New Developments in BPR Roughness Indicator And Tests on California Pavements

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Since 1949 extensive use has been made in California of a road roughness indicator built according to plans furnished by the Bureau of Public Roads (BPR) with modifications developed at the University of California. A report of test results in California and of certain modifications in the design and calibration of the roughness indicator was presented at the 1951 annual meeting of the Highway Research Board. The roughness indicator was developed by the Bureau of Public Roads to provide standardizable equipment for measuring road surface roughness. Research with the California unit has continued during the past four years to improve its accuracy and consistency as a standardizable unit and to obtain records of road roughness of thousands of miles of pavements on the state highways, city streets and on bridges in all parts of California.

Tests were conducted to determine the limitations of accuracy provided by the BPR double ball clutch integrator design and also the accuracy of an integrator constructed with a commercially available clutch. Measurements were made to determine the effect of changing the size of the test tire from 6.00 by 16, which is no longer available, to a 6.70 by 15 size tire which is now available. The effects were measured of an improved leaf-spring bearing design and of the use of standard universal joints instead of ball-socket joints in attaching the dashpots to the frame of the trailer.

The effects of varying amounts of out-of-roundness of the test tire were measured on various road sections. It was found that the road roughness index in inches per mile for certain pavements was increased by approximately 50 percent due to an out-of-roundness of 0.05 inches which corresponds to the amount of out-of-roundness frequently observed in measurements of passenger car tires by attendants at tire and wheel alignment shops where tire truing work in done.

To protect the test tire and roughness equipment from damage and excessive wear in moving it from one test section to the next test section, a special outrigger trailer was developed to carry the test trailer in a suspended position by the use of a hoist and special clamping devices. Detailed shop drawings for the outrigger trailer have been prepared.

The results of roughness measurements for all of the major types of pavement surfaces used on state highways, city streets, and on various types of bridge floors are reported, analyzed and correlated with the design features, age of the pavement and construction methods used in building these surfaces.

● RESEARCH dealing with the measurement of road roughness using the Bureau of Public Roads (BPR) roughness indicator with modifications developed at the University of California, has been under way for the past seven years. This research is a part of a general study of road surface properties at the University of California which in addition to road roughness covers such items as skid resistance, road and tire noise, tire wear and tractive resistance. The preliminary phases of this study, including a description of the BPR roughness indicator and certain modifications of this equipment developed at the University of California, were described in papers presented at the Annual Meeting of the Highway Research Board in 1950 and 1951. These papers were published in the Highway Research Board Bulletins 27 and 37.

Measurements of road roughness have been made on many different types of pavements on the major state highways in the eleven state highway districts in California, and on many pavements in California cities and on the major bridges and freeway overpass structures in the San Francisco Bay Area. Repeated measurements were made on selected pavements to provide a record of seasonal and long-term changes in the roughness of these pavements. While a major objective in this study has been to assemble and analyze the roughness measurements on many different pavement types in all parts of California, an important objective has also been the development of testing equipment and of calibration and testing methods which will assure greater consistency and accuracy in the test results than were possible when work on this project was started.

The road roughness tests conducted over a seven year period have demonstrated that the basic design of the BPR roughness indicator is sound and that it provides the simplest and most accurate method to measure road roughness which has been developed to date. The modifications made at the University of California on the BPR design were intended to improve the accuracy and dependability of the equipment, and to make it a standardizable unit as the Bureau of Public Roads intended it to be. The addition of the direct recording oscillograph equipment has made it possible to obtain a graphical record which is very useful in analyzing the roughness data and in identifying locations for visual inspection to determine the type and probable causes of the roughness observed on the oscillograph records. Many tests were run to determine the effect on the roughness measurements due to actual wear or simulated wear of critical parts of the equipment, which may be expected after many years of operation of the equipment over many thousands of miles of road.

The results of the tests reported in this paper are intended to provide road roughness data and graphical records of road roughness for many different types of pavements under many different conditions under which the BPR roughness indicator may be used. In the discussion of the test data, an explanation will be offered for the variable results obtained under different test conditions with this equipment. In addition certain limitations will be pointed out concerning the use of the equipment which should be recognized in the interpretation and evaluation of the test data.

With passenger car speeds on many rural highways and on some urban expressways today averaging 50 to 60 mph and top speeds exceeding 70 mph, smooth pavements are necessary not only to provide a comfortable ride at these speeds but also to provide greater safety in steering and braking of cars driven at high speeds. Highway engineers in many states are recognizing the need for providing smooth pavements as is evident by the increased use of devices such as the BPR roughness indicator to measure road roughness. This equipment is now in use in about 15 states and on the basis of the many

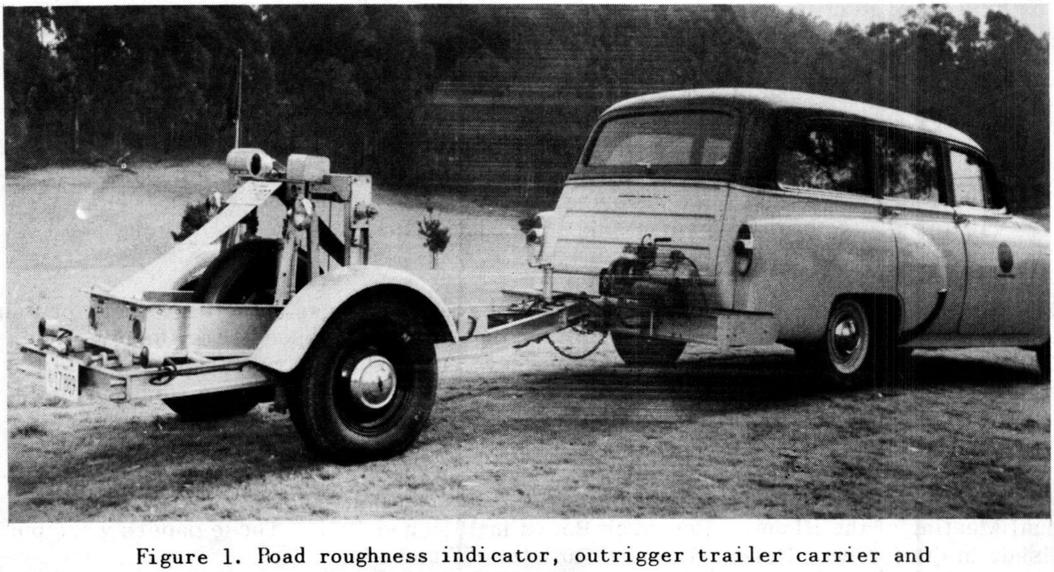

Figure 1. Road roughness indicator, outrigger trailer carrier and tow car.

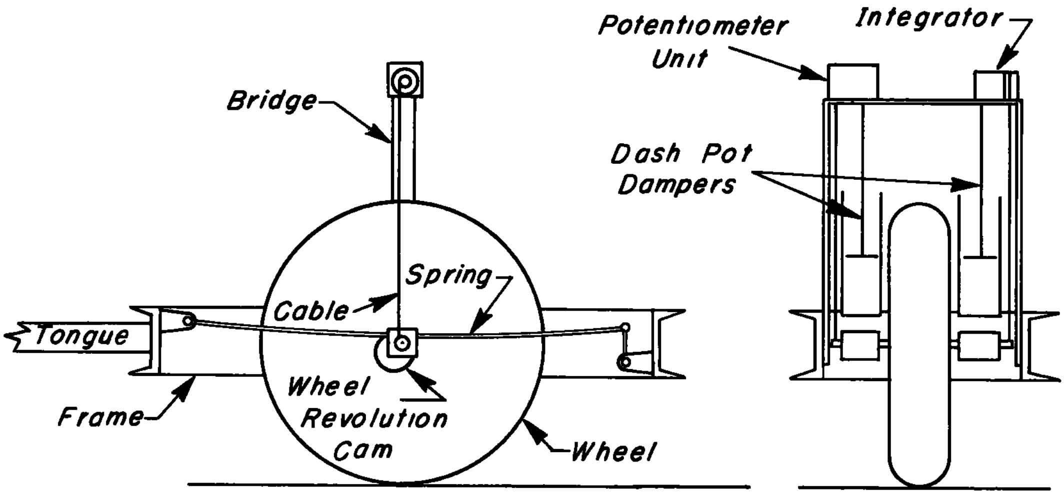

Figure 2. Schematic diagram of the essential elements of the Bureau of Public Roads road roughness indicator.

inquiries received during the past year concerning the equipment, it is expected that additional state highway departments will build similar equipment. The test results and operating experience with the BPR roughness indicator described in this paper should be of special interest to highway engineers who are now using similar equipment or who are contemplating using such equipment.

The roughness measurements can serve many useful purposes such as to provide a standard for new construction, for reconstruction and for maintenance. Roughness measurements are used by the Cities of Berkeley, Los Angeles and San Diego as a major item for rating the condition of streets and for programming street and highway work. The riding public judges a road largely by its smoothness or riding quality and it is, therefore, a matter of good public relations to construct and maintain pavements with as smooth a surface as is reasonably possible.

Description of the University of California BPR Roughness Indicator

The road roughness indicator used in the current research at the University of California was built in 1941 according to plans furnished by the U. S. Bureau of Public Roads. It was used in measuring the roughness of more than 1,000 miles of roads in Iowa, Kansas, Missouri and Wyoming in an extensive research program conducted by Iowa State College in cooperation with the Bureau of Public Roads. In 1949 this equipment was acquired by the University of California for the current research. Since 1949 it has been overhauled several times and modifications have been made for reasons mentioned above and to be described in greater detail in the discussion which follows.

A detailed description of the BPR roughness indicator is given in a paper by J. A. Buchanan and A. Catudal, entitled "Standardizable Equipment for Evaluating Road Surface Roughness," published in the 1940 Proceedings of the Highway Research Board. Briefly stated, this equipment consists of a single-wheeled trailer which is towed by a car or light truck (Figure 1). The BPR plans call for a standard four-ply 6.00 by 16 rib tread tire for the single wheel on the trailer. As the single-wheeled trailer is towed over a given section of road, the irregularities in the road surface transmitted through the tire to the axle of the wheel are measured in terms of the vertical movements of the axle. The vertical movements of the axle are transmitted by a wire cable to a double-acting ball clutch integrator which in turn transmits the accumulated vertical movements in inches to an electric counter mounted on a board in the tow car. A similar electric counter records the revolutions of the trailer wheel and thus provides an accurate measure of the travel distance. The roughness tests have been standardized at a speed of 20 mph and the measurements are recorded on a data sheet by an observer for each half mile section and/or at the end of each test section. The data are summarized by expressing the roughness of each section of road in terms of a standard unit known as the roughness index (RI), which is the roughness in inches per mile.

The essential elements of the BPR roughness indicator are shown in Figure 2. It should be noted that the wheel of the roughness trailer is supported by two light steel springs. Also, two specially designed dashpot dampers are attached to the axle of the wheel and the frame of the trailer to eliminate excessive bouncing or vibration of the tire as it rolls over rough spots on the pavement. Tests have shown that the tire and the dashpots provide excellent damping action such that the tire follows fairly closely the vertical profile of the pavement surface and thus the equipment provides a reasonably accurate measurement of the vertical movement of the wheel and tire on the paved surface.

Development of Direct Recording Oscillograph Equipment

The need for a graphical record of road roughness was discussed in both the 1950 and 1951 reports referred to above. Also, in these reports a description was given of the direct recording oscillograph equipment developed at the University of California and which has been used in the California tests to obtain graphical records of road roughness. This equipment has been very helpful for obtaining a detailed record of road roughness and for the analysis and interpretation of road roughness data as measured under many different conditions. In the latter part of this report many oscillograph records will be shown to aid interpreting the road roughness data and to provide an indication of the types of road roughness encountered under various test conditions.

Although wiring diagrams were shown in the 1951 report for the electronic amplifier, external bridge circuit and the power supply used with the amplifier, certain changes have been made in these wiring diagrams since 1951. The latest revisions of these wiring diagrams are shown in Figures 3 and 4.

IMPROVEMENTS IN THE DESIGN AND OPERATION OF THE BPR ROUGHNESS INDICATOR

The items in the design and operation of the BPR roughness indicator which were investigated at various times during the past seven years are the following:

1. Tire size, tread design, tire wear and roundness effects.

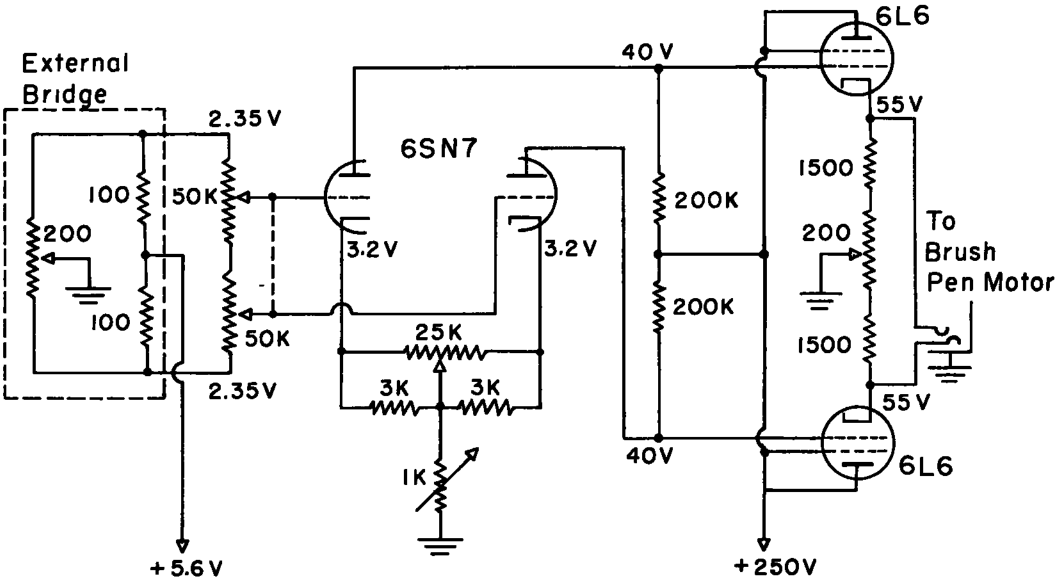

Figure 3. Electronic amplifier and external bridge wiring diagram used with BPR roughness indicator.

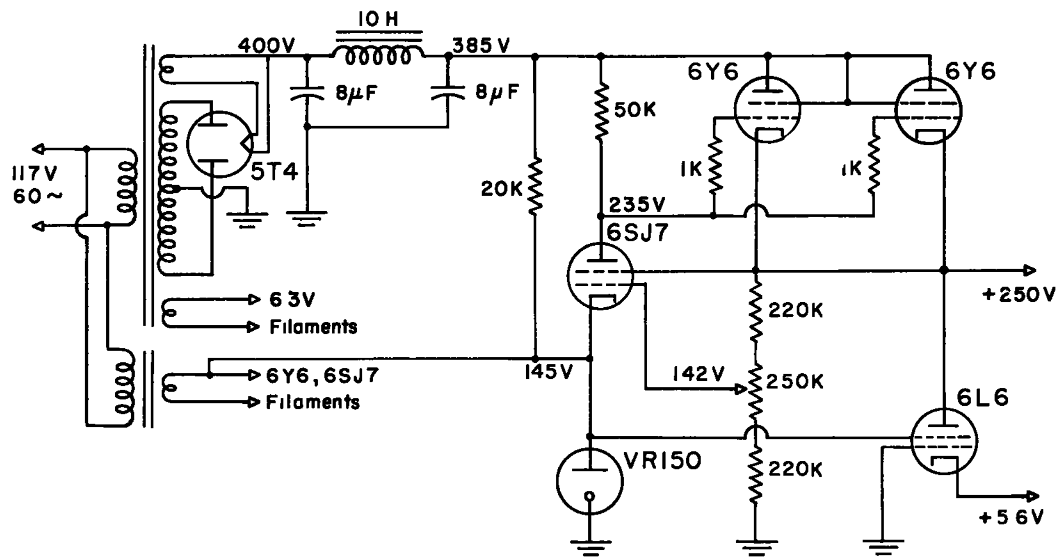

Figure 4. Wiring diagram for power supply used with electronic amplifier.

2. Oil leakage in the dashpot damping units, use of "0" rings, effect of worn joints and use of standard universal joints.
3. Improved leaf spring ball bearing design.
4. Improved integrator design - use of BPR clutch versus commercial clutch.
5. Development of equipment and method of calibrating integrator.
6. Improved wheel revolution counter design.
7. Effect of towing unit - use of outrigger trailer carrier.

Effect of Various Tire Factors

The early tests with a rib tread tire indicated that stone chips and gravel particles were picked up by the tread and were lodged in the grooves of the tread. 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 was adopted for use on the University of California trailer.

In recent years the size of tires for popular priced cars has been changed from 6.00 by 16 to 6.70 by 15. Accordingly the U.S. Rubber Company, which manufactured smooth 6.00 by 16 tires for use on the BPR roughness indicator, discontinued making the 6.00 by 16 tire several years ago. This company is now, however, making a 6.70 by 15 smooth tread tire for use with this equipment. This new tire may be obtained on special order from the factory.

The University of California roughness trailer was modified to permit running tests with the older size 6.00 by 16 tire and, also, with the new 6.70 by 15 tire. Tests were run with both of these tires on six different road surfaces with varying amounts of roughness. The results of these tests, shown in Table 1, clearly indicate that the change in tire size produced for all practical purposes no change in the roughness indexes as measured on these six surfaces. For four of the surfaces the difference in the roughness index was only 1 in. per mile which is well within the experimental error. On the roughest pavement, the difference amounted to 4 in. per mile but here again this is within the experimental error. The use of the new tire introduced a change in wheel revolutions per mile as

TABLE 1

COMPARISON OF TEST TIRES

Test Section	Pavement Type	Roughness Index, in per mile: 6 00-16 Synthetic Rubber Tire	6 70-15 Synthetic Rubber Tire
1	Bituminous	36	37
2	P C Concrete	60	61
3	Bituminous	73	75
4	Bituminous	133	132
5	P.C Concrete	157	158
6	Bituminous	295	291

was expected but even this change was rather small. For the new 6.70 by 15 tire, the wheel revolutions per mile under standard test conditions average 742 as compared to 736 for the older 6.00 by 16 tire.

TABLE 2

COMPARISON OF TEST TIRES

Test Section	Pavement Type	Roughness Index, in. per mile: Smooth Tread Natural Rubber Tire	Smooth Tread Synthetic Rubber Tire
1	Bituminous	68	66
2	P. C. Concrete	72	72
3	P. C. Concrete	166	164

Tests were run to compare the roughness index for three road surfaces using a 6.00 by 16 synthetic rubber tire which was less than one year old and a 6.00 by 16 natural rubber tire 10 years old. The results of these tests given in Table 2 show that there was no measurable effect due to age or to the type of rubber used. It should be mentioned here, however, that in making these comparison tests both tires were carefully checked for roundness prior to the test. As will be shown in the discussion which follows, large errors in the road roughness measurements are obtained if the tests are run with tires which are more than 0.03 in. out of round.

Effect of Tire Out-of-Roundness

In the early stages of this study, it was noted that if the test tire was not perfectly round, an increase in the roughness index was obtained which was directly related to the out-of-roundness of the tire. Since the effect of out-of-roundness of the test tire did not appear to follow a fixed pattern, it was decided to make a special study of this tire factor.

In general, tire out-of-roundness is of two types. One of these is in the form of a flat spot on the tire due to locked-wheel braking or for synthetic rubber tires, the flat spot may be caused by keeping the tire in a loaded position for a sufficient length of time to cause plastic deformation of the rubber in the tread. Another form of tire out-of-roundness is due to the wheel or tire or both not being centered accurately on the hub or axle of the wheel assembly.

The method used in this study to obtain an accurate measurement of tire out-of-roundness was by the use of a Federal Dial indicator with the tire and the indicator

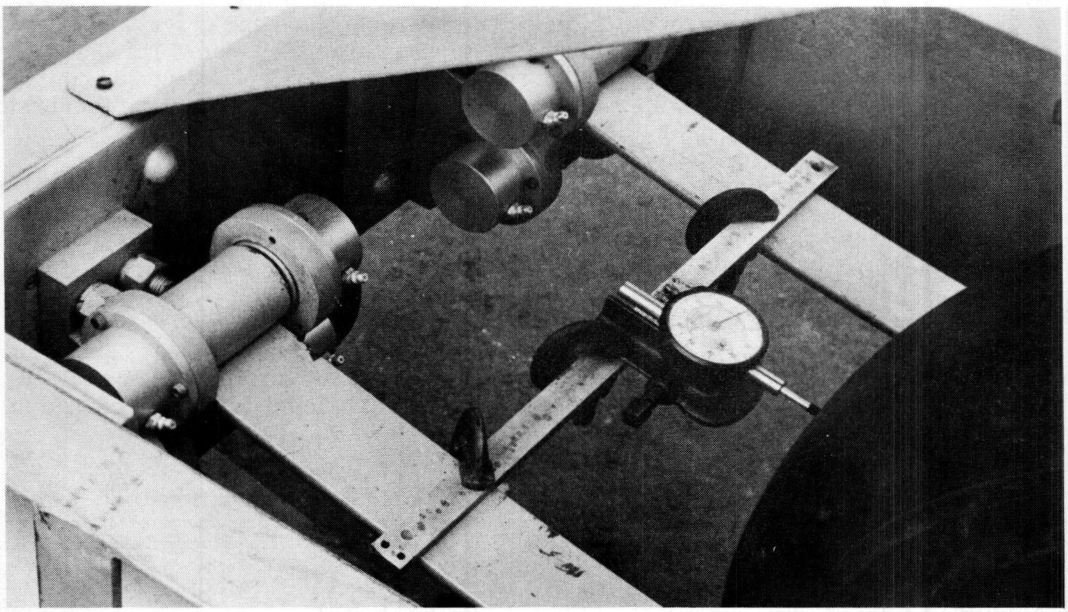

Figure 5. Method of measuring tire out-of-round using Federal Dial indicator. Also shown are the special grease cups with grease fittings used in redesign of ball bearing mountings for leaf springs.

mounted on the trailer as shown in Figure 5. With this method, readings could be made to the nearest 0.001 inch on the indicator.

To determine the effect on the road roughness measurements of varying amounts of out-of-roundness of the tire, the wheel was mounted in four different off-center positions resulting in out-of-roundness varying from 0.017 in. to 0.100 in. Tests were

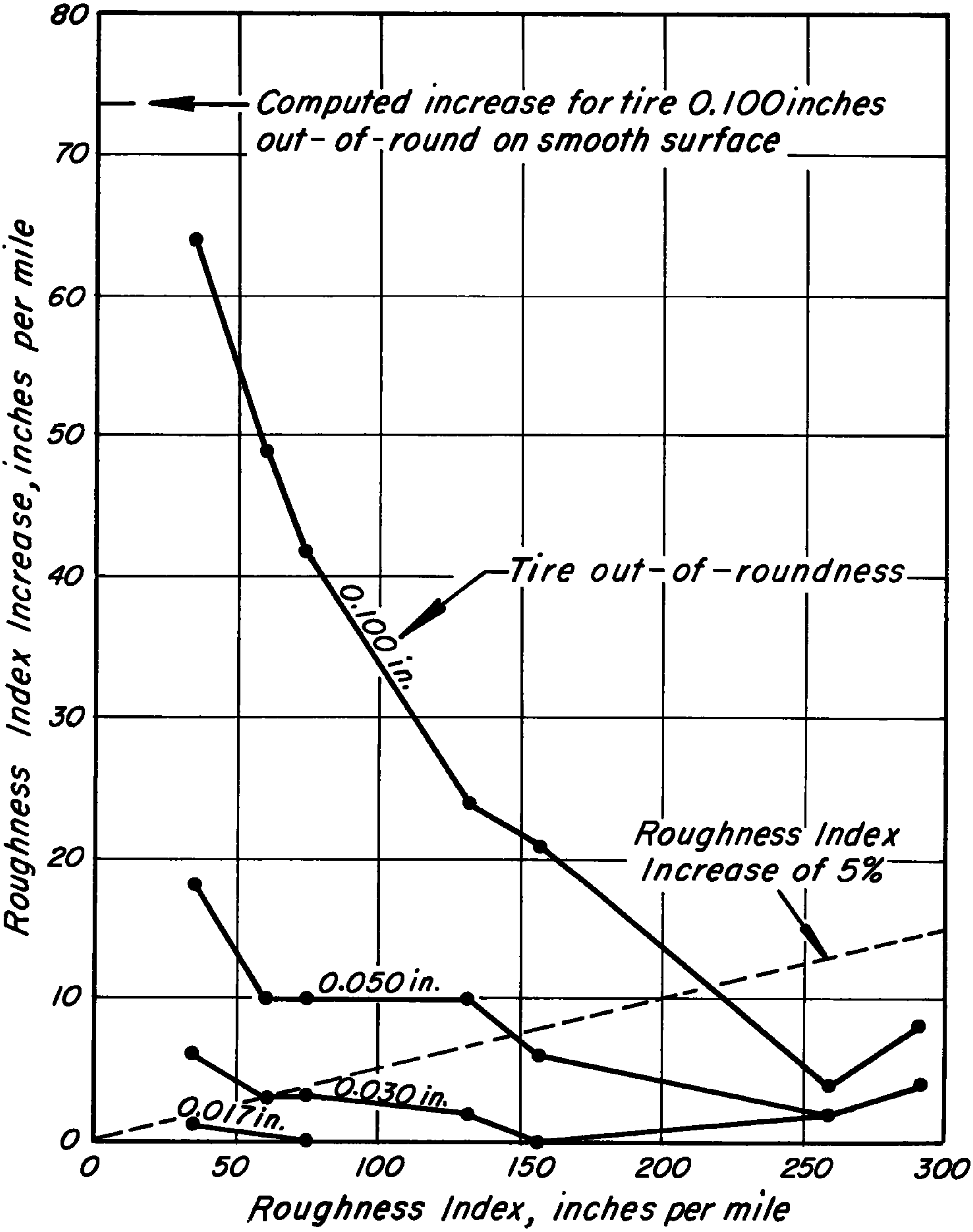

Figure 6. Effect of tire out-of-roundness on the roughness index measurement on various road surfaces.

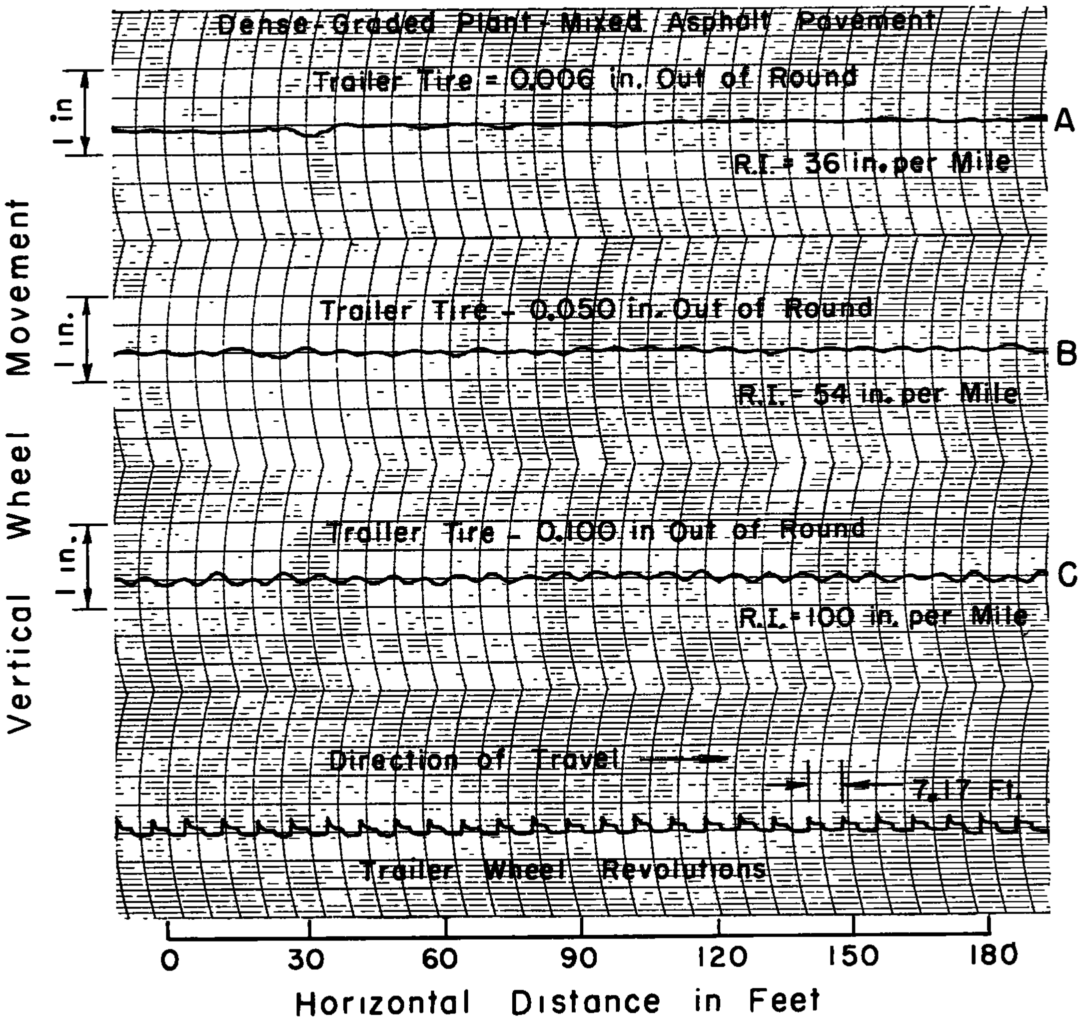

Figure 7. Roughness oscillograph records showing the effect of the use of a smooth trailer tire with varying amounts of out-of-roundness in tests on the same pavement.

then run on seven different road surfaces with roughness indexes for the standard test conditions ranging from 35 in. per mile to 300 in. per mile. The results of these tests, shown in Figure 6, indicated that the maximum increase in the roughness index due to tire out-of-roundness was obtained on the smoothest pavement. On this pavement with a tire out-of-roundness of 0. 100 in., the increase amounted to 64 in. per mile which is approximately a 200 percent increase. By assuming that the full 0. 100 in. out-of-roundness is effective during each wheel revolution the computed increase in road roughness will amount to 74 in. per mile which is only 10 in. per mile greater than the measured increase on a smooth pavement.

The tests with the off-centered tire indicated that the increase in road roughness falls off sharply as the pavement roughness is increased. Thus, with a pavement roughness of 250 in. per mile, the effect of tire out-of-roundness was almost entirely eliminated since on this pavement the increase for the 0. 100 in. out-of-round tire amounted to less than 5 in. per mile.

The effects of varying amounts of tire out-of-roundness on the same smooth asphalt pavement are shown in graphical form in the oscillograph records (Figure 7). These records provide some interesting patterns. It should be noted in Figure 7 that with the test tire 0.100 in. out-of-round, a sine-curve roughness pattern of considerable amplitude is obtained on the oscillograph record. The roughness of a smooth asphalt pavement will be raised from 35 in. per mile to 100 in. per mile with the test tire 0.100 in. out-of-round, and thus make this pavement appear to be rough riding when actually the rough ride should be attributed to an out-of-round tire condition.

While no attempt was made to determine the extent of tire out-of-roundness of tires on passenger cars in service, the reports of service stations equipped to do tire truing work, indicated that tire out-of-roundness of 0.05 in. to 0.10 in. was quite common. A common cause of tire out-of-roundness is that which results from the flat spots due to locked-wheel braking. To determine the extent of the flat spot tire wear caused by locked-wheel braking, braking tests were conducted and the tire wear resulting from these tests was measured in $\frac{1}{1000}$ in. units. The results of these tests are shown in Table 3. It should be noted that the wear in the central portion of the tread is only about one-half the wear along the outer edge of the tread. However, in a single stop from 60 mph with a skidmark 150 ft long, the depth of tread removed from the tire amounted to 0.070 in. This is evidence that locked-wheel braking can cause an out-of-round tire condition which can be as much of a factor in causing a rough ride as a poorly constructed pavement.

It is evident from the above discussion that special precautions should be taken to keep the BPR roughness indicator test tire in an in-round condition. Tire truing machines are now being used by certain tire service station operators which can reduce tire out-of-roundness to ± 0.001 in. with the tire mounted on the machine and with no load on the tire. It has been found that the mounting studs on the wheel hub may be off-center by as much as 0.010 in. and thus the tire may be out-of-round when mounted on the trailer due to an off-center mounting. To correct this error the studs should be carefully centered and a final check of tire-roundness made as shown in Figure 5. For accurate roughness measurements, the maximum permissable variation in test tire out-of-roundness as measured with a precision dial indicator should be ± 0.010 in. and the preferred maximum variation should be ± 0.005 in.

It should also be noted that synthetic rubber tires develop flat spots when standing in the same spot supporting a load. For this reason, the test tire should be held in an unloaded position except during tests as an extra precaution to keep the test tire within the permissable amount of out-of-roundness.

TABLE 3

PASSENGER CAR TIRE WEAR IN ONE SPOT OF TREAD OBTAINED IN A LOCKED-WHEEL BRAKING TEST

Initial Speed, mph	Average length of skidmarks, feet	Tire tread wear, $\frac{1}{1000}$ in. Along outer edge of tire tread	In central portion of tire tread
20	17	8	4
30	33	15	8
40	62	29	15
50	105	49	26
60	150	70	37

TABLE 4

EFFECT OF "0" RING INSTALLATIONS CALIFORNIA TESTS

Test Section	Pavement Type	Roughness in in. per mile for various types of "0" ring installations[a] 1	2	3	4
1	Bituminous	68	67	57	65
2	Bituminous	140	140	120	140
3	Concrete	166	170	155	168

[a] "0" ring installation:

1 "0" rings installed with recommended depth of cut in bushings of 0 090 in 6,000 miles of highway travel, very little fluid leakage.

2 Without "0" rings.

3. New "0" rings installed with recommended depth of cut in bushings of 0 090 in.

4 New "0" rings installed with depth of cut in bushings increased until very little drag was felt on piston rod and still with no fluid leakage

Effect of Dashpot Damping Units on Road Roughness

Observations in tests with the University of California roughness indicator and with a similar unit built by the City of San Diego, indicated that there were three or four features in the design and operation of the dashpot damping units which, if not properly controlled, could introduce large variations in the roughness measurements.

Tests by the Bureau of Public Roads indicated that the viscosity of the oil used

TABLE 5

EFFECT OF "0" RING INSTALLATION U S. BUREAU OF PUBLIC ROADS TESTS

Test Section	Pavement Type	Road Roughness (in per mile) Without "0" rings	With "0" rings
1	Concrete	142	119
2	Concrete	126	90
3	Bituminous	122	86

in the dashpots must be standardized and carefully controlled to obtain consistent results. Likewise, the height of the oil level was found to be an important item. Oil leakage presented quite a problem in some of the tests in California and to correct this difficulty "O" rings were installed in the bushings of the dashpots. It was found, however, that if the "O" rings were installed with a tight fit, considerable drag was introduced on the piston rod as it was raised and lowered. The effect of this drag resulted in a reduction of the roughness index values as shown in Tables 4 and 5. The tests with the University of California trailer indicated reductions of 10 to 15 percent in the road roughness values due to tightly fitting "O" rings. Similar tests by the Bureau of Public Roads indicated reductions as high as 30 percent according to the data shown in Table 5.

The data in Table 4 show that if the "O" rings are installed with a depth of cut in the bushings until very little drag is felt when raising and lowering the piston, no error is introduced due to the use of "O" rings and oil leakage can still be held to a minimum.

In this connection it should be mentioned that much of the wear in the dashpot bushings probably resulted from hauling the test trailer from one test site to another at speeds considerably in excess of 20 mph over fairly rough roads. Several years ago a special outrigger trailer carrier was built at the University of California to haul the test trailer from one test site to the next. The test trailer has for the past two years been operated only at 20 mph on the test sections and the difficulties with excessive bushing wear and oil leakage have for the most part been eliminated.

TABLE 6
COMPARISON OF JOINTS IN TEST UNIT AND EFFECT OF WEAR OR END-PLAY FOR BALL-THRUST JOINTS

		Roughness Index, in per mile			
			BPR Ball-Thrust Joints		
Test Section	Pavement Type	Standard Universal Joints	No End-Play	1/16-in end play, each side	1/8-in end play, each side
1	Bituminous	68	70	94	104
2	Bituminous	113	112	144	180
3	Bituminous	174	176	202	240

Another feature in the design of the dashpot units which our tests demonstrated could be responsible for large errors in the roughness measurements, were the ball-thrust joints where, after many thousands of miles of operation, excessive wear at the joints caused a small amount of end-play. The magnitude of the error in the road roughness values caused by varying amounts of wear and end-play at the ball-thrust joints is indicated in the test results given in Table 6 for three different pavements. To eliminate the end play referred to above, the ball-thrust joints were replaced with standard universal joints. Test results are given in Table 6 which show that the roughness index remained the same for tests on the same pavements for the trailer equipped with universal joints as for the trailer with the BPR ball-thrust joints with no end-play. With 1/8 in. end-play at the ball-thrust joints, the roughness index values were increased approximately 50 percent, as for example, from 70 in. per mile to 104 in. per mile and from 176 in. per mile to 240 in. per mile. A 50 percent error is much too large for satisfactory operation of road roughness equipment and it is evident that either the ball-thrust joint design should be changed or special precautions taken to eliminate end-play at the ball-thrust joints by providing a finer adjustment for seating the ball in the socket.

Improved Leaf Spring Ball-Bearing Design

The suspension system for the roughness trailer was designed to be as nearly frictionless as possible to prevent the variable damping effects commonly observed when an assembly of leaf springs or certain other types of suspension systems are used. For this reason light single leaf springs and ball bearing mountings were used. In general, this design has been satisfactory except for the difficulty in keeping the ball bearings clean and well lubricated. Even with sealed bearings, it was found that water and dirt accumulated in the bearings, caused corrosion and pitting of the bearings and prevented the desired low friction action of these bearings. Accordingly special grease cups with grease fittings were designed for all of the ball bearing mountings. Drawings for the special grease cup design and the mountings may be obtained through the Highway Research Board. In the new design the shields were removed from the ball bearings, thereby facilitating flushing the bearings with grease through the grease fittings by the use of a grease gun. The operation of flushing the ball bearings with grease requires very little time and we recommend that it be done at least once or twice a week if the roughness trailer is in continuous use.

Integrator Design - BPR Clutch Versus Commercial Clutch

The integrator is the most important part of the BPR roughness measuring mechanism. It consists of an over-running double ball clutch which accumulates or integrates the vertical movement in one direction only of the axle on which the test wheel is mounted. Over the seven year period in which this equipment has been used in California, there have been a number of difficulties encountered which contributed to inaccurate readings with the BPR integrator design. Some of these factors were discussed in the 1951 report, including changes in the design of the integrator. Additional improvements have been made in the integrator since 1951 and tests have been conducted to indicate the limitations of accuracy of the integrator with various modifications developed at the University of California.

Such factors as dirt and dust in the case, corrosion of the metal surfaces in the integrator, misalignment of the main shaft in the integrator, stretch in the cable, arching between the carbon brush and commutator, and variable tension in the springs of the rear ball clutch were items which caused most of the trouble with the integrator. The calibration device described in the 1951 report indicated that for certain conditions described above the integrator would "grab" or develop slippage which resulted in lower values of road roughness than the true values and for some of the other conditions the integrator would overthrow or introduce extra counts which resulted in higher readings than the true values.

The use of the six-pronged cam and the micro precision switch described in the 1951 report, eliminated the errors caused by the brush-commutator design. Since then a further modification has been made in the micro precision switch by changing it from a type L2 to a type W22 (Figure 8). The latter type switch does not improve accuracy but it provides a more compact design of the integrator.

Since erratic results have been obtained on certain occasions with the BPR double ball clutch design, a special study was made to determine the reasons for the erratic results and to find out how the errors caused by the clutch could be reduced or eliminated. To eliminate or reduce the errors caused by dust and water entering the integrator, a new dust-proof case was built, with heavy felt covering the cable opening through which the steel cable has to operate. While it was observed that the heavy felt was cut by the cable leaving a larger cable opening than desired, there was no indication that an objectionable amount of dust entered the case at this point. To prevent the formation of rust on the inner and outer races of the ball clutch, it was decided to experiment with a hard chrome finish for these parts. It was found, however, that with the hard chrome finish, all wedging action of the steel balls in the races was lost, causing 100 percent slippage and thus the clutch did not function at all. A new clutch was then built to BPR specifications and installed in the integrator. It was oiled using the light mineral oil specified by the BPR. The small clutch ball springs were brought to uniform tension to hold the steel balls firmly in place. The entire integrator was built with very close

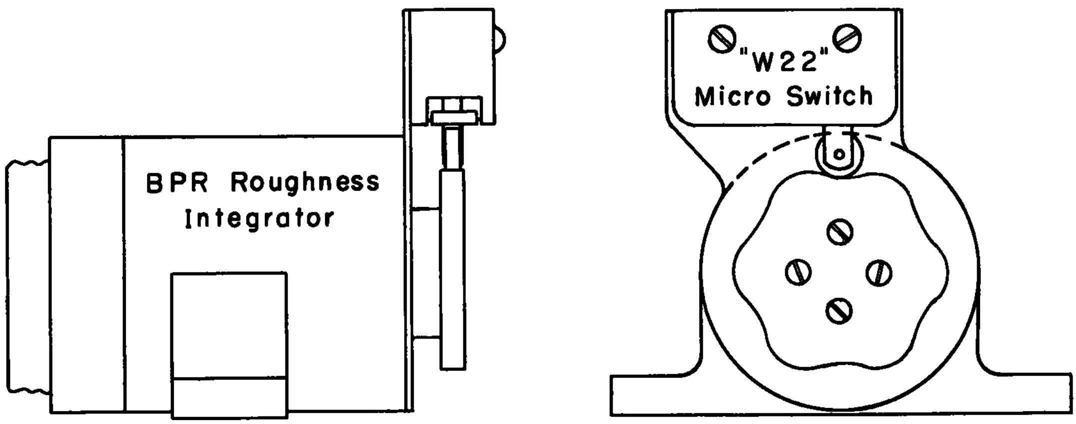

Figure 8. Modification to the BPR roughness integrator.

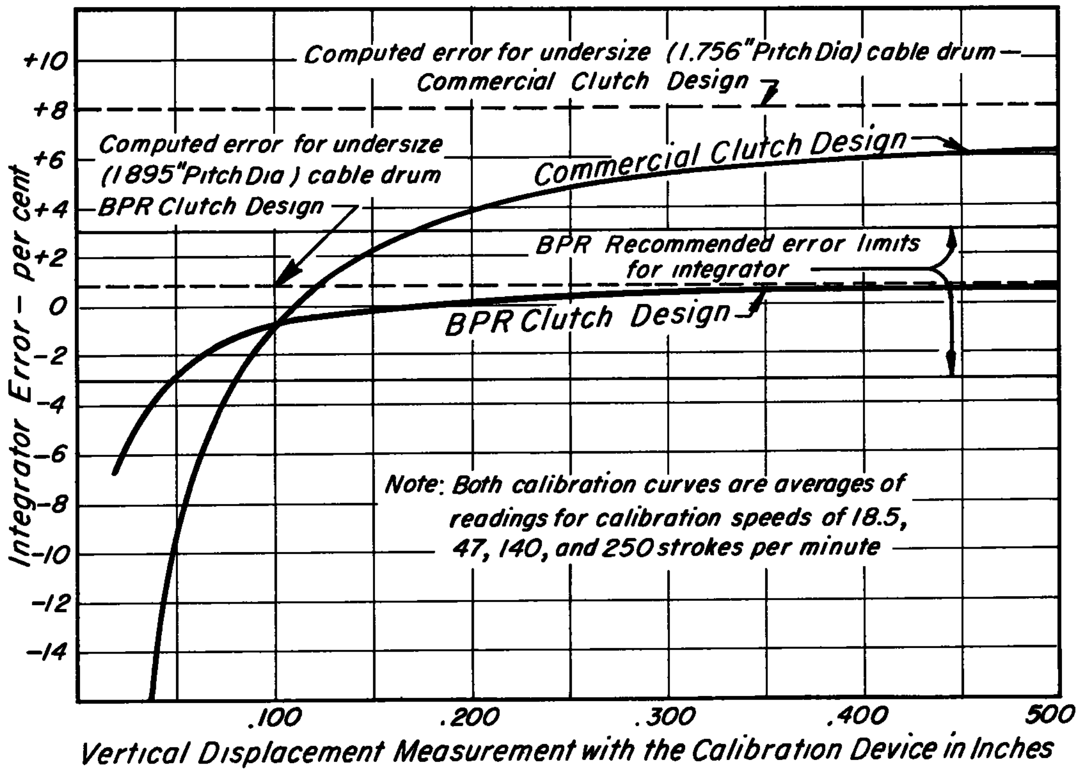

Figure 9. Comparison of the integrator error obtained in the calibration of the commercial clutch integrator and the BPR clutch integrator.

tolerances as called for by the BPR plans and specifications. The integrator was then calibrated at speeds ranging from 18½ to 250 strokes per minute.

The calibration results for the BPR clutch design shown in Figure 9, indicate that for vertical displacements from 0. 10 in. to 0. 50 in., the error in the measurements was within ± 1 percent. For vertical displacements under 0. 10 in., the error increased to about -6 percent for a displacement of 0. 025 in. These calibrations show that a mechanical clutch such as the BPR over-running double ball clutch will not pick up displacements under 0.05 in. within the ± 3 percent allowable error recommended by the Bureau. There are two design features of the BPR integrator which provide an explanation for the limitations in the sensitivity of the integrator. They are (1) the stretch in the steel cable which was discussed in the 1951 report and (2) the limit in displacement obtained as the result of the wedging or ratchet action and a certain amount of slippage of the steel balls in the clutch. The calibration curves in Figure 9 and the analysis and observations of the operation of the BPR integrator clearly indicate that at some point near a displacement of 0. 010 in., the limit of sensitivity of the mechanical type clutch is reached and that displacements lower than about 0. 005 in. are not recorded by this instrument. It should be recognized, however, that a displacement of 0. 005 in. per wheel revolution provides a maximum computed roughness index of 4 in. per mile which is so small that it has no practical significance in the evaluation of pavement roughness even for the smoother pavements where the measured roughness index values are in the range of 40 to 60 in. per mile.

Consideration was given to the possibility of reducing the cost of the integrator and possibly of improving the clutch action by using a commercial clutch. Accordingly, two Morse cam clutches No. B-203 were purchased at a cost of only $10. 00 each. A new integrator was built incorporating the commercial clutches in the design of the integrator. The Morse cam clutch was described by the manufacturers as a self-contained ratchet with an infinite number of teeth - one directional drive-over-running and free-wheeling.

The calibration results for the integrator built with the commercial clutch are given in Figure 9. It is evident from the calibration data that the commercial clutch provides the desired accuracy with ± 3 percent over such a small range of displacements (from 0. 08 in. to 0. 175 in.) that it is questionable if a Morse cam type clutch should be used in the design of the integrator. The BPR ball clutch design provided far superior accuracy on the basis of the calibration data in Figure 9 and is therefore recommended as the preferred design for a mechanical type clutch.

Test runs were made on many different pavements using the BPR roughness indicator equipped with both the BPR clutch and the commercial clutch integrator. In these tests both integrators were in operation at the same time. The results of the tests are shown in Figure 10. While the variations in units per mile do not appear to be large,

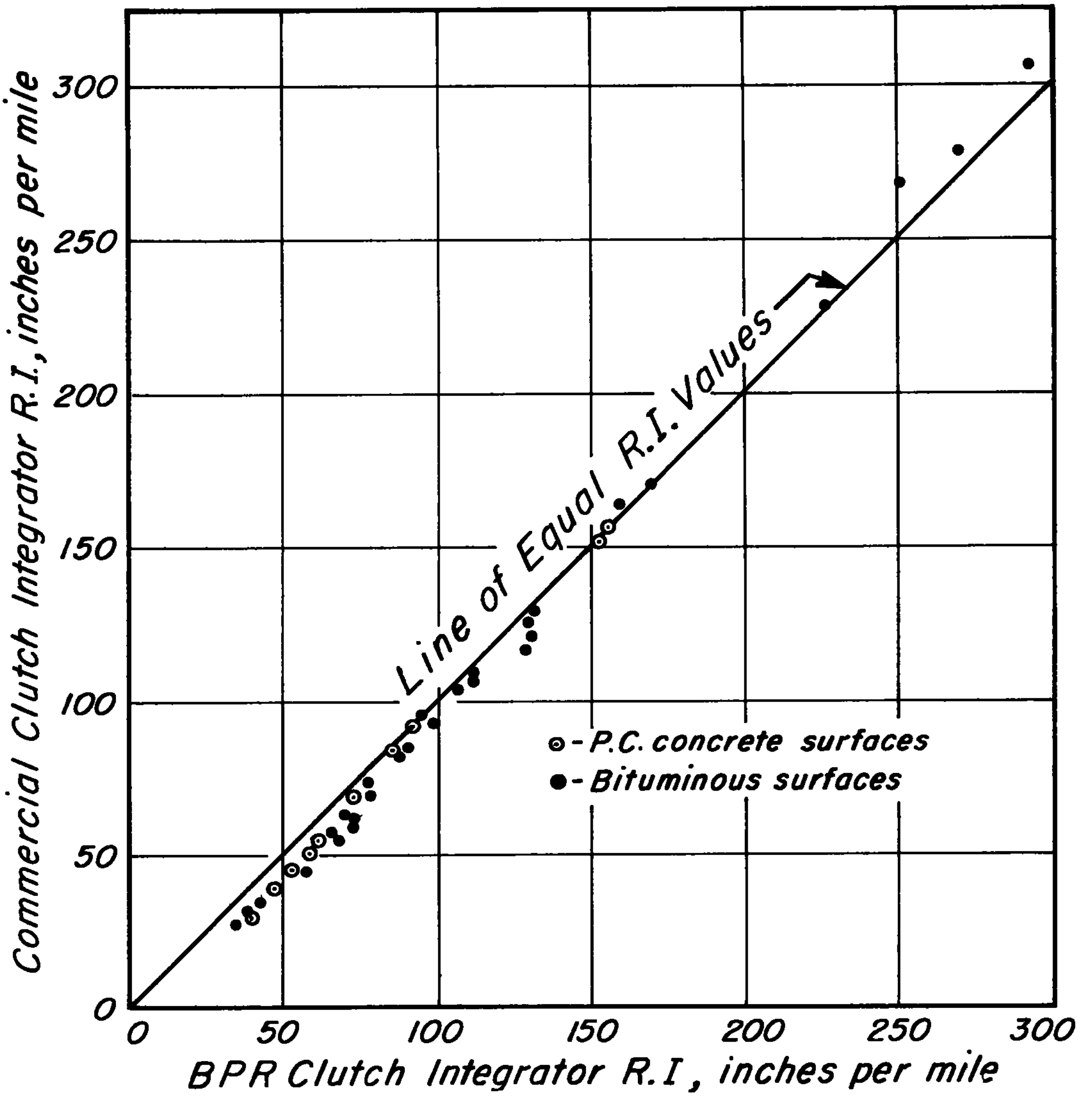

Figure 10. Comparison of roughness index (R.I.) on various surfaces measured with commercial clutch integrator and with BPR clutch integrator.

the errors or variations on a percentage basis are of the order of magnitude of ± 10 percent to ± 20 percent and thus do not comply with the ± 3 percent error specified by the Bureau. The results of these tests support the above recommendation that the Morse cam commercial clutch should not be used.

Equipment and Method for Calibrating Integrator

It is evident from the above discussion that the integrator is a rather complex and sensitive measuring device which must be ruggedly built to prevent damage when operated over rough pavements. It is highly desirable to have a fast and convenient method of calibrating the integrator periodically in the laboratory without requiring the operation of the tow car and the entire roughness indicator. The calibration unit developed by the University of California, described in the 1951 paper, has provided excellent calibration results during the past six years.

The data shown in Figure 9 were obtained by the use of the calibration device and it is doubtful if they could have been obtained by any other method. Since the integrator is a measuring device, it is highly desirable to know the limitations of the device or the errors which may be expected in its use. Also, for routine tests, it is desirable to be able to make use of a fast and convenient method of checking the integrator to be sure that it is functioning properly. All of this is accomplished with the University of California integrator calibration device.

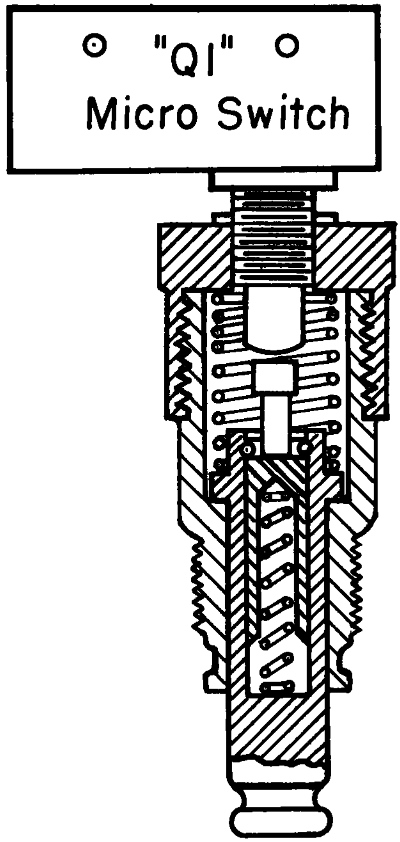

Figure 11. Use of micro switch in revolution counter design for BPR roughness indicator.

Improved Wheel Revolution Counter Device

To obtain the desired accuracy in the measurement of road roughness, it is necessary to have an accurate measurement of the distance traveled by the roughness indicator. In the BPR design of the roughness indicator, distance is measured by obtaining a record of the number of wheel revolutions of the test wheel on the roughness trailer. A contact switch operated by a cam on the hub of the test wheel closes the circuit of the magnetic counter once for each wheel revolution. With 736 wheel revolutions per mile for the 6.00 by 16 tire, it is evident that for satisfactory results when operating the roughness trailer over thousands of miles of road, the contact switch must be well built to keep out dust and water which are certain to cause excessive wear of the contact surfaces and fouling of the contact point. The sliding surfaces on the cam and plunger should be made of hardened steel and provision should be made in the design of this part of the contactor mechanism to keep the cam wiped clean and the surface lubricated with a light oil by the use of a felt wick and oil cup attachment which is a design feature not shown on the BPR plans.

The contact switch when built as shown on the BPR plans was continually giving erratic results due to wear, water and dirt fouling the contact point. The design of the contact switch was modified as shown in Figure 11 to make use of a sealed-in micro switch, Type Q-1. The installation of the felt wiper and oiler and the micro switch eliminated all of the difficulties previously encountered with the revolution counter mechanism. The new design has given excellent service during the past two years. Of course, the plunger of the contacter requires cleaning about once a month or every 1,000 miles or as needed depending upon its exposure to dust, dirt and water.

TABLE 7

ROAD ROUGHNESS INDEXES MEASURED IN REPEATED TESTS ON SELECTED CALIFORNIA PAVEMENTS

U S. 40 - Fairfield Bypass, P.C. Concrete

Test Date	Roughness Index, in per mile: No. Joints Continuous Reinforcement	Roughness Index, in per mile: Standard 15 foot joint spacing
4-18-50	38	42
8- 2-50	41	42
10-11-50	39	40
4-18-51	44	48
9-21-51	40	44
8- 5-52	45	45
9-11-52	52	61
7-28-53	45	45
5-25-54	48	50
10-24-55	50	40

Eastshore Freeway, Fallon St to 23rd Ave
Four Lanes of P.C Concrete - Passing Lanes

Test Date	Roughness Index, in. per mile: Southbound	Roughness Index, in. per mile: Northbound
7-21-49	53	56
1-24-50	55	54
2- 8-50	48	50
4-12-50	50	55
7-26-50	51	47
9-26-50	73	68
9-20-51	82	72
9-10-52	82	72
7-27-53	73	70
10-14-55	68	68

Oxford St, City of Berkeley, P C Concrete

Test Date	Roughness Index, in per mile
8-16-49	158
9-20-51	164
12-11-51	168
9-10-52	168
7-27-53	158
4-15-54	165
10-20-55	160

Eastshore Freeway, Plant-Mixes Surface, Open-Graded

Test Date	Roughness Index, in per mile
9-19-51	68
12-11-51	70
9-10-52	72
7-27-53	72
4-15-54	74
10-13-55	72

U.S 40, Vicinity Vacaville, Seal Coat, 3/8 in. Aggregate

Test Date	Roughness Index, in per mile
8- 2-50	73
4-18-51	83
9-21-51	77
9-11-52	69
12- 8-54	66

Calibration of Towing Unit-Use of Outrigger Trailer Carrier

While the BPR roughness indicator is a fairly simple and ruggedly built piece of equipment, it is a device which for satisfactory results should measure vertical displacements in highway pavements at 20 mph with a high degree of accuracy and with a precision of the order of 5 to 10 thousandths of an inch. Calibration of the integrator is an important aid in checking the accuracy of the equipment but there are many other parts of the roughness indicator such as the dashpot assembly, the revolution counter, the test tire and the ball bearing spring mountings which need periodic checking.

The method used for checking the accuracy of the University of California roughness indicator as a complete unit, has been by running repeated tests over a selected section of concrete pavement built to a high standard in a location where surface and structural failures of the pavement are not likely to develop. The continuously reinforced concrete pavement on U. S. 40 on the Fairfield Bypass has proven to be an excellent pavement for use in checking the general performance and accuracy of the entire roughness unit. Repeated tests have also been run on sections of the Eastshore Freeway, a city street in Berkeley and on an asphalt pavement with a seal coat on U. S. 40 near Vacaville.

The results of repeated tests are shown in Table 7. These tests were started in 1949 and have been run each year on certain pavements up to and including 1955. It should be noted that the roughness index values measured in September, 1952, on certain pavements were higher than usual. A careful checking of the equipment indicated that the test tire used in these tests had developed a flat spot making it more than 0.010 in. out-of-round. The increased roughness values measured on the Eastshore Freeway since 1950 were due largely to settlement and structural failure on a short section of this pavement. This section of pavement has been resurfaced and the roughness index values were reduced somewhat but the average values were still higher in the 1955 tests than in the 1949 tests.

Comparison of Roughness Indicator Test Units

At the present time, three BPR roughness indicator units are in operation on the

TABLE 8

COMPARISON OF TEST UNITS OREGON HIGHWAY DEPARTMENT AND UNIVERSITY OF CALIFORNIA ROUGHNESS TEST UNITS, NOVEMBER 14, 1951

Test Section	Roughness Index, in per mile State of Oregon Roughness Trailer	Univ of California Roughness Trailer
Oregon Redwood Highway		
Mile 1	82	92
Mile 2	84	94
Crater Lake Highway		
Mile 1	79	90
Mile 2	92	98

TABLE 9

COMPARISON OF TEST UNITS CITY OF SAN DIEGO AND UNIVERSITY OF CALIFORNIA ROUGHNESS TEST UNITS APRIL 28, 1954

Test Section	Roughness Index, in per mile City of San Diego Roughness Trailer	University of California Roughness Trailer
Florida Drive	89	94
Florida Street	214	219
Madison Ave	199	205
Arthur Ave	446	459
Marlborough Dr	246	248

West Coast. In addition to the University of California unit, the Oregon State Highway Department built and is running tests with a unit and the City of San Diego also has a unit. Tests were run in November, 1951 on the same sections of pavement to make a comparison of the roughness measurements obtained with the Oregon unit and the University of California unit. The results of these tests are shown in Table 8. Similar tests were run in April, 1954 to compare the roughness measurements obtained with the City of San Diego unit and the University of California unit. The results of these tests are shown in Table 9.

In general, the roughness index values obrained in the comparison tests of the Oregon, University of California and the San Diego roughness indicator units were of the same order of magnitude although the values for the University of California unit were 5 to 10 percent higher than for the other two units. In checking the various parts of the three units, it was concluded that there was less friction or damping action in the dashpots and leaf spring ball bearings of the University of California unit than in the other two units.

It is interesting to note here that the City of San Diego experienced some difficulty during the first month of operation of their roughness unit in obtaining consistent results. Considerable extra damping effect was observed when running tests on the same

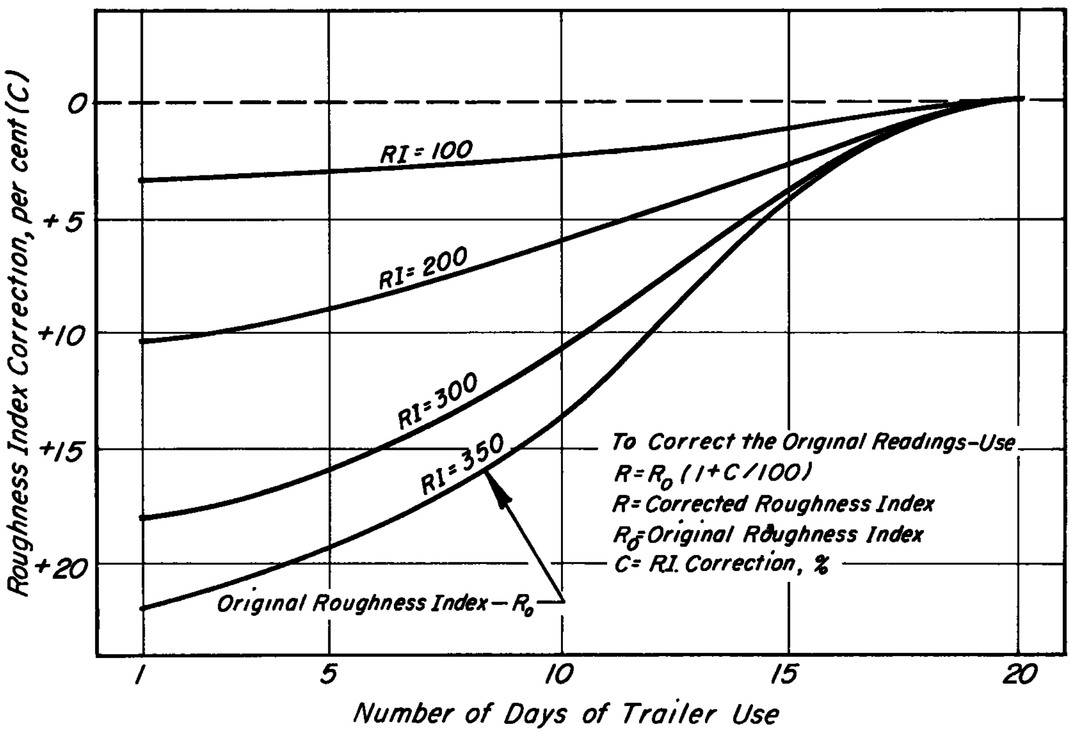

Figure 12. Correction curves used by the city of San Diego for adjusting the original roughness index readings during break-in period of BPR roughness indicator.

pavement. This extra damping effect decreased gradually during the first month of operation of the unit which was referred to as a "break-in" period. Correction curves were prepared as shown in Figure 12 for use in making corrections of the roughness index of pavements on which tests were run during the "break-in" period.

TABLE 10

EFFECT OF TOWING UNIT ON ROUGHNESS INDEX MEASUREMENTS ON P C CONCRETE PAVEMENT, U S 40, FAIRFIELD

	Roughness Index, in per mile			
Test Section	Hitch centered, trailer level	Hitch 6 ⅛-in high	Hitch 6 ⅛-in low	Bouncing on trailer hitch during test
1	46	43	44	-
2	45	43	44	44

On the basis of the seven years of tests and experimentation with the University of California roughness indicator, it is believed that if the modifications in the BPR roughness indicator proposed in this paper are made and if all the suggested precautions are taken to eliminate erratic results, consistent results and satisfactory operation of the BPR roughness indicator are reasonably certain to follow.

Dynamic Stability of the Roughness Trailer

Some concern has been expressed concerning the possible variable effects in the roughness measurements which might be attributed to the towing vehicle. The Bureau of Public Roads designed the roughness trailer to be dynamically stable so that the towing vehicle would in no way influence the roughness values measured with the trailer. In Table 10 the results of tests are given for four different towing conditions used to obtain a measure of the dynamic stability of the roughness trailer. The effects of three different heights of the trailer hitch were investigated and the effect also of bouncing on the bumper of the towing vehicle to which the trailer hitch was fastened was investigated. Since the test results were very nearly the same for all four test conditions, it may be assumed that the roughness trailer is dynamically stable.

Design and Use of Outrigger-Trailer Carrier

In the BPR Manual of Information Concerning the Operation and Maintenance of the BPR Roughness Indicator, a truck type towing vehicle is recommended for use with the roughness trailer, so that when the test sections are more than 100 miles apart, it is recommended that the trailer be placed within the towing vehicle when traveling from one test site to another. A suitable tow truck was not available at the University of California when the roughness tests were started and instead of the truck a passenger car was used as the towing vehicle. For the first four years the roughness trailer was towed at all times. It was found that towing the trailer caused a lot of wear on the various bearings and similar parts of the trailer. It also caused uneven tire wear. While the BPR design of the roughness trailer hitch provided excellent universal joint action when towing the trailer, it was not a good design for making a quick change in attaching or detaching the trailer to or from the towing vehicle. To correct all of the above difficulties in running tests with the University of California test trailer, an outrigger-trailer carrier was designed and built in 1953. The design of the outrigger-trailer carrier was patterned after the design of a similar unit built by the Oregon State Highway Department.

A general view of the outrigger-trailer carrier is shown in Figure 13. The trailer carrier is designed with a special spring suspension, electric trailer brakes, a cable hoist and frame to raise and lower the roughness trailer as needed, and with such other features as were needed to facilitate the running of tests with the roughness trailer and for transporting it from one test site to another.

In Figure 14 the roughness trailer is shown clamped in the raised position on the outrigger-trailer carrier. This is the position of the test trailer now used to move it from one test section to another. For running tests the clamps are removed and the test trailer is lowered with the cable hoist to the normal pavement position. The test trailer is attached to the outrigger-trailer carrier with the universal joint hitch shown on the BPR plans. There is no other connection between the test trailer and the outrigger-trailer carrier when it is lowered into position for running the roughness tests. By using a standard heavy duty ball and socket trailer hitch to attach the outrigger-trailer carrier to the towing vehicle, the outrigger-trailer carrier and the test trailer can be quickly and easily detached from the towing vehicle. A special wheel attached to the outrigger-trailer carrier near the hitch can be lowered in position to support the trailer carrier entirely on wheels and to facilitate moving the trailers by hand when they are detached from the towing vehicle.

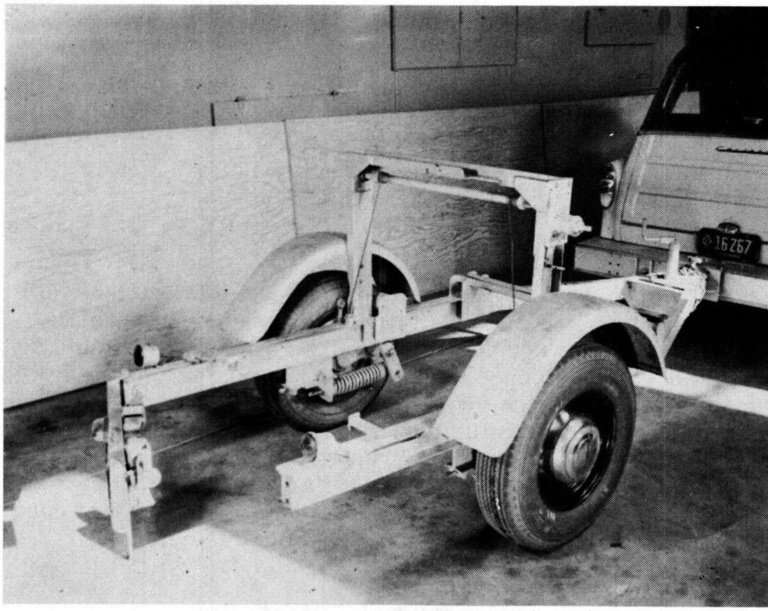

Figure 13. Showing open end of outrigger trailer carrier, trailer spring design, and cable hoist and frame, etc, used for BPR roughness indicator.

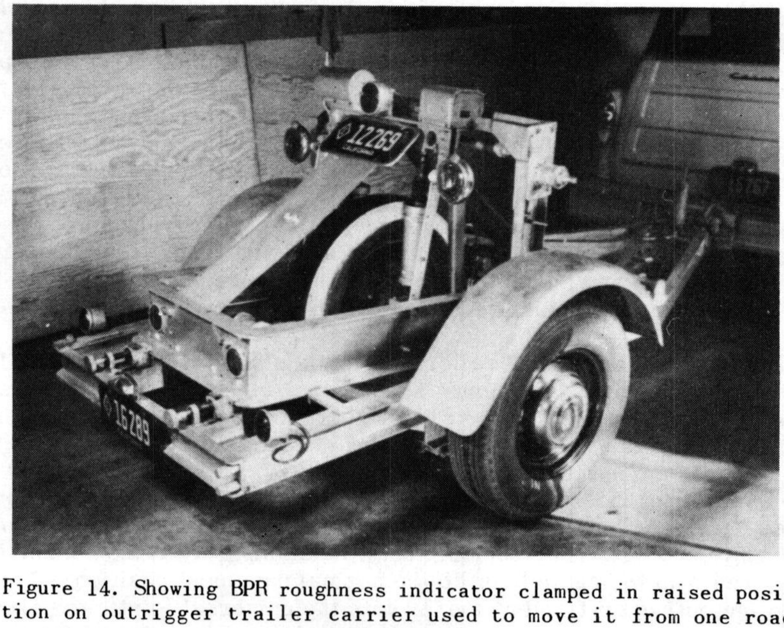

Figure 14. Showing BPR roughness indicator clamped in raised position on outrigger trailer carrier used to move it from one road test section to another.

The use of the outrigger-trailer carrier has eliminated much of the wear on the important working parts of the test trailer and has resulted in the elimination of many of the errors formerly encountered when the test trailer was towed from one test site to another. Detailed working drawings have been made for use in the construction of the outrigger-trailer carrier. A set of the working drawings may be purchased from the Highway Research Board.

RESULTS OF ROAD ROUGHNESS TESTS ON CALIFORNIA PAVEMENTS AND BRIDGES AND ON THE WASHO TEST ROAD

Road roughness tests have been run during the past seven years on many different types of pavements on state highways in all of the eleven state highway districts in California. A special study was made during 1955 of the roughness characteristics of pavements on various bridges and overpass structures in the San Francisco Bay Area. Repeated tests have been run on five sections of pavement selected partly for calibration test purposes and also as the basis of observing seasonal and annual changes in road roughness which might develop on these pavements. Oscillograph records were taken on many sections of pavements to provide a graphical record of road roughness under many different pavement conditions. Oscillograph records of selected sections of pavements will be presented and discussed in this report. Measurements of road roughness were made on all the pavement sections investigated in the WASHO Road Test. The complete report of these measurements is given in "The WASHO Road Test, Part 2: Test Data, Analyses and Findings" Special Report 22 of the Highway Research Board, 1955. Certain typical results of the road roughness measurements obtained on the WASHO Road Test pavement sections will be presented and discussed in this report.

Seasonal and Annual Variations in Road Roughness

The results of the repeated tests on selected pavements which were made to obtain a record of seasonal and annual changes of road roughness, are given in Table 7 and were discussed briefly in the section of this paper dealing with calibration tests. While small variations in the roughness values for all of the pavements are evident in the data given in Table 7, the greatest change in roughness was that obtained for the P. C. concrete pavement on the Eastshore Freeway. The increase in roughness of from 50 to 82 in. per mile for this pavement was due largely to settlement and structural failure of a section of the pavement about 200 ft in length. After resurfacing this section of pavement, the roughness was reduced to 68 in. per mile. On the basis of the roughness standards proposed in the 1951 report, all of the pavements for which data are given in Table 7, except the pavement on Oxford Street in the City of Berkeley, would be rated as excellent. Although small variations in roughness were observed which appeared to be related to temperature and pavement moisture effects on both the concrete and asphalt pavements, the long range effect of these factors could not be clearly established primarily because the BPR roughness indicator during the development stages of the first four years of this study lacked the accuracy and dependability required to determine these effects. Even with the improvements made on the roughness equipment at various times during the past seven years, the data in Figure 7 indicate that the variations of roughness are largely within the experimental error except for the major change referred to above for the roughness of the concrete pavement on the Eastshore Freeway.

The average and maximum roughness values for different types of pavement surfaces on rural state highways in California tested in 1954 and 1955 are shown in Figure 15. In general the lowest roughness values were measured on P. C. concrete pavements with a low value of 40 in. per mile, an average value on new concrete pavements of 66 in. per mile and on old concrete pavements of 88 in. per mile. On one section of new plant-mix asphalt pavement a low roughness value of 35 in. per mile was measured but the average roughness of the new plant-mix asphalt pavements was found to be 85 in. per mile and for plant mix pavements more than two years old, it was 81 in. per mile. The roughness values shown in Figure 15 were for asphalt pavements with seal coats. The roughness values for seal coats less than two years old averaged 80 in. per mile and for seal coats more than two years old, the average roughness index was 94 in. per mile. Under the proposed standard of roughness given in the 1951 report, all of the pavements would be given a rating of excellent although under the Minnesota standard

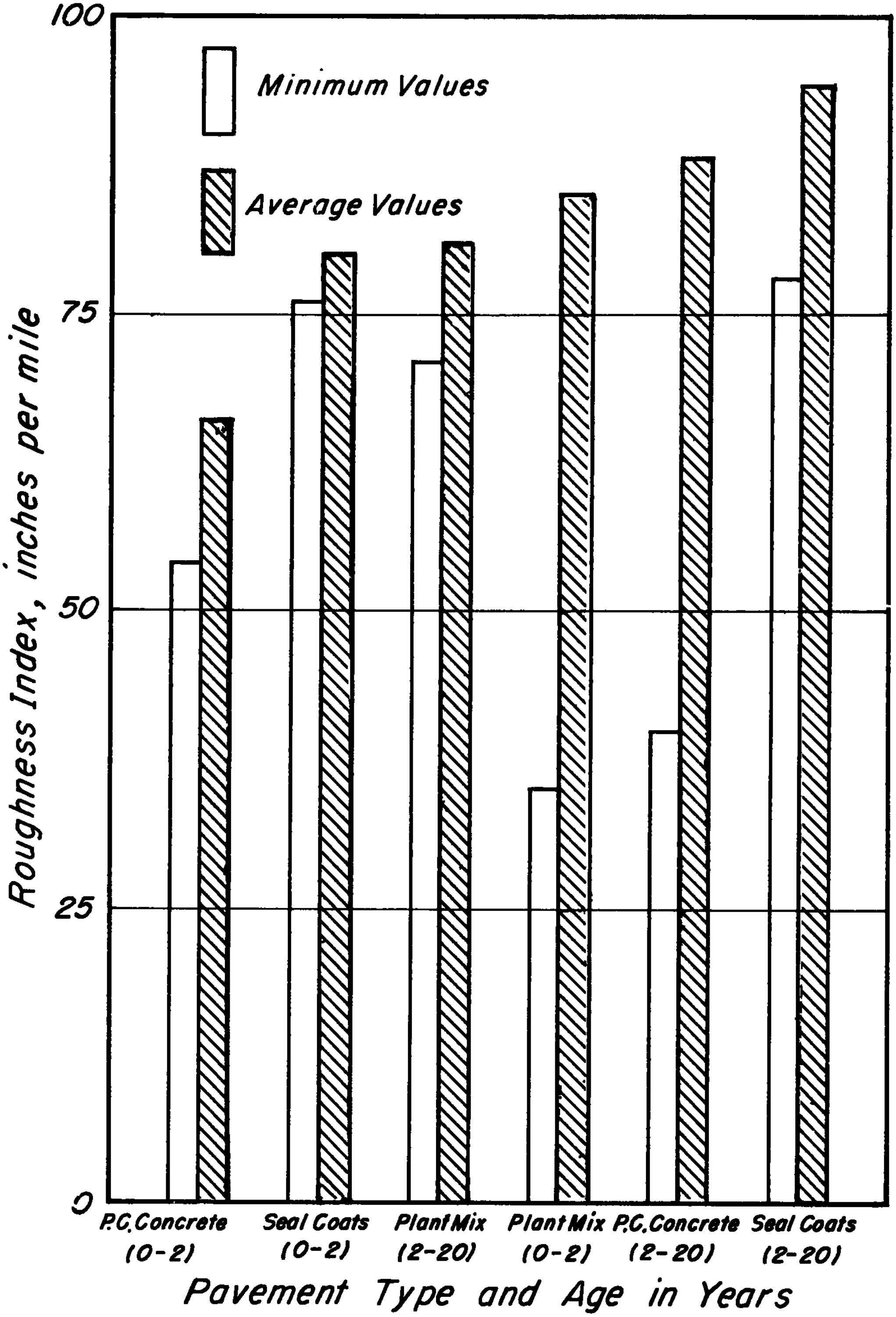

Figure 15. Roughness values for different types of pavement surfaces on rural state highways in California tested during 1954 and 1955.

for new pavements, pavements with a roughness index of 75 to 100 in. per mile are given a rating of fair. On the basis of the Minnesota standard, it may be assumed that certain pavements, notably asphalt pavements with seal coats, for which average roughness values of 80 to 94 in. per mile are given in Figure 15, were not built to an acceptable standard of smoothness.

The roughness of asphalt pavements with seal coats depends primarily on the roughness of the surface on which the seal coat is placed. The high values of roughness measured on seal coats in California is an indication that the seal coats were placed on new surfaces which were not built to an acceptable standard of pavement smoothness. Another consideration is that seal coats are frequently placed on old surfaces which are not patched or repaired to a high standard of pavement smoothness. The use of seal coat construction for filling holes and low spots and for leveling operations is almost certain to result in a rough pavement surface condition and should not be used on pavements where a high standard of surface smoothness or riding quality is desired.

In Figure 16 roughness oscillograph records are shown for certain typical sections

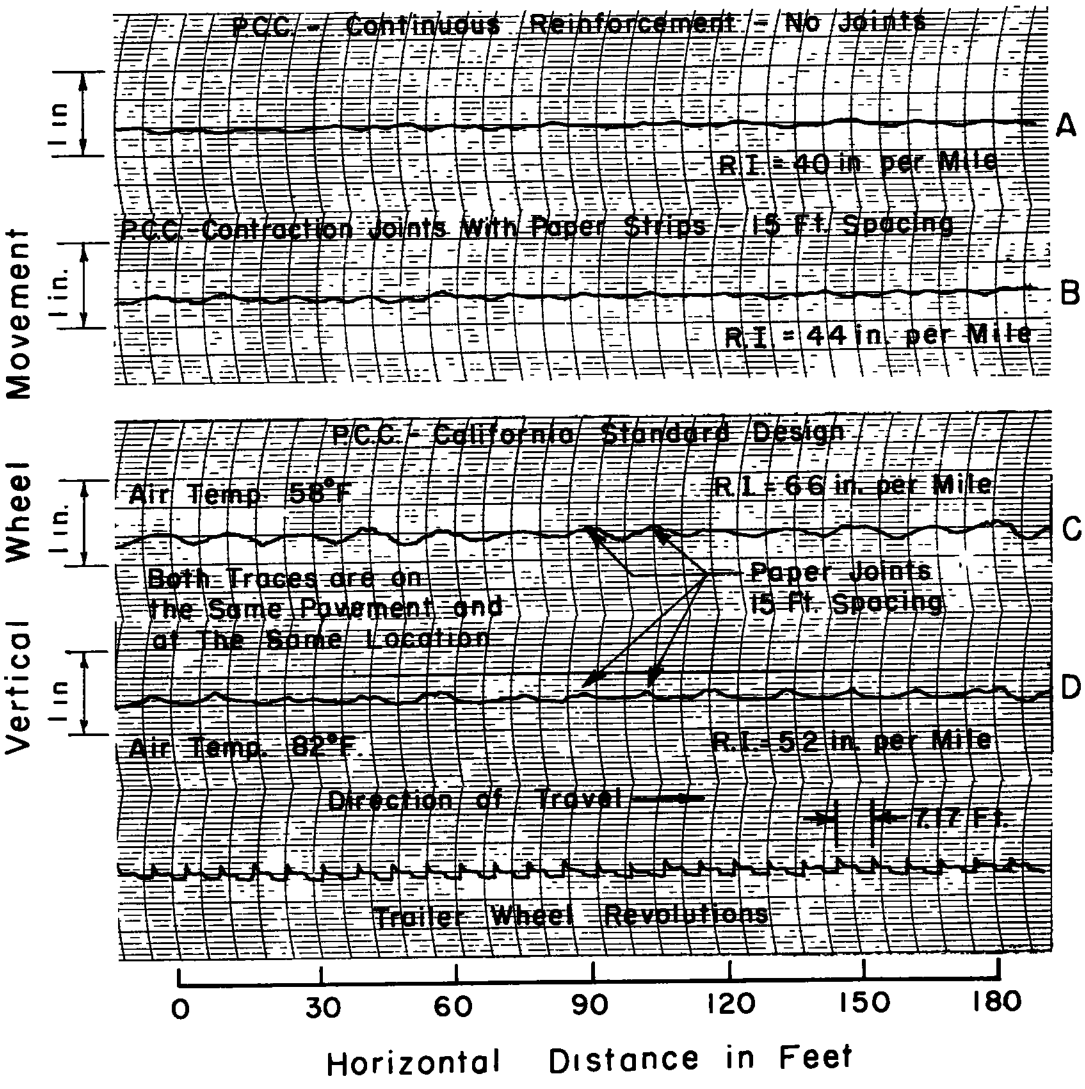

Figure 16. Roughness oscillograph records for P.C. concrete pavement.

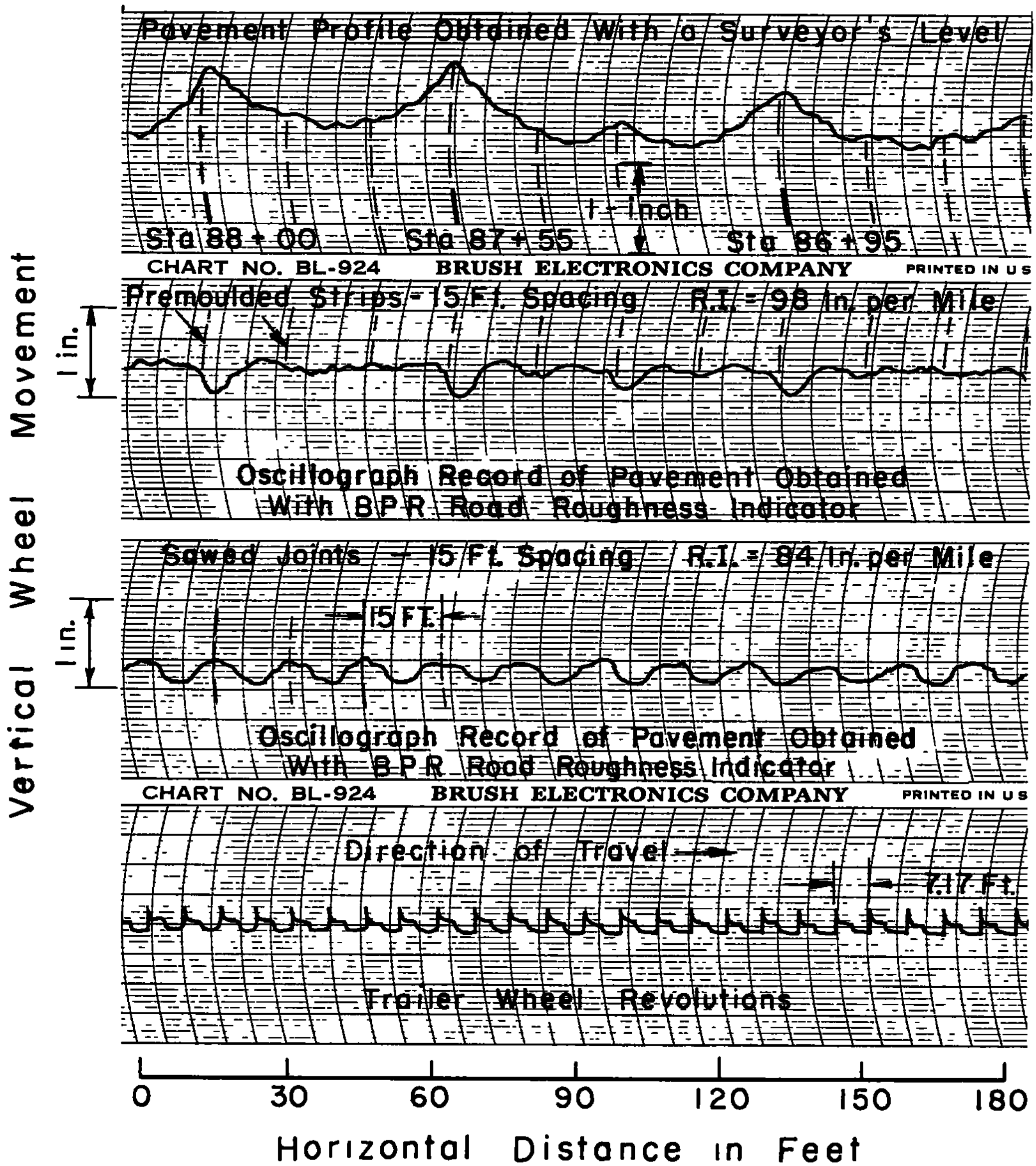

Figure 17. Roughness oscillograph records for P.C. concrete pavements constructed on an expansive type soil, with weakened plane contraction joints of (a) premolded strips and (b) sawed joints. A profile of a section of pavement (a) is also shown.

of P. C. concrete pavements. The records of the sections of pavement with roughness index values of 40 and 44 in. per mile indicate no substantial change in the surface characteristics of smooth concrete pavements construction without joints or with transverse contraction joints spaced 15 ft center to center. The two lower oscillograms in Figure 16 are intended to show the effect of an increase in air temperature on the roughness of concrete pavements. With an air temperature of 58 F, the roughness index was found to be 66 in. per mile whereas by mid-afternoon when the air temperature reached 82 F, the roughness of the same section of pavement was reduced to 52 in. per mile. The oscillograph record for the 82 F air temperature shows improved surface roughness with less warping of the joints than is evident in the oscillograph record for the same pavement with the air temperature at 58 F.

In Figure 17 roughness oscillograph records are shown for a section of P. C. concrete pavement constructed over an expansive type soil using weakened plane contraction joints constructed with thin premolded paper strips for part of the project and with sawed joints for the remaining portion of the project. A profile of a portion of the pavement with the paper joints obtained with a surveyor's level is also shown in Figure 17. Both the oscillograph records and the profile obtained with the surveyor's level indicate the presence of warped joints which contribute to the poor riding quality of these sections of pavement. While the roughness index values of 98 in. per mile and 84 in. per mile are above average for concrete pavements, they are not high enough to give these sections of pavement a low rating. The explanation for the relatively low roughness index values for these two sections of concrete pavement lies in the fact that the roughness was confined to the warping at the contraction joints, while the rest of the pavement was constructed with a smooth finish. Passenger cars with a soft spring suspension system could be operated over the warped joints with fairly good riding qualities but the ride on trucks with stiff springs and a long wheel base was very rough.

Roughness Measurements on Asphalt and Concrete Paved Bridge Floors

The use of finishing machines in the construction of both concrete and asphalt pavements has been an important factor contributing to the low roughness index values measured on concrete and asphalt pavements. In the construction of bridge floors, machine finishing equipment is frequently replaced by hand finishing methods. Also, there are other factors which may effect the smoothness of the paving on bridge floors, especially concrete bridge floors, such as, the method of forming or framing used, the size and shape of the floor panels, the width of the pavement and the provisions made for camber and plastic flow of the concrete.

In Tables 11 and 12 the results of roughness measurements are given for many paved bridge floors on freeway overpass structures and on the major bridges in the San Francisco Bay Area. Oscillograph records of certain typical sections of paving on bridge floors are shown in Figures 18 and 19.

TABLE 11

ROAD ROUGHNESS RESULTS ON P. C. CONCRETE PAVEMENTS ON BAYSHORE AND EASTSHORE FREEWAY OVERPASS STRUCTURES

Eastshore Freeway Overpass Structures	Roughness Index in. per mile
23rd Ave Overpass, northbound (1948)	134
23rd Ave Overpass, southbound (1948)	108
29th Ave Overpass (1948)	106
Fruitvale Ave Overpass	116
Hegenberger Road Overpass	78
98th Ave Overpass	109
Davis St Overpass	80
Albany Overpass (1935)	85
Bayshore Freeway Overpass Structures	**Roughness Index in. per mile**
Bayshore Freeway, elevated structure	
Average Roughness Index - 5th Street to 17th Street	158
Roughness Index - 5th Street to 9th Street	180
Army St Overpass	94
Alemany Blvd Overpass	105
San Bruno Overpass	83
San Francisco Airport Overpass	79
Millbrae Ave Overpass	84
Broadway Overpass	94

TABLE 12

RESULTS OF ROAD ROUGHNESS MEASUREMENTS MADE IN 1955 ON THE ASPHALT AND P.C. CONCRETE PAVED BRIDGE FLOORS OF THE MAJOR BRIDGES AND APPROACH STRUCTURES IN THE SAN FRANCISCO BAY AREA

San Francisco - Oakland Bay Bridge (opened to traffic 1936)	Roughness Index in. per mile
East Bay Crossing, Cantilever Section, P.C.C.	130
Yerba Buena Tunnel and Approaches, P.C.C.	71
West Bay Crossing, Suspension Section, P.C.C.	87
Fifth St Ramp, P.C.C., Average Roughness Index	108
Fifth St Ramp, P.C.C., Average Maximum Roughness Index	130
San Francisco - Oakland Bay Bridge Approaches (opened - 1955)	
Elevated Roadway, West Approach near 5th St, P.C.C.	198
Elevated Roadway, East Approach over Eastshore Highway, P.C.C.	141
Golden Gate Bridge (opened to traffic 1937)	
North Approach Anchor Span, P.C.C.	118
Suspension Section, P.C.C.	110
South Approach Anchor Span, P.C.C.	110
South Elevated Roadway Approach, Near Toll Plaza, Asphalt Paving	97
South Elevated Roadway Approach, P.C.C.	138
South Elevated Roadway Approach, S.E. of Toll Plaza, Asphalt Paving	138
Richmond - San Rafael Bridge - Under Construction (1955)	
West Side Crossing, Girder Spans, P.C.C.	128
West Side Crossing, Truss Spans, P.C.C.	129
East Side Crossing, Girder Spans, P.C.C.	110
East Side Crossing, Truss Spans, P.C.C.	118
Carquinez Bridge (opened to traffic 1927)	
South Approach Viaduct, Asphalt paving over P.C.C.	97
Cantilever Spans, P.C.C.	141
San Mateo - Hayward Bridge (opened to traffic 1929)	
West Side Crossing, Timber Trestle, P.C.C.	145
East Side Crossing, Timber Trestle, Asphalt Paving on P.C.C.	94
Open Grid Steel Bridge Floors	
Park St Estuary Crossing	103
High St Estuary Crossing	99
Mossdale - San Joaquin River Crossing	
Open grid steel bridge decking	127
Concrete in wheel tracks in open grid steel bridge decking	139

The roughness index values of concrete paving on the various bridge structures range from a low value of 78 in. per mile to a high value of 198 in. per mile. The latter value was measured on a new structure opened to traffic in 1955 and has been severely criticized by the riding public as a rough section of pavement. It is interesting to note that the roughness values for paving on structures built 20 years ago such as on portions of the San Francisco-Oakland Bay Bridge, the Carquinez Bridge, and the Albany overpass were less than 100 in. per mile while the roughness values for paving on a large number of recently built structures are considerably in excess of 100 in. per mile.

A variable pattern of roughness for concrete bridge floor paving is indicated in the oscillograph records in Figure 18. The Fifth St ramp on the Bay Bridge has a smooth surface finish but the rythmic corrugations are an indication of the lack of camber in the forming of the floor system during construction and of plastic flow after construction which caused a rough riding surface. There is no clearly defined pattern discernible in the oscillograph record for the concrete paving of the elevated structure with a roughness index of 198 in. per mile. The lack of a pattern in the oscillograph record is an indication of poor workmanship in the form work and in the final finishing operations in the construction of this pavement.

While the number of bridge floors with asphalt paving reported in this study is small, the roughness index values for the asphalt paving are in the range of 94 in. per mile to 138 in. per mile, indicating that the asphalt paving on bridge floors is smoother than the concrete paving. In the usual case the asphalt paving is placed as resurfacing on old concrete paving and, if it is placed with a finishing machine, it should be able to meet a high standard of pavement smoothness or riding quality.

In the construction of the concrete paving on the Richmond-San Rafael Bridge a special finishing machine is being used. The final finish, however, is obtained with a hand-

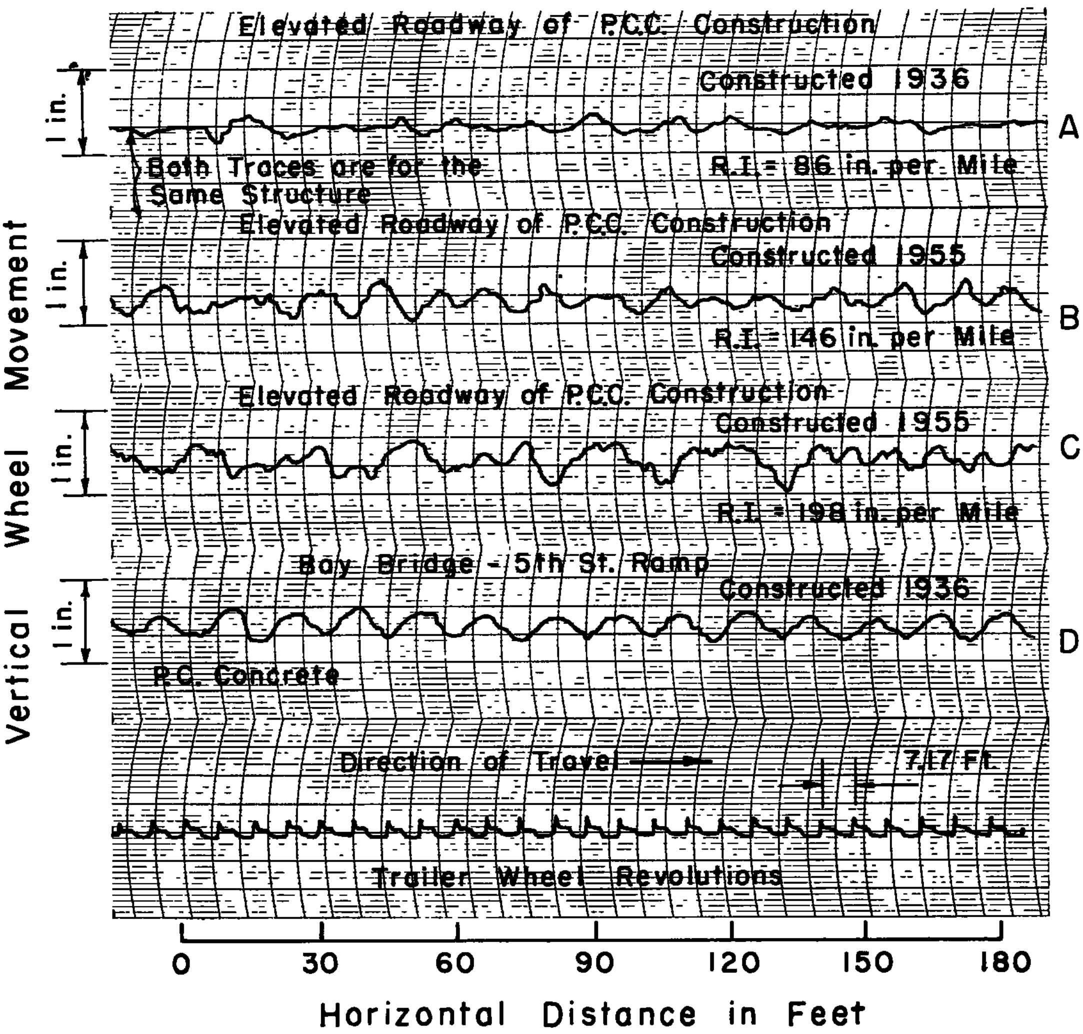

Figure 18. Roughness oscillograph records of P.C. concrete pavements on elevated roadway or bridge type structures.

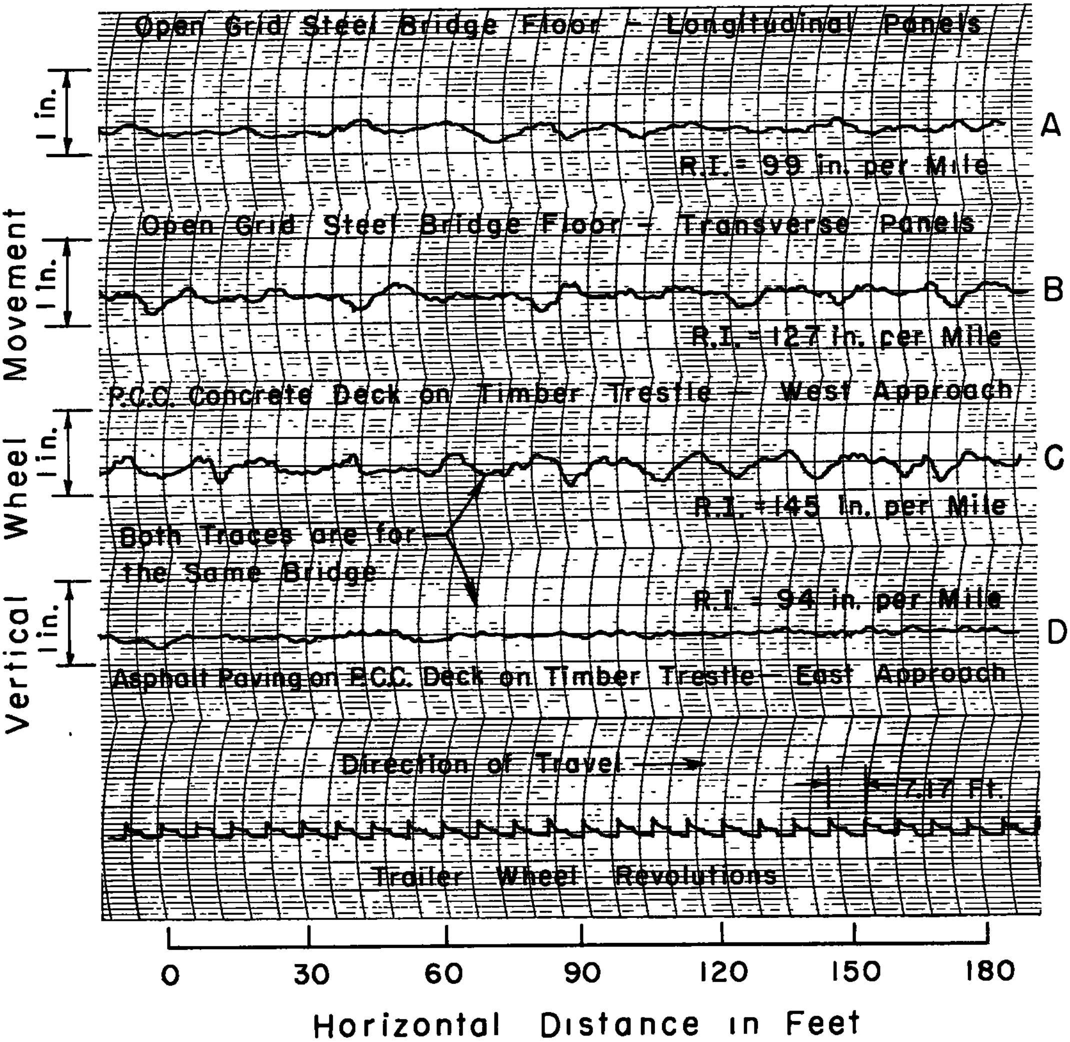

Figure 19. Roughness oscillograph records for four bridge floors.

operated longitudinal float. The roughness index values measured on the completed portions of this bridge vary from 110 in. per mile to 129 in. per mile. It is evident that the concrete paving on this bridge does not measure up to the high standard of smoothness obtained with the Johnson Finisher used on California state highway concrete pavement construction where the roughness index values are usually not greater than 70 in. per mile and they may be as low as 40 in. per mile.

Roughness Measurements on Open-Grid Steel Bridge Floors

The results of roughness measurements on open-grid steel bridge floors are given in Table 12. Typical oscillograph records for two open-grid steel bridge floors are shown in Figure 19. The roughness index values for the open-grid steel decking varied from 99 in. per mile to 139 in. per mile. The oscillograph records indicated that the use of transverse panels resulted in a roughness of 127 in. per mile as compared to 99 in. per mile for a floor system with longitudinal panels. This conformed to the general pattern of smoothness observed on concrete bridge floors in which lower roughness values were measured on floor systems with longitudinal beams and girders than on floor systems with transverse beams and girders or with large open square panels for which proper cambering was generally not provided.

TABLE 13

ROAD ROUGHNESS MEASUREMENTS ON SELECTED SECTIONS OF PAVEMENT OF THE WASHO ROAD TEST. A PARTIAL SUMMARY OF ROUGHNESS MEASUREMENTS MADE WITH THE UNIVERSITY OF CALIFORNIA BPR ROUGHNESS INDICATOR AS GIVEN IN THE WASHO REPORT, PART 2

Section	Test Date	Roughness Index, in. per mile: Outside Wheel Path, 18,000 lb Single Axle	Outside Wheel Path, 32,000 lb Tandem Axle	Inside Wheel Path, 18,000 lb Single Axle	Inside Wheel Path, 32,000 lb Tandem Axle
22-4	6-10-53	92	79	88	84
	11-11-53	82	79	65	70
	6- 3-54	104	88	83	85
14-4	6-10-53	79	75	88	75
	11-11-53	70	66	63	66
	6- 3-54	82	77	71	71
6-4	6-10-53	75	97	75	88
	11-11-53	92	193 (163)	79	114
	6- 3-54	201 (43)	304 (290)	97 (15)	220 (45)
Tangent Average	10-16-52	-	-	85	80
	6-10-53	82	81	82	81
	11-11-53	76	88 (178)	68	81
	6- 3-54	104 (43)	121 (305)	79 (15)	100 (45)

Parentheses indicate the linear feet of patching in wheel path.
Tangent averages include transitions
All roughness values are corrected for trenches and test holes but not for patching.
All tests taken in the direction of traffic.

Road Roughness Measurements on Selected Sections of Pavement of the WASHO Road Test

A partial summary of roughness measurements made with the University of California roughness indicator on selected sections of pavement of the WASHO Road Test is given in Table 13. The complete report of these measurements is given in the Highway Research Board Special Report 22. The measurements indicated that the various sections of pavement on the WASHO Road Test were built to an acceptable standard of smoothness and retained this smoothness until patching was required. The roughness measurements gave no clearly defined indication of progressive structural failure under the repeated heavy axle loads. It is interesting to note that on the 22- and 14-in. sections the effect of traffic was to improve the smoothness of the surface. Thus, the roughness index in one portion of the 22-in. pavement was reduced from 88 in. per mile to 65 in. per mile after being subjected to five months of intensive truck traffic. It is reasonable to expect that the heavy truck traffic tended to smooth out minor irregularities in the surface which were present when the pavement was opened to traffic and that therefore lower roughness index values were measured on these sections of pavement after they were subjected to the heavy truck traffic than prior to the opening of these sections to traffic.

The roughness data in the 6-in. sections show a progressive increase in road roughness although the increase reached significant amounts only after structural failure developed and patching was necessary. Thus in one portion of the 6-in. pavement the roughness index increased from 75 to 92 in. per mile after five months of intensive truck traffic and then seven months later it increased to 201 in. per mile after structural failure developed requiring 43 lineal feet of patching.

CONCLUSIONS

Seven years of tests, experimentation and development work with the BPR roughness indicator have demonstrated that the basic design of this equipment is sound and that it provides the simplest and most accurate method for measuring road roughness which has been developed to date. It is, however, a sensitive instrument which measures displacements as small as five-thousandths of an inch and it is important that all moving parts be built to the same uniform design standards such that the effects of wear, dust and excessive friction or damping effects will be minimized if this equipment is to be used as a standardizable unit for measuring road roughness. Also, special precautions must be taken in the operation and in the maintenance of the equipment to preserve the high degree of sensitivity in road roughness measurements of which it is capable. The use of an outrigger-trailer carrier to transport the roughness trailer from one test site to another is an important factor to protect the equipment from damage and excessive wear.

Roughness measurements on asphalt and concrete pavements in California built with modern pavement finishers have indicated that high standards of pavement smoothness and riding quality can be provided and in general have been provided. The roughness measurements of paving on bridge floors of the major bridges and freeway overpass structures in the San Francisco Bay Area indicate a general lack of acceptable smoothness or riding quality of this type of paving. Improvements in bridge-floor construction methods and in the final finishing operations can and should be developed to raise the riding quality of the paving on bridge floors to the same high standard which is now obtained on highway pavements.