Institute has built two outstanding skid test units which will be described, and extensive studies on snow and ice make it the world's leading authority on research in skid resistance and traction on snow and ice.

France has been very active in skid research since 1936 when the first Stradographe was built. The Stradographe has been widely used in making comparative measurements with other skid test units on roads in other parts of Europe.

An extensive program on major highways in northern and western Germany and Berlin has been carried out with two truck-trailer testing units since 1957. One of the test vehicles is stationed in Berlin and the other is stationed at the Research Laboratory in Inzell. Each year comparative measurements are made with the two units on the same pavements in the vicinity of Inzell. A brief description of the German testing apparatus and the results of tests with this unit will be given.

Skid Prevention Research in England

The largest road research laboratory in the world operated by a single agency is the British Road Research Laboratory with headquarters in Harmondsworth. More than 350 engineers, scientists, mathematicians and economists are currently employed in the three locations where research is now being conducted—at Harmondsworth, Langley, and Crowthorne. Research is also conducted by staff members stationed in British Colonies and nations of the Commonwealth in Africa, Australia, and the Far East.

Mr. C. G. Giles is in charge of all laboratory and field research on skid resistance, slippery pavements, effects of tire types and tire hysteresis properties, vehicle effects, braking, steering control, and the analysis of accidents and accident records in which skidding is reported as a major factor.

In the past 30 years, the Road Research Laboratory has developed many different testing devices and vehicles to measure the coefficients of friction of pavements and aggregates used in pavement construction. Most of the measurements have been made in the field, but some measurements and studies have been made in the laboratory. At the present time four different devices are being used to measure the coefficients of friction of pavements and aggregates:

1. A pendulum-type portable skid tester (Fig. 14).
2. A passenger car sideway-force friction tester (Fig. 15).
3. A passenger car high-speed braking force friction tester (Fig. 16).
4. A large heavy truck skid test unit referred to as the Juggernaut which is still in the development stage but is intended to be used for testing the braking forces which can be developed over a wide range of tire sizes and wheel loads.

The pendulum-type portable skid tester is a light-weight portable manually-operated instrument that can be used both for field and laboratory tests. The results have been correlated with those of passenger car friction testers in extensive field tests and agree quite well with the results of tests made at 30 mph with passenger cars equipped with

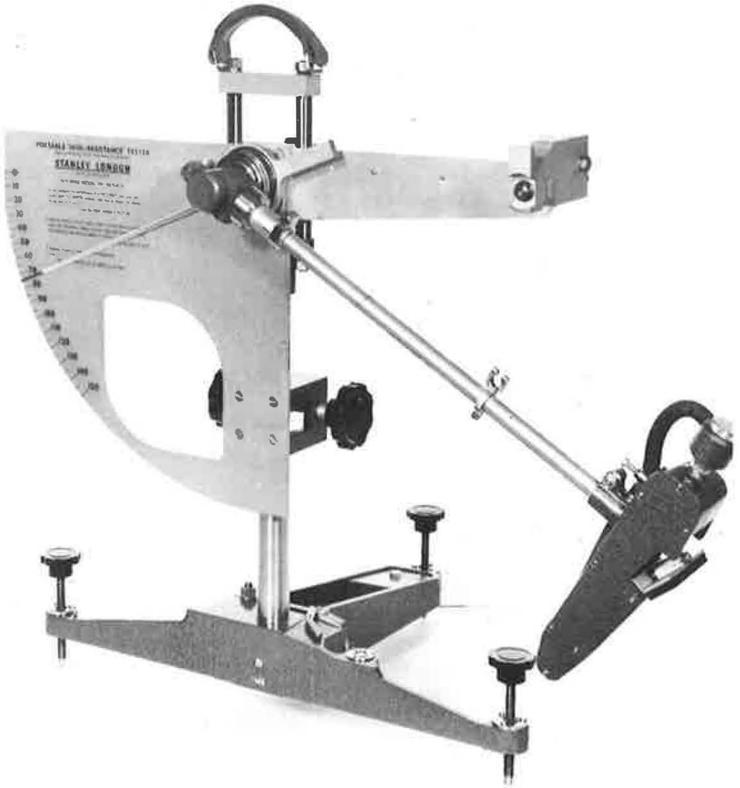


Figure 14. British portable pendulum-type skid resistance tester.

Figure 15. British sideway-force skid resistance test car.

Figure 16. British car and trailer for braking-force skid resistance measurements at speeds up to 100 mph.

patterned tires. For best results it is important that the physical properties of the rubber, such as its hardness and resilience, be the same for the slider used in the portable tester and for the tires on the test car.

Based on the results of an extensive program of tests over a period of about five years, the portable tester provided a simple and reasonably accurate method for measuring the relative slipperiness of wet pavements. The readings have been correlated with risk of skidding accidents that are likely to occur on a given section of highway and thus give some indication as to when and where de-slicking treatments are necessary. More than 150 British portable skid testers are now in use in England, Europe, the United States and in many other countries. Each tester was carefully checked and calibrated by the Road Research Laboratory before it was delivered. In the calibrations of the testers checked so far, they agree with an accuracy of ± 3 percent.

The passenger car sideway-force friction tester (Fig. 15) involves the use of a test wheel mounted within the wheel base of the cars in such a way that various loads can be carried by the test wheel and it can be turned to the desired test angle for making measurements of the sideway friction forces. The test car is normally operated at a speed of 30 mph, the standard speed for this test. When tests are not being run, the test wheel is allowed to castor about vertical kingpins and thus rolls freely with no sideskid forces. During the tests, the wheel can be quickly set to the desired test angle, usually at about 20 degrees, with a hydraulic ram. A parallel-link suspension system is used to obtain a true measure of the sideway force. To record the load and sideway force, a direct measuring system is used in which the outputs from pressure capsules operate pens attached to Bourdon tubes. The paper on which the record is made is driven by a direct drive from one of the free-running wheels of the car.

The sideway-force type of apparatus has been used by the Road Research Laboratory for more than 30 years. The results with this equipment have provided the desired accuracy and consistency which, under uniform road conditions, have yielded coefficients of friction with a standard error of 0.01.

The most important advantage claimed for the use of the sideway-force test car method is that it permits running friction tests with a continuously rotating wheel over long sections of highway under wet pavement conditions without damaging the tread of the tire or introducing variable test results obtained in the continuous locked-wheel type of braking. In the locked-wheel braking test method of measuring coefficients of friction of pavements with a car and trailer (Fig. 16) used by the Road Research Laboratory, and also widely used in Europe and the United States, continuous testing along the whole length of a given road cannot be used because the locked wheel causes excessive local heating and tire damage within the area of contact. For high-speed locked-wheel braking tests, the brakes are applied only for 1 to 2 seconds and thus many tests must be run using appropriate random sampling procedures to obtain accurate test results.

Tests have shown that locked-wheel braking is the most hazardous type, but is most frequently used by motorists in making emergency stops. Lower friction values are obtained in locked-wheel braking tests on wet pavements than in the sideway-force type of measurement. The car-trailer braking test method is better adapted for running high-speed tests up to 100 mph than the sideway-force test car method. It is for these reasons that the British Road Research Laboratory uses both methods in its extensive studies of skid resistance and the braking performance of test vehicles on wet pavements.

The Juggernaut is still in the development stage, but with this test vehicle it should be possible to obtain road friction test values over a wide range of conditions including wheel loads from 500 to 10,000 lb, tire sizes from the small passenger car to the largest truck and bus, and tire pressures from 10 to 300 psi. Many different combinations of braking forces and sideway-friction forces which have not been measured heretofore under actual road conditions, will be covered in this and other investigations.

There is practically no information available concerning the friction forces which can be developed on wet pavements when heavy trucks and buses are required to make emergency stops or when they tend to skid sideways at road speeds of 30 mph or more. The Safety Section of the U. S. Interstate Commerce Commission has reported a high incidence of skidding accidents for intercity buses operated at moderately high speeds on wet pavements. The tests with the Juggernaut should supply the information now lacking on skidding hazards of buses and trucks operated on wet pavements. It should be helpful in establishing the corrective measures.

The Road Research Laboratory, the Dunlop Research Center, and Dr. Tabor at Cambridge University have been engaged in extensive studies to determine the advantages provided by high hysteresis loss rubber tires. These tires are referred to as "dead" rubber tires because the resilience of the rubber used in the tread is only about one-half as large as that heretofore used in the tread of GRS synthetic and natural rubber tires. At the Dunlop Research Center, Mr. Gough, who for many years has been concerned with tire research and development, reported that British motorists are demanding the new dead rubber tires due to their evident advantages in providing improved performance on wet pavements, corners, sharp curves, and especially because they contribute to softer, more comfortable and quieter riding.

The Dunlop Research Center is conducting a long-range program to develop the tires not only for cars, trucks, and buses, but also for jet airplanes where tire pressures of 200 to 300 psi are under investigation along with tire behavior under emergency landing speeds of 400 mph or higher. The cell block, in which tire tests are conducted on large rotating drums involving tire speeds of 500 mph, is constructed with reinforced concrete walls which appear to be about 4 ft thick. Elaborate instrumentation has been developed for these tests in which all controls and recordings are of the remote control electronic type in a separate room. Continuous records are maintained of speed, tire pressures, tire temperatures and many different types of force measurements. TV monitoring is used to observe such phenomena as the standing-wave pattern developed in the tread at high speeds or of any other condition of the tire which may be an indication of impending failure.

A general plan of the Proving Ground (Fig. 17) contains a brief description of the types of pavements used and certain test operations. An interesting demonstration on the skid pad showed the marked improvement in the skid resistance and cornering ability on wet pavements for tires produced during the past 12 years. A typical rear-end breakaway in a cornering test to establish the maximum speed on a 100-ft radius curve is shown in Figure 18. In a series of tests with three different sets of tires, the breakaway speed on the 100-ft radius curve for tires produced from 1950 to 1955 averaged about 24 mph; for tires produced from 1956 to 1960, 27 mph; and for the newest type of dead rubber tires, about 32 mph. The computed sideway-force friction coefficients for each of these tests were 0.38, 0.49 and 0.68, which indicates that an increase of about 80 percent in the sideway-frictional resistance of tires has been developed during the past 12 years by improvements in the tread rubber and design.

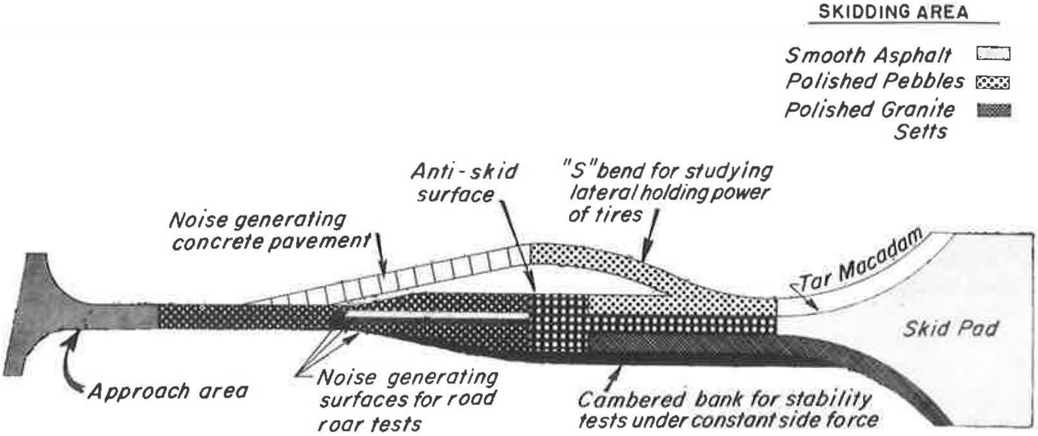


Figure 17. Dunlop Proving Ground.

Figure 18. Dunlop cornering test to establish maximum breakaway speed on a marked 100-ft radius curve.

Figure 19 shows three types of surfaces as an illustration of the types of pavements used at the Dunlop Proving Ground for running skid resistance, tire roar, and steering control tests. The granite setts were previously in use for 25 years on English roads and were carefully re-laid to provide an accurate replica of the service conditions which caused them to polish under traffic, resulting in a slippery when wet pavement with very low coefficients of friction. There is extensive use of granite setts on city streets and on mountain roads in Europe. Presumably, the granite setts were used on steep grades in Switzerland and Germany to provide high skid resistance. However, it is now well established by test that granite setts are probably the least effective type of paving material for skid resistance when wet.

Skid Resistance Research in France, Germany, and Sweden

Demonstrations were carefully planned for all phases of operation of the equipment on pavement sections under investigation in each of the countries visited. Large, heavy truck-type test vehicles were used in all of the demonstrations. In Paris, a pendulum-type portable skid tester was also used. In Stockholm, a new three-wheel trailer Skiddometer runway and pavement tester was included. Oscillograph recording equipment was installed in the oversize cab or in a special compartment of the truck used as the towing or test vehicle.

The French Stradographe friction test vehicle (Fig. 20) is the most widely used skid test vehicle in Europe. From 1936 to 1960 it was manufactured in France by Albert Collet and was installed on a 4-ton Citroen truck. The apparatus measures the

Figure 19. Test sections, Dunlop Proving Ground—tar macadam, granite setts, and portland cement concrete.

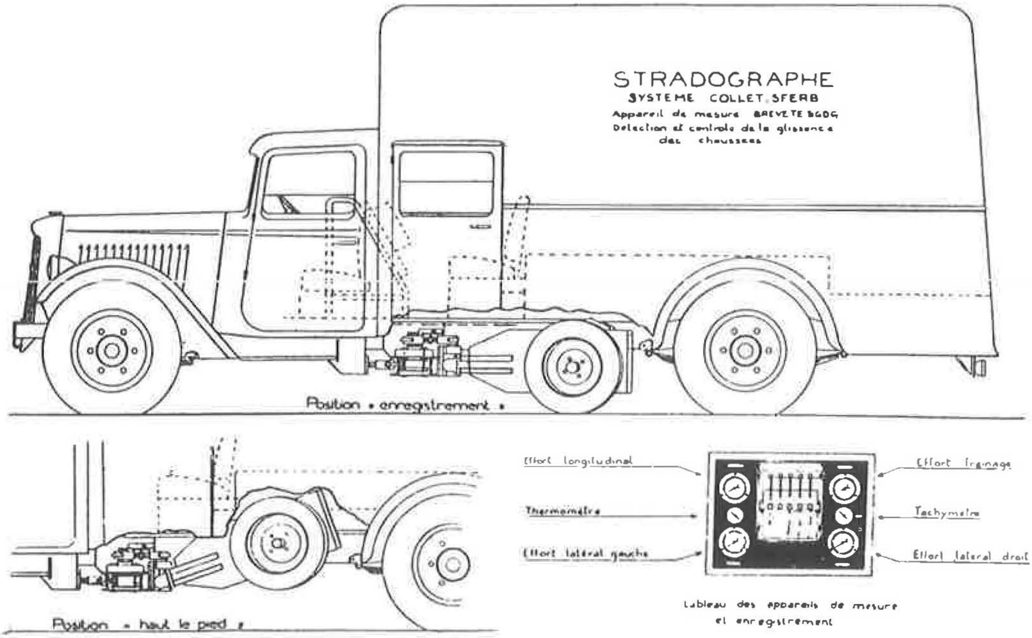


Figure 20. French Stradographe sideway-force skid resistance test vehicle.

sideway-friction coefficient for the test wheel mounted underneath the truck between the front and rear wheels. During the test, the wheel is inclined at an angle of 15° in the direction of travel. The sideway-friction forces are measured with a hydraulic dynamometer and are recorded on chart paper. The forces can also be read directly on gages mounted on an instrument board. From the measured friction forces, the mean sideway-force coefficient of friction can be computed. The test wheel is equipped with a smooth tread tire and the tests are generally run at a fixed speed of 40 mph.

The City of Paris Highway Authorities (Directeur Technique de la Voirie Parisienne) have constructed two truck-trailer skid test units, one measuring sideway-friction forces and the other measuring braking forces at a constant rate of slip. The test wheels in both units are equipped with smooth tread tires and the coefficients of friction in comparative tests correlate very well.

The City of Paris sideway-force skid tester provides the same type of measurements as the British passenger car sideway-force skid tester. Although the load on each of the test wheels of the Paris skid tester is about double the load on the British test wheel, the results obtained in a series of comparative tests with the two vehicles equipped with smooth tires established an excellent correlation in the coefficients of friction.

The German skid test vehicle (Fig. 21) is one of two identical testers towed by similarly equipped trucks, which have been used to measure the skid resistance of pavements in all parts of West Germany and West Berlin since 1957. The unit consists of a single-wheel trailer designed to measure locked-wheel (100% slip) braking forces. The wheel is equipped with a hydraulic brake system which is connected with an automatically controlled electrical air-pressure system to provide a fixed sequence of locked-wheel braking for 1 to 2 seconds, and free rolling for about 2 seconds. In this way a continuous record of the friction forces over a given section of highway can be obtained without causing tire damage or erratic readings from continuous locked-wheel braking. The test unit has a parallel-link suspension system to prevent load transfer

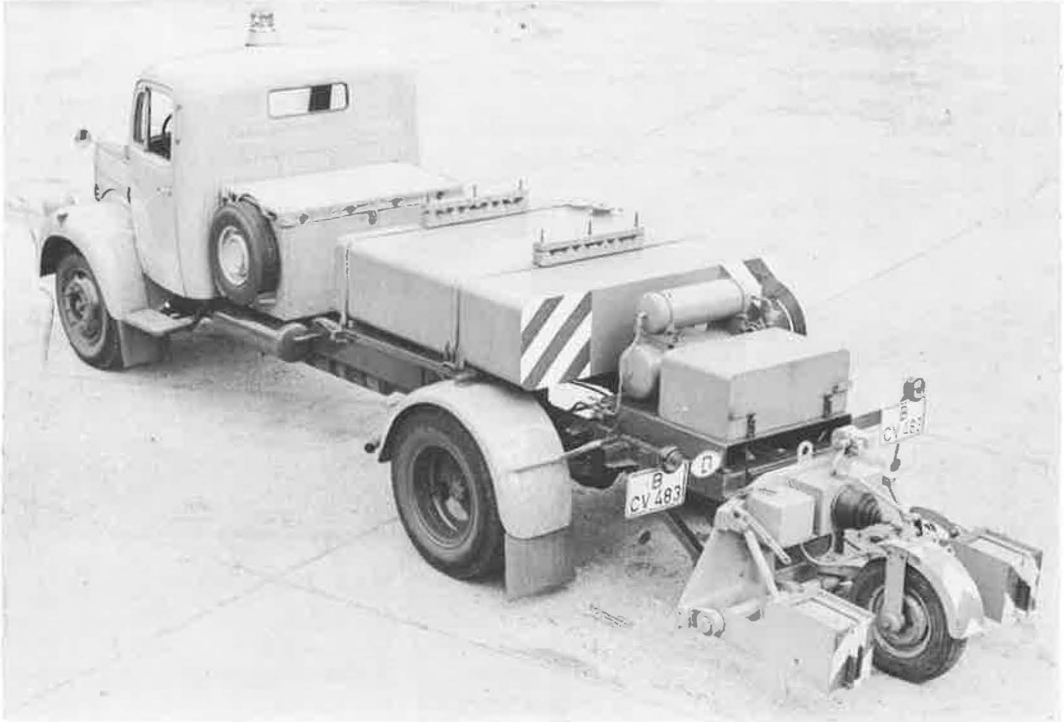


Figure 21. German braking-force skid resistance test vehicle.

during braking. The braking forces are measured in terms of the torque reaction by means of a spring dynamometer and are recorded on a moving wax paper strip using a stylus attached to a Bourdon tube. A record of test wheel revolutions is also shown on the strip. The wheel can be raised by a hydraulic jack when it is not being used.

The Swedish Road Research Institute has built five different friction test vehicles since 1949, all of which were designed to measure the braking-force coefficients of friction at a controlled slip ratio. The vehicle (2) is the latest model built by the Institute and is the most completely instrumented (Fig. 22). In many respects it is the finest and best-equipped skid test vehicle operating in Europe or America. A single test wheel mounted under the truck within the wheelbase is connected to the driving wheels by a series of gears and a variable V-belt transmission. In this way it is possible to vary the slip ratio to any value and measure the coefficients of friction. Usually the tests are made with a slip ratio of 17 to 20 percent because the maximum coefficient of friction is developed on many pavements with this ratio.

A feature of this test vehicle is that during a braking test with fully controlled slip, the brake reaction torque is transmitted from the test wheel to the driving wheels of the truck and thus used to help propel the truck. This unique design makes it possible to reduce greatly the power requirements of the truck during the controlled slip braking tests. Measuring the coefficients of friction at incipient skid at a controlled slip ratio also permits continuous operation over long sections of highway.

In the demonstration of this vehicle, several interesting recordings were obtained which indicate the remarkable accuracy and versatility of the equipment. Figure 23 shows recordings in locked wheel braking (100% slip) on wet asphaltic concrete pavements. The distance markings as measured with a fifth wheel, the braking force, the zero force line and the wheel revolution markings are shown. Figure 24 shows recordings for braking with 17 percent slip on a dashed traffic paint line on wet asphaltic concrete. This record clearly shows the fast response of the electronic equipment and indicates accurately the change in the coefficients of friction for the paint line and for the asphaltic concrete.

Comparative Measurements on German Roads with the French Stradographe, and the German and Swedish Vehicles

In 1960, the most comprehensive program of comparative skid resistance measurements made thus far in Europe, was conducted on German roads with low, medium and high coefficients of friction. The measurements were made with the French Stradographe (owned and operated by the Danish Road Research Laboratory) and the German and Swedish skid test vehicles and thus provided extensive data for a comparison of the sideway-force coefficients, the incipient-skid coefficients at 17 percent slip, and the

Figure 22. Swedish braking-force skid resistance test vehicle.

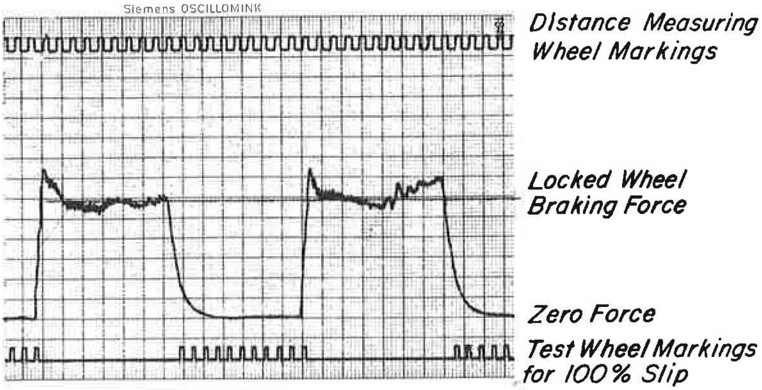


Figure 23. Recording from locked-wheel skid resistance measurements on wet asphaltic concrete pavement, Swedish vehicle.

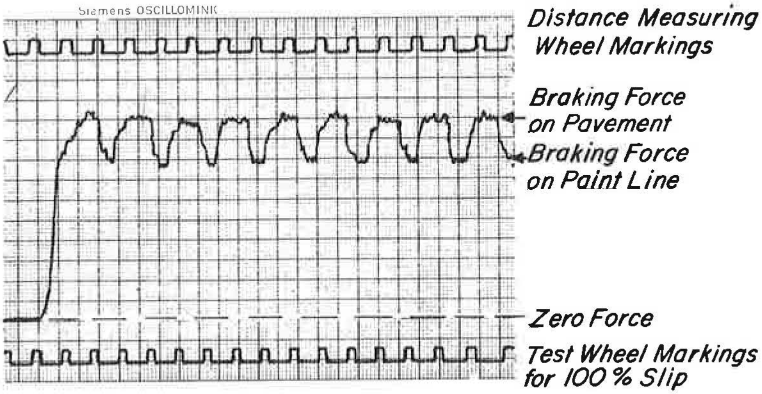


Figure 24. Recording from 17 percent slip braking-force skid resistance measurements on a dashed traffic paint line, Swedish vehicle.

locked-wheel or 100 percent slip coefficients. The results are highly significant because they directed attention for the first time to the important variations in the coefficients of friction measured for the three basic types of tire friction with three well-designed vehicles operated on the same pavements.

The following summary is based on a report presented at the 1961 Slipperiness Committee of the Permanent International Association of Road Congresses Meeting in Paris by Professor Dr. Ing. Habil B. Wehner of the Technical University of Berlin.

Two types of test tires were used, one with an excellent non-skid tread pattern and the other with the tread worn smooth by abrasion. The tires were specially produced with the same rubber composition, and 11 different sections of asphaltic and portland cement concrete pavements were selected. The test wheel for each vehicle operated in the same track at speeds of 20, 40, 60 and 80 km/hr or 12, 25, 37 and 50 mph. Unfortunately, the Stradographe vehicle had a breakdown and was not able to make measurements at speeds higher than 60 km/hr on most of the surfaces.

Figure 25 shows the results for the German and Swedish vehicles in the locked-wheel (100% slip) tests. Inasmuch as the loads, tires and type of test were identical, the results should have been identical. In general, the correlation was reasonably satisfactory, particularly in establishing a ranking or rating of the relative slipperiness of the 11 pavements. However, a greater decrease in the coefficients of friction with an increase in speed was obtained with the German vehicle than with the Swedish. These differences were more clearly evident in results for the pattern tire than for the smooth

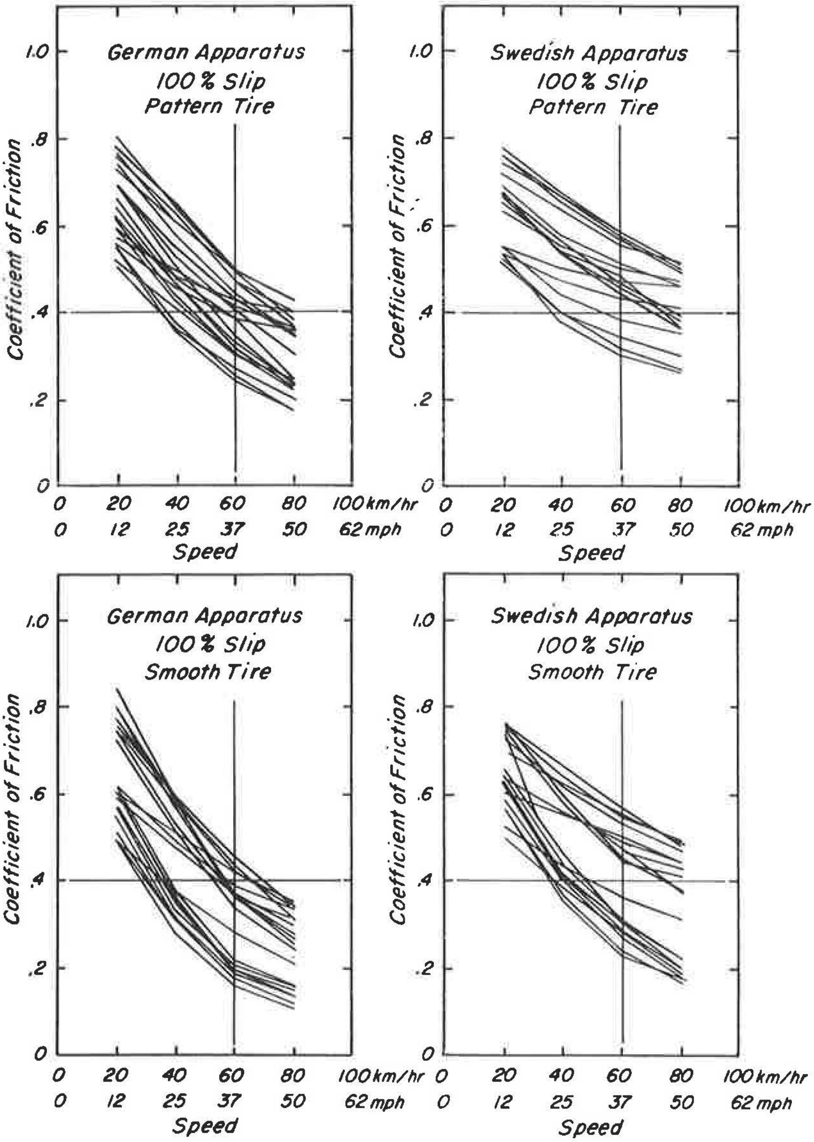


Figure 25. Comparative measurements of skid resistance on wet road surfaces in West Germany.

tire. No satisfactory explanation was given for these differences, although Dr. Wehner reported that since the Swedish watering system was operated by spraying under pressure and the German system operated under a gravity system with the water flowing freely in front of the test wheel, this may have caused the differences. Measurements made during a rain without using the watering systems were in closer agreement.

Figure 26 shows the results for the Swedish test vehicle for the incipient-skid coefficient of friction (17 to 20% slip) and for the Stradographe for the sideway-force coefficient. The coefficients of friction are considerably higher than those in the locked-wheel tests particularly for the pattern tire. Thus, for the Swedish test vehicle, the lowest coefficient for the pattern tire in the locked-wheel tests at 50 mph was 0.25, whereas with the same test vehicle and tire, the lowest incipient-skid coefficient was 0.50. On surfaces with high coefficients, there was only a small decrease in the incipient-skid coefficient with an increase in speed, for example from 0.80 to 0.78.

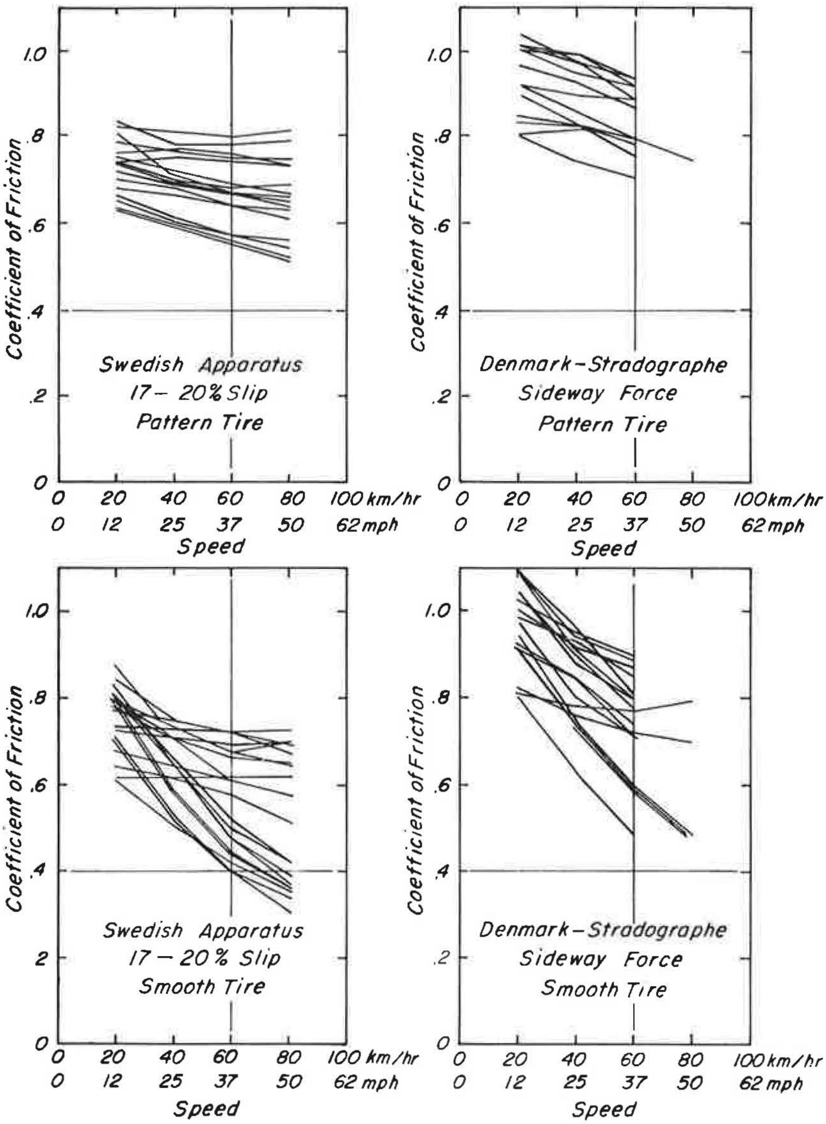


Figure 26. Comparative measurements of skid resistance on wet road surfaces in West Germany.

The widest spread in the coefficients of friction on the various surfaces measured with the Swedish vehicle was obtained in the incipient-skid measurements at 50 mph with the smooth tread tire. In fact, Figures 25 and 26 indicate that the best correlation in rating slipperiness can be obtained on the basis of tests with smooth tread tires at speeds in the range of about 35 to 50 mph. It is unfortunate that the data for the Stradographe are incomplete, but Figure 26 indicates that smooth tread tires provide a far better indication of the relative slipperiness of pavements than tests with a pattern tread.

An interesting new development in the Swedish Road Research Institute studies is the new runway and pavement skid test trailer shown in Figure 27. This Skiddometer is used to provide a rapid and direct recording of the coefficients of incipient skid on wet, dry, icy, or snow-covered pavements and airport runways. It is a three-wheel trailer with two large wheels supporting a load of about 2,100 lb and a smaller test wheel in

Figure 27. Swedish 3-wheel trailer and runway and road skid resistance test vehicle (Skiddometer).

the center with a controlled uniform load of 1,085 lb. The test wheel is designed to provide a slip of about 15 percent as the trailer is towed forward at 10 to 50 mph.

The Skiddometer can be towed by a light truck or a passenger car with moderate horsepower because it is built with the same design as the Swedist Test Vehicle No. 5 in which about 80 percent of the braking power developed by the test wheel is fed back to the larger supporting wheels as a propelling force. The incipient-skid forces developed by the test wheel are measured in terms of the torque in the shaft between the wheels and are transmitted electronically to a moving strip of paper fed into the recorder and controlled by the rotation of the left wheel of the trailer. The recorder is housed in a watertight metal case mounted on the trailer. All operations of the trailer and recorder are remotely controlled by the driver or observer in the tow vehicle.

The Skiddometer is a well-designed, ruggedly built vehicle reduced to the simplest form that now can be developed and still retain many of the excellent design features of the larger Swedish Test Vehicle No. 5. It is now available commercially.

Skid Resistance Research in Spain and Italy

Skid test trailers have been built and resistance measurements taken in Spain and Italy. The climatic conditions in these countries are such that the skidding hazards are not as great as in northern Europe. Consequently, only a limited amount of study has been devoted to slippery pavements and skid prevention.

The skid test equipment developed by Professor Escario at the laboratory of Transportation and Soil Mechanics in Madrid, and by Dr. Ariano at the Road Research Institute at Milan, differed in many respects when compared with the designs developed by the British, French, German, and Swedish research laboratories. The Spanish test unit consists of a test wheel attached to a chassis assembly supported on a steel frame. The wheel is rotated in its free position at the desired speed by means of an auxiliary motor. When the desired speed is reached, the spinning wheel and chasis assembly is dropped onto the pavement surface, thereby introducing a braking force depending on the coefficient of friction or skidding resistance of the pavement surface. The rate of deceleration is obtained by means of accurate time measurements recorded on paper.

From the observed rate of deceleration and the weight of the test wheel assembly, the coefficient of friction can be computed.

The Italian unit developed by Dr. Ariana consists of a two-wheel trailer equipped with hydraulic brakes which may be applied at either or both wheels. A water tank is mounted on the vehicle used to tow the trailer and wets the section of pavement to be tested. Two traction dynamometers are used to measure the friction forces between tire and pavement. Time and distance traveled are recorded by a tape recorder mounted on the trailer. Coefficients of friction at any given test speed can be computed from the tape recorder data.

Comparative measurements have been made for both the Spanish and the Italian skid test units and the French Stradographe. The Spanish spinning-wheel method provides a measurement of the incipient-skid coefficient of friction which, in the comparative tests with the Stradographe, correlated quite well. The coefficients measured with the Italian trailer in the locked-wheel braking tests were considerably lower than those of the Stradographe. In this respect, the results of the Italian and French vehicles were very similar to those of the German and French measurements shown in Figures 25 and 26.

Skid-Resistance Properties of European Pavements

The predominating types of European pavements are fine-grained dense-graded asphalt concrete. In parts of northern Europe, and especially England and Scotland, many of the newer pavements are built with a coarse-textured surface such as the tar macadam surface shown in Figure 19. On heavily traveled roads in Germany, surface treated seal coats and roughening courses are constructed with $^1/_8$- to $^3/_8$-in. granite chips to provide the desired high skid resistance.

A large part of the European city street paving, especially in the older parts of the cities, consists of granite or basaltic stone setts, cobblestones, brick and large flat stone slabs on flag stones. Under modern rubber-tired traffic many of these surfaces are developing a fine-grained polished surface texture which cause them to be very slippery when wet. Dr. Wehner reported locked-wheel coefficients of friction of 0.20 or less with the German test vehicle on basaltic stone setts. Many of the pavements surfaced with stone setts and cobblestones are very rough riding and difficult to keep clean. Consequently, they are being replaced or resurfaced.

The mileage of portland cement concrete pavements in Europe is relatively low. However, many new highways in England, Italy, France, and Germany, are paved with portland cement concrete. In general, the traffic has not been heavy enough to cause polishing, so skidding on these pavements has not yet developed to the point where special treatments are necessary.

The British Road Research Laboratory has found that some older concrete pavements have polished under traffic and are slippery when wet. They have experimented with various treatments such as acid-etching, roughening with bush hammering, a flailing machine or an acetylene torch, and by using a surface treatment consisting of epoxy-resin and 1/8-in. stone chips. The epoxy-resin treatment and roughening with a flailing machine provided the greatest improvement in skid resistance during the first year of tests.

CONCLUSIONS

1. Extensive programs in skid prevention research are being conducted in northern Europe where accident reports indicate a high incidence of skidding accidents. Fifteen to 20 percent of all accidents reported were skidding accidents versus 5 to 6 percent in the United States.

2. Great progress has been made during the past 10 years in developing equipment to measure the skid resistance of pavements, correlating the coefficients of friction measured by the skid test vehicles, and in establishing skid resistance standards for new construction, re-surfacing, or de-slicking treatments.

3. At the British Road Research Laboratory and the Swedish Road Research Institute, some of the world's finest and most completely instrumented equipment for measuring skid resistance has been developed.

4. For the routine measurement of skid resistance in Europe, extensive use is made of equipment and test procedures which provide a continuous record of the coefficients of friction on wet pavements for one to two miles. The two outstanding types of equipment used are the sideway-force vehicles in England and France and the braking-force incipient-skid test vehicle in Sweden.

5. Smooth tread tires are widely used for routine measurements of skid resistance. Locked-wheel braking tests cause a greater amount of tread damage to pattern tires than smooth tires. This contributes to large unpredictable variations in the coefficients of friction. For these reasons continuous measurements are made with sideway-force and braking-force incipient-skid vehicles equipped with smooth tires.

6. An important new tire development is the use of rubber with high hysteresis losses referred to as "dead" rubber tread stock. Coefficients of friction were reported 0.10 to 0.20 higher on wet pavements for the dead rubber tires than for GRS synthetic or natural rubber tires.

7. Tests conducted by the British Road Research Laboratory have indicated that there is good correlation between the resilience of rubber and the coefficients of friction on wet pavements. The coefficients with dead rubber tires of 20 to 30 percent resilience are 0.10 to 0.20 higher than those with GRS synthetic rubber tires with a resilience of 55 to 60 percent.

8. Wet pavement cornering tests at the Dunlop Proving Ground indicated a 60 to 80 percent improvement in the sideway-force skid resistance of tires developed in the past 12 years. This is due to improvements in tread rubber and design which involves cuts, siping and multi-rib tread.

9. In comparative measurements of the skid resistance of the French, German, and Swedish skid test vehicles on 11 pavements in Germany, the coefficients of friction measured at 35 to 50 mph provided the widest dispersion and thus formed the best basis for rating slipperiness. The widest dispersion was obtained at 50 mph with the French and Swedish test vehicles.

10. Traffic-worn stone setts are slippery when wet and are being replaced by the coarse-textured roughened types of asphalt surfacing.

11. For polished portland cement concrete pavements in England, roughening with flailing machines and epoxy-resin treatments with stone chips have been found to be the most effective corrective methods.

12. Research is well coordinated by the Committee on Slipperiness of the Permanent International Association of Road Congresses.

REFERENCES

1. Moyer, R. A., "Skid Resistance Measurements with a New Torque Device." HRB Bull. 348 (1962).
2. Kullberg, Gösta, "Method and Equipment for Continuous Measuring of the Coefficient of Friction at Incipient Skid." HRB Bull. 348 (1962).

South Dakota Roughometer Comparison Tests—1962

ROBERT A. CRAWFORD and DONALD W. ANDERSON, Assistant Research Engineers, South Dakota Department of Highways; and
W. E. CHASTAIN, SR., Assistant Engineer of Research and Planning, Illinois Division of Highways

• THE South Dakota Department of Highways obtained a commercially produced Bureau of Public Roads type road roughness indicator in March 1960 for use in a flexible pavement research study (1). After using the equipment during 1960, 1961 and 1962 and comparing roughness data with three similar machines at different times, it was obvious that the results obtained with any one machine varied from time to time for various reasons and that the results obtained with different machines at any specific time would not necessarily be in agreement. This raised some doubt as to the reliability of the data being obtained with the equipment, and suggested additional study of the equipment.

It was decided to invite personnel from neighboring States that used similar devices to bring their roughometers to South Dakota for the purpose of comparing, calibrating and standardizing the equipment. It was believed that the comparative studies would lead to a better understanding of the capabilities and limitations of the equipment, and also provide a means for comparing roughness index values being obtained by the various participating agencies. During the week of August 20, 1962, roughometers from seven organizations were assembled at Sioux Falls. The organizations represented included the highway departments of North Dakota, South Dakota, Nebraska, Minnesota, Iowa, and Illinois and the Bureau of Public Roads.

During the course of the AASHO Road Test at Ottawa, Ill., another machine was developed to provide a measure of pavement roughness. This device is called the CHLOE longitudinal profilometer (2), and has been used in the determination of the present serviceability index (PSI) (3) at the Road Test project and of various other roads. Use was made of the PSI in the mathematical formulas that were developed to describe the results of the pavement research in the AASHO Road Test. By correlating results obtained with the longitudinal profilometer and the roughness indexes obtained with the roughometers, it has been demonstrated that a present serviceability formula can be developed for each roughometer for which sufficient correlation data are available (4, 5). This correlation provides an essential linkage for maximum application of the AASHO Road Test results by the States. For this reason, and because some attending personnel had not seen this equipment in operation, a CHLOE profilometer was brought from Illinois for this series of tests. Figures 1 and 2 show some of the equipment assembled.

SELECTION OF TEST LOCATIONS

Sioux Falls was selected as headquarters for the roughometer tests because of the large number of paved highways with various characteristics in the immediate area, and because of the availability of adequate meeting and housing facilities. Several miles of both bituminous and portland cement concrete highways exhibiting roughness indexes from very low to very high were needed. The test sections should also be located in a compact area so that travel time from section to section could be kept at a minimum.

Many miles of Interstate, Federal, State and county highways were tested with the South Dakota roughometer to find highways satisfying the criteria. A circuit meeting

---

Paper sponsored by Committee on Road Surface Properties Related to Vehicle Performance.

Figure 1. Assembled equipment.

Figure 2. Assembled equipment.

most requirements was found directly northeast of Sioux Falls. It formed a square with sides about seven miles long. The south side was a new section of portland cement concrete Interstate highway, the east side was a bituminous State highway with a medium rough chip seal, the north side was a county road with a rough bituminous surface treatment, and the west side was an old portland cement concrete Federal highway. To obtain a smoother bituminous surfacing, a 6-mi stretch of county highway southwest of Sioux Falls was selected. The northeast circuit was used in both directions providing 48 miles, and the southwest section was run in a southerly direction only, providing 6 more miles for a total of 54 test miles (Fig. 3 and Table 1). These 54 miles provided roughness indexes as measured with the South Dakota device ranging from approximately 75 to 160 in. per mi for portland cement concrete, and from 65 to 185 in. per mi for bituminous-surfaced roads.

TEST EQUIPMENT AND PROCEDURES

In tests of this nature, an attempt must be made to eliminate as many extraneous variables as possible to obtain comparable results. This was done, insofar as was practicable. Possible differences caused by such factors as wind and temperature variations were minimized by having the tests conducted in one week and completing each series with all machines in a few hours. Other factors that might lead to minor differences, such as differing techniques of operation used by the individual crews operating the machines, could not be controlled. Each unit had a different driver and operator. Although the techniques used by each crew could be expected to vary, no attempt was made to utilize the same personnel for all equipment. Also, drivers operating the same vehicle on successive runs could not be expected to follow exactly the same wheelpaths each time. For these and similar reasons, the results obtained with different machines and successive runs with the same machine, can be expected to vary. However, such differences are not believed to have a significant effect on the ultimate results.

An important source of variation is the inherent difference built into each machine. Although all seven of these devices were constructed to Bureau of Public Roads' specifications, there are significant differences such as tire size, tire tread, sensing and recording systems, and such possible influencing factors as standard and automatic transmissions and suspension differences in the towing vehicles. Table 2 gives some of the significant characteristics of each of the roughometers.

Most of the variables that could be eliminated or controlled satisfactorily were concerned with the procedures used in obtaining the roughness indexes.

It was necessary to conduct all testing in the outer wheelpath to obtain the required range in roughness. The hitch in one vehicle had to be altered slightly to allow it to tow the roughometer in this path.

The wheel revolutions per mile for each roughometer were determined by running each machine over an accurately measured mile a number of times. The revolutions per mile on different devices varied from 735.5 to 754 depending on tire size. The results were compared with the revolutions per mile used by each organization in its normal operations and differences of up to 2.4 revolutions per mile were found.

A warm-up of approximately five miles was given all machines when starting tests in the morning or after any period of inactivity in an effort to bring all components up to stabilized operating temperature before measurements were begun. Because some of the roughometer trailers could not be supported by means other than the main wheel when not in use, they developed flat tire areas by standing. An important function of the 5-mi run was to help remove the flat area that is prone to develop on the tire when it remains in the same position under load over a considerable period of time. Arrangements used by some of the agencies indicated that auxiliary means for supporting the trailers so that the wheels swing free when the devices are not being used in recording are feasible, and it is recommended that some such system be adopted.

To obtain a measure of reproducibility of results for each machine, it was decided to run each test mile five times with each roughometer. All runs were made at 20 mph with each run at approximately the same time so that possible influence of temperature and wind could be held to a minimum. Minor difficulties with some of the equipment caused delays, but most problems were easily handled at the State maintenance shop.

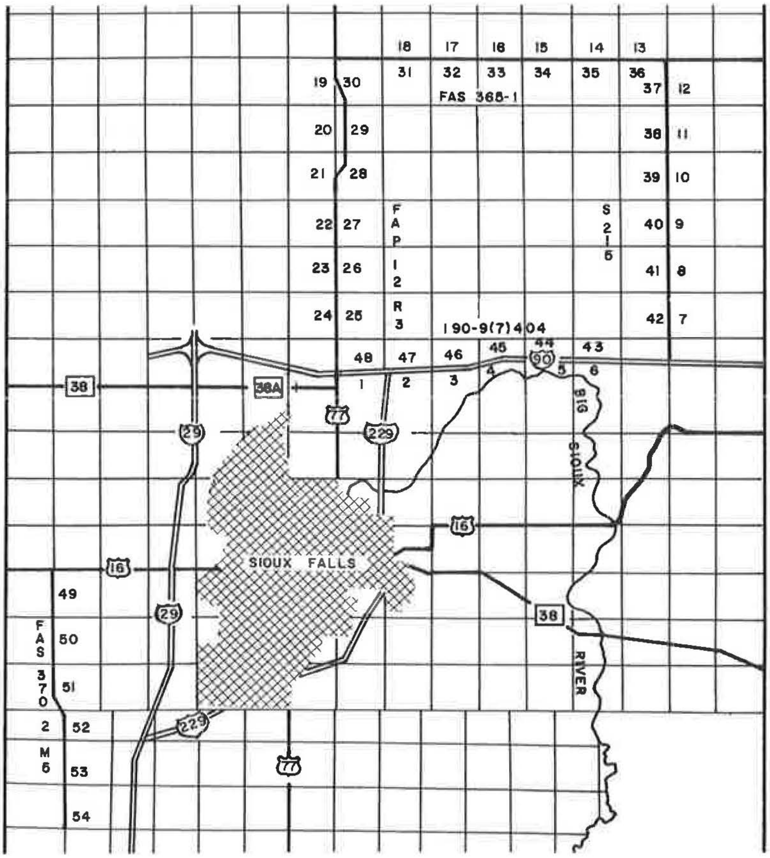


Figure 3. Test section location.

TABLE 1
TEST SECTION DATA

Route	Sections	Project	Surfacing Type	Pavement Width (ft)	Thickness			Year Built
					Surfacing (in.)	Base Course (in.)	Subbase (in.)	
Interstate 90	1-6 43-48	I 90-9(7)404	P. C. concrete	24	9	0	4 to 10	1962
S. Dak. 11	7-12 36-42	S-21-5	Bit. asphalt mat	24	1½	5 to 6	5 to 15	1954
County 122	13-18 31-36	FAS 265-1	Bit. surface treatment	24	3/4	6	0	1949
U.S. 77	19-30	FAP 12 R 3	P. C. concrete	20	9, 6, 9	0	4	1933
County 139	49-51	S-616 (1)	Bit. asphalt mat	24	2	8	0	1957
County 139	52-54	FAS 370 (2)	Bit. asphalt mat	24	1½	5	0	1955

TABLE 2

ROAD ROUGHNESS INDICATOR SPECIFICATIONS

State	Tow Vehicle	Trailer	Recording Method
Iowa	1962 Internt. Travelall S 100, V-8, 3-speed trans.; tachometer used to maintain correct operating speed.	BPR spec.; 6.70 × 15 General st. road tread.	Mech. integ.
N. Dak.	1958 Chev. Apache 38 panel, V-8, 4-speed trans.	BPR spec. by Soiltest; 6.70 × 15 special treadless.	Mag. rdg. head.
Ill.	1961 Chev. Apache 30 panel, V-8, 4-speed trans.	BPR spec.; U. S. Royal 6.70 × 15 special treadless.	Mech. integ.
Neb.	1960 Chev. Apache 30 panel, 6-cyl., 4-speed trans.	BPR spec.; Goodyear 6.00 × 16 ribbed implement.	Mech. integ.
S. Dak.	1960 Chev. Apache 30 panel, V-8, 4-speed trans.	BPR by Soiltest spec.; 6.70 × 15 U. S. Royal special smooth tread.	Mag. rdg. head operating Berkely elec. counter; a mech. integ. operating mag. counter.
Minn.	1961 Ford F-100 panel, V-8, auto. trans.	BPR spec.; 6.00 × 16 Armstrong hwy. tread.	Mech. integ. and Mag. rdg. head.
BPR	1961 Plymouth sta. wag., V-8, auto. trans.	BPR spec. by BPR; 6.00 × 16 U. S. Royal tread.	Mech. integ. operating mag. counter.

One exception was the South Dakota machine. After three complete circuits, it consistently yielded higher readings than most others. A small amount of wear was found in the universal joints supporting the dampening devices. They were replaced and the next two runs produced results which were about 10 percent lower than the first three. The new readings were found to be consistent with the majority of the other roughometers. Because this change had altered the characteristics of the device significantly, an additional three runs were made with the South Dakota machine so that five complete runs would be available with the alterations. The results of the first three runs are given in Tables 3 and 4, and the results of the last five, in 5 and 6. For data comparison and analysis, only the last five runs were used.

Results obtained with the other devices are given in Tables 7 through 13. All machines recorded roughness information by one method only except those of South Dakota and Minnesota. These two were equipped with both mechanical and electrical devices. Each set of data is presented in a separate table.

A CHLOE longitudinal profilometer was used in conjunction with the roughometers during this series of tests. The major difference in these two types of equipment is the means by which the relative roughness or smoothness of a road is measured. The

TABLE 3
SOUTH DAKOTA MECHANICAL INTEGRATOR[1]

Section	Run No. 1A	2A	3A	Avg.
1	103	101	105	103
2	96	99	99	98
3	85	89	90	88
4	85	88	88	87
5	83	84	87	85
6	101	102	101	101
7	119	119	120	119
8	108	108	105	107
9	117	118	116	117
10	105	101	104	103
11	131	130	128	130
12	112	110	108	110
13	139	138	138	138
14	159	156	151	155
15	182	175	169	175
16	173	171	164	169
17	182	191	183	185
18	201	204	193	199
19	183	184	180	182
20	175	177	172	175
21	168	171	165	168
22	162	161	159	161
23	139	140	138	139
24	140	146	146	144
25	135	138	134	136
26	138	138	140	139
27	152	156	152	153
28	159	163	162	161
29	160	163	161	161
30	161	167	156	161
31	207	215	213	212
32	184	191	188	188
33	202	207	196	202
34	198	206	194	199
35	158	159	155	157
36	131	143	135	136
37	118	112	119	116
38	108	105	108	107
39	104	105	107	105
40	126	124	126	125
41	114	111	113	113
42	123	129	127	126
43	99	103	103	102
44	84	86	87	86
45	81	84	88	84
46	88	89	92	90
47	98	99	102	100
48	99	99	99	99
49	—	70	68	69
50	—	75	71	73
51	—	92	84	88
52	—	87	83	85
53	—	76	74	75
54	—	80	78	79

[1] Readings obtained before repair of equipment.

TABLE 4

SOUTH DAKOTA MAGNETIC READING HEAD[1]

	Run No.			
Section	1A	2A	3A	Avg.
1	103	104	109	105
2	97	100	102	100
3	86	92	94	91
4	87	90	92	90
5	85	87	91	88
6	103	104	105	104
7	119	120	119	119
8	108	109	107	108
9	118	119	116	118
10	102	100	107	103
11	133	131	131	132
12	113	112	110	111
13	141	140	142	141
14	160	157	155	157
15	183	179	174	180
16	172	175	167	171
17	185	193	186	188
18	202	206	199	202
19	184	188	187	186
20	178	179	176	178
21	173	175	172	164
22	164	166	164	173
23	142	143	145	143
24	143	148	149	147
25	142	142	140	141
26	139	141	143	141
27	156	160	159	158
28	161	168	169	166
29	165	175	167	169
30	161	163	161	162
31	206	218	220	215
32	185	195	191	190
33	198	215	203	205
34	197	206	196	200
35	156	160	159	158
36	137	146	140	141
37	116	112	119	116
38	109	106	113	109
39	106	107	108	107
40	127	126	128	127
41	115	112	116	114
42	124	128	130	127
43	103	106	108	105
44	88	89	91	89
45	90	86	88	88
46	85	92	93	90
47	101	100	102	101
48	100	100	103	101
49	—	—	73	73
50	—	80	75	77
51	—	95	89	92
52	—	91	89	90
53	—	79	79	79
54	—	83	82	83

---

[1] Readings obtained before repair of equipment.

TABLE 5
SOUTH DAKOTA MECHANICAL INTEGRATOR

Section	Run No.					Avg.
	1	2	3	4	5	
1	95	94	93	92	93	93
2	84	88	88	86	87	87
3	79	79	81	81	81	80
4	81	81	82	80	79	81
5	79	77	80	79	80	79
6	96	92	96	92	92	94
7	110	105	109	107	109	108
8	94	98	100	99	100	98
9	103	105	109	108	109	107
10	87	94	99	93	94	93
11	116	119	123	118	119	119
12	97	100	106	102	104	102
13	118	125	128	131	126	126
14	141	139	140	139	141	140
15	157	154	164	158	163	158
16	149	149	148	152	151	150
17	167	157	166	162	168	160
18	181	175	186	181	178	180
19	161	157	159	163	164	161
20	156	154	156	159	159	157
21	144	146	150	148	150	148
22	140	141	147	148	144	144
23	122	123	126	128	125	125
24	130	127	131	133	129	130
25	118	120	124	125	121	122
26	120	122	126	127	125	124
27	134	138	142	140	140	139
28	143	145	149	150	150	147
29	141	147	144	147	143	144
30	143	144	146	145	142	144
31	178	181	184	186	187	183
32	160	166	165	168	167	165
33	173	177	175	179	179	177
34	167	167	171	174	177	171
35	136	134	137	141	140	138
36	115	122	123	121	123	121
37	101	106	105	105	105	104
38	94	100	97	98	98	97
39	94	93	91	99	93	94
40	109	110	110	111	111	110
41	99	104	104	102	102	102
42	112	111	113	113	116	113
43	93	92	91	96	94	93
44	77	79	80	79	78	79
45	75	75	75	78	75	76
46	80	81	80	81	82	81
47	89	87	88	92	88	89
48	89	90	90	91	90	90
49	69	62	68	66	63	66
50	68	70	70	67	68	69
51	82	82	80	79	79	80
52	80	77	83	82	85	81
53	75	77	72	71	73	74
54	77	74	75	76	75	75

TABLE 6

SOUTH DAKOTA MAGNETIC READING HEAD

	Run No.					
Section	1	2	3	4	5	Avg.
1	89	92	96	94	95	93
2	84	86	91	89	91	88
3	78	81	83	83	83	82
4	79	81	84	83	82	82
5	77	80	83	82	83	81
6	92	95	95	94	95	94
7	104	104	110	108	107	107
8	93	97	100	98	98	98
9	103	107	109	107	107	107
10	88	93	97	95	93	89
11	116	120	124	120	121	120
12	98	99	104	103	101	101
13	121	125	130	132	130	128
14	139	140	140	140	142	140
15	160	157	165	160	164	161
16	152	152	152	155	154	153
17	165	166	168	166	170	165
18	185	172	188	180	182	181
19	162	163	164	164	167	164
20	157	157	159	161	163	159
21	146	150	154	151	156	151
22	141	143	149	149	147	146
23	125	127	128	130	127	127
24	132	127	134	133	132	132
25	118	122	125	127	124	123
26	122	125	126	130	127	126
27	136	141	143	143	143	141
28	145	147	151	152	149	149
29	144	146	146	148	146	146
30	145	143	148	148	146	146
31	178	183	185	188	191	185
32	162	166	168	169	170	167
33	176	179	178	184	184	180
34	170	165	174	177	182	174
35	138	137	138	143	143	140
36	118	123	124	126	127	124
37	101	104	105	105	104	104
38	95	94	96	98	96	96
39	94	93	91	95	93	93
40	110	109	109	110	112	110
41	99	100	101	101	101	100
42	113	111	112	112	116	113
43	95	95	94	97	95	95
44	79	80	81	80	80	80
45	77	77	77	80	78	78
46	81	83	83	83	82	82
47	91	90	91	94	91	91
48	91	90	91	92	92	91
49	71	64	70	68	66	68
50	70	71	71	68	71	70
51	85	82	82	80	80	82
52	82	78	86	82	86	83
53	76	77	74	72	73	74
54	77	76	76	76	74	76

TABLE 7

NORTH DAKOTA MAGNETIC READING HEAD

	Run No.					
Section	1	2	3	4	5	Avg.
1	106	103	102	104	103	104
2	100	100	100	99	99	100
3	—	88	89	89	90	89
4	—	90	90	89	90	90
5	—	86	88	87	88	87
6	104	102	103	104	104	103
7	141	140	139	144	139	141
8	125	126	125	127	128	126
9	138	136	137	138	134	137
10	124	120	127	124	124	124
11	140	140	145	145	144	143
12	124	124	131	124	124	126
13	142	136	135	136	137	137
14	—	156	157	156	155	156
15	—	176	170	176	174	174
16	166	169	168	168	168	170
17	185	185	182	177	175	181
18	—	198	192	198	195	196
19	186	190	184	183	185	186
20	186	187	177	177	179	181
21	170	174	170	165	166	169
22	164	168	159	159	161	162
23	140	140	139	140	139	140
24	143	147	145	143	146	145
25	134	—	133	135	137	135
26	136	—	134	134	138	136
27	152	—	153	152	158	154
28	162	—	168	158	163	163
29	160	—	163	160	160	161
30	160	—	162	159	162	161
31	202	—	—	199	199	200
32	184	—	—	183	181	183
33	195	—	190	188	193	189
34	198	—	191	192	190	193
35	158	—	157	157	156	157
36	140	—	136	135	136	137
37	140	—	136	133	137	137
38	129	—	130	129	131	130
39	122	—	127	128	128	126
40	142	—	142	140	142	142
41	138	—	130	134	141	136
42	152	—	148	151	147	150
43	100	—	101	101	103	101
44	87	—	86	87	88	87
45	84	—	84	84	90	86
46	92	—	92	91	93	92
47	98	—	99	97	101	99
48	98	—	100	100	99	99
49	76	—	73	73	77	75
50	81	—	80	80	80	80
51	96	—	94	91	93	94
52	90	—	91	92	92	91
53	81	—	83	82	83	82
54	82	—	84	84	83	83

TABLE 8

NEBRASKA MECHANICAL INTEGRATOR

	Run No.					
Section	1	2	3	4	5	Avg.
1	82	83	86	87	89	85
2	73	77	79	79	82	78
3	68	71	74	73	74	72
4	65	68	70	70	73	69
5	64	68	70	73	72	69
6	83	87	90	89	90	88
7	91	97	94	96	96	95
8	79	79	78	80	79	79
9	94	95	97	94	96	95
10	73	74	78	78	79	76
11	106	105	111	108	108	108
12	78	81	81	82	85	81
13	118	118	110	113	113	114
14	136	137	137	137	142	138
15	156	155	147	153	157	154
16	144	144	148	151	149	147
17	170	167	154	154	152	159
18	173	181	169	172	182	175
19	167	169	170	164	174	169
20	165	164	165	161	171	165
21	144	146	146	146	148	146
22	136	139	140	141	141	139
23	113	112	115	114	114	114
24	119	117	122	117	120	119
25	109	110	111	111	113	111
26	113	113	114	115	114	114
27	134	138	135	137	141	137
28	144	144	145	145	150	146
29	140	144	144	150	149	145
30	139	144	144	143	150	144
31	181	181	185	186	191	185
32	163	157	161	160	163	161
33	184	190	180	175	177	181
34	181	178	178	183	177	179
35	130	137	133	136	137	135
36	115	116	112	116	118	115
37	86	87	83	93	87	87
38	80	81	84	84	84	83
39	77	80	78	84	79	79
40	101	101	102	102	104	102
41	88	90	90	91	91	90
42	101	101	101	101	103	101
43	84	88	89	90	89	88
44	68	69	71	72	71	70
45	64	66	68	69	68	67
46	70	72	73	75	73	73
47	81	80	83	85	84	83
48	83	85	84	87	84	85
49	–	48	46	51	49	49
50	–	49	48	51	51	50
51	–	67	64	61	64	64
52	–	66	73	69	71	70
53	–	55	57	57	58	57
54	–	58	58	57	57	58

TABLE 9

MINNESOTA MECHANICAL INTEGRATOR

	Run No.					
Section	1	2	3	4	5	Avg.
1	100	100	101	98	105	101
2	92	92	91	94	96	93
3	87	88	87	88	89	88
4	88	86	86	88	88	87
5	86	89	88	87	89	88
6	104	107	105	106	106	106
7	109	115	113	116	118	114
8	95	97	99	100	102	99
9	107	110	109	109	115	111
10	96	97	96	97	99	97
11	113	116	–	118	120	117
12	106	100	102	105	110	105
13	119	118	124	124	122	121
14	133	135	140	137	134	136
15	142	141	143	143	150	144
16	140	137	137	144	144	140
17	147	146	143	149	148	147
18	153	150	154	155	155	153
19	136	135	136	134	128	134
20	125	134	140	133	135	133
21	123	136	137	141	131	134
22	133	129	133	126	135	131
23	123	118	123	127	126	123
24	125	127	126	125	127	126
25	120	121	121	121	123	121
26	122	119	124	122	122	122
27	132	132	142	136	140	136
28	130	135	150	148	145	142
29	134	139	135	142	140	138
30	123	132	129	129	131	129
31	165	168	165	169	169	167
32	153	148	152	152	167	154
33	155	154	156	157	164	157
34	155	156	153	147	152	153
35	130	134	130	133	133	132
36	114	113	115	118	115	115
37	106	108	110	108	108	108
38	102	103	103	106	106	104
39	104	105	101	103	108	104
40	116	116	114	109	115	114
41	102	107	109	110	112	108
42	114	110	116	113	115	114
43	103	101	104	103	107	104
44	87	81	88	86	89	86
45	82	82	84	86	86	84
46	88	90	90	86	89	87
47	98	98	101	102	101	100
48	99	96	100	100	100	99
49	–	72	70	70	71	71
50	–	74	71	72	74	73
51	–	78	78	84	79	80
52	–	79	82	83	81	81
53	–	72	73	72	72	72
54	–	73	74	73	74	73

TABLE 10

MINNESOTA MAGNETIC READING HEAD

	Run No.					
Section	1	2	3	4	5	Avg.
1	101	101	94	104	107	101
2	97	97	83	92	101	94
3	89	92	65	83	92	84
4	90	89	81	86	91	87
5	88	90	82	89	90	88
6	104	110	95	104	111	105
7	112	123	98	121	123	115
8	101	105	—	102	108	104
9	108	120	—	115	120	116
10	101	104	83	103	105	99
11	117	124	—	125	125	123
12	108	103	98	111	116	107
13	118	123	129	132	133	127
14	132	148	148	145	149	144
15	142	153	153	151	162	152
16	144	156	158	159	158	155
17	147	164	153	167	170	160
18	152	170	166	170	175	167
19	130	167	165	166	166	159
20	125	161	162	161	163	154
21	120	152	154	156	153	147
22	137	148	149	145	149	146
23	120	128	131	128	130	127
24	122	133	133	129	131	130
25	104	126	126	124	127	121
26	117	124	125	126	127	124
27	130	143	—	147	149	142
28	130	144	126	157	155	142
29	129	137	144	153	153	143
30	129	126	145	147	151	140
31	167	189	187	189	189	184
32	155	172	179	177	187	174
33	155	181	180	187	185	178
34	154	183	176	175	175	173
35	133	147	145	144	149	144
36	112	127	132	128	129	126
37	105	100	115	114	115	104
38	97	95	108	111	110	104
39	111	96	106	107	113	107
40	101	108	123	118	126	115
41	117	98	116	117	121	114
42	121	103	123	123	126	119
43	103	102	99	106	109	104
44	87	84	90	89	91	88
45	83	81	87	89	88	86
46	89	88	94	88	92	90
47	98	98	104	105	105	102
48	99	98	103	104	102	101
49	—	76	74	75	75	75
50	—	80	76	76	78	77
51	—	88	87	89	85	87
52	—	85	89	90	88	88
53	—	77	77	76	77	77
54	—	79	77	80	78	79

TABLE 11

IOWA MECHANICAL INTEGRATOR

	Run No.					
Section	1	2	3	4	5	Avg.
1	103	98	102	98	104	101
2	93	94	93	92	97	94
3	88	88	90	87	89	88
4	86	86	84	83	86	85
5	85	86	85	86	86	86
6	101	101	101	101	100	101
7	112	109	115	107	114	111
8	99	95	99	95	100	98
9	113	110	110	108	115	111
10	99	93	95	94	97	96
11	125	121	120	124	125	123
12	101	100	98	97	104	100
13	127	124	126	121	125	125
14	144	144	144	141	146	145
15	159	156	156	152	155	156
16	155	154	155	149	156	154
17	166	160	159	157	160	160
18	184	175	180	175	187	181
19	165	165	167	158	160	163
20	164	162	166	156	161	162
21	154	154	158	148	150	153
22	151	152	152	145	147	149
23	129	127	131	124	125	127
24	131	130	131	124	126	128
25	127	124	126	121	122	124
26	128	125	127	126	125	126
27	147	147	148	145	145	146
28	153	153	154	148	151	152
29	152	151	152	144	149	150
30	155	153	153	149	150	152
31	183	181	181	173	170	178
32	165	162	160	167	162	163
33	176	178	173	173	168	174
34	177	177	174	175	168	175
35	144	142	141	141	141	142
36	126	126	122	120	126	124
37	106	103	106	101	102	104
38	101	100	97	97	95	98
39	98	96	94	92	93	95
40	117	116	114	112	111	114
41	107	105	105	106	99	104
42	116	115	114	111	113	114
43	103	102	101	101	98	101
44	86	86	86	84	83	85
45	83	83	83	82	80	82
46	88	87	87	87	85	87
47	96	98	95	96	95	96
48	97	98	95	98	97	97
49	–	70	70	70	67	69
50	–	71	70	70	69	70
51	–	83	81	81	80	81
52	–	81	77	76	73	77
53	–	76	73	74	73	74
54	–	72	75	71	71	72

TABLE 12

ILLINOIS MECHANICAL INTEGRATOR

Section	Run No. 1	2	3	4	5	Avg.
1	91	94	92	93	97	93
2	85	85	83	87	90	86
3	78	79	77	79	81	79
4	76	78	77	79	82	78
5	76	78	76	79	82	78
6	93	95	93	94	97	95
7	102	101	100	104	108	103
8	90	87	86	88	94	89
9	100	102	99	100	104	101
10	87	87	86	87	94	82
11	114	111	112	118	117	115
12	91	94	89	92	94	92
13	121	120	120	118	122	120
14	136	136	135	140	149	139
15	158	155	151	157	165	157
16	148	158	142	151	157	151
17	148	159	149	155	162	155
18	180	174	172	180	182	177
19	157	165	167	167	170	165
20	160	171	165	167	171	167
21	146	154	150	156	154	152
22	143	152	149	153	151	149
23	119	127	122	124	124	123
24	124	134	129	130	130	129
25	102	122	124	119	123	121
26	124	123	126	123	126	124
27	141	142	145	140	144	142
28	156	153	160	149	157	155
29	143	147	151	141	147	146
30	145	156	154	147	147	150
31	185	194	190	176	195	188
32	159	166	168	160	175	166
33	179	177	182	167	183	178
34	175	176	140	170	189	170
35	136	138	140	136	141	138
36	119	123	127	120	128	123
37	92	100	101	96	97	97
38	89	93	92	87	91	90
39	85	92	89	85	88	88
40	104	113	109	106	110	108
41	90	95	96	91	94	94
42	106	107	112	111	109	109
43	91	92	96	91	89	92
44	76	77	79	75	76	77
45	74	74	76	74	72	74
46	77	78	81	77	78	78
47	75	87	88	86	84	86
48	89	91	92	88	89	90
49	–	56	60	58	62	59
50	–	61	62	63	66	63
51	–	78	79	79	79	79
52	–	73	74	79	78	76
53	–	69	72	71	71	71
54	–	66	65	69	65	66

TABLE 13

BUREAU OF PUBLIC ROADS MECHANICAL INTEGRATOR

	Run No.					
Section	1	2	3	4	5	Avg.
1	99	99	99	102	98	99
2	90	90	92	92	88	90
3	80	80	80	83	80	80
4	81	82	79	80	80	80
5	81	81	79	82	79	80
6	98	97	97	98	96	97
7	114	112	111	111	109	111
8	96	96	95	92	94	95
9	108	110	107	108	109	108
10	92	97	93	94	95	94
11	122	121	122	120	123	122
12	99	97	97	96	98	97
13	128	123	124	120	123	124
14	142	138	138	139	139	139
15	156	158	152	159	161	157
16	155	153	154	157	157	155
17	159	160	159	161	161	160
18	175	172	173	172	172	173
19	165	168	164	163	166	165
20	164	162	162	161	161	162
21	153	150	150	151	152	151
22	148	149	147	147	147	148
23	126	122	124	124	126	124
24	130	135	130	129	130	131
25	120	120	120	122	123	121
26	122	121	122	120	122	122
27	140	146	143	138	143	142
28	147	151	149	148	150	149
29	149	148	149	147	148	148
30	150	151	152	149	150	150
31	185	184	190	189	189	187
32	165	166	167	166	167	166
33	181	179	181	176	172	178
34	174	175	176	174	173	174
35	138	140	143	139	138	140
36	123	123	123	123	121	123
37	106	108	110	107	105	107
38	96	96	99	98	99	98
39	94	93	95	94	95	94
40	117	114	114	114	112	114
41	106	100	104	109	103	102
42	116	114	113	112	112	113
43	96	95	96	97	94	96
44	79	78	79	79	77	79
45	75	73	74	75	74	74
46	83	82	84	82	81	82
47	92	91	89	91	92	91
48	88	91	90	91	89	90
49	–	62	63	63	62	62
50	–	66	66	67	67	66
51	–	81	76	81	81	80
52	–	76	85	79	79	79
53	–	68	68	69	69	68
54	–	71	71	71	72	71

Figure 4. CHLOE profilometer in operation, followed by warning truck.

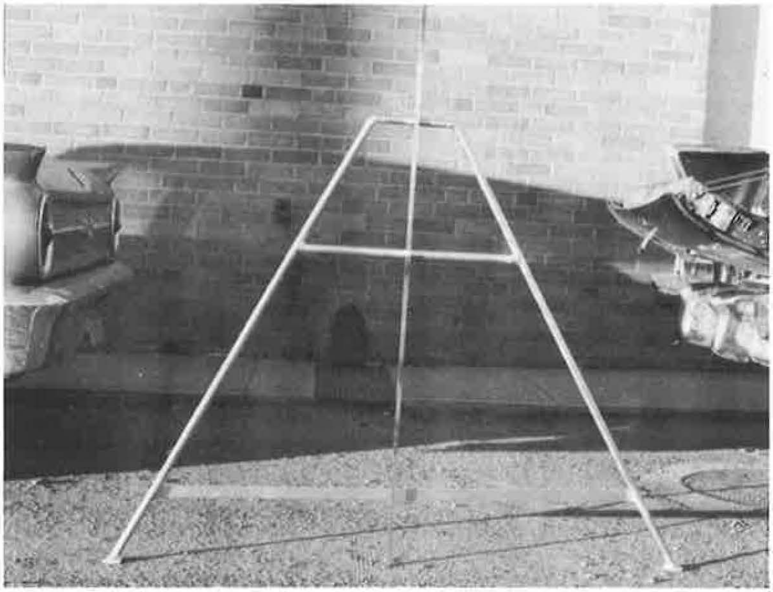


Figure 5. Rut depth measuring device.

roughometer measures the vertical movement of a wheel with respect to a datum as the wheel traverses irregularities in the driving surface; the CHLOE longitudinal profilometer measures the angular deviation of the road surface from a datum which is parallel to the overall road surface. The roughometer operates at 20 mph; the CHLOE from 3 to 5 mph.

The CHLOE profilometer was first used on the AASHO Road Test, and is now being used by the Illinois Division of Highways primarily for calibrating the roughometers. It also has been used as the standard from which PSI formulas for several roughometers have been derived.

TABLE 14

LONGITUDINAL PROFILOMETER DATA

Section	N	Y	Y^2
1 A	995	18,409	341,789
1 B	1,002	18,373	338,007
2 A	1,006	18,336	335,648
2 B	999	18,629	348,131
3 A	1,006	18,246	332,088
3 B	1,006	18,552	342,784
4 A	1,003	18,528	343,322
4 B	998	18,405	340,215
5 A	1,008	18,565	342,845
5 B	1,004	18,628	346,282
6 A	1,003	18,773	352,243
6 B	1,004	18,603	346,155
7 A	985	18,311	343,535
7 B	983	18,567	353,147
8 A	995	18,019	360,458
8 B	988	18,704	356,110
9 A	979	18,210	338,738
9 B	976	18,285	344,597
10A	877	26,073	336,605
10B	987	18,278	340,936
11A	981	18,375	346,211
11B	986	18,512	352,252
12A	961	18,019	343,427
12B	979	18,422	348,654
13A	981	18,830	365,624
13B	1,002	19,390	377,872
14A	996	19,112	371,890
14B	1,003	19,425	378,235
15A	991	19,052	373,602
15B	1,000	19,394	380,380
16A	1,005	19,616	388,472
16B	976	19,179	380,599
17A	989	19,336	381,538
17B	979	18,930	373,326
18A	1,004	19,207	368,577
18B	970	18,744	368,498
19A	997	18,802	358,270
19B	995	19,107	371,007
20A	988	18,546	353,210
20B	993	19,268	376,994
21A	1,012	18,882	355,892
21B	1,003	19,602	386,884
22A	997	19,267	375,935
22B	989	18,866	363,520
23A	997	19,169	371,089
23B	995	19,085	368,637
24A	1,000	19,122	368,490
24B	957	18,308	352,162
25A	1,124	21,219	403,277
25B	993	18,863	360,615
26A	984	18,712	357,942
26B	968	18,375	350,873
27A	996	18,877	360,861
27B	994	19,207	373,841
28A	994	19,193	374,323
28B	993	18,864	361,790
29A	996	18,899	361,471
29B	995	18,896	364,092
30A	995	18,543	87,375
30B	999	19,252	374,402
31A	1,006	21,109	446,689
31B	1,003	19,388	375,892
32A	991	18,756	365,036
32B	998	18,745	355,623
33A	992	18,353	346,269
33B	1,003	18,397	340,907
34A	989	18,568	352,912
34B	991	18,231	341,241
35A	1,001	19,138	368,728
35B	1,002	19,144	369,320
36A	992	18,266	339,572
36B	995	18,158	335,948
37A	920	17,096	320,944
37B	954	17,516	326,720
38A	959	17,878	335,696
38B	982	18,171	338,317
39A	980	18,061	335,551
39B	966	18,008	338,468
40A	973	17,981	334,863
40B	950	17,725	333,491
41A	988	18,384	343,506
41B	939	17,170	317,842
42A	928	17,562	335,738
42B	956	18,102	347,298
43A	1,009	18,937	356,401
43B	1,006	18,404	337,740
44A	1,003	18,771	352,069
44B	1,003	18,302	334,602
45A	1,007	18,593	344,097
45B	1,005	18,347	335,493
46A	1,008	18,651	345,921
46B	1,010	18,933	355,693
47A	1,009	18,367	335,113
47B	1,004	18,807	353,247
48A	1,005	18,657	347,717
48B	1,001	18,579	345,619
49A	1,005	19,201	367,295
49B	998	18,886	356,682
50A	990	18,513	347,393
50B	978	18,229	341,115
51A	992	18,572	349,298
51B	995	18,601	349,505
52A	975	18,190	340,296
52B	979	18,260	342,214
53A	970	17,910	331,452
53B	993	18,383	341,203
54A	995	18,335	338,467
54B	993	18,522	346,208

TABLE 15

PRESENT SERVICEABILITY INDEX DATA

Surface	Mi.	$\overline{SV}$	C + P /1,000 Sq Ft	$\overline{RD}$	PSI	Avg.
Concrete	1	6.7857	—	—	3.81	
	2	6.2374	—	—	3.86	
	3	4.6300	—	—	4.06	
	4	4.8305	—	—	4.03	
	5	3.6461	—	—	4.22	
	6	6.8415	—	—	3.80	3.96
Asphalt	7	21.0256	—	0.14	-[a]	
	8	17.9550	—	0.29	-[a]	
	9	14.6433	—	0.15	-[a]	
	10	18.0172	—	0.10	-[a]	
	11	25.8917	—	0.14	-[a]	
	12	30.1471	—	0.18	-[a]	
Asphalt	13	26.2458	545.7	0.19	-[a]	
	14	27.4577	356.5	0.24	-[a]	
	15	46.2676	445.5	0.28	-[a]	
	16	36.6917	410.6	0.24	-[a]	
	17	43.4678	245.5	0.24	-[a]	
	18	29.2410	378.0	0.32	-[a]	
Concrete	19	30.0672	9.8	—	2.44	
	20	32.0506	27.0	—	2.21	
	21	28.0038	5.1	—	2.58	
	22	27.8270	8.0	—	2.53	
	23	18.6665	2.0	—	2.95	
	24	17.4926	1.9	—	3.01	2.62
Concrete	25	16.9394	4.2	—	2.97	
	26	15.1175	1.8	—	3.12	
	27	21.6384	2.5	—	2.83	
	28	27.6497	9.3	—	2.52	
	29	31.4296	21.5	—	2.27	
	30	25.7115	10.3	—	2.55	2.71
Asphalt	31	17.5290	325.4	0.45	-[a]	
	32	54.9345	349.8	0.24	-[a]	
	33	40.2847	366.4	0.25	-[a]	
	34	40.4019	370.3	0.23	-[a]	
	35	23.9811	311.0	0.22	-[a]	
	36	30.2638	362.6	0.19	-[a]	
Asphalt	37	34.3069	—	0.16	-[a]	
	38	16.5975	—	0.17	-[a]	
	39	20.7434	—	0.16	-[a]	
	40	20.5797	—	0.16	-[a]	
	41	20.6055	—	0.30	-[a]	
	42	32.4922	—	0.16	-[a]	
Concrete	43	5.5793	—	—	3.94	
	44	2.9461	—	—	4.34	
	45	2.6957	—	—	4.39	
	46	3.7346	—	—	4.19	
	47	4.2561	—	—	4.11	
	48	6.0644	—	—	3.88	4.14
Asphalt	49	0.7867	—	0.17	-[a]	
	50	7.9316	—	0.15	-[a]	
	51	11.3232	47.4	0.15	-[a]	
	52	8.1202	54.6	0.23	-[a]	
	53	4.1039	4.4	0.13	-[a]	
	54	2.6631	0.8	0.09	-[a]	

---

[1] The PSI formula for the dense-graded bituminous concrete of the AASHO Road Test does not apply to chip-seal asphalt treatments.

The CHLOE operated at such a slow speed that time did not permit the determination of the slope variance for the entire length of each test mile. A 500-ft section located at the midpoint of each half of every test mile was measured and marked. This provided two 500-ft profilometer test areas in each mile, or roughly a 20 percent sample. The slope variance readings were obtained in the outer wheelpath only, as were the roughometer data. As a safety precaution during operation, a large truck with a flashing amber light was driven immediately behind the profilometer to warn traffic of the slow moving test equipment on the highway (Fig. 4).

Besides the slope variance, it is necessary to measure cracking, patching and rut depth to use the present serviceability index formulas developed at the AASHO Road Test. The cracking and patching were determined in the single lane in both 500-ft sections on all 54 mi. The rut depth was measured on flexible pavements only. Measurements were obtained every 25 ft within each 500-ft section, and were alternately taken in the inner and outer wheelpaths. The rut depths were measured with the device shown in Figure 5. This device was constructed with a distance of 4 ft between the support legs.

The readings taken with the longitudinal profilometer are given in Table 14. Calculated slope variances, cracking, patching, and rut depth measurements, and the calculated present serviceability indexes for the portland cement concrete pavements are given in Table 15. The present serviceability index formula developed at the AASHO Road Test for a dense-graded bituminous concrete surface does not apply to chip-seal bituminous surfaces; therefore, no present serviceability indexes are presented for them.

ANALYSIS OF DATA

The measurement of road surface roughness has assumed considerable importance in view of the methods adopted for determining the performance of the pavements of the AASHO Road Test. The PSI used to describe the pavement performance being rendered at a given moment in time is a combination of mathematical values obtained from a series of physical measurements including pavement roughness.

As indicated previously, other investigators have found that the BPR-type roughometer may be used to furnish roughness measurements in determining the PSI of pavements. By correlating roughometers with equipment used to determine roughness at the Road Test, or with equipment which has been previously correlated with that equipment, highway agencies may use them in applying the present serviceability concept. This concept has proved valuable in studying the performance of existing pavements, and also in studying and applying the results of AASHO Road Test pavement studies.

The major analysis of the present study was directed toward the development of PSI equations for each of the BPR-type roughometers that participated. The total analysis covered the use of the machines on both portland cement concrete and chip-sealed bituminous-surfaced pavements. However, it became obvious early in the analytical work that the slope-variance profilometer, and probably the roughometers, were reacting differently to the bituminous chip seals as used in South Dakota than to the flexible pavement of the AASHO Road Test. Therefore, the PSI equations for the bituminous pavements of the Road Test were not applicable to the chip-sealed surfaces, and no PSI equations are reported.

Detailed analyses of the data for the individual machines and comparisons of results obtained by the individual machines are not covered in this report. However, it is assumed that each participating State will make such analyses for its own machine.

An indication of how the machines performed with respect to each other may be obtained from Figures 6 through 9, which show a relatively rough and relatively smooth section of each portland cement concrete and bituminous surfacing.

The PSI equations evolved through correlations of each machine with the Illinois machine based on results of the measurements of the segments of pavement. The Illinois machine was the only one which was correlated with the CHLOE profilometer based on separate roughness recordings for the 500-ft sections for which slope-variance values were determined with the profilometer.

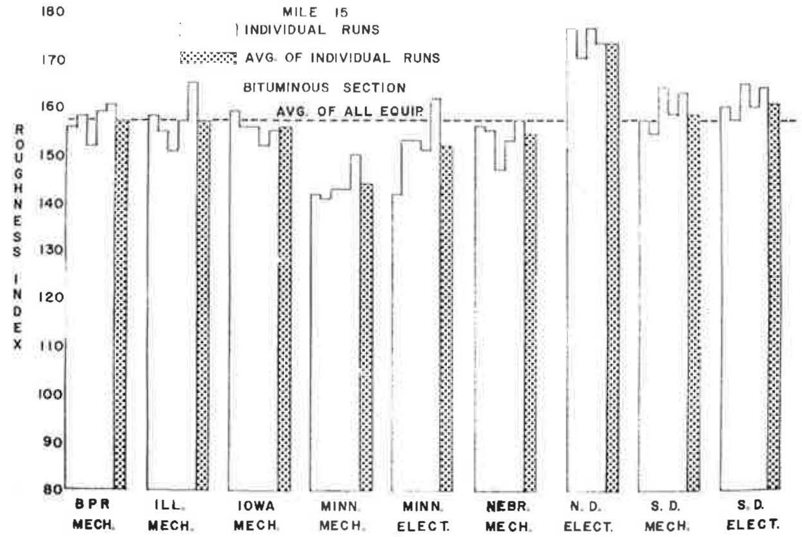


Figure 6 Machine performance.

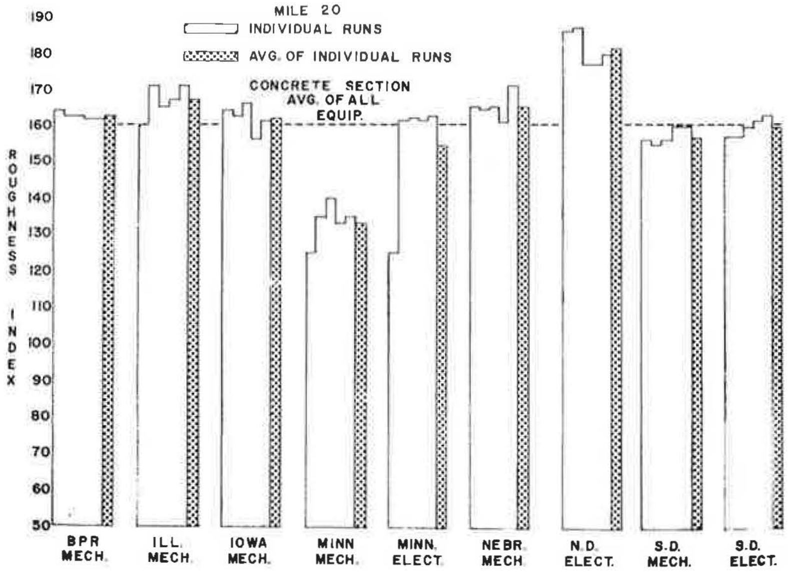


Figure 7. Machine performance.

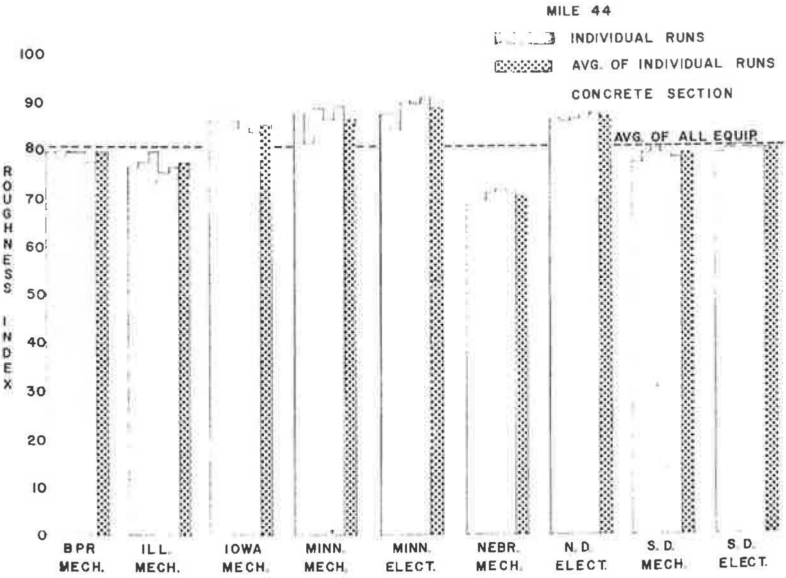


Figure 8. Machine performance.

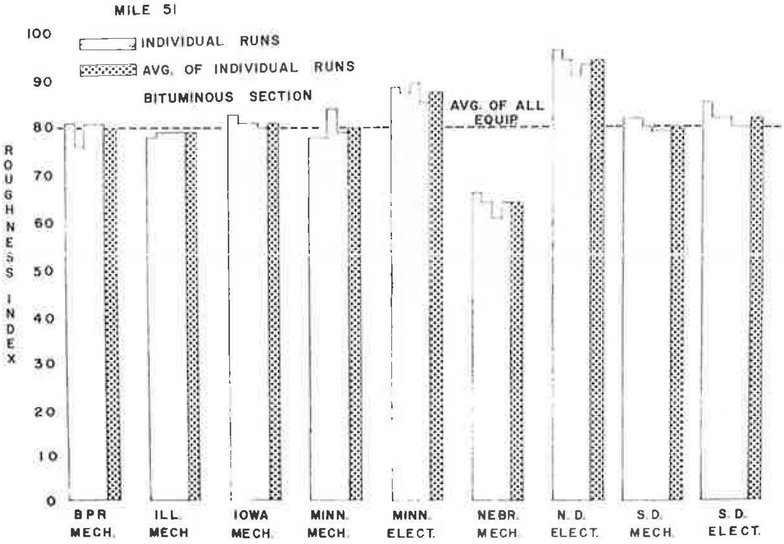


Figure 9. Machine performance.

The relationships between roughness readings obtained with the Illinois machine and the others were obtained by linear regression analyses. In this type of analysis, a straight line is established in which the sum of the squares of the deviations of the individual points from the line is at a minimum. In Figures 10 through 25 the equations are for the lines of best fit, and standard deviations S_y and coefficients of correlation r are also shown. Correlations are very good in all cases.

The CHLOE profilometer is a simplified version of the AASHO Road Test longitudinal profilometer used to determine the present serviceability index values of pavement sections. The slope-variance output of the CHLOE has been made the same as that of the longitudinal profilometer, and it appears that the two devices yield very similar results. Therefore, the Road Test PSI equations are applicable directly for use with the CHLOE profilometer. The simplified device was not fully developed until the Road Test neared completion; hence, the reliance on the more complicated version in the Road Test studies.

The present serviceability equations as developed at AASHO using slope-variance measurements are:

For portland cement concrete pavement:

$$PSI = 5.41 - 1.80 \log (1 + \overline{SV}) - 0.09\sqrt{C + P}$$

in which

PSI = present serviceability index;
$\overline{SV}$ = mean slope variance in the two wheelpaths as measured by the profilometer or CHLOE;
C = lineal feet of cracking per 1,000 sq ft of pavement area (including the lengths taken parallel or perpendicular to the pavement, whichever is greater, of all cracks that are sealed, opened, or spalled at the surface for a width of ¼ in. or more for at least half of their length); and
P = square feet of bituminous pathhing per 1,000 sq ft of pavement area.

For bituminous concrete pavement:

$$PSI = 5.03 - 1.91 \log (1 + \overline{SV} - 0.01\sqrt{C + P} - 1.38\, \overline{RD}^2$$

in which

C = square feet of cracking per 1,000 sq ft of pavement area (including only cracking that has progressed to the stage where cracks have connected together to form a grid-type pattern or where the surfacing segments have become loose); and
$\overline{RD}$ = mean depth of rutting in both wheelpaths measured in inches under a 4-ft straightedge.

All other terms are as previously defined.

Following a series of correlative tests in 1960, correlation equations were established between the Illinois roughometer and the profilometer. Regression lines were developed for $\log (1 + \overline{SV})$ regressed on $\log \overline{RI}$, where $\overline{SV}$ is the slope variance measured with the profilometer and $\overline{RI}$ the roughness measured with the roughometer. Separate equations were established for portland cement concrete surfaces and dense-graded bituminous concrete surfaces as used in the Road Test.

In the present study, similar regression analyses were performed for measurements on the 500-ft sections, and the results are shown in Figures 26 and 27. The correlation for portland cement concrete pavement is quite satisfactory; the correlation for bituminous surfaces is less satisfactory.

A comparison between these correlation equations and those originally developed for the Illinois machine (dash lines are used to indicate the original equations) shows a slight change for the rigid pavement equation, and a more significant change for the flexible pavement equation. The difference between the original and new correlations for concrete pavement can be attributed logically to changes in the Illinois machine over the past two years. The significant difference between the original and new correlations for flexible surfaces is attributable mainly to the different responses of the machines to the South Dakota and Illinois surfaces. For this reason, the final step in developing PSI equations using Road Test data was limited to portland cement concrete pavements.

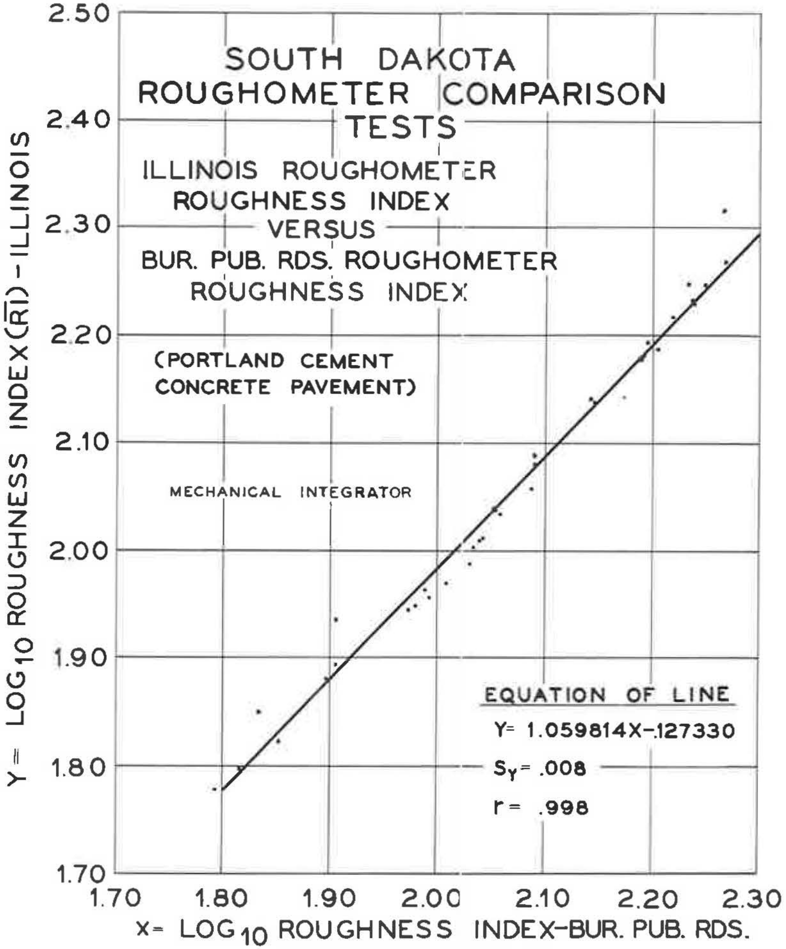


Figure 10. Machine performance.

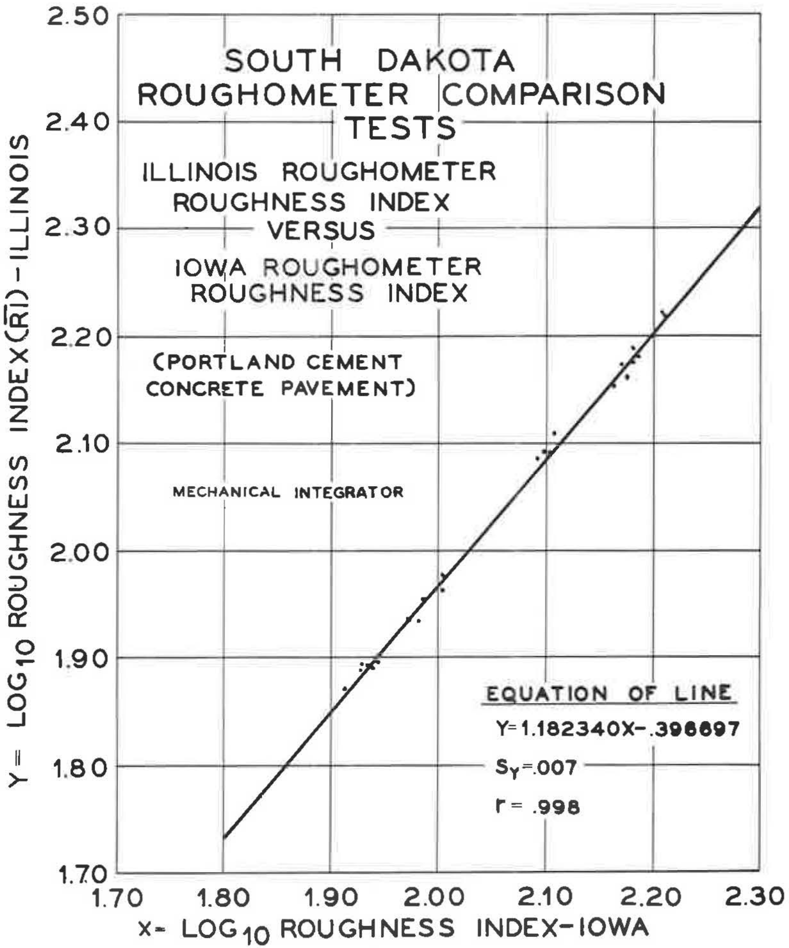


Figure 11. Machine performance.

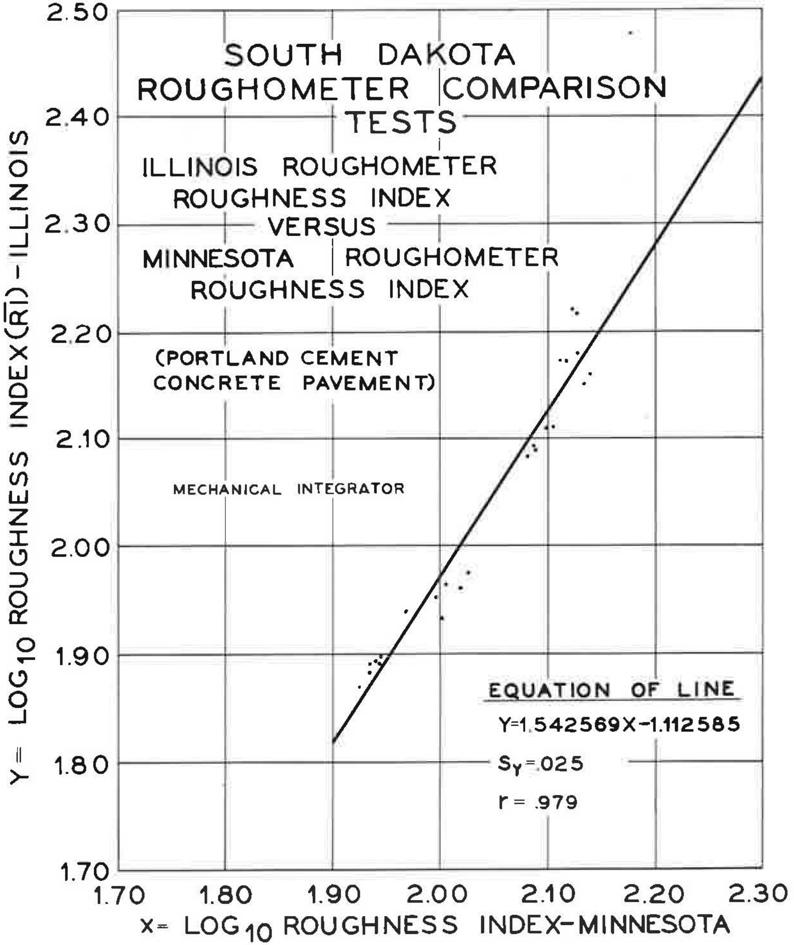


Figure 12. Machine performance.

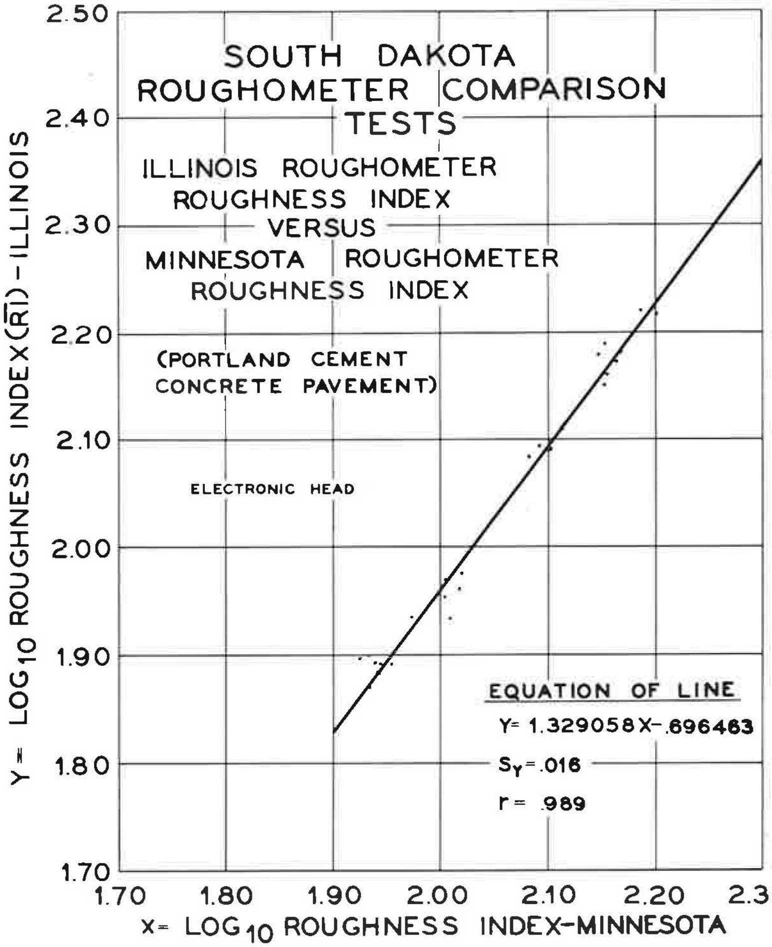


Figure 13. Machine performance.

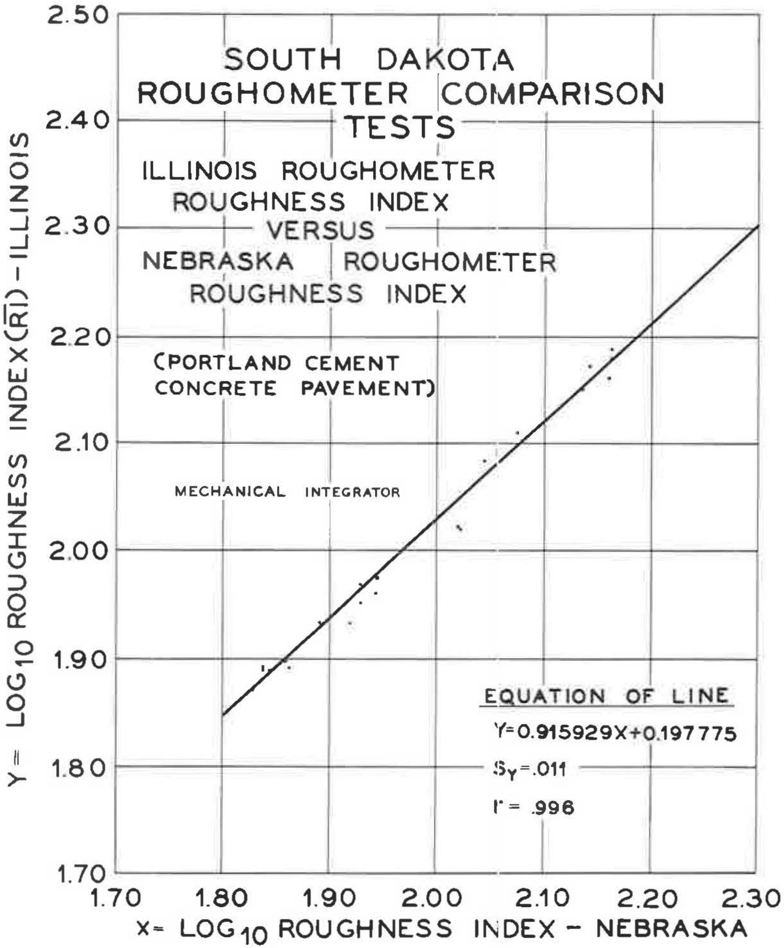


Figure 14. Machine performance.

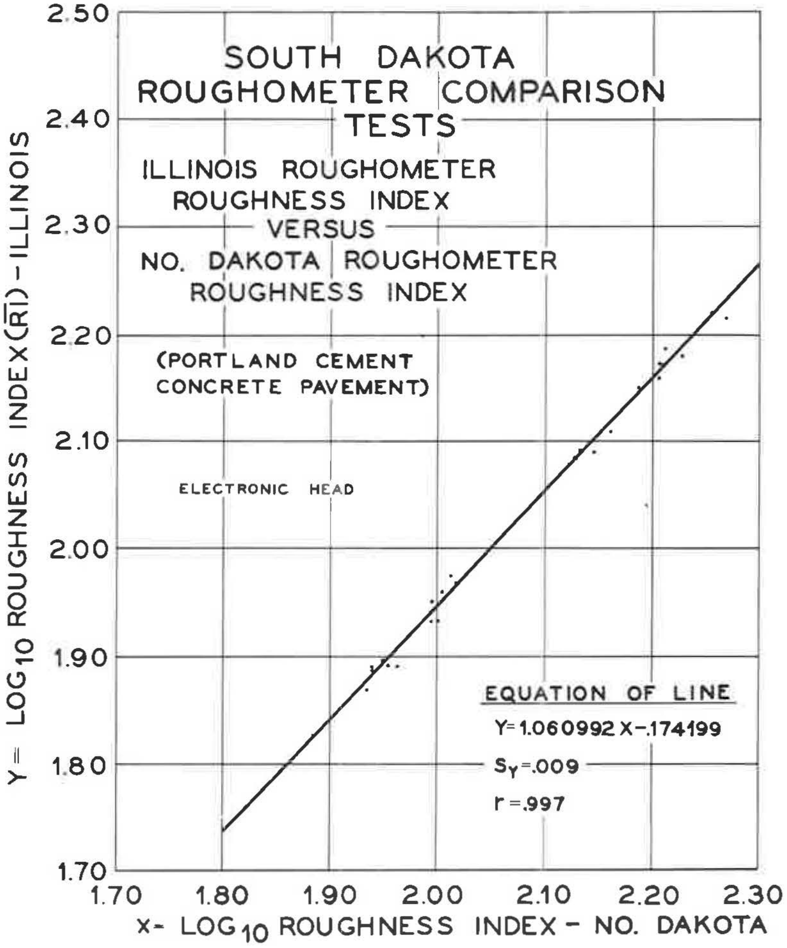


Figure 15. Machine performance.

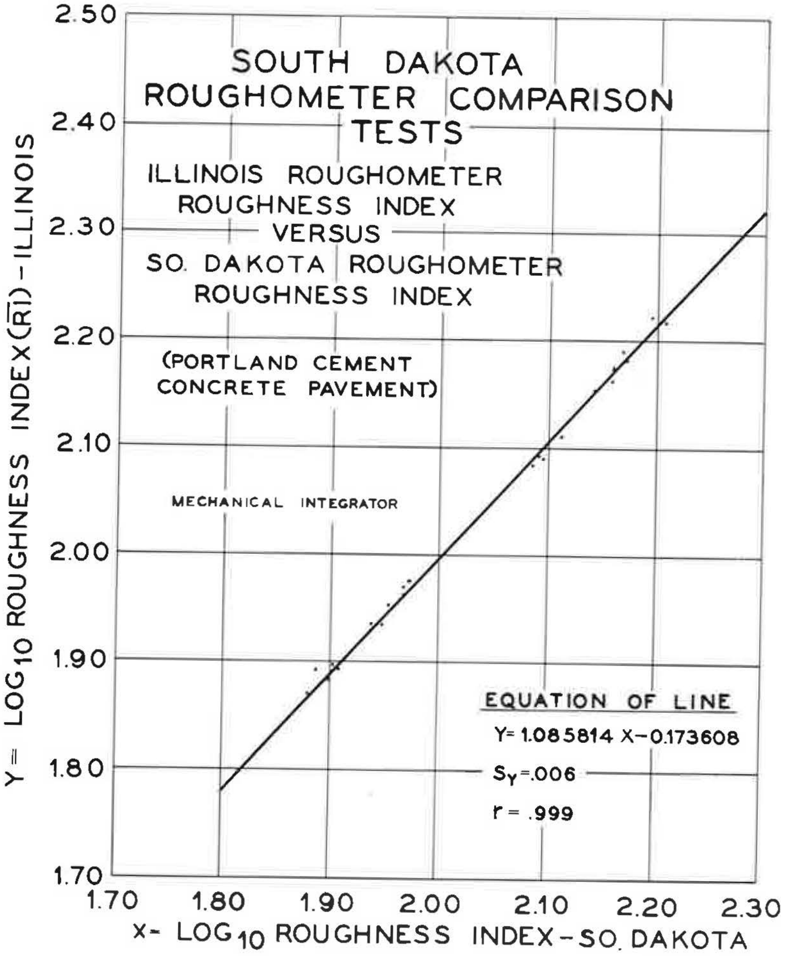


Figure 16 Machine performance.

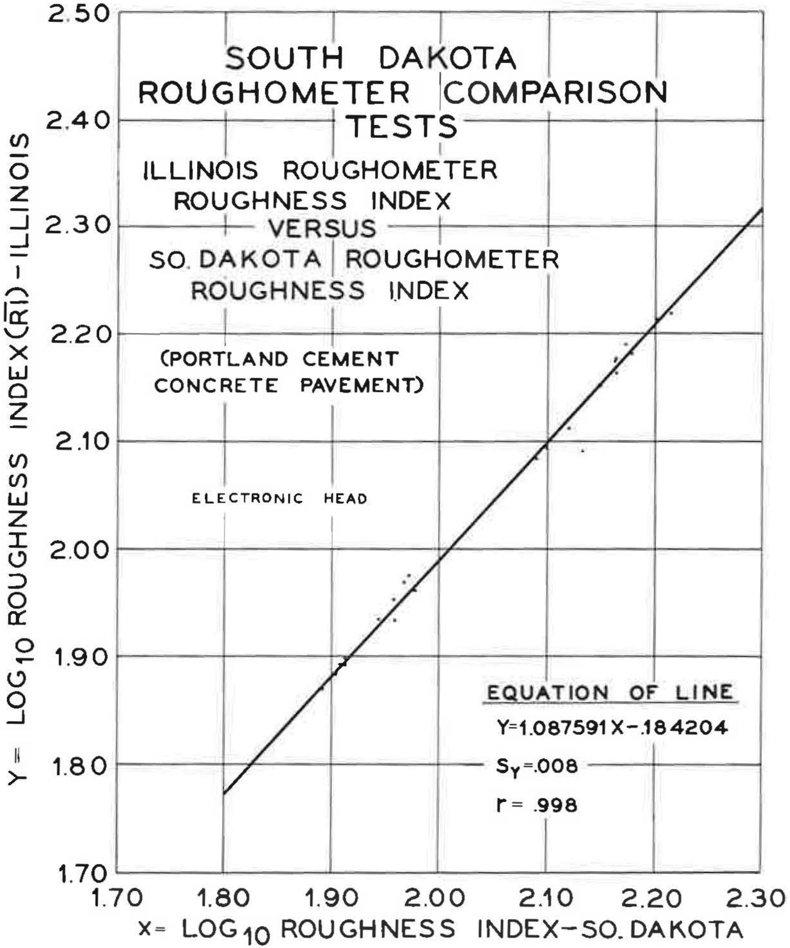


Figure 17. Machine performance.

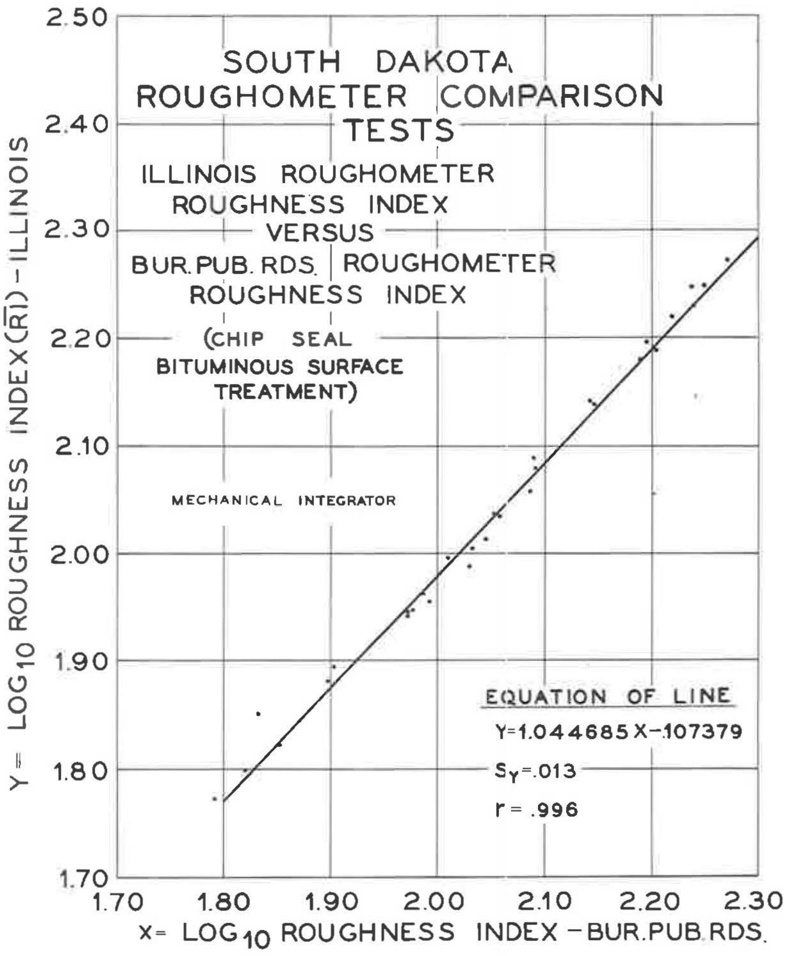


Figure 18. Machine performance.

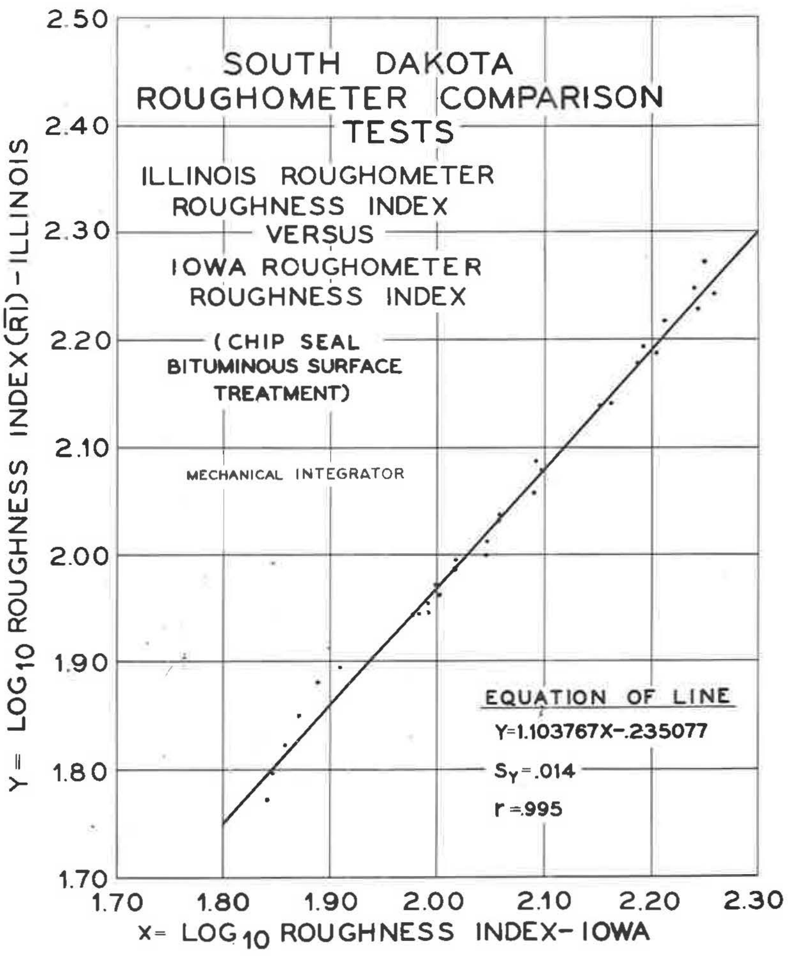


Figure 19. Machine performance.

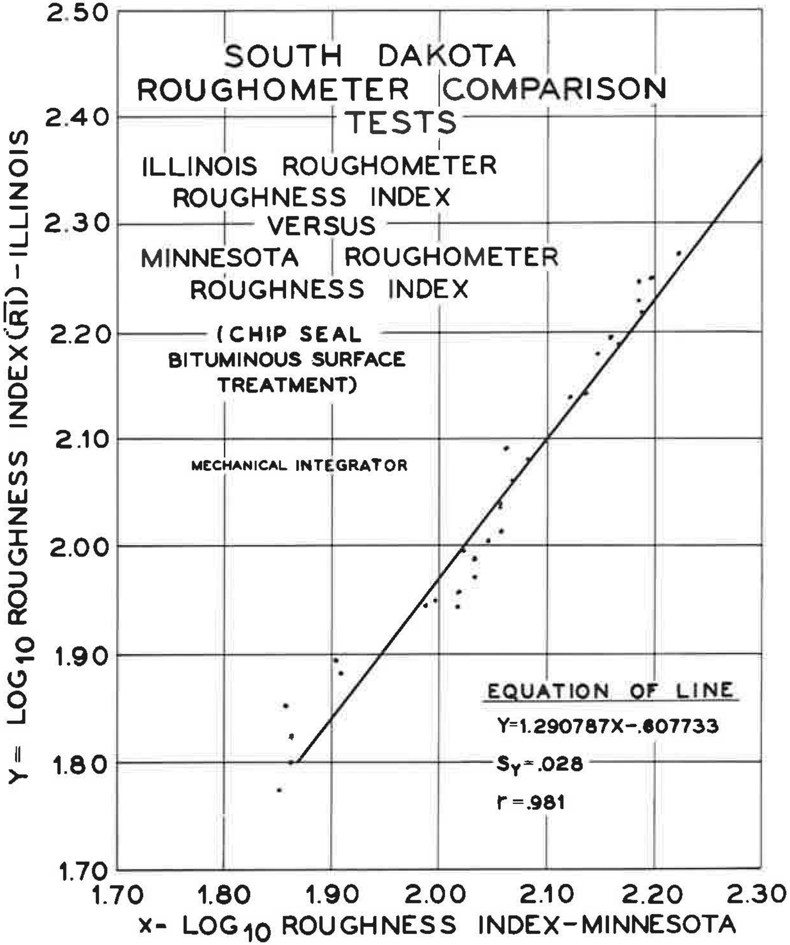


Figure 20. Machine performance.

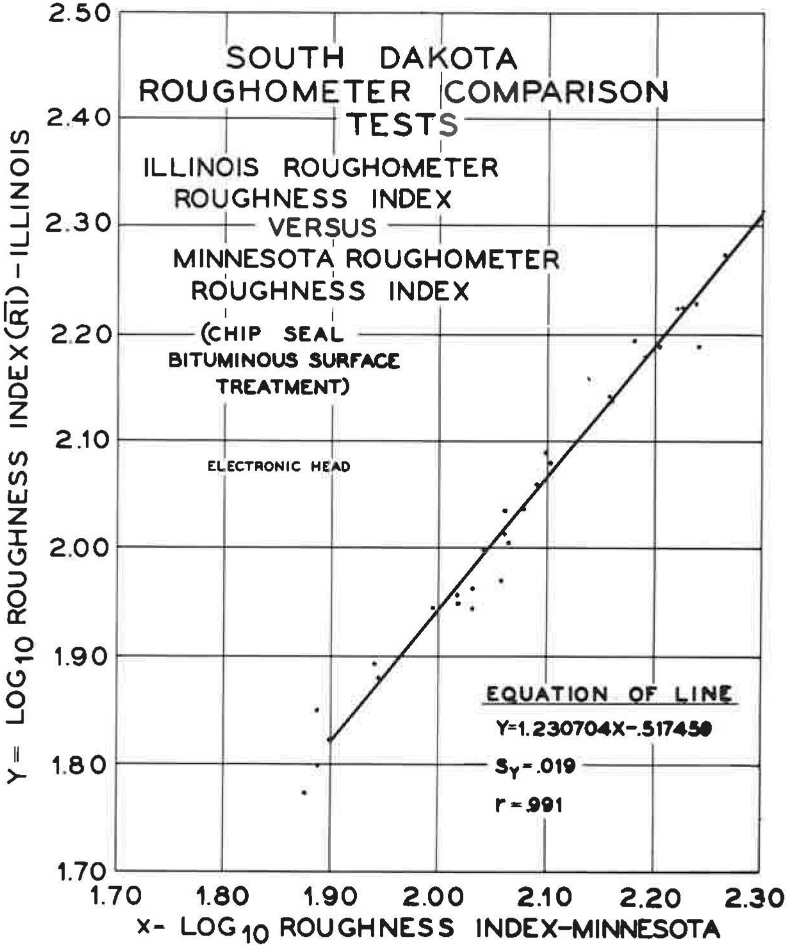


Figure 21. Machine performance.

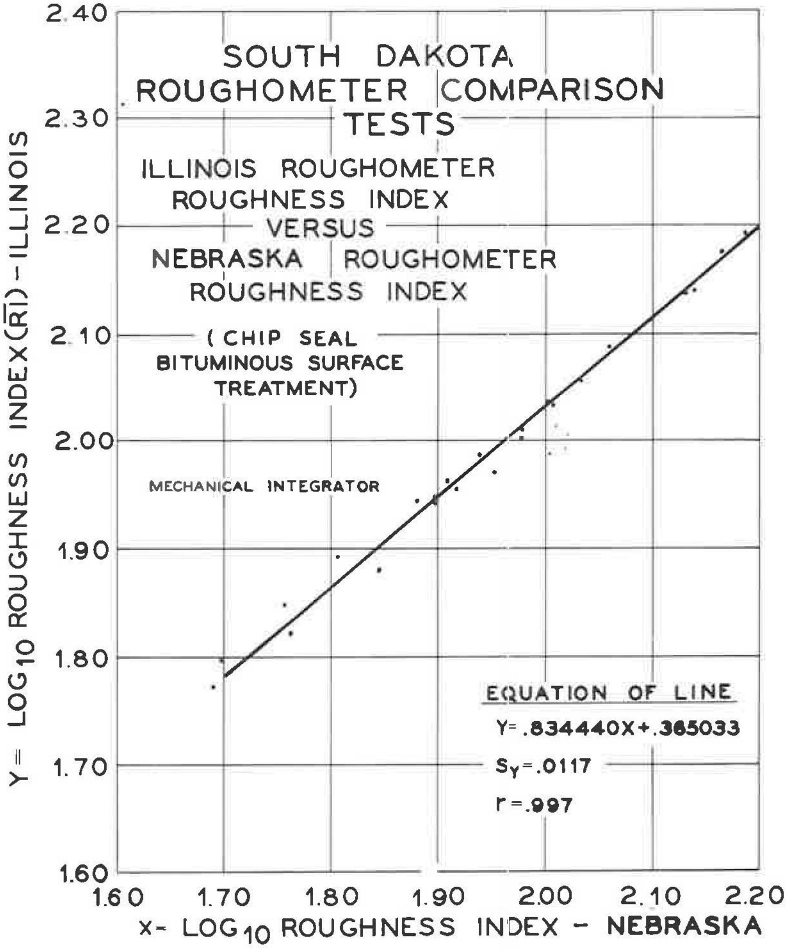


Figure 22. Machine performance.

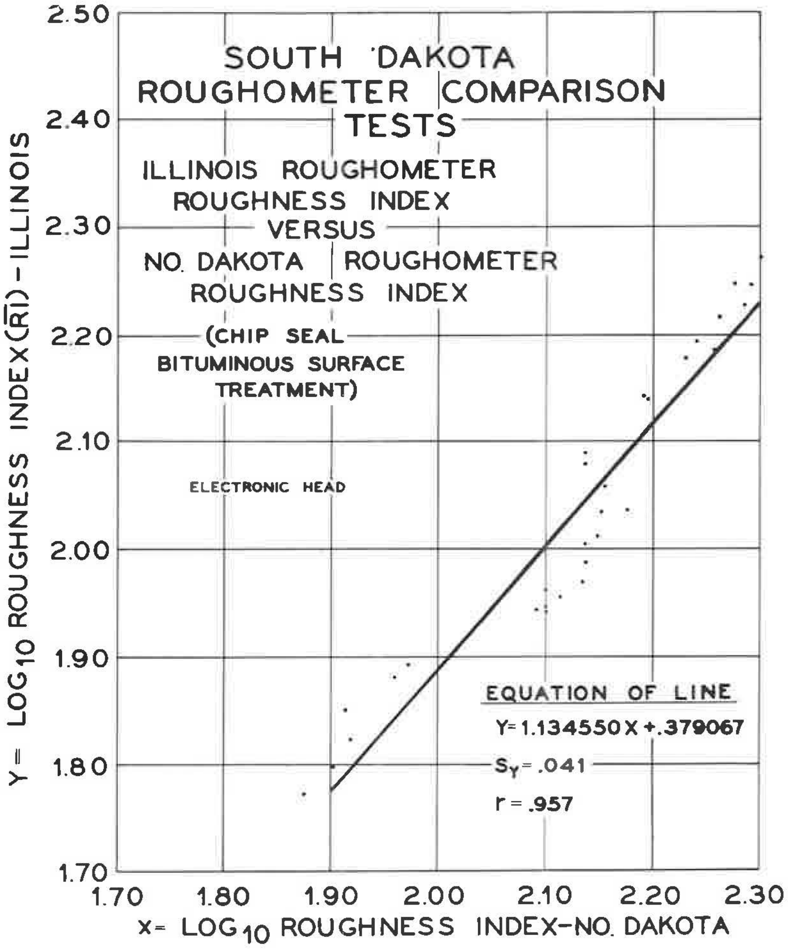


Figure 23. Machine performance.

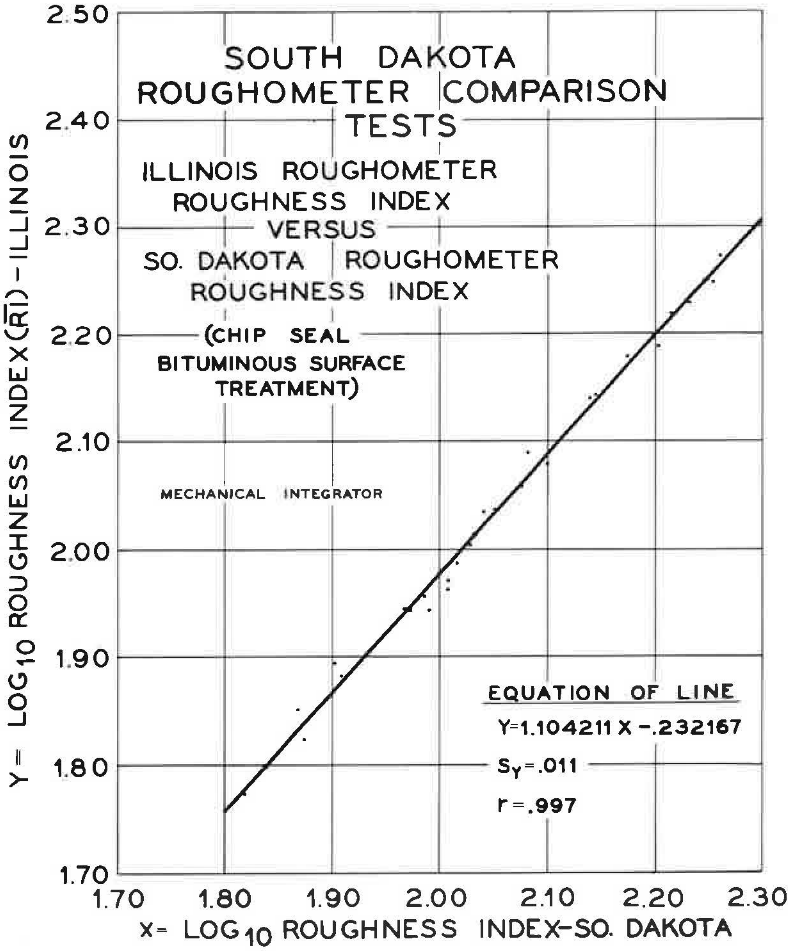


Figure 24. Machine performance.

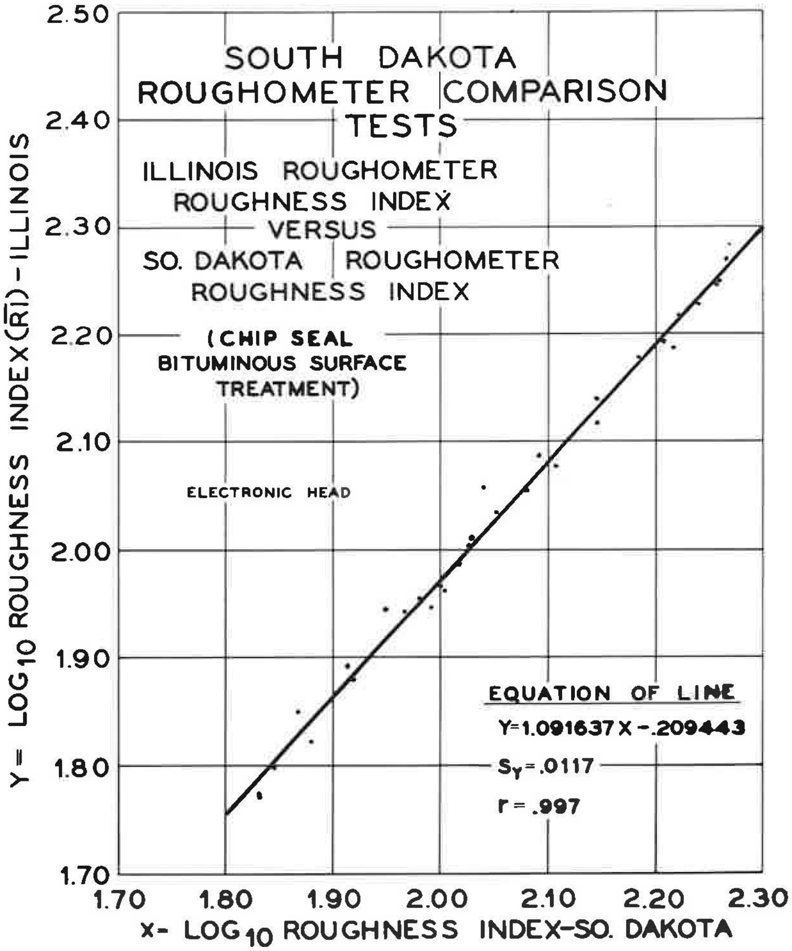


Figure 25. Machine performance.

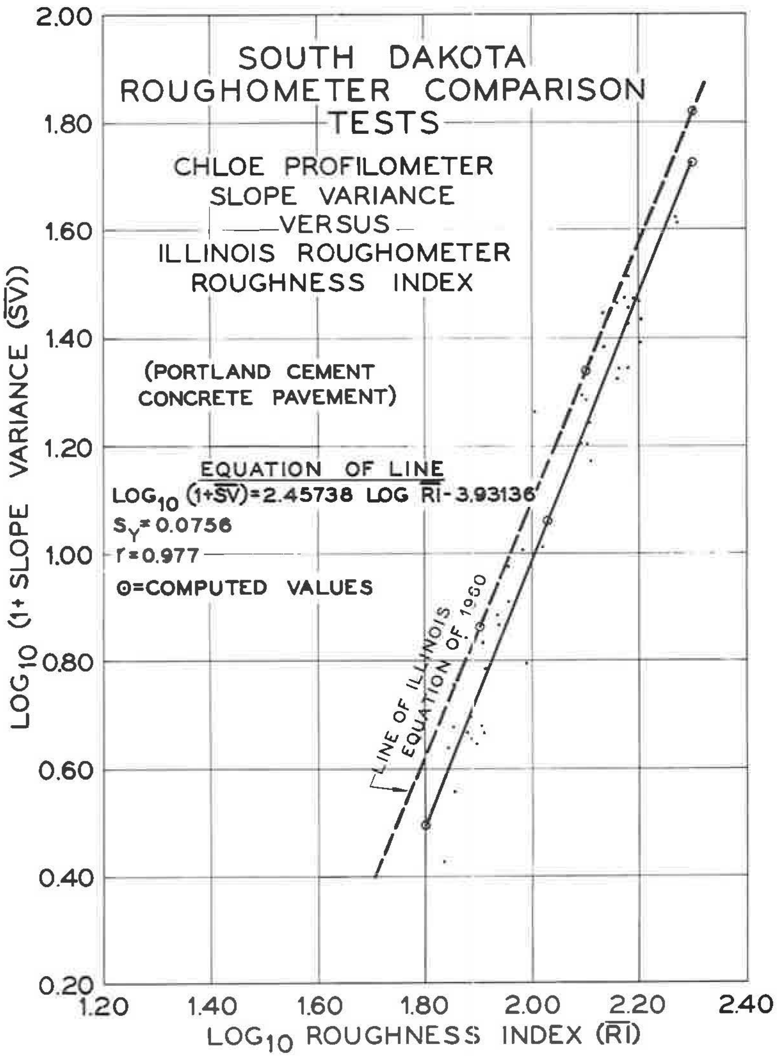


Figure 26. Machine performance.

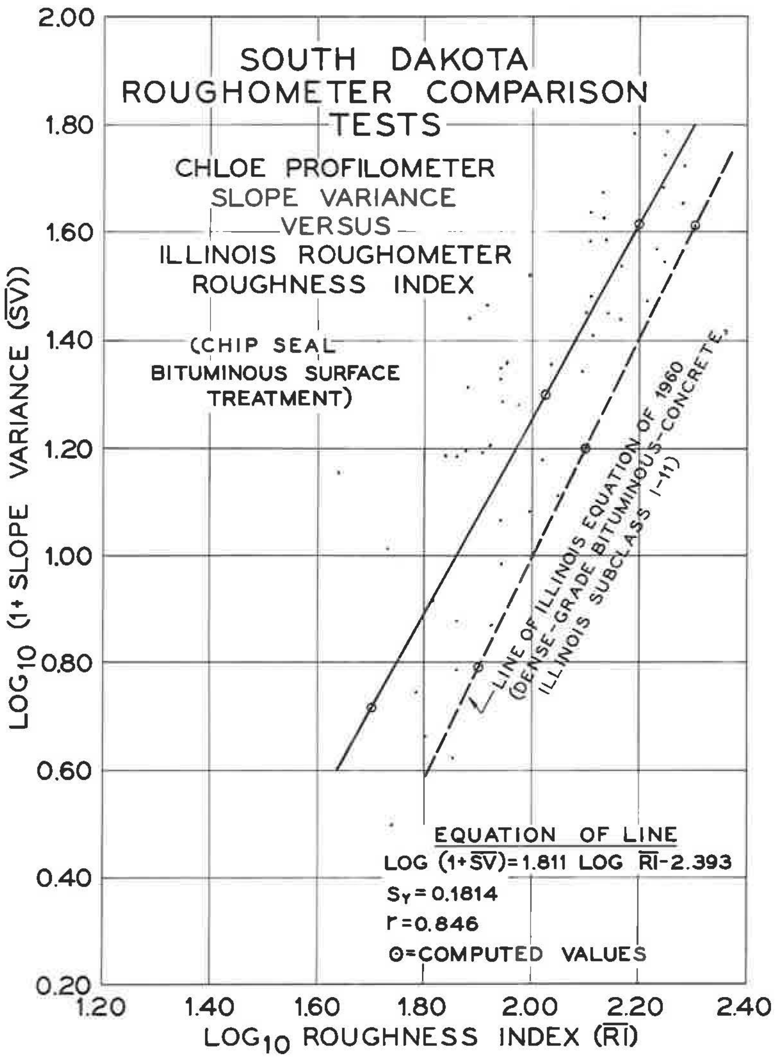


Figure 27. Machine performance.

TABLE 16

PRESENT SERVICEABILITY INDEX EQUATIONS[1]
DETERMINED BY SOUTH DAKOTA COMPARISON TESTS, 1962

Agency and Recording Method	PSI Equation
BPR mech. integ.	$PSI = 12.96 - 4.64 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
Ill. mech. integ.	$PSI = 12.41 - 4.37 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
Iowa mech. integ.	$PSI = 14.14 - 5.17 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
Minn.	
Mech. integ.	$PSI = 17.27 - 6.75 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
Magn. rdg. head	$PSI = 15.45 - 5.81 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
Neb. mech. integ.	$PSI = 11.54 - 4.01 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
N. Dak. mag. rdg. head	$PSI = 13.17 - 4.64 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
S. Dak.	
Mech. integ.	$PSI = 13.17 - 4.75 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$
Mag. rdg. head	$PSI = 13.21 - 4.76 \log_{10} \overline{RI} - 0.09\sqrt{C + P}$

---

[1] Portland cement concrete surfaces only.

Having determined the mathematical relationship between readings obtained with the Illinois device and the CHLOE profilometer, a PSI equation for the Illinois machine was obtained by simple substitution of terms developed for the slope-variance profilometer. Equations for each of the other devices that took part in the study were established on the basis of the relationships that were developed between the Illinois and the other roughometers (Table 16). Two equations are given for machines with both mechanical and electronic reading heads.

RESULTS

Some of the roughometers provided readings consistently higher than the average; others, consistently lower readings. Deviations from the average also differed somewhat in the high and low ranges. Overall, however, the readings and correlations are considered to be remarkably consistent, particularly for the rigid pavement.

Long-term variations in the BPR-type roadometer equipment are indicated by the differences in the results of the 1960 and 1962 correlations of the Illinois device with the slope-variance profilometer (Figs. 26 and 27). For satisfactory comparisons between roughness index readings made at different times by any one of these devices, it is apparently necessary that they be adjusted to a constant base. In Illinois, the 1960 calibration of the machine has been accepted as the base to which all subsequent readings are adjusted.

It is concluded that the BPR-type roughometer is a well-designed and reliable piece of equipment. Experience in the tests indicated, however, that it is a delicate scientific device and must be handled as such. Breakdowns and erratic readings sometimes occur, but these usually can be detected without great difficulty by the operators after they have gained some experience. Most malfunctions can be corrected in the field and false readings recognized before they are reported.

To discuss the results obtained with the CHLOE longitudinal profilometer (Table 14), a brief explanation of its operation is necessary. The profilometer measures the slope variance at approximately 6-in. intervals. This provides about 1,000 readings in a 500-ft section. The number of counts in each section is shown in the column headed N in Table 14. The slope-variance readings are fed into a binary computer in the towing vehicle which sums and records the readings (Y). It also computes and records the sums of the squares of the slope-variance readings (Y^2).

Although successive runs were not made on any section with the CHLOE to check its reproducibility, experience indicates that wide deviations are unlikely. The device is so constructed that there is no reason to believe that its output had changed since its original construction and correlation.

There is some indication (Table 14) that the CHLOE profilometer may not have consistently yielded a complete series of slope-variance readings for the chip-seal surfaces and some of the rougher surfaces elsewhere. For these sections, the count values (N) were frequently well below the 1,000 that would be expected for a measured 500-ft length. It is possible that in some instances extremely sharp slope variations were skipped entirely, and at other times were beyond the limits of the machine and were recorded lower than actual. However, this is not believed to have occurred with any great frequency.

Overall, the results obtained with the CHLOE profilometer are credible and satisfactory for use in the correlations reported herein with respect to portland cement concrete pavements.

The CHLOE profilometer operated satisfactorily except for a short-circuited switch and a broken circuit. Such malfunctions can be repaired without much difficulty by someone familiar with the maintenance of electronic equipment. The major disadvantages in its use were the limited coverage due to its slow speed, and the constant danger during its operation in the faster-moving regular traffic stream.

It was apparent that the reaction of both the CHLOE profilometer and the BPR-type roadometers was influenced by the surface texture of the bituminous chip-seal treatments to the extent that the PSI formulas developed for the flexible pavements of the AASHO Road Test were not applicable. The inconsistencies substantiated the belief that a high priority should be assigned to further study of the development of PSI formulas for surface textures differing appreciably from those of the AASHO Road Test. Such a study might well include such paved surfaces as brick and sheet asphalt, and although no verification was possible through the South Dakota study, it should also include bituminous-concrete resurfaced rigid pavements to determine the influence of reflection cracking on the PSI formula.

The South Dakota Department of Highways conducted a series of auxiliary tests in which its roughometer was used to record roughness of 11 bituminous mat pavements prior to and immediately following the application of a chip seal. The roughness indexes were found to have increased on each project following the application, ranging from 14 in. per mi to 37 in. per mi and averaging 24 in. per mi.

Although deficiencies were found in both the BPR-type equipment and the CHLOE profilometer, their overall behavior was encouraging. The behavior or the BPR-type devices was particularly encouraging, and no reasons were apparent that would indicate that they should be supplanted by other equipment or that their use should be curtailed. However, frequent calibrations are necessary to furnish reliable results, and occasional tests of the magnitude and scope of the South Dakota tests are necessary for wide-area correlation.

REFERENCES

1. Crawford, R. A., "Flexible Pavement Research in South Dakota." HRB Bull. 321, 40-62 (1962).
2. "The AASHO Road Test: Report 5, Pavement Research." HRB Special Report 61E, 10 (1962).
3. Carey, W. N., Jr., and Irick, P. E., "The Pavement Serviceability-Performance Concept." HRB Bull. 250, 40-58 (1960).
4. Chastain, W. E., Sr., "Application of Road Test Formulas in Structural Design of Pavement." HRB Special Report 73, 299-313, Table 1 (1962).

5. Chastain, W. E., Sr., and Burke, J. E., "Experience with a BPR-Type Roadometer in Illinois." HRB Bull. 328, 52-58 (1962).
6. "The AASHO Road Test: Report 5, Pavement Research." HRB Special Report 61E, 300 (1962).