ROUGHNESS AND SKID RESISTANCE MEASUREMENTS OF PAVEMENTS IN CALIFORNIA

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SYNOPSIS

In this paper results of measurements of road roughness and skid resistance are given for more than 50 different road surfaces in California The test methods and equipment used were described in last year's report of the Committee on Road Surface Properties as published in the Highway Research Board Bulletin No. 27. An important objective in these tests has been the development of testing equipment and of calibration and testing methods which will assure greater consistency and accuracy in the test results, wherever this equipment is used, than has been possible heretofore.

It is believed that the basic design of the Bureau of Public Roads roughness trailer used in these tests is fundamentally sound and that it provides the simplest and most accurate measure of road roughness which has been developed to date. Various test and calibration procedures, however, indicated that under certain conditions inconsistent results were obtained which could be corrected by modifications developed at the University of California in the design of the trailer. Also, an important new feature added to the trailer, was the oscillograph equipment which provides a continuous record of road roughness. Records of the integrated values of road roughness and the corresponding oscillograms can be taken at the same time and the results correlated

The details in the design of the trailer improvements and of the oscillograph equipment are given together with the design details for the calibration equipment. The calibration and testing procedures which are proposed in this paper will make the equipment standardizable and will permit making reliable comparisons of the roughness of road surfaces wherever this equipment is used

Integrated roughness values of 40 in. per mi. have been recorded on new p.c. concrete pavements on three different construction jobs in California. These values are approximately one-half of the values for the smoothest p.c. concrete in the middle west and eastern United States as measured with similar equipment. The remarkable smoothness of p c. concrete pavements in California may be attributed largely to the use of the Johnson finishing machine which removes all major and minor surface irregularities by a succession of planning and floating operations requiring as many as 6 to 8 passes of the finishing machine. Roughness values in the range of 56 to 60 in. per mi. have been measured on the smoothest asphalt pavements in California. These values are only slightly lower than the values measured on the smoothest asphalt pavements in Virginia. They were obtained both in Virginia and in California on hot plant mix pavements designed to provide maximum stability and where

superior workmanship with asphalt finishing machines and flat rollers eliminated practically all surface irregulatities. The roughness valuse for asphalt seal coat type surfaces were approximately double the values obtained on plant mix jobs laid with finishing machines.

The skidding resistance measurements were made on dry and wet surfaces by three different methods (1) towing a trailer with a truck at constant speed and recording the speed and braking effort with one trailer wheel locked, (2) locking all wheels of a passenger car and measuring the total stopping distance, and (3) locking all wheels of a passenger car and recording the speed and rate of deceleration by means of electronic and oscillograph equipment.

The major objective in these tests was to develop testing equipment and testing methods which would yield the most accurate and complete information in regard to the skid resistance of road surfaces for which published data are available It was also proposed to measure the skid resistance on certain types of surfaces, such as the open grid steel bridge floors, for which published skid resistance values have heretofore not been available

The truck-trailer method provided the greatest ease and flexibility of operation of the methods used because it permitted operation at constant speed on roads carrying high traffic volumes without interfering with traffic or creating a hazard when running the wet tests Also the use of electric brakes permitted a wide variation in the braking forces up to the maximum impending-skid (rolling wheel) braking force and the maximum sliding (locked wheel) braking force The passenger car braking tests required the use of auxiliary watering equipment, a flag man, and large signs to control traffic while the tests were being run These tests, however, represent a common form of braking when making an emergency stop and the oscillograms showing the deceleration at any given speed provided an excellent method for comparing the tire-road friction as measured by the truck-trailer (constant speed) method with the passenger car deceleration method

Braking tests were made at speeds from 10 to 50 mph in the truck-trailer method and from 10 to 40 mph in the passenger car braking tests except on certain slippery wet surfaces where it was found to be too dangerous to attempt a braking test with the passenger car from 40 mph. The skid resistance of each surface was checked with three types of tires (1) synthetic rubber with a non-skid tread pattern, (2) natural rubber with a non-skid tread pattern similar to that on the synthetic rubber tires, and (3) synthetic rubber with tread worn smooth.

Skid resistance measurements were made on more than 50 surfaces using the truck-trailer method with check measurements on 6 representative surfaces by the other two methods

The friction values ranged from a maximum of 0 8 on dry pavements at low speeds to a value approaching 0.1 on wet sections of glazed asphalt pavements at 50 mph. Values in the range of 0 2 to 0.3 were obtained on the worn open-grid steel bridge floors in the wet tests indicating a slippery-when-wet condition for surfaces of this type. The impending-skid friction values were from 10 to 100 percent higher than the sliding-skid friction values for corresponding speeds on the same surface

The coefficients of friction computed from the total stopping distances represent the average friction over the entire speed range and include both the impending-skid and sliding-skid friction values The

stopping distance friction values are usually reported in terms of the initial speed and on this basis are 10 to 15 percent higher than the corresponding values for the given speed on the same surface as measured in the truck-trailer and passenger car decelerometer tests. The oscillograms showing a continuous record of the instantaneous braking forces in the truck-trailer method and of the deceleration and speed in the passenger car tests provide a most interesting, accurate and detailed record of skid resistance and braking performance under many different road conditions which should be very helpful in determining the pavement design and construction practices which provide a high degree of skid resistance or which contribute to the slippery-when-wet condition. Charts and tables are presented in the paper giving the detailed results of the skid tests with interpretations to indicate the skid resistance of all the major types of surfaces and the factors which influenced the values obtained in the tests

In the report of the Committee on Road Surface Properties presented last year at the Annual Meeting and published in Bulletin No. 27, a brief summary of the previous work in measuring road roughness and the skid resistance of road surfaces was given. Also given in the report were preliminary test results and a description of the equipment currently being used by the Institute of Transportation and Traffic Engineering of the University of California at Berkeley.

During the past year further improvements have been made in both the road roughness and the skid resistance test equipment at the University of California. An important objective in this work has been the development of testing equipment and of calibration and testing methods which will assure greater consistency and accuracy in the test results and which may lead to the adoption of a national standard for measuring road roughness and skid resistance. Many devices and methods have been developed by previous investigators to measure road roughness and skid resistance, but the results especially of the road roughness measurements varied greatly and were expressed in so many different units as to make comparisons meaningless.

It is believed that the basic design of the BPR roughness indicator is fundamentally sound and that it provides the simplest and most accurate method to measure roughness which has been developed to date. The improvements made on the trailer and the addition of a direct recording oscillograph to obtain a graphical record of roughness, are recent developments in the current research by the Institute which should make this equipment more acceptable as a standard for measuring road roughness. A detailed description of the improvements and related standardizing features in the use of the BPR roughness indicator are given in this report.

Skid resistance measurements in the current study were made on various road surfaces by three different methods partly for the purpose of determining variations in the test results by the three methods and also to determine the advantages and disadvantages of each method which should be considered in establishing standard test equipment and procedures. Special attention was given to obtaining greater accuracy, versatility and mobility of the test equipment than was obtained in previous studies. A detailed description of the testing equipment and procedures and a discussion of the test results in measuring skid resistance is given in the latter part of the report.

IMPROVEMENTS IN DESIGN AND CALIBRATION TECHNIQUES OF THE BPR ROUGHNESS INDICATOR

The road roughness indicator used in the current research at the University of California was built in 1941 from plans furnished by the U.S. Bureau of Public Roads. For the first year and a half, it was used in measuring the roughness of more than 1,000 mi. of roads in Iowa, Kansas, Missouri, and Wyoming in an extensive road research program sponsored by Iowa State College. Following this intensive use, it was kept in storage until June 1949 when it was acquired by the University of California for the current research. Although the results of the roughness tests with the BPR indicator were highly satisfactory, it was recognized that certain improvements in design and in the calibration of the unit would be highly desirable to improve its accuracy, consistency, and general utility, especially if it were to be considered for adoption by the highway departments in the various states and cities as standard equipment for measuring road roughness.

The following items in the design and operation of the trailer were investigated and will be described in the discussion which follows: 1. Tire type and roundness requirements. 2. Oil leakage in dashpot damping units. 3. Improved integrator design. 4. Equipment and method for calibrating integrator. 5. Integrator cable. 6. Development of direct recording oscillograph equipment. 7. Calibration of the roughness trailer unit.

Tire Type and Roundness Requirements- The BPR plans and specifications call for a standard four-ply 6.00 by 16 rib tread tire for the wheel on the trailer. The early tests using a trailer with a rib tread tire, indicated that on certain surfaces stone chips and gravel particles were picked up by the tread and were lodged in the grooves of the tread pattern. This had the effect of increasing the roughness by an unpredictable amount. To correct this condition, a four-ply 6.00 by 16 tire with a smooth tread has been used in all of the tests with the Institute trailer.

Another important tire item not covered in the BPR specifications, is that of checking the roundness of the tire. The first indication that the tire on the Institute trailer was not perfectly round, was in the oscillograms for the roughness of a smooth p.c. concrete pavement. In these oscillograms, it was noted that there was a continuous ripple, resembling a sine wave with a period or cycle of 7.2 ft. Measurements of tire diameters showed that the tire was 0.061 in. out of round. It was obvious that this had an appreciable effect on the roughness measurements and steps were taken to correct this defect. The tire was placed in a large turning lathe and by using a special carborundum grinding tool, the tire tread was ground down to within 0.001 of an inch tolerance in tire diameters. Subsequent oscillograms on smooth concrete pavements showed no evidence of the sine wave type ripples previously observed.

The above experience clearly indicates the need for checking the tire for cleanness since it is obvious that if patches of mud, oil or asphalt are permitted to stick to the tire, the roughness readings will be increased by an unpredictable amount.

Oil Leakage in Dashpot Damping Units- An annoying feature in the operation of the trailer, was the leakage of oil past the bronze bushings at the top of the dashpots of the damping unit. This leakage which amounted to as much as a half a pint of oil in one day's operation was caused by the wear of the bushings which had developed after many thousands of miles of operation of the trailer. Instead of replacing the worn bushings, it was decided to machine grooves in the bushings and insert rubber "O" rings which should have as good or better sealing effect than new bronze bushings. A further advantage of the "O" rings is that they can easily be replaced if further wear or leakage develops. The use of the rubber "O" rings effectively stopped all oil leakage.

Improved Integrator Design - The integrator (See Fig. 1) is the most important part of the BPR roughness measuring mechanism. It has given us more trouble and required more attention than any other part of the roughness unit. A careful check of the integrator indicated excessive wear largely because the case was not dustproof. Also there was some misalignment of parts, such as of the main shaft, which caused the integrator to "grab" and resulted in lower values for road roughness than the true values. The worn parts in the integrator were replaced, the shaft was realigned and a dustproof cover was built to enclose the entire integration unit.

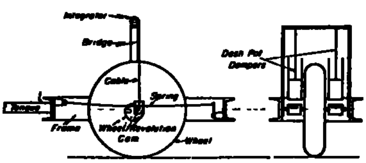


Figure 1. Schematic Diagram of the Essential Elements of the Bureau of Public Roads Road Roughness Trailer

The most serious difficulty with the integrator has been at the point of contact between the carbon brush and the commutator plate. It was noted that there was arcing at this point for each break of the magnetic counter contact. The arcing caused pitting in the insulating material of the commutator and this in turn caused excessive brush wear and thin coatings of carbon to be deposited over large areas of the commutator. The carbon coatings caused erratic double readings, especially on very smooth surfaces. Various corrective measures were tried out to prevent the arcing and brush wear but it was finally decided to replace the brush-commutator design with a six-pronged cam Micro Precision Switch design (Fig. 2). The six-pronged cam was attached to the back face of the integrator and is operated by the same shaft which operates the commutator plate. The Micro Precision Switch, Type L-2, is mounted in such a way that each complete rotation of the cam actuates the switch six times, thereby recording six inches of road roughness which is also the value obtained with a properly functioning brush contact design. The six-pronged cam Micro Switch design has given no trouble and, since it is much easier to build than the brush-commutator design, it is recommended as the preferred design.

While we were experimenting to correct the arcing trouble in the brush-commutator design, we used a low current relay and several condensers in the system. When we changed over to the cam design, we retained the relay and the condensers since in this way the arcing across the Micro Switch and relay contact points was reduced and this should increase the life of Micro Switch and the relay.

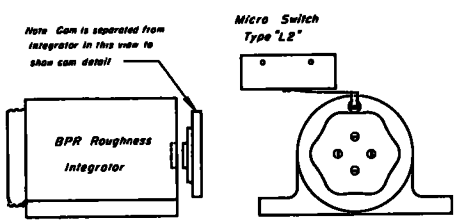


Figure 2 Modification to the BPR Roughness Integrator

Equipment and Method for Calibrating Integrator - Since the accuracy of the measurements with the BPR roughness indicator depends largely on the accuracy of the integrator, a calibrating device for the integrator which meets the general recommendations as given in the BPR Manual of Instructions, should serve a very useful purpose. The unit developed by the Institute for this purpose is shown in Figure 3. It consists of a 1/60 horsepower motor running at 1800 rpm acting through a gear reduction box which permits operation at 20, 50, and 150 rpm. On the drive shaft from the gear box, a cam having a T-slot and set screw arrangement is fitted so that one end of the connecting rod can be set at any radius from 0.001 to 0.75 in. The cam is used to actuate a Micro Switch which operates the magnetic counter normally used to count the wheel revolutions of the trailer but which in the calibration of the integrator, counts the number of revolutions or repititions of "roughness" of known displacement for which the cam is set. The other end of the connecting rod is attached to a slider which moves with a reciprocating action and is clamped to the integrator cable. The integrator measures the "roughness" in inches for a predetermined number of revolutions of the cam. The cam can be set to give a reciprocating stroke of from 0.002 in. to 1½ in. at a frequency of from 20 to 150 cycles per minute. Typical results of a calibration of the integrator are given in Table 1. It should be noted that for a small amplitude of 0.101 in., the "roughness" as measured by the integrator was exactly the same as that measured by the calibrating unit. As the amplitude was increased, the error increased to a maximum of 2.8 percent which is within the maximum error (±3 percent), specified in the BPR Manual of Instructions.

The calibration unit developed by the Institute provides a fast and convenient method of calibrating the integrator. The entire unit, including base plate, only weighs about 15 pounds. It can be attached directly to the frame of the trailer with two bolts and the calibration can be made without dismantling any part of the trailer.

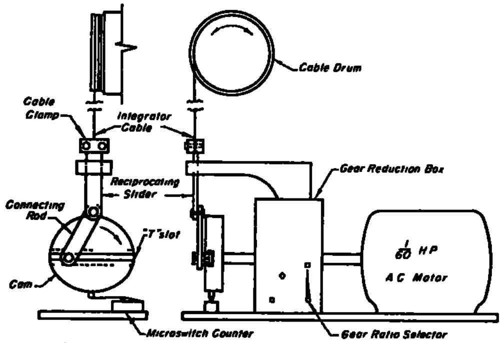


Figure 3. Schematic Diagram of the Calibration Unit for the Roughness Integrator

Integrator Cable - The BPR plans for the trailer specify that the cable used with the integrator should be a Roebling stainless steel wire cable or equivalent with a diameter of 3/64 in. consisting of 3x12x0.005 in. diameter wires. The Roebling cable could not be obtained in the San Francisco-Oakland Area and various substitutes were tried out by using the integrator calibration unit. A radio dial cable of the specified diameter was used in the first trial. This cable elongated 0.01 in. with each stroke or cycle and, therefore, introduced errors in the range of 1 to 10 percent depending upon the amplitude of the stroke. A bronze fish leader with a nylon core and with an over-all diameter of 3/64 in. elongated 0.018 in. per stroke. The tests with this cable produced even poorer results than the tests with the radio dial cable. A stainless steel cable of the type used in airplane controls was finally located which had the required size, strength and pliability. The results

TABLE 1

TYPICAL RESULTS OF ROUGHNESS INTEGRATOR CALIBRATION

Amplitude of Stroke Inches	Speed Cycles per Minute	Total Cycles	Correct Reading Inches	"Roughness" Integrator Reading Inches	Percent Error
0.101	150	1000	101	101	0
	50	1000	101	101	0
	20	1000	101	101	0
0.253	150	1000	253	258	+2.0
	50	1000	253	256	+1.2
	20	1000	253	256	+1.2
0.504	150	1000	504	517	+2.6
	50	1000	504	517	+2.6
	20	1000	504	519	+2.8

of calibration tests with this cable are given in Table 1 and since the error for all frequencies and magnitudes of stroke ranged from 0 to 2.8 percent, this cable was accepted as meeting the BPR specifications.

Development of Direct Recording Oscillograph Equipment - The need for a graphical record of road roughness was discussed in last year's report published in Bulletin 27. Also, given in the report was a general description of the direct recording oscillograph equipment developed at the University of California which makes it possible to obtain a graphical record of the road roughness as measured by the BPR Roughness Indicator. During the past year there have been a number of inquires requesting a more detailed description of this equipment including the wiring diagrams. This information is now available and will be covered in part in this report.

The close-up view in Figure 4 shows the latest developments in the trailer design. The two items of major importance shown in this figure are the integrator and the potentiometer. The latter serves as the pick-up unit which is used to obtain the graphical record with the direct recording oscillograph. Both the integrator and the potentiometer units are now housed in dustproof cases mounted on the trailer frame. A schematic diagram of the oscillograph equipment using batteries as the power source is shown in Figure 5. Wiring diagrams for battery operation are given in Figures 6 and 7.

During the past year a Chevrolet Carry-all was fitted out for use in various types of road tests. A small Homelite generator was mounted on the rear bumper to supply 110 volt 60 cycle current for the oscillograph and other equipment. With this new power supply available for road tests, the carry-all was equipped for use in the roughness tests as the towing vehicle and the electronic equipment was modified to use the portable power supply instead of the batteries. The wiring diagram for use with a portable power source is shown in Figure 8.

The oscillograms obtained with the portable power source are in every respect the same as those obtained using batteries as the power source if the tests are run over the same section of road. The portable power unit has a higher initial cost and is not as easy to install as the battery unit. However, there is some difficulty in keeping the batteries fully charged in an extended testing program and for such a program the portable power supply is more dependable and may in the long run cost less than if batteries are used.

The calibration of the integrator, discussed earlier in this report, may be considered as the first important step in the calibration of the trailer. A road calibration test of the roughness trailer, involving the use of artificial obstructions of known height and size, is proposed as the second and final step.

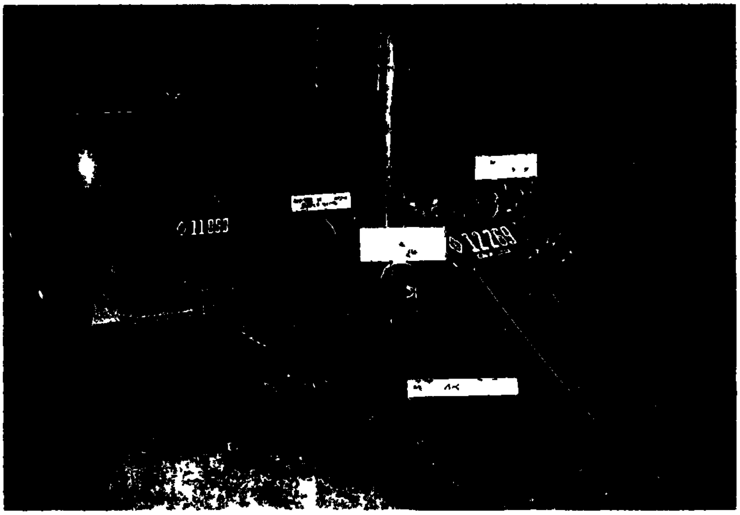


Figure 4. Road Roughness Indicator

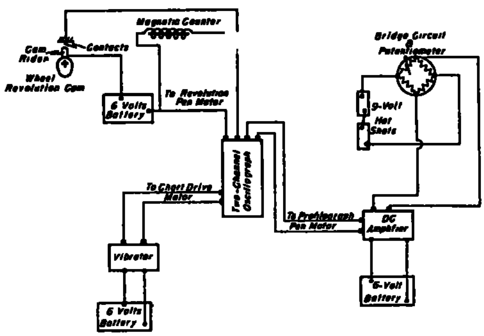


Figure 5. Schematic Diagram of the Essential Elements of the Profilograph Equipment for Battery Operative Conditions

Calibration of the Roughness Trailer- In our study of methods for standardizing the BPR trailer, it appeared desirable to develop a standard method such that the results of tests in the various states with a BPR type trailer would be directly comparable.

The following is a description of the proposed calibration test which has been tried out in the current research of road roughness at the University of California. Included also is a brief discussion of the results of this test.

The road test for calibrating the trailer in our study consisted (1) in measuring the roughness of a 1/4 mi. section of smooth p.c. concrete pavement; (2) a given number of obstructions of known dimension (see Table 2) were then placed on this section and the roughness again measured by having the trailer run over all of the obstructions; (3) the difference in the roughness values in these two measurements represents the roughness due to the artificial obstructions and provides a direct basis of comparison for trailers used in various states; and (4) as a final check oscillograms were taken in all of the tests so that the effect of each type of obstruction on the graphical record of roughness could be determined.

The results of the trailer calibration test are given in Table 2. It should be noted that for a 1/2 in. diameter road the measured roughness is about one-half the total height of the rods, for plates 6 in. wide of the same thickness as the rods, the measured roughness was double their total height, and for plates 18 in. wide the roughness was about three times their total height.

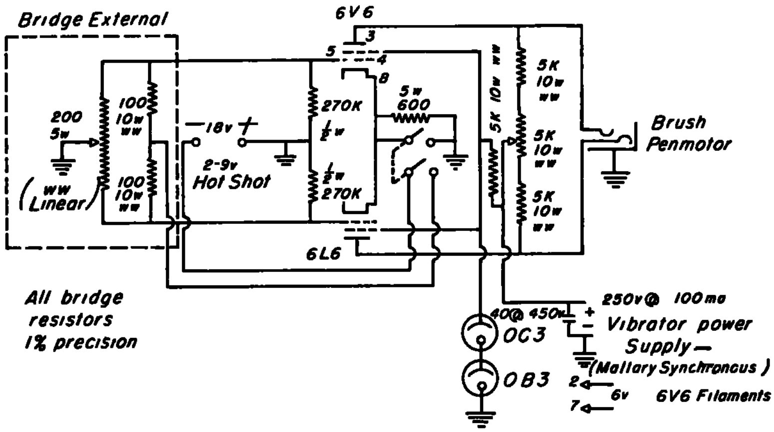


Figure 6 Electronic Viagraph and External Bridge Circuit for Battery Operating Conditions

TABLE 2

RESULTS OF CALIBRATION TESTS OF UNIVERSITY OF CALIFORNIA ROUGHNESS TRAILER

Length of Test Section Miles	Type of Obstruction	Number of Obstructions	Roughness, Inches	Total Height of Obstructions Inches	Roughness Caused by Obstructions Inches
1/4	None	0	12		
1/4	½-in dia steel reinforcing rod	20	16½	10	4½
1/4	½-in.x6-in.* steel plate	20	33	10	21
1/4	½-in.x18-in.* steel plate	7	22	3½	10
1/4	½-in x18-in steel plate	(20)**	(54)	(10)	(29)

*The 6-inch and 18-inch dimension is in the direction of travel of trailer.

**The values shown in ( ) are computed for 20 plates and are based on the test results for 7 plates.

The oscillograph records taken in the calibration tests are shown in Figure 9. A study of the traces in this figure clearly indicates the action of the trailer as it runs over the various obstructions. A comparison of measurements and records of this type should indicate differences in the action of the trailer in similar tests made by different trailers built to the same design standards. Of course, if all the trailers are built to the same design standard of proven accuracy, there should be no appreciable difference in the results of tests under like pavement conditions.

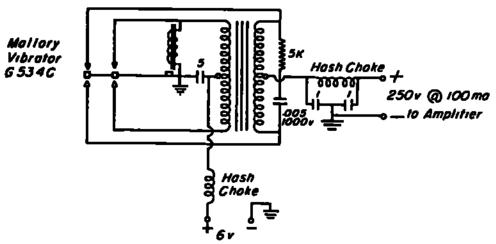


Figure 7 Electronic Viagraph Amplifier Power Source

For greatest accuracy in the calibration tests, the following precautions should be taken. Care should be taken in placing the obstructions to obtain a true measure of the obstructions. Thus, in placing the 1/2 in. rods, they should not be placed in a low joint since by so doing the full height or diameter of the rod cannot be measured. Nor should the plates be placed directly over joints or close to joints. Deformed reinforcing rods were used instead of the smooth bars because the smooth bars roll too easily and it is difficult to keep them properly aligned for the test.

RESULTS OF ROUGHNESS MEASUREMENTS ON PAVEMENTS IN CALIFORNIA

Roughness measurements have been made on more than 700 mi. of pavement surfaces in California with the BPR trailer during the past year and a half. The results of the measurements on pavements on rural state highways in California are given in Table 3 and Figure 10. These data were taken on state highways in

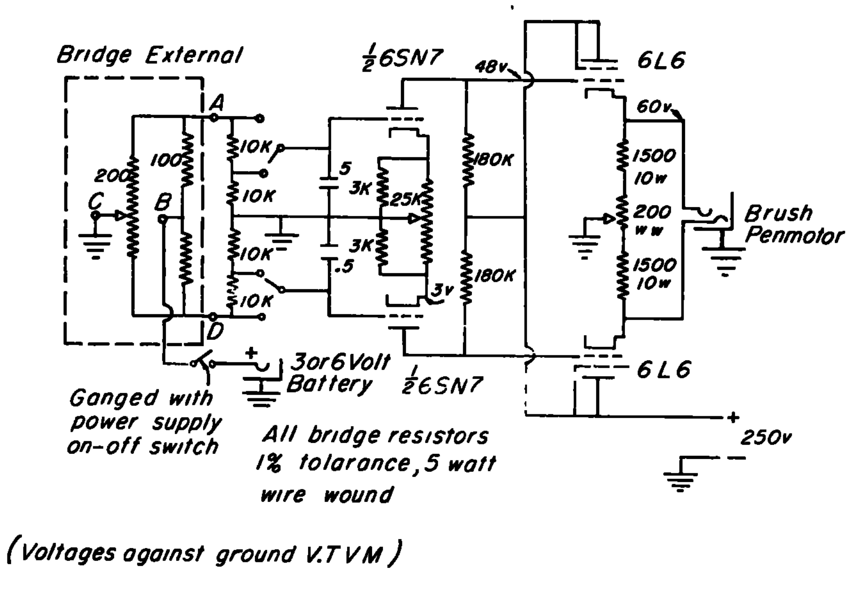


Figure 8. Electronic Viagraph Amplifier and External Bridge Circuit for Portable Power Conditions

northern California on routes US 40, US 50, US 99, and US 101. The pavement surfaces were of three types: (1) p.c. concrete built with a Johnson Finisher, (2) asphalt plant mixed surfaces (including asphaltic concrete) placed with asphalt finishing machines followed by heavy three-wheel and tandem rollers, and (3) asphalt surfaces with seal coats using various types of cover material applied with mechanical spreaders and made level and smooth by the use of drag brooms and medium weight tandem rollers.

The surfaces on which the tests were run were divided into two age groups, 0 to 2 and 2 to 20 years. It should be noted in Table 3 and Figure 10 that the lowest roughness values were obtained on the p.c. concrete pavements less than 2 years old with an average value of 52 in. per mile and a minimum value of 38 in. per mile. The asphalt plant mixed surfaces in the low age group ranked second in smoothness with an average value of 71 in. per mile and a minimum value of 52 in. per mile. The surfaces with an asphalt

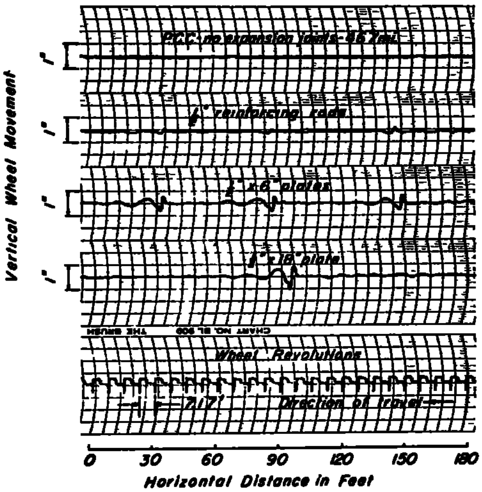


Figure 9. Roughness Oscillograph Records of Rods and Plates on a Smooth Pavement

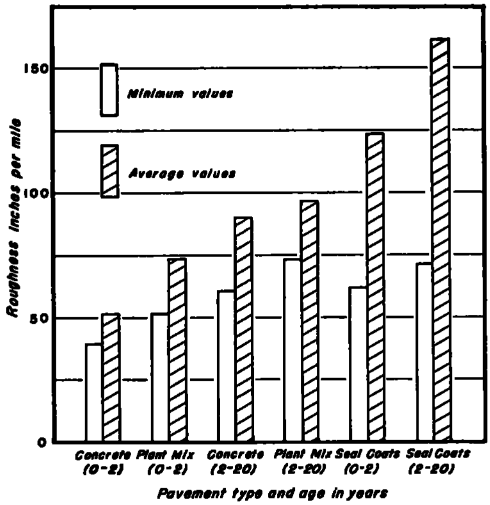


Figure 10. Roughness Values for Different Types of Pavement Surfaces on Rural State Highways in California

TABLE 3

RESULTS OF ROAD ROUGHNESS MEASUREMENTS ON PAVEMENTS ON RURAL STATE HIGHWAYS IN CALIFORNIA

Pavement Type	Age Years	Length Miles	Roughness in inches per mile		
			Maximum	Average	Minimum
P.C. Concrete	0-2	93	75	52	38
	2-20	41	136	91	62
Asphalt plant mixed	0-2	108	98	71	52
	2-20	72	148	97	71
Asphalt seal coat	0-2	87	188	124	62
	2-20	83	325	161	71

seal coat gave the highest roughness values with an average value of 124 in. per mile and a minimum value of 62 in. per mile for the low age group. There was a marked increase in roughness on all the surfaces in the 2 to 20 year age group but the values on the asphalt seal coat type surfaces were by far the highest with an average value of 161 in. per mile and a maximum value of 325 in. per mile.

As was mentioned in the report last year, the roughness values measured on the p.c. concrete pavements in California were consistently lower than the values reported for similar road surface types in other states where roughness tests with the BPR Indicator have been run. Likewise, the roughness values on bituminous pavements were also very low although the minimum California value for an asphalt plant mixed surface is only 10 units lower than the 62-in. per mile minimum value reported by Shelburne in 1948 for a bituminous concrete pavement in Virginia. It should be mentioned here that the values in this year's report for the smooth concrete and asphalt surfaces are from 10 to 20 units lower than the values reported for these surfaces last year. The lower values were obtained this year only on smooth surfaces after all the improvements in the BPR Indicator described earlier in this report were made. Similar low values were obtained in some of last year's test runs on these surfaces and could have been given in last year's report, but it was decided that the higher values given in last year's report should stand until we were confident that the lower values were correct.

Our studies during the past year have been directed toward the elimination of all errors or inaccuracies in the measurement of road roughness with the BPR Indicator. We believe that we have eliminated all of the sources of error and that the values reported this year are correct.

In regard to the low values of roughness on the pavements in California, credit should go to the Division of Highways for developing pavement finishing equipment and finishing methods during the past 20 years which have produced smooth surfaces. The key to building smooth concrete pavements in California may be attributed largely to the skillful use of the Johnson Finisher developed in California in 1936. The construction of smooth asphalt pavements is also largely due to the use of finishing machines, California played a leading part in developing asphalt finishing machines as is indicated by the fact that the first asphalt finishing machine used in this country in 1927 was an adaptation of a concrete finishing machine by C. S. Pope who was then Construction Engineer for the California Division of Highways. While many improvements in asphalt pavement construction have been made since that time, the one single factor

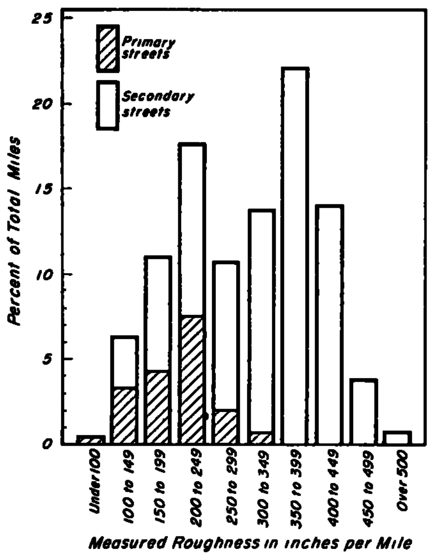


Figure 11 Distribution of Surface-Roughness Measurements for the Major and Secondary Streets of Berkeley

TABLE 4

EFFECT OF VARIATIONS IN SLAB TEMPERATURES ON THE ROUGHNESS OF THREE SECTIONS OF PORTLAND CEMENT CONCRETE PAVEMENTS

Tests Conducted October 16, 1950

Time PST	Temperatures in Degrees Fah. Ambient	Surface	At depths below surface 1-in.	4-in.	7-in	Roughness in Inches/Mile in Pavement Sections A	B	C
5:00 am						45	56	98
6.00	57	61	63	69	71	41	50	98
7:00	59	62	63	68	70	39	48	100
8 00	61	64	65	68	70	39	45	96
9:00	76	75	73	70	70	39	44	94
10·00	84	84	82	73	71	40	45	94
11 00	92	94	93	80	76	42	45	92
12.00	94	96	98	84	80	43	46	92
1 00 pm	91	94	99	84	80	39	41	94
2 00	90	99	101	88	83	42	45	96
3:00	91	97	101	91	86	46	48	98
4:00	90	94	98	92	88	48	49	100
5:00	85	91	92	93	90	50	52	100
6.00	79	81	86	89	88	54	56	102

Description of three sections of concrete pavement on US 40 near Fairfield, California.

Section A - P.C.C. - 1 year old, continuous reinforcing with no expansion joints.

Section B - P.C C. - 1 year old, dummy joints on 15-ft centers

Section C - P.C.C. - 8 years old, 15-ft joint spacing. Pumping has occurred on this section, and every joint has been "mudjacked" and subsealed.

Slab thickness for all pavements is 8 inches.

which has contributed most to the construction of smooth asphalt pavements has been the development and continual improvement of asphalt finishing machines.

City streets are generally conceded to be much rougher than rural highways and the measurement of the roughness of the 200 mi. of city streets in Berkeley provided clear-cut evidence to support this view. The results of the roughness measurements in Berkeley are shown in Figure 11 and indicate that the secondary streets are rougher by far than the major streets. The extreme roughness of secondary streets is evident when it is noted that the roughness values for about 20 percent of the total street mileage in the city exceeded 400 in. per mile. It should be recognized that the major streets carry a high percentage of the city's traffic, were built to a higher standard, and have received better maintenance than the secondary streets and should therefore be smoother than the secondary streets.

Some interesting results are given in Table 4 which indicate the sensitivity of the equipment when used to measure temperature warping effects on three sections of p.c. concrete pavement. Hourly changes in roughness of one to two inches per miles were observed with a maximum change of 16 in. per mile on new pavement and 10 in. per mile on old pavement over a period from 5 a.m. to 6 p.m. These data show that temperature warping is a factor in the roughness measurements on concrete pavements and should be considered when making close comparisons of the roughness of concrete pavements.

SURFACE ROUGHNESS STANDARDS

An important objective when making roughness tests is to use the measured values to classify or rate pavement surfaces in terms of riding quality such as excellent, good, fair, and rough. The tentative standards for evaluating road roughness of rural highways given in last year's report were as follows:

Roughness Index (in. per mi.)	Riding Qualities
Below 100	Excellent
100 - 150	Good
150 - 200	Fair
Above 200	Rough

On secondary city streets, where the average maximum operating speeds are in the range of 25 to 30 mph, the roughness values can be increased for the same classification in riding quality. The tentative standards proposed for secondary city streets based on the Berkeley Study are as follows:

Roughness Index (in. per mi.)	Riding Qualities
Below 100	Excellent
100 - 200	Good
200 - 300	Fair
300 - 400	Rough
Above 400	Very Rough

The Minnesota Department of Highways has been using a BPR Roughness Indicator since 1940. Mr. Swanberg, Engineer of Materials and Research reported in a letter dated December 4, 1950, that "the BPR machine has been used very successfully during and after construction of pavements to assist in obtaining smoother riding pavements. Our measurements indicate that concrete pavements can be built with a roughness index as low as 52 in. per mile. Most of our pavements, both bituminous and concrete, recently built are in the range of 65 to 80 in. per mile. If the roughness index exceeds 90 in. per mile, roughness in riding is quite apparent and if it exceeds 100, it is rough. One project built in 1946 gave a roughness of 116 in. per mile and was so rough in riding that it resulted in newspaper criticism." On the basis of their experiences in checking the roughness of new pavements, the Minnesota Department of Highways has tentatively adopted the following standards:

Roughness Index (in. per mi.)	Riding Qualities
Below 75	Good
75 - 100	Fair
Above 100	Poor

It is interesting to note the general agreement in the results of the Minnesota tests on new pavements with the results on California pavements in the 0-2 year age group. The Minnesota standards, however, are much higher than the tentative standards recommended in last year's report and again given in this report and they are higher for a very good reason. The Minnesota tests are made during and after construction as a measure of the acceptability of the job. Their tests have shown, as have the California tests, that pavements can be built to meet their roughness standards. It is entirely proper and reasonable to expect that new pavements should be built to meet the Minnesota standards. The tentative standards proposed last year and again given in this report, represent a more liberal evaluation of the roughness of pavements of all ages. They were set up to indicate need for reconstruction or corrective treatment and were not intended to be used as a measure of the acceptability of new construction.

The Minnesota roughness standards can serve a very useful purpose in the construction of pavements with good riding qualities. The success enjoyed by Minnesota in the use of the BPR Roughness Indicator suggests the need for the use of this equipment in all states. Its use would, no doubt, result in improvements in the design and operation of mechanical finishing equipment and finishing methods for the construction of both p.c. concrete and the various types of asphalt pavement. By its use engineers and contractors could insist and would obtain higher standards of workmanship in building good riding quality into the road. Finally, of course, it should be recognized that the public judges whether a road is good or bad largely on the basis of its riding qualities and an accurate measure of roughness with a machine such as the BPR Roughness Indicator should give the public and the engineer a reliable measure of the riding qualities of all pavement surfaces.

SKID RESISTANCE TESTS

In last year's report published in the Highway Research Board Bulletin No. 27, a brief description was given of some of the preliminary instrumentation and testing to measure the skid resistance of road surfaces and bridge floors in California. During the past year, many improvements and additions to this equipment have been made and tests have been run on more than 50 pavement surfaces to measure their skid resistance under various test conditions. In this report, the important items of test equipment not covered in last year's report will be described followed by a description of typical pavement surfaces and bridge floors and by a discussion of the test results when measuring the skid resistance of these surfaces under various test conditions.

The major objectives in the current research of skid resistance at the University of California are (1) to develop equipment and testing methods which will provide three independent measurements of skid resistance of road surfaces, (2) to improve upon the accuracy of the measurements and to make an exhaustive study of skid resistance of many different surface types and test conditions not adequately covered in previous studies, (3) to provide the background experience which will be helpful in developing standard procedures for making skid resistance measurements and (4) to provide the basic information concerning factors which cause slippery road conditions and to determine the construction methods or corrective measures which should be adopted to prevent the slippery condition.

In this testing program the skid resistance of various surfaces is being determined by three independent measurements: (1) by measuring the maximum braking force on one wheel of a trailer in the towing-trailer method, (2) by measuring the minimum stopping distance in locked wheel passenger car braking tests and (3) by measuring the deceleration at any given speed in the locked wheel passenger car braking tests. The results of all the tests are reduced to a common unit, the coefficient of friction, which is a ratio of the braking force provided by one or more wheels to the load carried by the wheel or wheels. Thus, if the braking force on a given wheel is 400 lbs. and the weight on the wheel when this force is acting is 1000 lbs., then the coefficient of friction is 400/1000 or 0.4.

Skid Test Equipment - In the towing-trailer method, a two wheel trailer equipped with electric brakes is used. For the general run of tests, the trailer is loaded to provide a typical passenger car axle load of 1,820 lbs. The tow truck is an FWD truck with a rating of 172 horsepower at 2600 RPM. This truck has ample reserve power so that it can be operated at various uniform speeds up to 50 mph with the brake on one trailer wheel locked. The truck is equipped with water tanks and spray nozzles for running the wet road tests. Also, in the body of the truck are the various instruments and controls to run the tests which were described in last year's report.

In the passenger car stopping distance tests a carryall is used instead of a conventional passenger car since the carryall is better adapted for installing the various items of equipment used to obtain a graphical record of speed and deceleration in the braking tests. The carryall is also being used as the tow vehicle in the road roughness tests which are generally run in conjunction with the skid resistance tests.

A general view of the road surface test equipment ready to set off for the day's tests is shown in Figure 12. The carryall with the two fifth wheels used in the stopping distance and deceleration tests is shown in Figure 13. One of the fifth wheels is a Wagner Stopmeter used to measure stopping distance and the other fifth wheel is equipped with a magneto generator which provides an accurate measure of speed which can be read directly with a volt meter type speed indicator or which can be recorded as one of the traces on the oscillograms taken in these tests.

A schematic diagram of the equipment in the truck body used in the truck-trailer skid tests is shown in Figure 14. It should be noted that the truck is well equipped to make all the measurements which are required in these tests, including the measurement of braking forces, speed, time, slope or grade of the road, and temperature of the air or of the road surface. A Multiflex

Figure 12. General View of Road Test Equipment

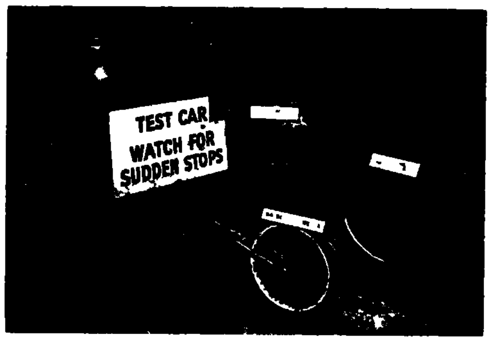


Figure 13. Carryall and Fifth Wheels Used in Braking Tests

Timer has been installed during the past year to provide accurate timing of all operations by means of a single push button control. Thus, in a typical test, the following sequence and timing is controlled by the Multiflex Timer using an all-electric control system. The first operation after pushing the button consists of opening the solonoid valve which operates the spray nozzles. Two seconds later the motor which runs the paper on the oscillograph recorder is started followed in three seconds by the electric brake application. The brake on one trailer wheel is applied for 2 to 4 seconds depending upon the speed maintained during the test and the type of surface being tested. After the brake is released, the water is shut off and the paper is permitted to run two seconds to complete the record for one test run. Separate manual controls are also provided to facilitate operation under certain special test conditions. The photograph of the interior of the truck body in Figure 15 shows the general arrangement of the equipment and the control panel.

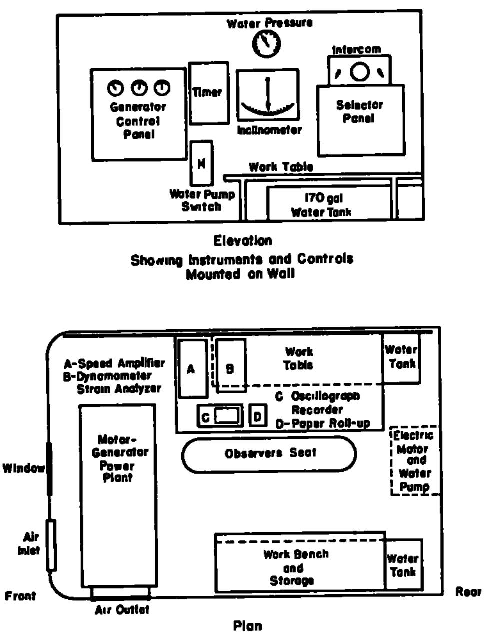


Figure 14 Schematic Drawing of Truck Body Used for Truck-Trailer Skid Tests

The general details in the design of the trailer and the equipment on the trailer are shown in Figure 16. The trailer is constructed along conventional lines with certain special provisions required to run locked wheel and the variable force braking tests. The trailer is equipped with a soft suspension system consisting of long leaf springs, coil springs and hydraulic shock absorbers designed to keep the trailer body as free as possible from vibrations caused by road roughness. Excessive vibrations of the trailer and of the truck were encountered in some of the early tests and the effect of these vibrations was reflected in the oscillograph records to such an extent as to greatly impair their accuracy. By increasing the load on the truck body and by installing

Figure 15. Truck Interior Showing Equipment Used in Truck-Trailer Braking Tests

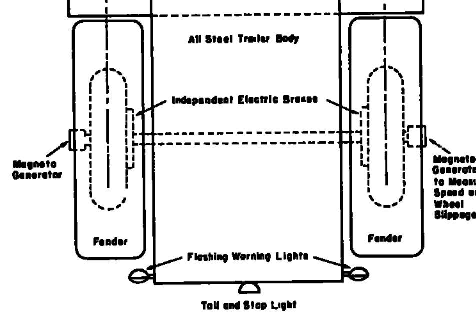


Figure 16. Schematic Drawing of Trailer Used for Truck-Trailer Skid Tests

shock absorbers on both the truck and trailer, the vibrations were greatly reduced and as a result of these changes satisfactory oscillograms are now obtained. The trail-wheels are free rolling when the brakes are released. A magneto-generator is attached to each wheel for the purpose of obtaining an accurate measure of speed and wheel slippage.

The maximum braking force at each speed is measured with an SR-4 strain gage dynamometer, of the proving ring type. In the calibration of the dynamometer, it was found that the braking forces can be measured to an accuracy of + or − 2 percent for forces up to 2,000 lb. The dynamometer is attached to the tow-truck and trailer directly in line with the longitudinal axis of the wheel being braked. It is fitted with universal joints and a short length of chain to eliminate torsion or any other restraint not directly induced by the braking force. The tongue of the trailer is suspended in a cradle in such a way that only vertical forces can be transmitted by it to the truck. The general details of the trailer hitch, dynamometer and the water sprinkling system are shown in Figure 17.

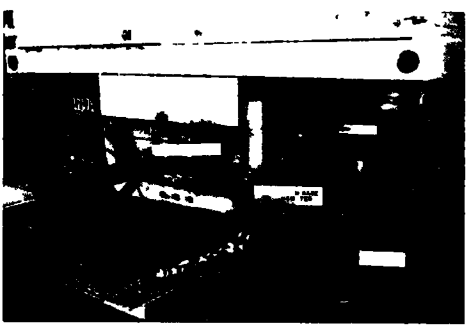


Figure 17. Trailer Hitch, Dynamometer, and Sprinkling Equipment Used in Truck-Trailer Braking Tests

Typical oscillograms obtained in braking tests on dry and wet p.c. concrete pavements using the truck-trailer towing method are shown in Figure 18. The speed in both of these tests is shown in the speed trace to have been held constant at 40 mph. In these tests the brakes were applied with the wheels locked for two seconds. It will be noted that the maximum braking force was recorded for less than 1/10 of a second at the beginning of the braking period and a force almost as large when the brakes were released. The braking forces between these two peaks were about 20 percent lower than the maximum but held to a fairly uniform value. This lower uniform

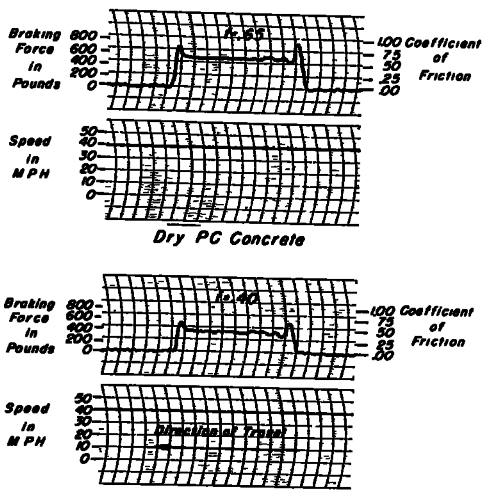


Figure 18. Braking Test Oscillograms Truck-Trailer Towing Method

braking force is used in this report as the best measure of the locked or sliding wheel braking force for the given tire and road surface condition. The maximum braking forces shown in these oscillograms at the instant the brakes were applied and again just before they were released, are believed to represent the maximum braking forces developed for the skid-impending (rolling wheel) condition. This was verified later in the skid-impending tests where the maximum braking forces were maintained during the full two seconds of braking.

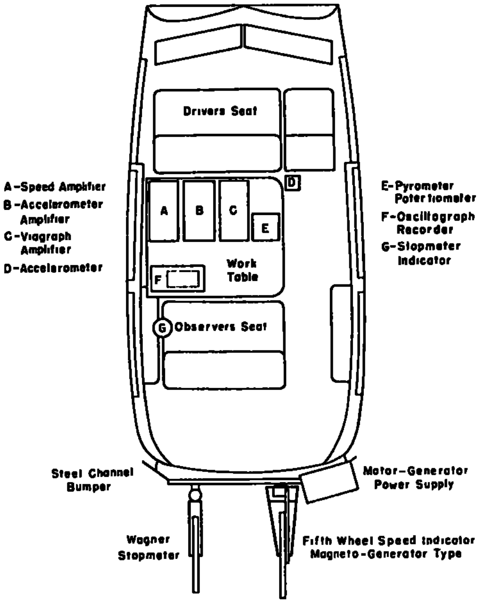


Figure 19 Schematic Drawing of Carryall Used for Passenger Car Skid Tests

A general layout of the equipment used in the passenger car stopping distance tests is shown in Figures 19 and 20. In this test the braking distance is measured with the Wagner fifth wheel Stopmeter. The Stopmeter is tied in with the stoplight circuit so that the instant the brakes are applied the braking distance is measured by means of the fifth wheel, and after the car stops, the observer in the car reads the stopping distance on the Stopmeter Indicator dial (Fig. 20). Another feature in the use of the Carryall, is the measurement of the instantaneous deceleration rate at various speeds in the locked-wheel stopping tests using a Statham linear decelerometer (Fig. 21). The Statham decelerometer is a sensitive transducer or pickup device which measures linear acceleration or deceleration from 0 to 2 g. The acceleration or deceleration is recorded by the use of a special amplifier and a Brush direct-recording oscillograph. An accurate oscillograph record of speed during the test is obtained by the use of a fifth wheel, speed amplifier and the Brush oscillograph shown in Figure 20.

Typical oscillograms obtained in passenger car stopping distance tests on dry and wet p.c. concrete pavements are shown in Figure 22. Both of these tests were locked wheel braking tests from an initial speed of 40 mph. Each oscillogram

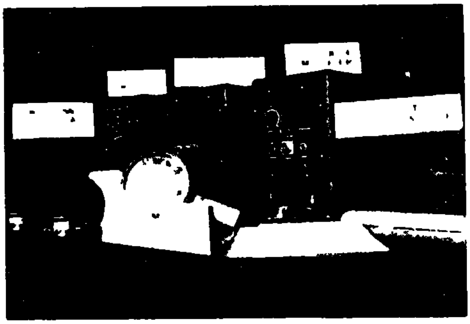


Figure 20 Carryall Interior Showing Equipment Used in Deceleration Tests

shows a deceleration trace and a speed trace. The time in seconds and a scale indicating the coefficients of friction are also shown on each oscillogram. As was noted in the description of the truck-trailer braking test oscillograms, the passenger car braking test oscillograms also reveal some interesting braking characteristics which can only be observed by means of a record of this type. Thus, the initial braking forces for the impending-skid condition (wheels rolling) are high but as soon as the wheels are locked, the rate of deceleration and the friction values are reduced by 20 to 30 percent. Then as the braking continues and the speed of the car is reduced, the rate of deceleration and the friction values increase and at very low speeds return to approximately the same value as the maximum values when the brakes were first applied. The changes in deceleration were more pronounced in the tests on wet pavements than in the tests on dry pavements.

Figure 21. Statham Accelerometer Used to Measure Acceleration or Deceleration

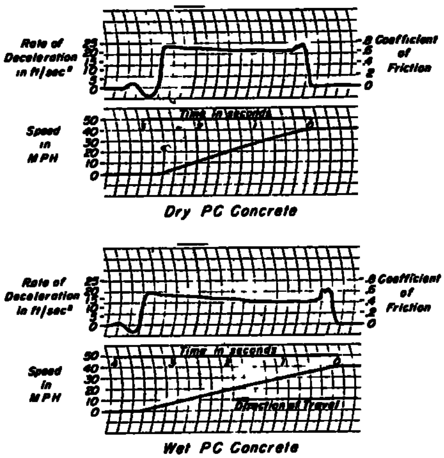


Figure 22. Braking Test Oscillograms Passenger Car Deceleration Method

The negative deceleration or oscillation effect which appears on the oscillogram in Figure 22 at the instant the car is stopped is caused by the excessive pitching when the load transfered from the rear to the front axle is released. The pitching angle for various rates of deceleration was measured by photographic methods and for the Carryall test car it was found to vary in a straight line with a maximum observed pitching angle of 1°30' for a rate of deceleration of 24 ft. per sec.² The pitching angle when the car is stopped appears more pronounced than it actually is because as the transfered load is released the car oscillates through approximately double the pitching angle observed during the period when the brakes are applied.

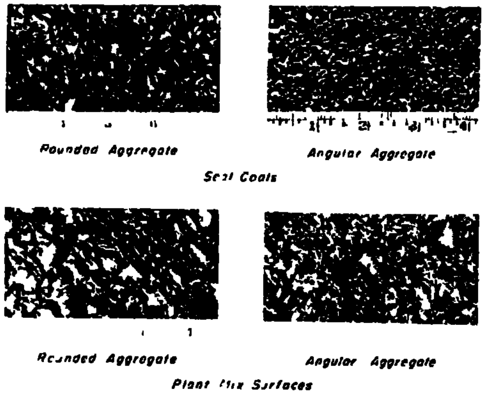


Figure 23 Typical Coarse Asphalt Surfaces

Description of road surfaces and tires - The road surfaces on which tests were run may best be described by referring to the texture prints shown in Figures 23 to 26. In Figure 23 are shown typical texture prints of four types of open graded asphalt surfaces in California. The open graded textures shown here are obtained in both the plant mixed and seal coat type of asphalt pavement construction. Angular crushed stone and rounded gravel aggregate with maximum sizes up to ½ or ¾-in. maximum are used in these pavements with the results as shown in these texture prints. In Figure 24 texture prints are shown which are typical of four types of dense graded asphalt surfaces in California. The dense graded textures are also obtained in both the plant mixed and the seal coat type of asphalt pavement construction. The dense grading in the plant mixed construction is obtained by using a well graded mixture of coarse and fine aggregate and filler with the proper amount of asphalt and compaction to give it high stability and high density. The dense graded seal coats are obtained by using well graded screenings or sand cover which after rolling and under the action of traffic in hot summer weather develops a tight seal. To protect some of the porous plant mixed surfaces against raveling, a very light seal coat known as a Class D or fog seal consisting of a penetration type asphaltic emulsion has been used in California and certain other western states without the addition of cover material. It will be seen from the texture print of this type of surface shown in Figure 24, that it has a glazed appearance similar to bleeding asphalt type surfaces. As will be shown later, the test results for skid resistance on glazed asphaltic surfaces have in all cases indicated that these surfaces are dangerously slippery when wet. For this reason the California Division of Highways adopted a policy during the past year to apply fine screenings or sand cover on all Class D (fog seal) type seal coats. A texture print of a Class D seal coat with sand cover is shown in Figure 24.

The p.c. concrete surfaces in California have for many years been given a sandy textured finish as shown in the texture print in Figure 25 by the use of the Johnson Finisher which is equipped with a burlap drag. The scrubbing action of the tires removes many of the sand grains on the surface of concrete pavements after 4 or 5 years and this action combined with the accumulation of oil drippings on the pavement, as shown in the outer lane of the four-lane divided concrete highway in Figure 25, is responsible for a 10 to 25 percent reduction in the friction values on old concrete pavements when wet as compared to the values on new concrete pavements when wet.

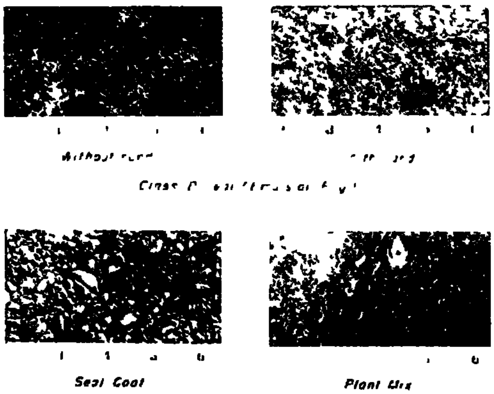
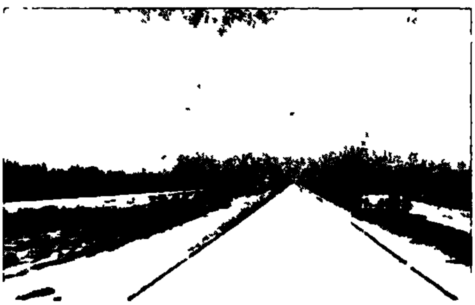


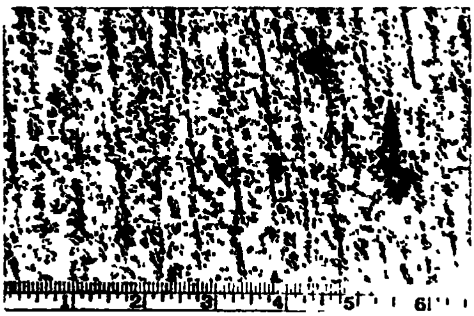
Figure 24 Typical Dense-Graded Asphalt Surfaces

Skid resistance tests were run on 12 open-grid steel bridge floors of two general types as shown in Figure 26. The two general types of bridge floor on which tests were run are the Irving Type V Mesh consisting of alternate straight bars and crimped bars and the U. S. S. I-Beam-Lok. The patterns in the open-grid design of both types are clearly shown in Figure 26. It should be noted that the welding of certain connections on the U. S. S. I-Beam-Lok causes slight roughness or irregularities on the surface which are not present on the Irving Type V Mesh. The scrubbing action of the tires has a polishing effect on both types of open grid steel bridge floors after 2 or 3 years, which, as will be shown later, increased the skid resistance of these surfaces in the dry tests and reduced the skid resistance in the wet tests.

Description of tires - Three tire types were used in these tests (1) Natural rubber tires with a rib tread pattern (2) Synthetic cold rubber tires with the same rib tread pattern as the natural rubber tires and (3) Synthetic rubber tires with a smooth tread. The tires were all furnished by one manufacturer and each type of the new tires was made from the same run of tread stock. All of the tires were standard 100-level, 6.70 by 15, 4-ply tires. The new tires were all given a break-in run of about 500 mi. before they were used in the skid resistance tests. The tread pattern and general condition of the tires used in the test is shown in Figure 27. The same tires were used both in the tests with the trailer and with the Carryall.



General view of P C Concrete showing oil slick in outer lane



Close-up of P C Concrete

Figure 25. Typical Concrete Surface on a Four-Lane Divided Highway

RESULTS OF SKID RESISTANCE TESTS

The skid resistance of rubber tires on various types of road surfaces is a complex phenomenon influenced by many variable factors and test conditions. While an effort has been made in this investigation to explore the effect of all the variables, this phase of the testing program has not been completed. The test results to date have revealed the effect on skid resistance of many variables which have been summarized in the discussion which follows to include:

1. Friction values as measured by three different testing methods.
2. Effect of angular aggregate, rounded aggregate and bleeding asphalt.
3. Effect of open-graded versus dense-graded road surface construction.
4. Friction values on new and old p.c. concrete and on concrete with oil drippings.
5. Friction values on new and old open-grid steel bridge floors.
6. Seasonal effect on various surfaces.
7. Effect of locked-wheel versus impending-skid braking on various surfaces.
8. Effect of wheel load.
9. Effect of tire type.
10. Effect of speed and wet versus dry surface condition.

The two variable factors, the effect of speed and wet versus dry surface condition, listed as item 10, are an important consideration in a study of all of the remaining factors listed and these effects will therefore be discussed with each of the first 9 items.

Friction Values as Measured by Three Different Testing Methods - The friction values as measured by three different testing methods, (1) truck-trailer, (2) stopping distance and (3) rate of deceleration, are given in Figures 28 and 29 based on tests on four different types of road surfaces. The friction values in all of these tests are expressed in terms of the common unit, coefficient of friction (f). In the truck-trailer method, the coefficient of friction is the ratio of the braking force as measured with the dynamometer and the effective wheel load during the test. In the stopping distance method the average coefficient of friction is computed using the standard stopping distance formula:

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

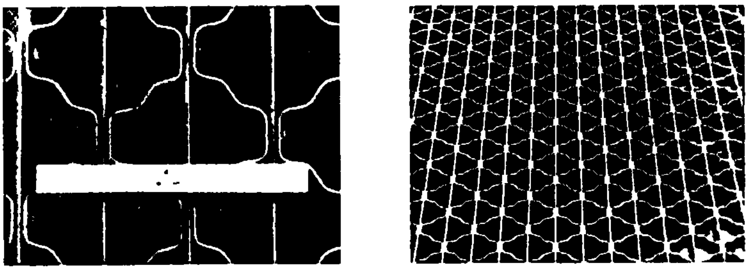
where f = average coefficient of friction

V = initial speed in mph at the time the brakes are applied.

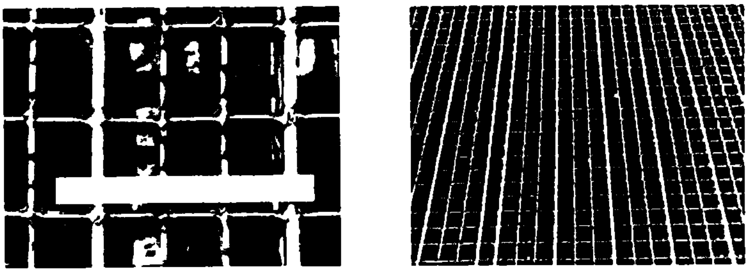
S = stopping distance in feet

In the rate of deceleration method, the coefficient of friction is the ratio of the measured deceleration at any given speed in the test to the deceleration of gravity, 32.2.

It is interesting to note that the friction values as measured using the truck-trailer and the rate of deceleration methods were very nearly the same at corresponding speeds, whereas the values based on the stopping distance method and when plotted in terms of the initial speed, were about 25 percent higher than the values obtained by the other two methods. The higher values obtained using the stopping distance method may be explained in part by the fact that the friction values are average values over the entire stopping distance and thus they can be considered as the fric-



Irving Open Grid, Type "V"



U S I-Beam

Figure 26. Typical Open-Grid Steel Bridge Floor

tion values for the average speed instead of the initial speed. However, even if this change is made the friction values by the stopping distance method will still be higher than the values by the other two methods. An additional reason for the higher values is that the stopping distance method combines the effect of impending-skid and sliding-wheel braking forces while only the sliding-wheel braking forces are measured in the other two methods. Since the impending-skid braking forces are 25 to 100 percent greater than the sliding-wheel braking forces, the higher friction values as reported for the stopping distance method in Figures 28 and 29 are fully accounted for.

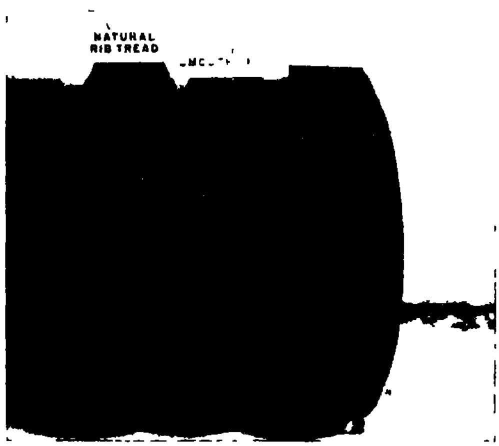


Figure 27 Three Tire Types Used in Braking Tests

It should be noted that the test data in Figures 28 and 29 are for wet surfaces and they show the marked reduction in friction values as the speed increases which has been reported for similar tests in previous investigations. Thus, the friction value for rounded aggregate was about 0.5 at 5 mph and dropped to 0.32 at 50 mph; for angular aggregate it was 0.55 at 5 mph and 0.36 at 50 mph, for p.c. concrete pavements it was 0.58 at 5 mph and 0.41 at 50 mph; and on the fog seal coat surface it was 0.24 at 10 mph and 0.14 at 40 mph. The tires used in these tests were the cold rubber synthetic type. The tests were run in November and December after some heavy rains had washed the surfaces and made them cleaner and less slippery than before the rains.

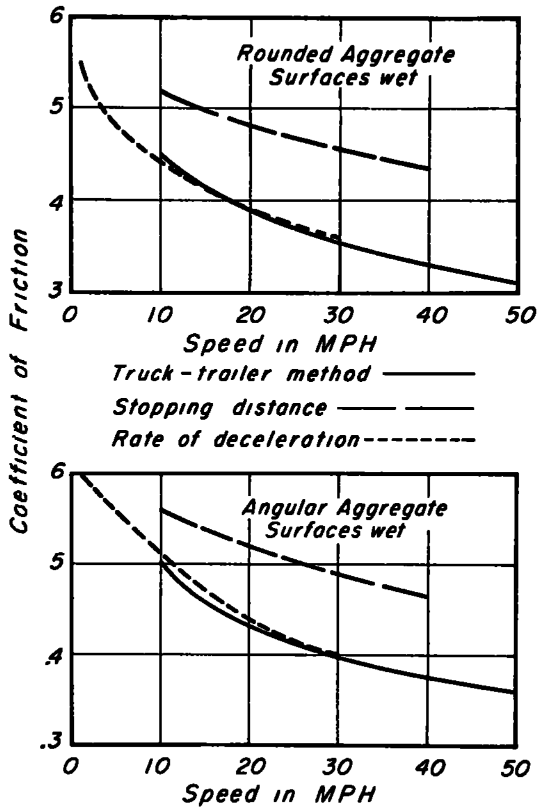


Figure 28. Comparison of Results Obtained by Different Methods of Testing Skid Resistance of Open-Graded Asphalt Surfaces

The truck-trailer method as used in this investigation has the following advantages and disadvantages;

1. Tests can be run with a minimum of interference with traffic over a wide range of speed of from 10 to 50 mph.

2. There is practically no hazard as far as loss of control of the test vehicle is concerned.

3. Accurate independent measurements can be made of the impending-skid braking force at any given speed up to 50 mph.

4. The tests can easily be standardized as to load, tire types, tire size, and the general test procedures.

5. The wet tests are easy to make, do not require an auxiliary water truck, use less than 1/10th the amount of water used when sprinkling road with water truck, and do not create a skidding hazard to other traffic on the road.

6. The equipment used in the tests is highly specialized and the investment cost is quite high, amounting to about $6,000, not including the cost of the truck. The cost of operation is relatively low and consists largely of the cost of operating the truck.

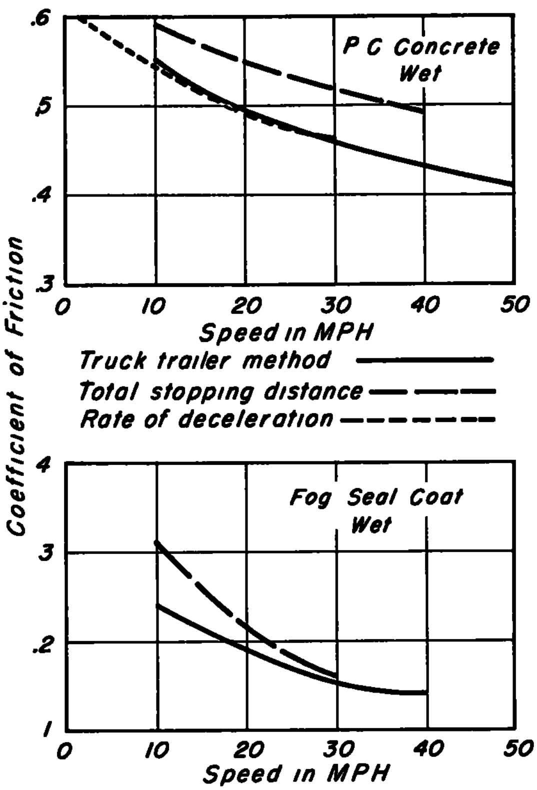


Figure 29. Comparison of Results Obtained by Different Methods of Testing Skid Resistance

The passenger car stopping distance and rate of deceleration methods have the following advantages and disadvantages:

1. The locked wheel braking tests closely simulate actual vehicle operation and provide an accurate measure of the road and tire friction developed by a passenger car when making an emergency stop for similar road and tire conditions.

2. The cost of equipping a car for the stopping distance tests using an A.A.A. detonator is less than $50 and when using a Wagner Stopmeter is less than $300. The cost of equipping a car for the tests by the rate of deceleration method is approximately $1,500. These prices do not include the cost of extra or special tires and wheels.

3. The tests require the use of special traffic control measures such as a flagman and warning signs.

4. The tests are hazardous at speeds above 30 mph, especially on slippery wet surfaces.

5. This type of braking tests combine the effect of impending-skid and locked-wheel braking forces which are not the same for all makes of cars. For this reason the results are not reproducible for all makes of cars.

6. In tests with the same car with adequate brakes properly adjusted, consistent results are obtained on any given surface for the same test conditions.

7. The wet tests require the use of a water-truck and the liberal application of water over a 12-ft. width preferable near the center of the road, thereby creating a skidding hazard to other traffic on the road.

Effect of Angular Aggregate, Rounded Aggregate and Bleeding Asphalt - The results of tests on asphalt seal coat surfaces using the truck-trailer method are given in Figure 30. The tests were run in the summer season and the values given are for the synthetic cold rubber tires with the rib tread pattern. The surfaces in these tests were classified into three groups, (1) surfaces with angular aggregate used as cover material, (2) surfaces with rounded aggregate used as cover material and (3) surfaces with excess asphalt causing bleeding of the asphalt and a glazed surface. It will be noted that the friction values both in the dry and wet tests follow the same order with the highest values obtained on the angular aggregate, the lowest on the bleeding asphalt, and the friction values on the rounded aggregate occupying a median position.

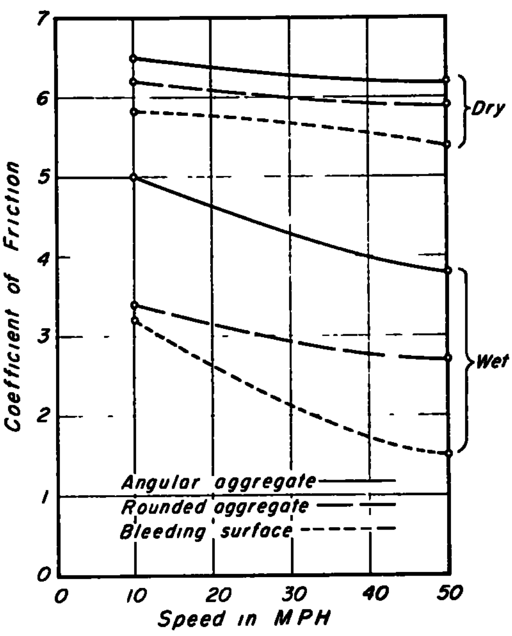


Figure 30 Skid Resistance of Asphalt Seal Coats

The friction values in the wet tests were in general about one-half to one-third of the values obtained in the dry tests. In the wet tests on the bleeding asphalt surfaces at 50 mph, the exceptionally low value of 0.15 was obtained as compared with 0.54 in the dry tests at the same speed on the same surface. The results for the bleeding asphalt are in good agreement with the results of similar tests reported in previous investigations. There can be no doubt that with friction values indicating stopping distances more than 3 times greater for the wet bleeding asphalt surfaces than on dry asphalt surfaces, corrective measures should be taken immediately wherever bleeding is observed to prevent this type of slippery-when-wet condition.

The friction values for the rounded aggregate were about 25 percent lower than for the angular aggregate in the wet tests. These results indicate that a substantial improvement in skid resistance may be obtained by the use of angular rock chips and sharp sand instead of rounded pebbles and sand particles. The results further suggest the advisability of using crushed gravel in preference to uncrushed gravel to provide high skid resistance on asphalt surfaces when wet.

Effect of open-graded versus dense-graded road surface construction - The results of the tests on open-graded versus dense-graded plant mixed asphalt pavement construction are shown in Figure 31 and indicate that the friction values are influenced more by the angularity or sharpness of the aggregate then by the open-graded or dense-graded effects. The friction values were 10 to 25 percent higher in the wet tests for the open-graded angular aggregate surfaces than for the dense-graded surfaces or for the open-graded rounded aggregate surfaces. The values in the wet tests on these surfaces were 1/2 to 2/3 as large as the values measured in the dry tests with the greatest difference at the higher speeds where the frictional requirements are greatest.

An analysis of the test data and

of road surface characteristics in general indicate that the friction values on dense-graded surfaces can be as high as for open-graded surfaces if angular aggregate is used and if there is no excess asphalt in the mix. Of course, a slight excess in the percent asphalt will have a more pronounced effect in reducing the friction values for the dense-graded than for the open-graded construction.

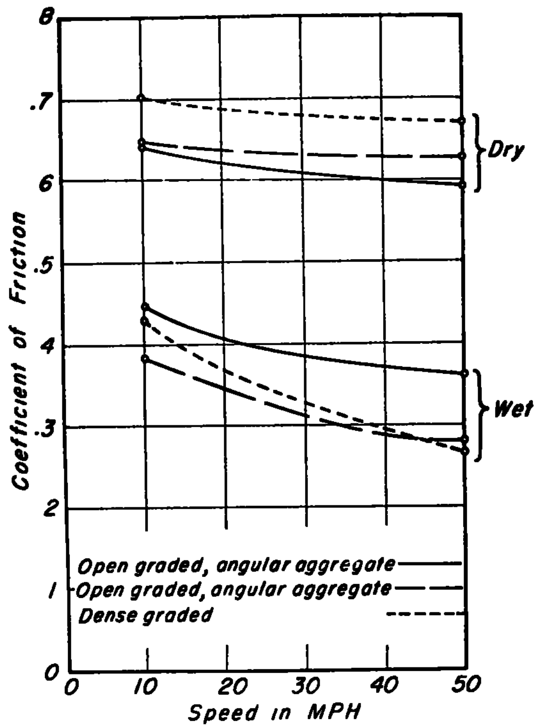


Figure 31 Skid Resistance of Asphalt Plant Mix Surfaces

An important advantage of the open-graded over the dense-graded construction observed in the wet tests and when driving on various types of pavements in rainy weather, is the complete absence of splash which is encountered in rainy weather on all dense-graded surfaces. The splash, during or immediately after rains, coats the windshields of cars with muddy water and thin films of mud which impairs visibility and is difficult to remove.

Taking all factors into account, an open-graded plant mixed surface using properly graded angular aggregate up to 3/8-in. maximum size should provide high skid resistance, high stability, a smooth riding surface, no splash during or after rains, and, if light colored aggregate is used, will provide good light-reflecting properties for night driving.

Friction Values on P. C. Concrete Pavements - The results of tests on p.c. concrete pavements given in Figure 32 show a much smaller spread in values than on any other major surface type. The tests on concrete

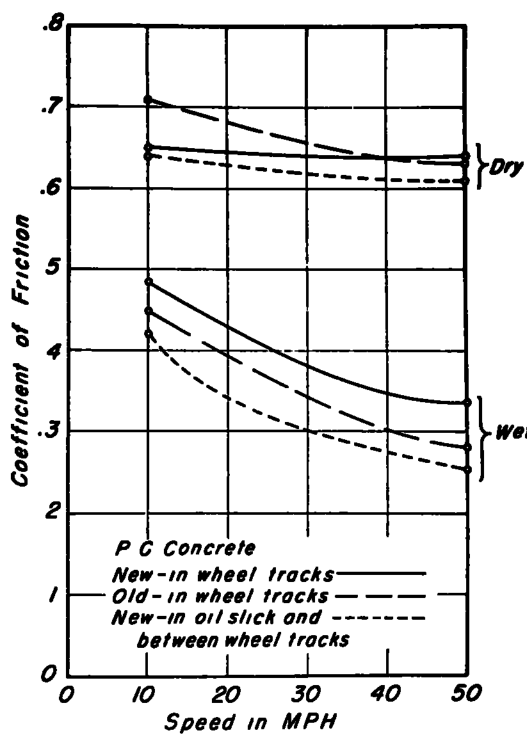


Figure 32. Skid Resistance of New (Less Than Two Years) and Old P C. Concrete Pavement Showing the Effect of the Oil Slick

pavements were conducted in the same way as the tests on asphalt pavements discussed above and the results are directly comparable.

The friction values on new concrete pavements were only slightly lower than on the asphalt pavements built with angular aggregate. However, as traffic wore off the sharp sand grains on the surface coated the surface with oil drippings, and the friction values in the wet tests were gradually reduced over a period of three or more years. The greatest change was observed in the wet tests at 50 mph with coefficients of friction of 0.34 for new concrete pavements, 0.28 for old concrete pavements and 0.25 for concrete pavements coated with oil drippings.

As will be shown later, the friction values for all paved surfaces can be increased by the cleansing action of water either by flushing or by heavy rains. Thus, an increase of 20 percent in the friction values on concrete was observed after heavy rains when compared with the results obtained just previous to the heavy rains. No other practical method has been developed to improve the skid resistance of old concrete pavements.

These test results suggest that to develop the maximum skid resistance in concrete pavements, it is desirable to develop a sandy texture in the final finishing operation preferably the skillful use of a fibre or wire broom. Finishing methods which bring excess cement paste to the surface should not be used because excess cement paste on the surface is certain to give the concrete a glazed finish which the test results have consistently shown is the main cause of slippery-when-wet pavements.

Friction Values on New and Old Open-Grid Steel Bridge Floors - The results of the tests on ten old and new open-grid steel bridge floors given in Figure 33 show that the friction values on these surfaces in the dry tests were higher than the corresponding values for any other surface type while in the wet tests the friction values were quite low, especially the values obtained in the tests on the older floors worn smooth by traffic. In fact, the friction values on the worn floors were so low at the higher speeds that they should definitely be considered as slippery when wet. The coefficients of friction in the wet tests at 50 mph on the I-Beam-Lok floors averaged 0.185 and on the Irving Type V they averaged 0.215 as compared with coefficients of 0.735 and 0.730 respectively obtained in the dry tests at the same speeds on the same floors. These results indicate minimum stopping distances on these floors three to four times greater when wet than when dry which is why they should be classified as slippery-when-wet.

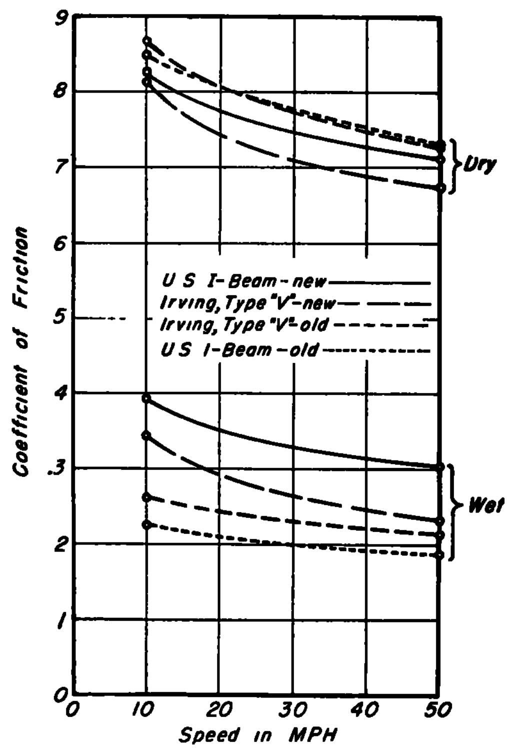


Figure 33. Skid Resistance of Open-Grid Steel Bridge Floors

The wet tests on new floors (less than 2 years old) showed that the

I-Beam-Lok floors provided higher skid resistance than the Irving Type V, with average coefficients of 0.305 for the former and 0.235 for the latter obtained in tests at 50 mph. The I-Beam-Lok floors when new had a more abrasive surface than the Irving Type V Floors due to the presence of welded fillets (See Fig. 26) which increased the friction values. The wear effect of traffic caused a greater change in skid resistance on the I-Beam-Lok floors than on the Irving Type V as indicated by the lower friction values obtained on the older worn I-Beam-Lok floors.

Open grid steel bridge floors have been reported to be slippery when wet in certain areas and corrective measures have been tried out. Thus, considerable skidding was experienced on an open grid steel bridge floor on a lift span at Jacksonville, Florida, until the floor was painted with a battleship deck paint containing an abrasive which apparently solved the problem. One objection to this treatment is that it has to be renewed every six months. Other methods tried involve the use of steel sections with raised buttons or small ridges on the top surface and the use of a portable machine for cutting small grooves in the top exposed edges of the grid bars. However, it is not known how effective the above methods are in improving the skid resistance of the steel grid bridge floors. Until a satisfactory treatment is developed, it is recommended that such bridges be posted with slippery-when-wet signs and with restricted speed signs.

Seasonal Effect on Various Surfaces- The majority of the braking tests on the various road surfaces were run during the dry season in August and September using the truck-trailer method. It was observed that the heavy rains in November and December 1950, had a cleansing effect which resulted in a marked increase in the friction values in the wet tests on these surfaces as shown in Figures 34 and 35.

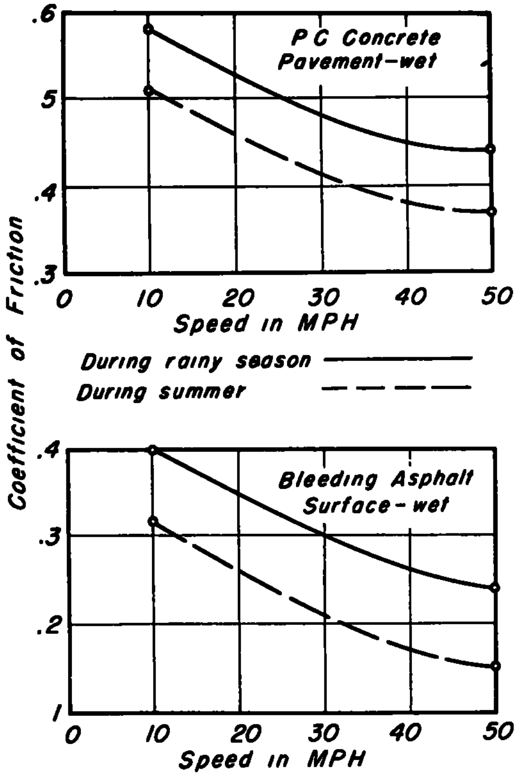


Figure 34. The Effect of Seasonal Differences on the Skid Resistance of a P. C. Concrete Pavement and a Bleeding Asphalt Surface

A fairly consistent increase of 0.07 to 0.10 in the coefficient of friction was noted as being due to the effect of the heavy rains. This change greatly benefited the bleeding asphalt surfaces where the summer tests gave an average value of 0.15 at 50 mph and after the heavy rains this value was increased to 0.24. On the wet p.c. concrete pavements the coefficients were raised from 0.37 to 0.44. Similar changes were noted on asphalt surfaces with angular aggregate and with rounded aggregate.

Higher friction values have been observed in the winter tests than in the summer tests in previous investigations but the reason for the higher values was not determined. The California tests indicated that the cleansing effect of heavy rains is probably the most important reason for the higher skid resistance measured in the winter tests when compared with the summer tests.

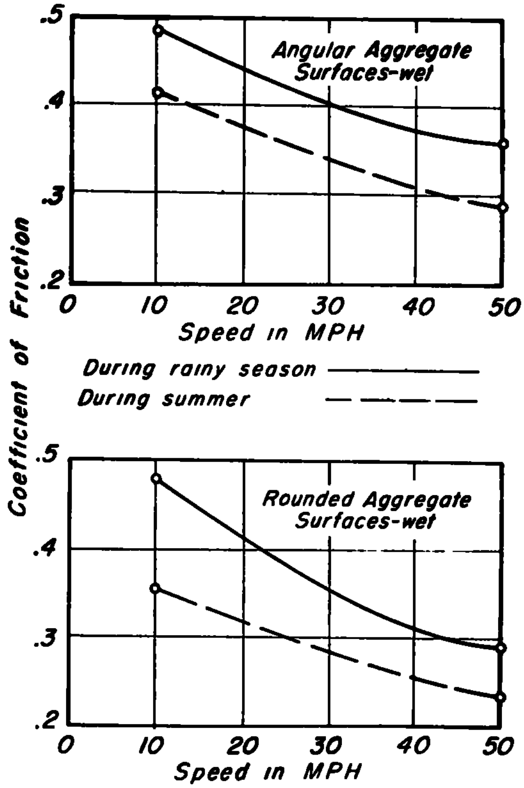


Figure 35. The Effect of Seasonal Differences on the Skid Resistance of Open-Graded Asphalt Surfaces

Effect of Locked-Wheel Versus Impending-Skid Braking on Various Surfaces - The instrumentation used in the truck-trailer braking tests provided an excellent opportunity to study the effect of locked-wheel bracking versus impending-skid braking on the maximum friction values obtained in tests of this type on certain representative surfaces. Typical oscillograms obtained in the impending-skid and locked-wheel braking tests are shown in Figure 36. These oscillograms show that a uniform speed of 40 mph was maintained in the tests. The braking force in each test was increased gradually until the maximum impending-skid force was reached. This force was held for about one second after which a further attempt to increase the braking force resulted in locking the brakes. On the wet p.c. concrete surface, the measured friction value of 0.70 obtained for the impending-skid condition was reduced to 0.44 for the sliding-wheel condition and on the wet bleeding asphalt the corresponding friction values were 0.54 and 0.26.

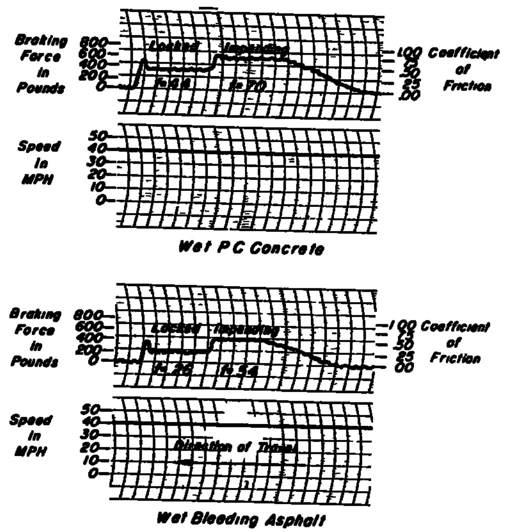


Figure 36 Oscillograms of Impending Skid and Locked Wheel Conditions

The results of the tests to measure the effect of locked-wheel versus impending-skid braking are given in Figures 37 and 38. The impending-skid friction values were 80 to 100 percent higher than the locked-wheel values on all surfaces except the open-grid steel bridge floor where the values were only about 10 percent greater.

These tests show the marked advantage of braking in such a way as to avoid sliding the wheels since shorter stopping distances can be obtained with the rolling wheel type braking and steering control is also improved if the wheels are not locked. The test results indicate that many surfaces which give low friction values and are rated as slippery on the basis of the locked-wheel braking tests, can give relatively high friction values if the brakes are not locked. The results of this series of tests as given in Figure 38 also indicate the marked advantage of tires with a good tread pattern over tires with a smooth tread. Thus, the impending-skid friction value at 50 mph on bleeding asphalt was 0.52 for a good tread tire and 0.30 for a smooth tread tire as compared with 0.22 and 0.15 respectively for the locked-wheel friction values.

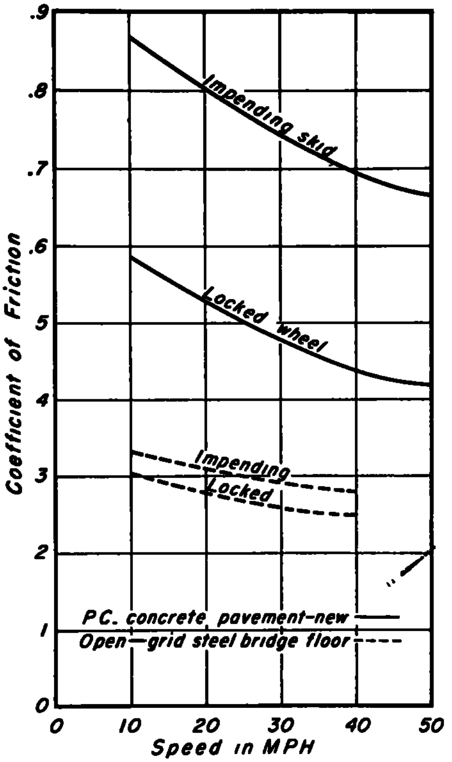


Figure 37. The Effect of Locked Wheel Versus Impending Skid Braking on Skid Resistance of Wet Surfaces

Effect of Wheel Load - The results of tests with two different wheel loads are shown in Figure 39 and indicate that the coefficients of friction for the light wheel load of 460 lbs. were about 10 to 20 percent higher than for the normal passenger car wheel load of 875 lbs. The greatest change in the friction values due to wheel load was observed in the low speed range.

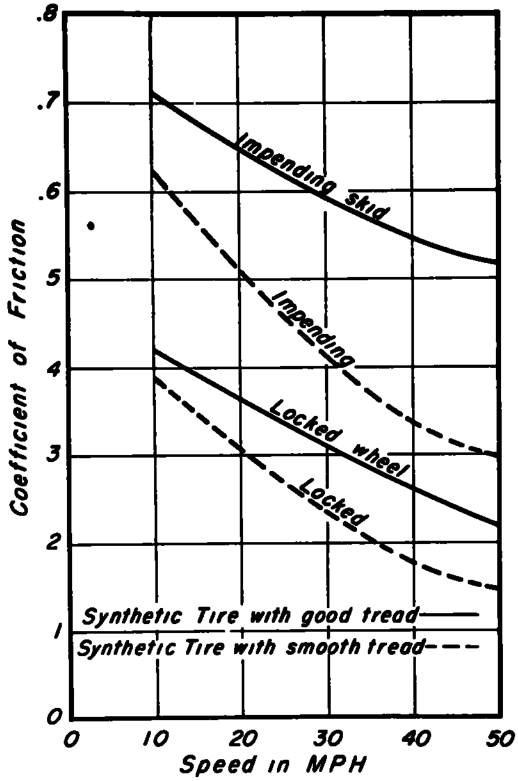


Figure 38. The Effect of Locked Wheel Versus Impending Skid Braking on Skid Resistance of a Wet Bleeding Asphalt Surface

Effect of Tire Type - Skid resistance measurements were made on six different road surfaces using three tire types, synthetic rubber with a rib tread, natural rubber with a rib tread and synthetic rubber with a smooth tread. The results of these tests given in Figures 40 to 42 indicate that the friction values for the synthetic and natural rubber tires with a rib tread were very nearly the same. The friction values for the synthetic rubber tires were about 5 percent higher than the values for natural rubber for all surfaces except the new p.c. concrete surface, where the friction values for the natural rubber tires were higher within a speed range of 10 to 30 mph.

The friction values obtained with the synthetic smooth tread tires were substantially lower than the values obtained for the other two tire types on all surfaces except the new p.c. concrete and the open-grid steel bridge floor. On the new concrete pavements the friction values were about the same for all three tire types. On the steel bridge floor they were the same at 10 mph but there was a gradual change in the friction values with an increase in speed so that at 40 mph the friction values with the smooth tread tires were about 12 percent higher than the values obtained with the other two tires.

The results of tests in previous investigations have indicated that the skidding hazard on slippery wet pavements is much greater when cars are equipped with smooth tread tires than when they are equipped with tires having a good tread pattern. The results of the tests given in Figures 38, 40, 41 and 42 fully substantiate the previous findings in regard to the increased hazard caused by smooth tread tires. The smooth tire hazard is not as great on open-graded asphalt plant mix surfaces as it is on the bleeding asphalt surfaces, but it is still a skidding hazard which every motorist should avoid by maintaining a good tread pattern on all tires.

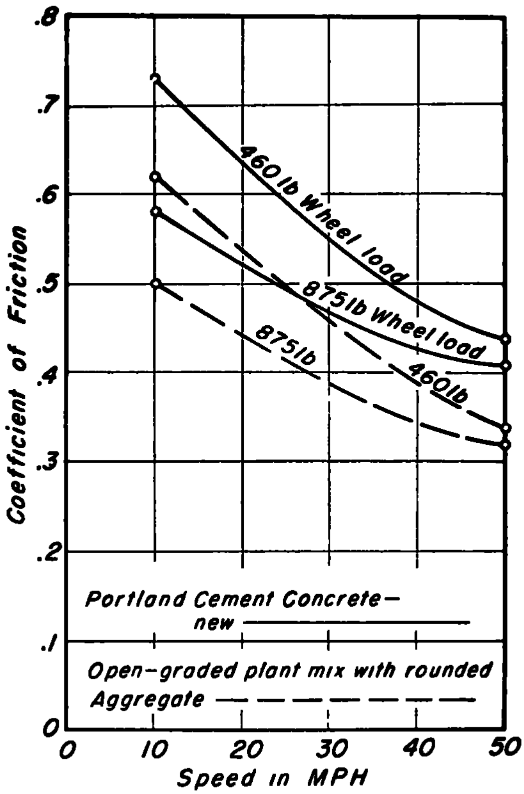


Figure 39 The Effect of Wheel Load on the Skid Resistance of Wet P. C. Concrete and Plant Mix Asphalt Surfaces

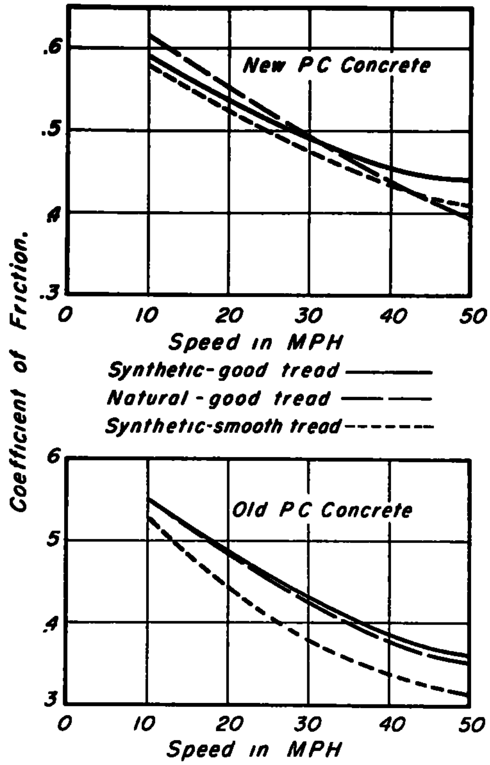


Figure 40. The Effect of Different Type Tires on Skid Resistance for Wet P. C. Concrete Pavements

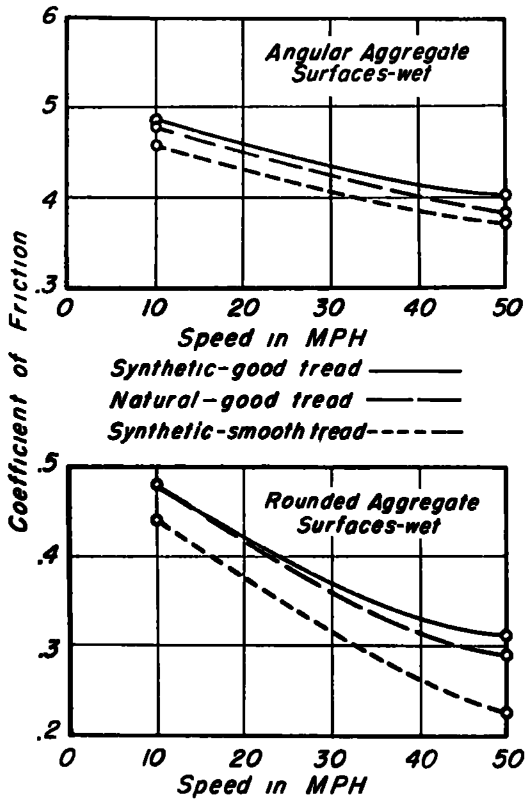


Figure 41 The Effect of Different Tire Types on Skid Resistance for Wet Open-Graded Asphalt Surfaces

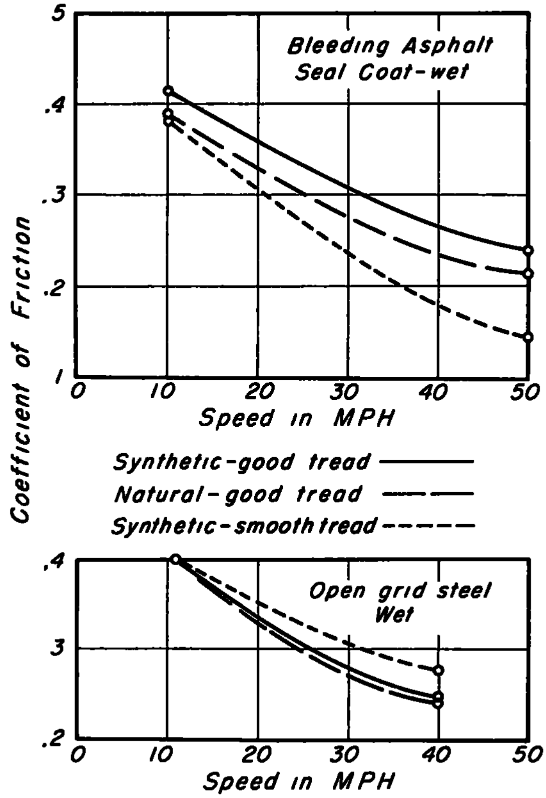


Figure 42 The Effect of Different Type Tires on Skid Resistance for Wet Bleeding Asphalt Surfaces and Wet Open-Grid Steel Bridge Floors

SUMMARY AND CONCLUSIONS

The more important results and conclusions in the current investigation of road roughness and skid resistance in California may be summarized as follows:

Road Roughness -

1. The BPR Roughness Indicator with the improvements and recording equipment of the type developed at the University of California provides a convenient, accurate, and rapid method for measuring the riding qualities of a pavement surface.

2. Check tests and calibration equipment and calibration methods developed in the California studies indicated that reproducible results can be obtained with the improved machine.

3. The improved machine is recommended for use as standard equipment for measuring road roughness and for making comparisons of the roughness or riding qualities of new pavements and of old pavements of all types in all parts of the nation.

4. Roughness standards are proposed for use in evaluating the acceptability of new construction and for scheduling the reconstruction of old pavements.

5. A standard method of measuring road roughness promotes good public relations because the public judges the acceptability of a road surface largely in terms of its riding qualities.

6. The high type pavement sur-

faces on rural state highways in California were found to have the best riding qualities of all the various types of surfaces tested. The average roughness for new p.c. concrete pavements was 52 in. per mi. and for new asphaltic concrete and plant mixed pavements it was 71 in. per mi. The roughness for the older pavements was 40 to 90 percent higher than for the new pavements.

7. The roughness of asphalt surfaces with seal coats was almost double the roughness measured on the high type pavements, with average values of 124 in. per mi. for new seal coat treatments and 161 in. per mi. for the older surfaces of this type.

8. The widest spread in roughness values was obtained in the measurements of the roughness of city streets with values ranging from less than 100 in. per mi. to over 500 in. per mi.

9. The improved BPR Indicator provides a valuable tool for the construction engineer to compare the effectiveness of various types of road finishing equipment and methods in building pavements with good riding qualities.

Skid Resistance -

1. The equipment and testing methods described in this report were used to obtain three independent measurements of the skid resistance of road surfaces for many test conditions, including some not covered in previous Highway Research Board reports on this subject.

2. The truck-trailer method is an accurate, fast and flexible method for measuring the skid resistance of dry and wet road surfaces. The initial cost of the test equipment is high. The operating costs are low. This method is recommended for use in an extensive and continuing program of skid resistance tests.

3. The stopping distance method is a simple and inexpensive method of measuring the relative skid resistance of dry and wet road surfaces for the locked-wheel type of braking. This type of test is hazardous. The results are limited to total stopping distances and are not reproducible for all makes of cars but are reproducible if the same car is used in all of the tests. This method is recommended for use in a limited program of skid resistance tests.

4. The rate of deceleration method provides an accurate graphical record of skid resistance over the entire speed range within which it is safe to run the tests. This method is a refinement of the stopping distance method. The equipment costs are high. The method provides interesting brake test records of limited application and is recommended for use only in special studies of braking and of skid resistance properties of tires and road surfaces.

5. The test data of skid resistance in this report covering such factors as the effect of increased speed, dry versus wet surfaces, use of sharp gritty aggregate, glazed or polished surfaces, excess asphalt, and smooth tread versus new tread tires checked reasonably closely similar data as given in previous Highway Research Board reports on this subject.

6. The friction values for rounded aggregate were about 25 percent lower than for angular aggregate in the wet tests.

7. Slightly higher friction values were obtained on open-graded surfaces than on dense-graded surfaces although the sharpness or grittiness of the aggregate was a major factor influencing the test results.

The open-graded surfaces are preferred because they are less likely to develop bleeding or glazing, they eliminate splash during or after rain, and they provide better light reflecting properties for night driving than dense-graded surfaces.

8. The friction values on open-

grid steel bridge floors were very high in the dry tests but they were dangerously low in the wet tests. Traffic has a polishing wear effect on the steel grid floors which caused a reduction in the friction value on the older floors.

9. Heavy rains in November and December increased the friction values measured on various surfaces during the previous summer season by 20 to 60 percent.

10. The impending-skid friction values were 50 to 100 percent higher than the locked wheel values on all types of asphalt and p.c. concrete surfaces on which tests were run. This is an indication of the extent of the hazard caused by locked-wheel braking.

11. The friction values for the synthetic rubber tires with a good tread were about 5 percent higher than for natural rubber tires in the wet tests on the various paved surfaces.

12. These tests indicated that the greatest skidding hazard is encountered when braking a car equipped with smooth tread tires with all wheels locked or sliding on a wet glazed asphalt surface. Friction values as low as 0.10 were measured for this test condition and indicated stopping distances 5 to 6 times longer than the stopping distances from same speed on a dry asphalt surface.

ACKNOWLEDGMENTS

The authors wish to acknowledge, with sincere appreciation, the help given by all those who have assisted in this investigation Special credit should be given to Messrs Gale Ahlborn and Al Grabher for their work in building test equipment and in running the field tests. Mr. J. R Hall, Electronics Engineer and Mr R G. Newcomb, Senior Laboratory Mechanic, designed and built the SR-4 strain gage dynamometer, the road roughness recorder and calibration equipment, and certain other items of test equipment used in both the roughness and skid resistance tests

The authors wish to acknowledge the cooperation of the California Division of Highways for their assistance in running the skid resistance tests by furnishing a flagman and water truck. Special thanks are extended to the Four Wheel Drive Auto Company for the use of the truck which they built specially for this project and to the Goodyear Tire and Rubber Company for furnishing all of the tires used in the tests

DISCUSSION

ERNEST G. WILES - *Bureau of Public Roads* - It is gratifying to note the increased interest throughout the country in developing and in utilizing equipment for measuring the surface roughness of pavements. The work by Professor Moyer, both in the middle west and in California that has been reported from time to time to the Highway Research Board, has done much to stimulate interest in the single wheel trailer type of equipment.

The seven items of design and operation that were investigated by Professor Moyer and are described in this paper are of particular interest and will be discussed briefly. Item 1, relating to tire type and roundness requirements, is quite important. There is no doubt but that a tire with a smooth tread would entirely correct the difficulty experienced with an all-rib tire which has some tendency to collect loose particles from the pavement surface. The all-rib tread was selected because it offered the minimum effect of tread pattern in a tire that could be obtained readily through commercial outlets.

There may be some question as to whether the method used to make the tire round would always correct the difficulty that was found to exist. If the variations in radius were caused by the wheel rim being out of round, it would seem better to correct this condition first in order that the tire bead could be seated on a rim with constant radius. Also after the tire is mounted, instead of checking the tire diameter and grinding down the tread to the tolerances indicated, it would seem to us to be better to measure the radius of the tire-wheel combination while supporting its normal or operating load. In this way variations in radius due to carcass stiffness or other conditions of the tire can be detected and corrected. Investigation of this tire eccentricity problem at the Road Research Laboratory in England gave informative data from which it was concluded that maximum variations in loaded radius should not exceed .05 inch. If the tolerances referred to by the authors were maintained for the tire in a loaded condition, the variations in radius would fall well inside those established by the English work. The Bureau of Public Roads has found that with present-day tires it is desirable to balance the tire-wheel combination both statically and dynamically, since any unbalanced weight has a tendency to affect the magnitude of the roughness readings.

The use of rubber "O" rings, as suggested by the authors, may effectively seal the dashpot units and prevent them from leaking oil. However, if the seal is too tight the friction developed between the "O" ring and the piston shaft may cause enough additional damping to decrease the roughness readings. When changes of this type are made, definite comparisons between the two methods are necessary to establish conclusively that the change or improvement does not affect the roughness readings.

The redesign of the commutator end of the integrator, substituting a six-pronged cam and microswitch for the commutator, is admittedly an improvement for reasons cited in this report, although the original design has given satisfactory service over thousands of miles with due attention to the condition of the commutator.

The Bureau of Public Roads has not advocated any particular calibration device for the integrator, realizing that various users of the roughness equipment might already have available some device that would be suitable for such a purpose. The calibration device described by the authors is, no doubt, suitable for the purpose. However, since the paper does not describe the method used to determine the length of stroke of the calibration device, it might be of interest to mention what was learned at the Bureau of Public Roads regarding this measurement. It was found necessary to measure the stroke of the calibration device under actual operating conditions in order that any overthrow, lost motion or play in the linkage of the reciprocating mechanism would be included in the stroke measurement. To accurately measure the stroke with the machine operating, a micrometer forming part of the circuit of a "magic eye" electronic tube was used as a contact detector. This gave a very sensitive indication of the stroke limit under dynamic conditions.

The substitution of an airplane control cable for the integrator cable that is specified on the Bureau of Public Roads drawings should not be considered an improvement since the airplane cable, in size, strength and pliability, essentially duplicates the Roebling stainless steel cable specified. It does indicate another source for this construction item.

It may be of interest to mention another means for obtaining a continuous graphical record of the spring movement of the roughness trailer that has been used by the Bureau of Public Roads and is apparently satisfactory. By cementing an SR-4 electrical resistance strain gage to one of the single-leaf supporting springs and connecting it to a Brush direct-inking oscillograph, a continuous recording of the changing strain in the spring is made as the trailer travels along a pavement. It was found that the deflection and strain are in linear relationship and thus the strain variations can be expressed in terms of spring deflection. A good correlation has been obtained between integrated deflection values obtained from the graphic record and those shown on the counter attached to the integrator. In general, it appears to us that the continuous record is of value principally for developing detailed information regarding special pavement conditions.

The development of a method of standardizing the overall performance of a given roughness indicator is most desirable, as the authors have recognized. Whether or not the method that is suggested is entirely satisfactory is, we believe, open to question. Our own experience with attempts in this direction was not encouraging. With the more widespread use of equipment of this type, with or without major or minor modifications, it is obvious that different levels of roughness index values are certain to result. A common denominator is badly needed. Perhaps through planned programs of cooperative tests this project committee can provide such a standardizing procedure.