

# Calibration and Use of BPR Roughometer at the AASHO Road Test

W. RONALD HUDSON, Assistant Rigid Pavement Research Engineer, and  
ROBERT C. HAIN, Assistant Chief, Data Processing and Analysis,  
AASHO Road Test, Highway Research Board

The primary problem is using the Bureau of Public Roads roughometer at the AASHO Road Test has been the variability of the instrument. Frequent calibration has been found to be necessary. Using the Road Test profilometer as a standard, a method has been developed whereby the whole dynamic system of the roughometer can be calibrated. This paper describes the calibration technique for the roughometer and its use at the AASHO Road Test, including methods for making present serviceability determinations.

● THE PRIMARY PURPOSE of a highway or highway system is to serve the riding public. A pavement that provides a smooth ride is presumed to be serving better than one which offers a rough ride, other factors being equal. The importance of pavement roughness has long been recognized. Many devices, including single-wheel indicators and multiwheel profilometers, have been developed to measure roughness. One of the earliest of these instruments was developed for use on the Bates Road Test in 1923 (1). Numerous devices have followed (2, 3, 4, 5). In 1941 a relatively simple, standardizable instrument, the road roughness indicator, was introduced by the Bureau of Public Roads. For simplicity this instrument is referred to in this paper as the BPR roughometer (6). Since its conception, considerable development work has been done on this device by the Bureau of Public Roads, the University of California (7, 8), and Purdue University (9), among others; and many improvements have been made in its operation. At present the BPR roughometer is the most widely used type of road roughness indicator in the United States. Table 1 gives the agencies owning one of these instruments.

The basic roughometer used at the AASHO Road Test was constructed by the Bureau of Public Roads. The details of the device are those reported by Buchanan and Catudel (6) in 1941, with slight modifications. The complete plans are available from the Bureau of Public Roads (10). The roughometer consists of a single-wheel trailer towed by a light truck (Fig. 1). The wheel is suspended on two single-leaf springs (Fig. 2). A smooth tread 6.70 x 15, 4-ply tire is mounted on the wheel. Irregularities of a pavement surface are recorded as differential movement of the axle relative to the frame of the device. This movement is transmitted by a strong wire cable to a double-acting ball-clutch integrator that converts the upward vertical motion to unidirectional rotary motion. This rotary motion actuates a microswitch that records roughness in inches on a mechanical pulse counter in the towing vehicle. The dashpot dampers have ball-joint end connectors but do not employ "O" rings.

## The Roughometer and the Present Serviceability Concept

The primary purpose of the AASHO Road Test was to determine significant relationships between a known number of specified axle loads and the performance of pavements

TABLE 1  
ORGANIZATIONS PRESENTLY POSSESSING ROUGHOMETERS

1. AASHO Road Test	13. Louisiana State Highway Department
2. Illinois Toll Road	14. Maryland State Highway Department
3. BPR Region 9	15. Michigan State Highway Department
4. BPR Division of Research	16. Minnesota State Highway Department
5. Waterways Experiment Station	17. Missouri State Highway Department
6. Alabama State Highway Department	18. North Carolina State Highway Department
7. Connecticut State Highway Department	
8. California State Highway Department	19. North Dakota State Highway Department
9. Illinois State Highway Department	20. Oklahoma State Highway Department
10. Indiana State Highway Department	21. Oregon State Highway Department
11. Iowa State Highway Department	22. South Dakota State Highway Department
12. Kansas State Highway Department	23. Virginia State Highway Department
	24. Wisconsin State Highway Department



Figure 1. Standard BPR roughometer.

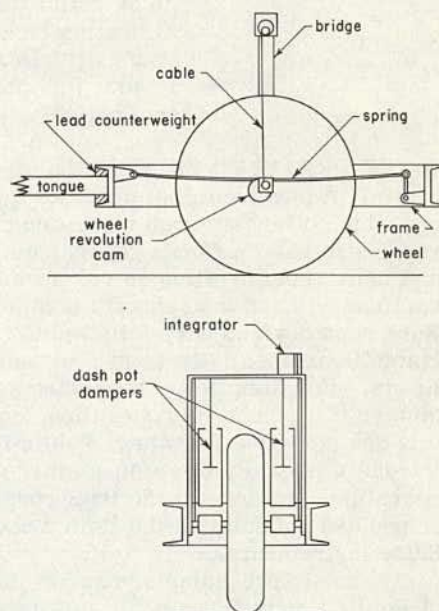


Figure 2. Schematic diagram of BPR roughometer.

of various designs. To help define performance, a broad term with several definitions, the concept of present serviceability was established. This concept is fully described elsewhere (11). Briefly, it consists of having a panel representing highway users subjectively rate a section of pavement usually  $\frac{1}{4}$  mi long. The average panel rating of a section is defined as its present serviceability. The present serviceability ratings of several sections of pavement are regressed on physical measurements of these sections made coincidentally with the ratings. For any pavement, an estimate of mean panel serviceability rating can then be made at any time, using physical measurements alone.

The following definitions are taken from Carey and Irick (11):

**Present Serviceability**—The ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic in its existing condition.

**Present Serviceability Rating (PSR)**—The mean of the individual ratings made by the members of a specific panel of men selected for this purpose by the Highway Research Board.

**Present Serviceability Index (PSI) or Estimated Present Serviceability Rating**—A mathematical combination of values, obtained from certain physical measurements of a large number of pavements, so formulated as to predict the PSR for those pavements within prescribed limits.

**Slope Variance (SV)**—A summary statistic which describes the variation in slope, sampled at 1-ft intervals, of a continuous slope record produced by the AASHO profilometer.

For clarity, other notations and definitions will be useful, as follows:

$BR_s$  = Roughness reading, in inches per mile, of the standard BPR roughometer operated at a speed of  $s$  miles per hour.

$AR_s$  = Roughness reading, in inches per mile, of the AASHO Road Test modified roughometer (AASHO roughometer) operated at a speed of  $s$  miles per hour.

$PSI_{abc}$  = An estimated serviceability rating, where  $abc$  is a three-digit code which uniquely identifies the particular equation used to estimate PSR. This code is necessary to identify the estimation equation with regard to three factors:

- $a$  = type of pavement to which applicable; i. e., rigid or flexible;
- $b$  = data used to derive the equation. As the rating panel rated more sections new equations were developed from the additional data. As additional data were gathered to relate slope variance to  $AR_{10}$ , new equations were developed;
- $c$  = measuring instrument. There are equations involving each of the three methods used to measure roughness; i. e., the profilometer, the roughometer, and the rut depth gage.

$C(\text{rigid pavement})$  = Major cracking, in feet per 1,000 square feet of pavement area. Major cracks are sealed cracks and those cracks which are spalled to a width of  $\frac{1}{4}$  in. for one-half their length on the slab surface. Measurement is made on the longitudinal or transverse projection of the crack, whichever is greater.

$P(\text{rigid pavement})$  = Bituminous patching, in square feet per 1,000 square feet of pavement area. Area cracking which is awaiting matinenance may also be included in this category.

$C(\text{flexible pavement})$  = Area cracking, in square feet per 1,000 square feet or surface area, which has progressed into a definite pattern joined in both directions.

$P(\text{flexible pavement})$  = Repair of the surface either by skin patching or deep patching, in square feet per 1,000 square feet of surface area.

$\overline{RD}$  = Average rut depth of both wheelpaths, in inches, measured at the center of a 5-ft span in the most deeply rutted part of the wheelpath. The measurements are made at 20-ft intervals on long sections (over 500 ft) and at 5-ft intervals on short sections.

The physical measurements useful in formulating a PSI have been as follows:

1. Mathematical functions of wheelpath profile.
2. Responses of vehicles to wheelpath roughness.
3. Pavement rutting.
4. Physical damage.

It should be noted that certain mathematical functions of these measured variables, combined in a multiple regression, satisfactorily predict PSR. However, these measured variables only approximate the over-all three-dimensional profile of a pavement. Other functions, or more complete three-dimensional profiles, might yield statistically better predictions of PSR.

The roughometer essentially measures the response of a vehicle to wheelpath roughness. Therefore, as could be expected, its output is correlated with PSR. The serviceability rating sessions from which data were obtained to relate present serviceability to physical measurements are described by Carey and Irick (11). During two of the sessions the AASHO roughometer was used to obtain physical measurements. Figures 3, 4, 5 and 6 show the associations between average wheelpath slope variance ( $\overline{SV}$ ), average wheelpath roughness ( $\overline{AR}_{10}$ ), and present serviceability rating (PSR).

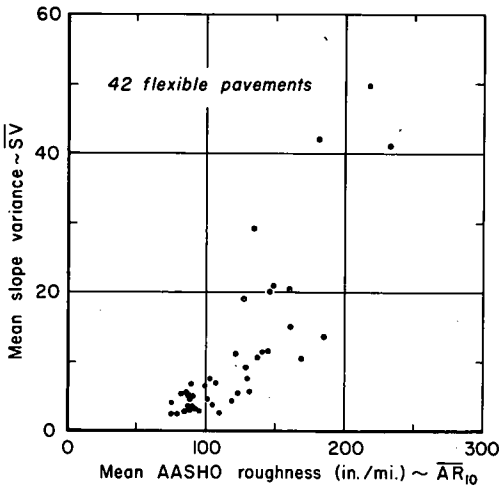


Figure 3. Slope variance vs roughness.

Analyses of these data show that there is a higher statistical association between PSR and  $\log(1 + \overline{SV})$  than there is between PSR and  $\log \overline{AR}_{10}$ . However, although  $\log \overline{AR}_{10}$  does not explain as much of the variation in PSR as  $\log(1 + \overline{SV})$ , it does explain a significant amount if the hypothesis of no association is used. Therefore, the roughometer is an instrument which can be used to predict serviceability.

#### USE OF ROUGHOMETER AT ROAD TEST

##### Modifications

Due to the widespread use of the roughometer, one was purchased for use at the Road Test. Ordinarily the BPR roughometer is not used on pavements as short as Road Test sections which vary in length from 100 ft to 240 ft. On a 100-ft section the standard counter, which counts in inches, has a resolution of  $(5280/100) R = 52.8 R$  inches per

mile, where  $R$  is the roughness of the section in inches. On a 240-ft section the resolution is  $22R$  inches per mile. These increments are not small enough for measuring small changes in the roughness of a short section. Additional error is encountered on short sections because of the 20-mph speed. At this speed it is difficult to mark the beginning and end of a section. To alleviate this problem, the operating speed was reduced to 10 mph and a digital output counter was constructed to record roughness in tenths of inches. A discussion of these changes follows:

**Speed.** The dynamic characteristics of the roughometer vary with speed. This variation has been studied at the AASHO Road Test. The results (Fig. 7) show that the maximum recorded roughness occurs at approximately 8 mph. At slower speeds the

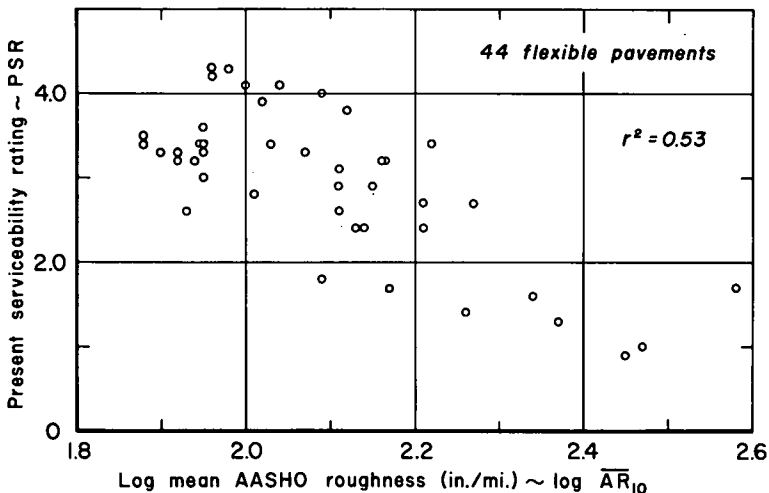


Figure 4. Present serviceability rating vs log mean AASHO roughness.

instrument shows less reaction and at faster speeds the frequency response of the indicator is slower than the input. Other research has shown this same type of relationship between speed and indicated roughness (9). Furthermore, the roughness recorded at 10 mph is highly correlated with the roughness recorded at 20 mph, as shown in Figure 8. Knowing of this correlation, the roughness of short sections can be predicted. Comparisons can then be made with other roughometers run at standard speed (20 mph). From these considerations the 10-mph travel speed was selected for use at the Road Test.

**Counter System.** Several methods were tested to record roughness in units smaller than 1 in. These methods included (a) decreasing the circumference of the input drum on the integrator from 6 in. to 1 in., thus increasing the counts on the six-lobed cam to six per inch; (b) magnifying the vertical displacement of the cable through a three-to-one pulley system, thus increasing the count to three per inch; and (c) replacing the cam and microswitch arrangement with a flexible shaft drive and a high-speed mechanical counter, thus increasing the count to ten per inch. All of these methods were unsatisfactory. The first two failed because the standard pulse counter has a maximum speed of about 600 counts per second. On rough pavements the increased count ratios often resulted in counts which exceeded the maximum speed of the counter. Method three failed because the force required to turn the shaft and the gears was excessive. Wear and slippage in the ball-clutch was inevitable.

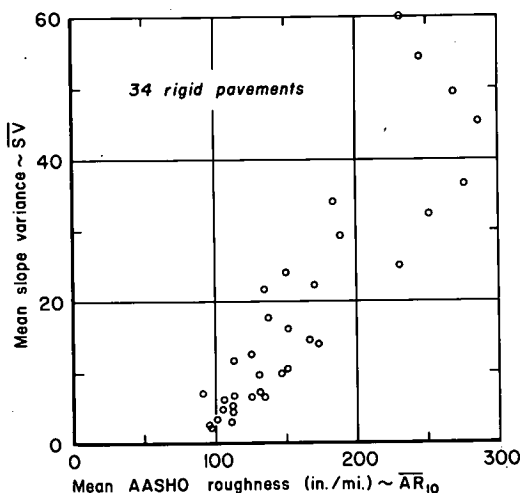


Figure 5. Mean slope variance vs mean AASHO roughness.

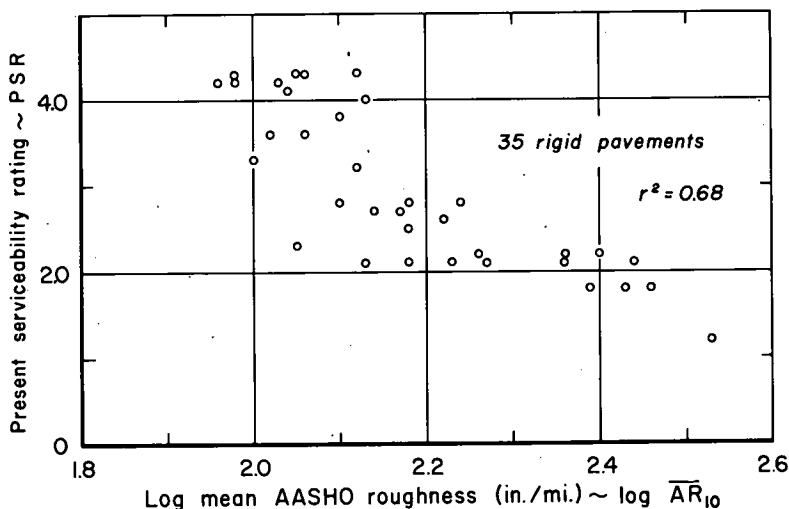


Figure 6. Present serviceability rating vs log mean AASHO roughness.



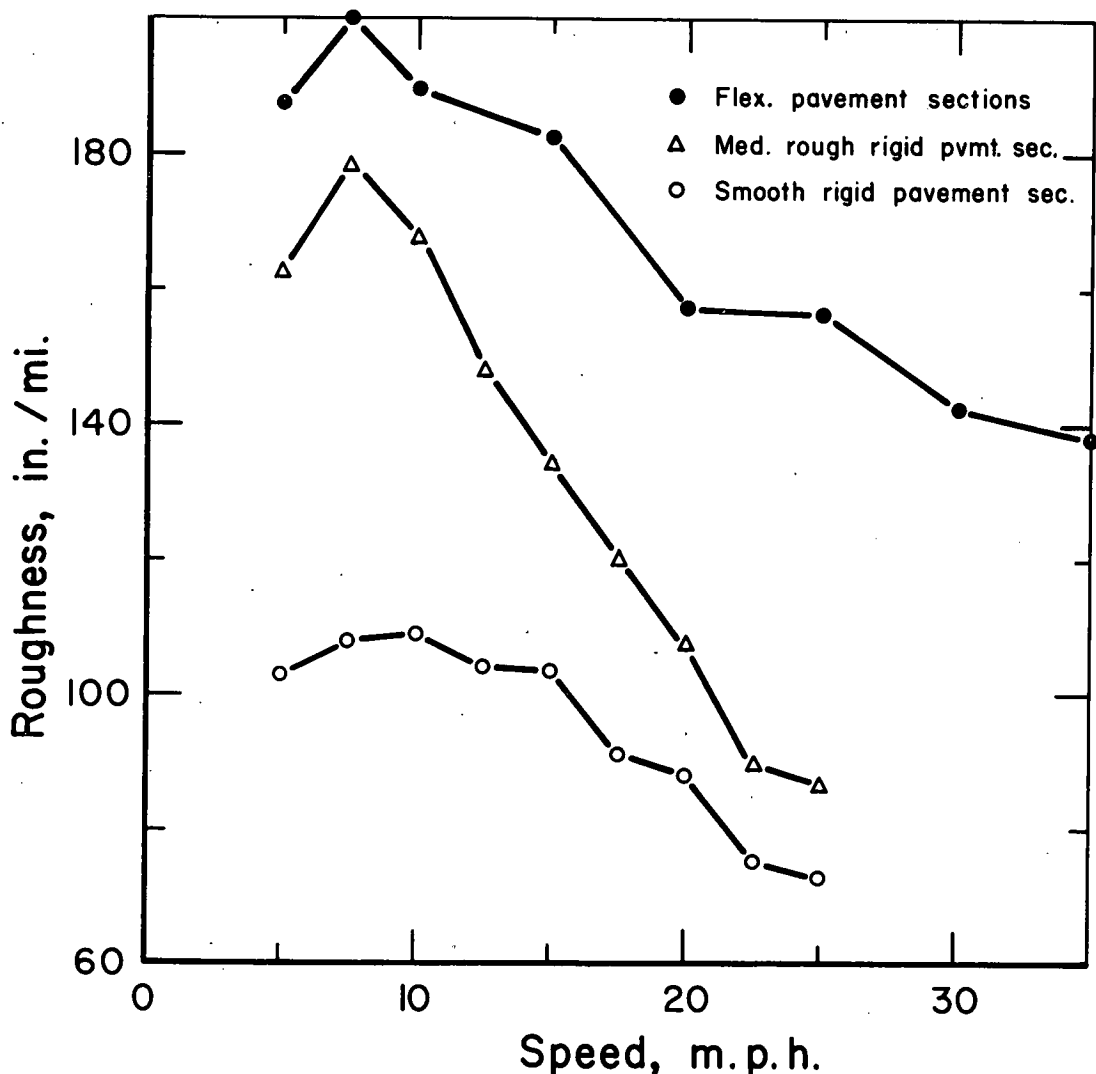


Figure 7. Indicated roughness vs speed.

To overcome the counter-speed deficiency, an electronic counter system was devised by Henry C. Huckins, Chief of the Instrumentation Branch at the Road Test. Two 5-in. diameter discs with 30 holes evenly spaced around their peripheries were attached to an extension of the integrator shaft (Fig. 9). The holes in one disc were offset an equal peripheral distance from the holes in the other disc. A fixed light source between the discs was used to impulse a pair of photocells as the light passed through the holes in the rotating discs. A flip-flop circuit was used to accept impulses from the two photocells alternately. This arrangement was necessary to prevent flutter in the impulse pickup if a hole stopped in line with the light source. The following relationship is true with this counter:

$$\frac{60 \text{ counts per rev.}}{6 \text{ in. per rev.}} = 10 \text{ counts per in.}$$

The counts are displayed on a visual decade counter and recorded by hand. Figure 10 shows the wiring diagrams for this counting system. This method proved to be the most satisfactory for the Road Test use. Automatic recording equipment should be considered for continuous operation over long periods of time.

With the exception of these two modifications, the AASHO roughometer (Fig. 11) and its method of operation at the Road Test were standard.

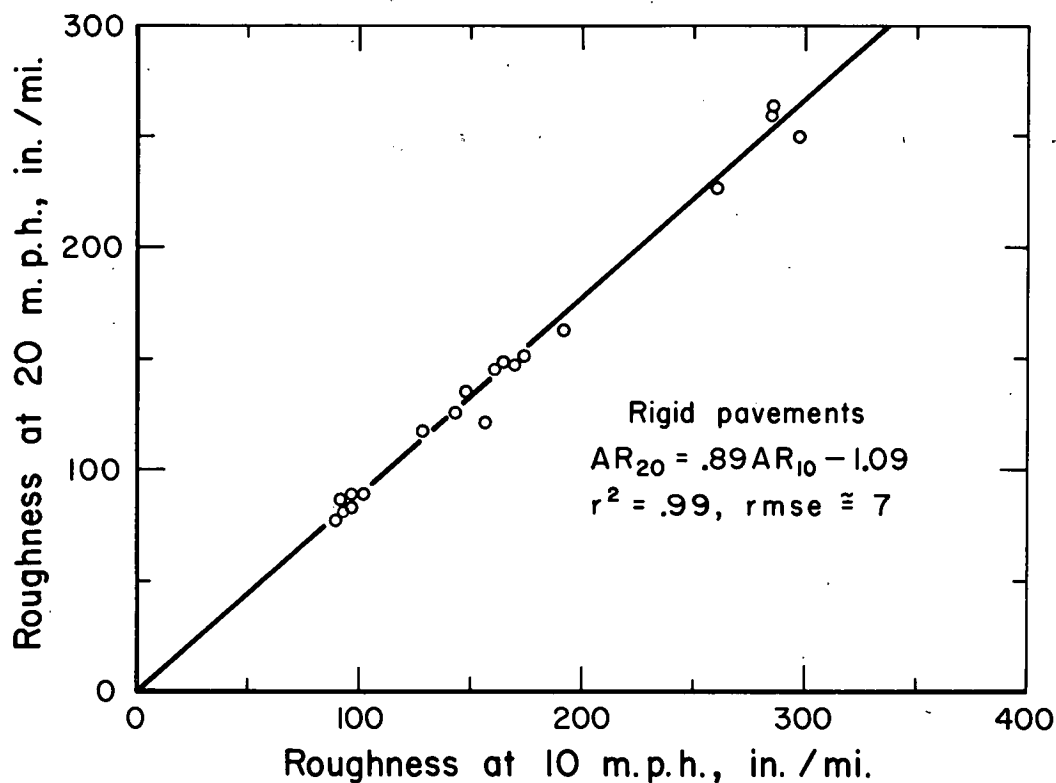


Figure 8. Roughometer speed correlation.

#### Roughness History of Test Section

The Road Test staff felt that it would be worthwhile to record the roughness of all test sections periodically with the roughometer in order to provide a record that could be used to compare the history of Road Test sections with pavements in service in the various States. Such comparisons could be helpful in adapting the results of the Road Test for future use. To fulfill this need, the roughometer was run over all sections on the Road Test every four to six weeks. The record of these runs will be made available along with other Road Test data for future comparison. Figures 12, 13, 14, and 15 show sample plots of  $AR_{10}$  vs axle applications for some failed and unfailed flexible and rigid test sections.

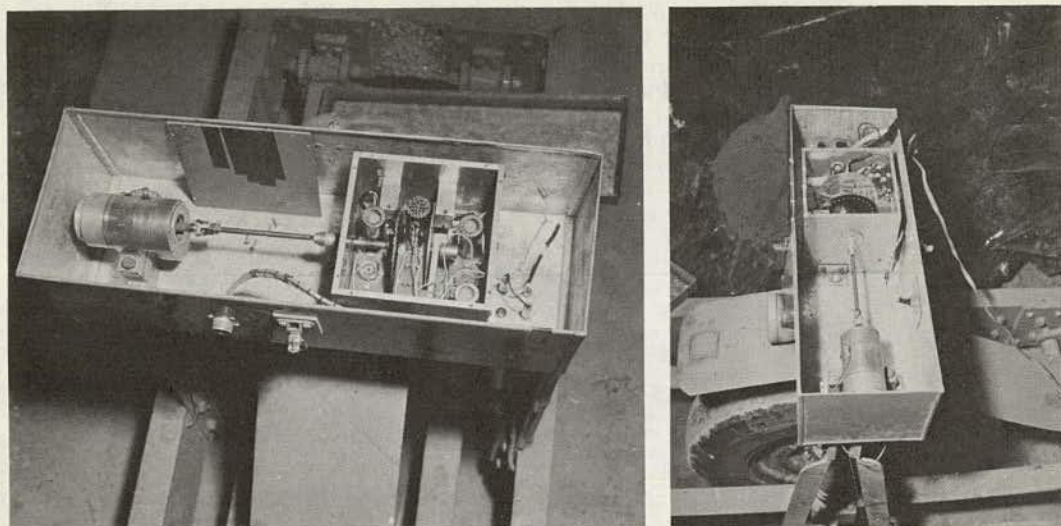


Figure 9. Side view (a) and top view (b) of electronic counter.

### Rapid Determination of PSI

The main use of the roughometer at the Road Test was the rapid, efficient estimation of present serviceability. Normally the PSI was obtained biweekly using profilometer slope measurements. However, when a single section was in acute distress, it was easy to send the roughometer to make the measurements. It was primarily to provide this service that all development work was done on the roughometer.

At the beginning of the Road Test the following equations were used to rapidly estimate PSR:

$$\text{PSI } 113 = 11.92 - 3.95 \log \overline{\text{AR}}_{10} - 0.03 \sqrt{C + P} \quad (1)$$

$$\text{PSI } 213 = 9.37 - 2.61 \log \overline{\text{AR}}_{10} - 0.12 \sqrt{C + P} \quad (2)$$

It quickly became apparent that these equations were giving a biased estimate of serviceability and that a new correlation was necessary. The primary causes of this bias were (a) the development of the final electronic counter after the development of the serviceability equations, (b) the continual change of the dynamic response characteristics of the instrument as observed on a standard pavement, and (c) a discrepancy between  $\log(1 + \overline{\text{SV}})$  and  $\log \overline{\text{AR}}_{10}$  caused by the different numerical range of these variables. As two numbers become smaller the logarithm of their average moves closer to the logarithm of the larger number. Slope variance normally varied between 0 and 100, whereas  $\overline{\text{AR}}_{10}$  varied between 70 and 400 in. per mile. Therefore,  $\log(1 + \overline{\text{SV}})$  reflected more the influence of a rougher wheelpath than did  $\log \overline{\text{AR}}_{10}$ . This effect was most apparent and troublesome on sections where the two wheelpaths had widely different roughnesses.

These three characteristic differences between the profilometer and roughometer equations were remedied by, first of all, finding an equation

$$\hat{\text{SV}} = K_0 + K_1 \overline{\text{AR}}_{10} \quad (3)$$

in which

- $\hat{\text{SV}}$  = estimated slope variance;
- $\overline{\text{AR}}_{10}$  = wheelpath roughness (inches per mile) of the AASHO roughometer at 10 mph; and
- $K_0, K_1$  = constants determined by least squares regression analysis.



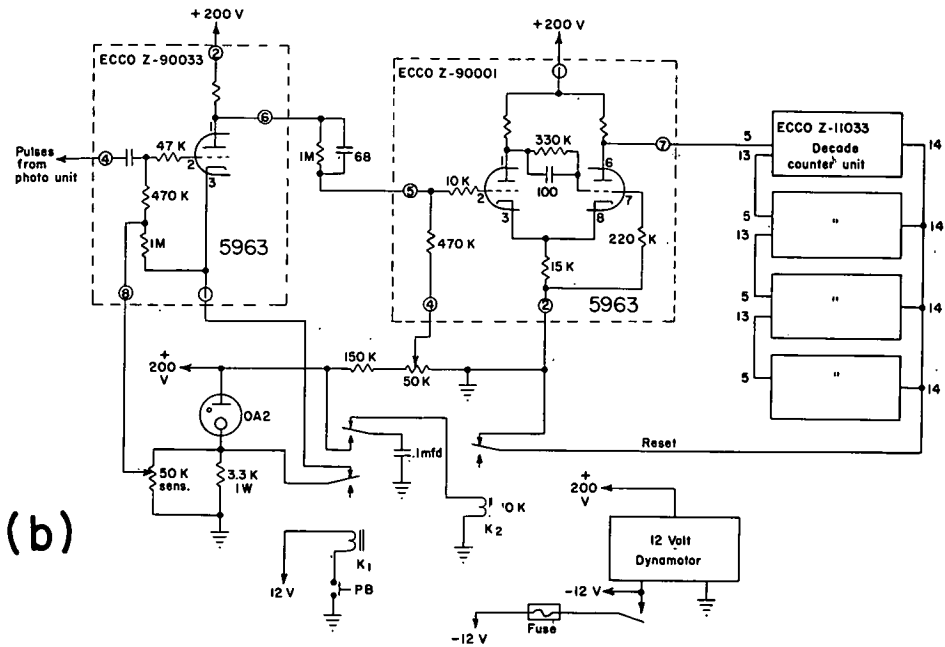
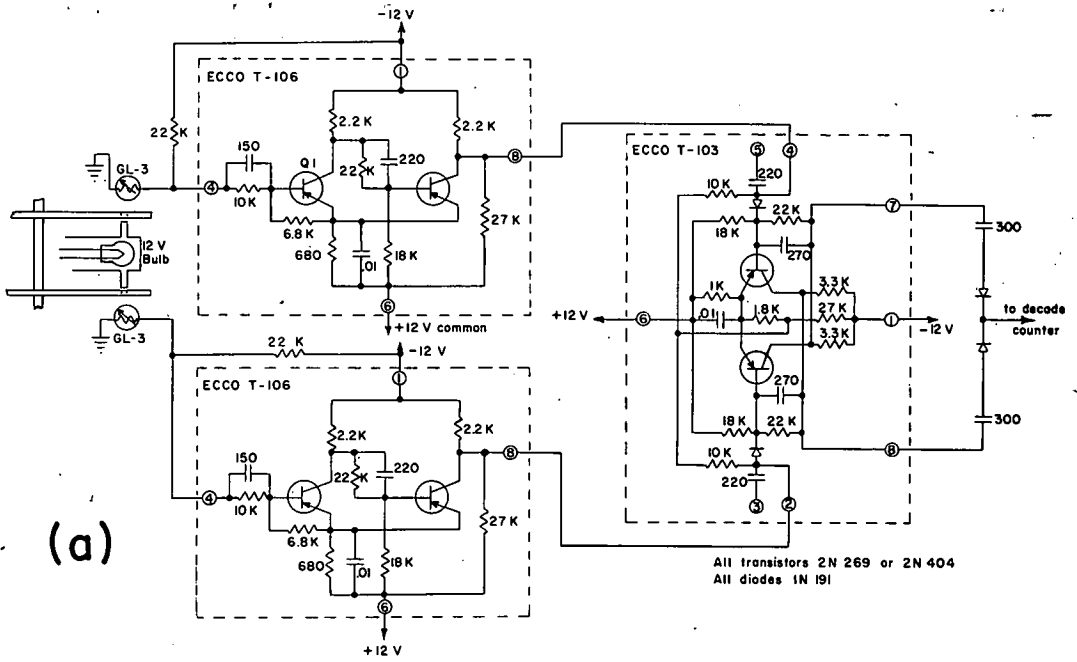


Figure 10. Wiring diagrams for roughometer (a) photo pickup and (b) counter chassis.

Eq. 3 was then substituted into the profilometer slope variance equation

$$\text{PSI 211} = A_0 - A_1 \log(1 + \overline{SV}) - A_2 \sqrt{C + P} \quad (4)$$

to derive

$$\text{PSI 214} = A_0 - A_1 \log(1 + K_0 + K_1 \overline{AR}_{10}) - A_2 \sqrt{C + P} \quad (5)$$

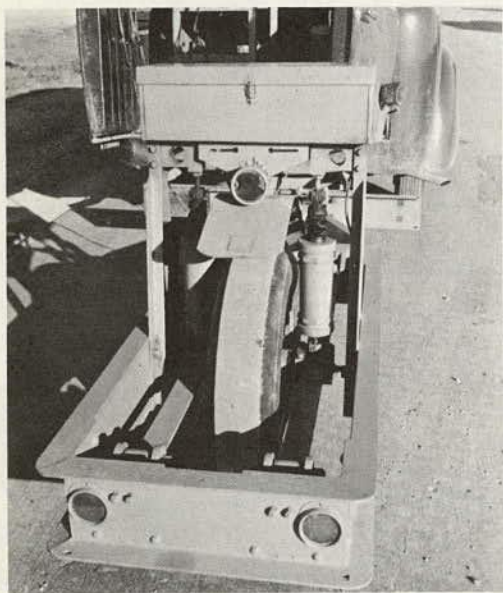


Figure 11. Rear view of AASHO roughometer.

To obtain estimates of  $K_0$  and  $K_1$  supplementary investigations were made. During a three-day period, in fact a normal period for taking pavement profiles, the profilometer and roughometer were run as coincidentally as possible over all Road Test sections. 210 rigid pavement and 150 flexible pavement sections were selected for this study. Wheelpath SV and  $\overline{AR}_{10}$  were correlated for the 420 rigid and 300 flexible wheelpaths.

However, only about 5 percent of the rigid pavement wheelpaths were even moderately rough (i.e., had a slope variance larger than 10). A poor squared correlation coefficient ( $r^2 = 0.47$ ) resulted, but the root mean square error (rmse = 13 slope units) was satisfactorily low. Because the resulting equation (PSI 214) better represented the correlations between PSR,  $\overline{SV}$ , and  $\overline{AR}_{10}$  for short Road Test sections than did the rating session equation (PSI 213), it was used until more short, rough sections became available for correlation.

For flexible pavements the squared correlation coefficient was 0.31 and the root mean square error was 12 slope units. This

correlation suffered from the same defect as the rigid correlation—there were relatively few rough sections available. Nothing more was done with a roughometer equation for flexible pavements because other methods of estimating PSR were available.

A more complete experiment was performed in the spring of 1960. Within a two-week period the profilometer and roughometer were run coincidentally on 20 rigid pavement sections. The sections were either 120 or 240 ft long. The roughness readings ( $\overline{AR}_{10}$ ) in inches per mile were corrected using the calibration concept explained in a later section. The corrected roughnesses and slope variances for the 40 wheelpaths are given in Table 2. The regression equation obtained is shown in Figure 16. It should be noted that both SV and  $\overline{AR}_{10}$  were assumed to be measured with error. Therefore, there were two possible regression lines. Slope variance was regressed on  $\overline{AR}_{10}$  inasmuch as this is the way the equation was used.

The equation,

$$\hat{SV} = 0.40 \overline{AR}_{10} - 34 \quad (6)$$

was substituted into the Road Test profilometer equation

$$\text{PSI 221} = 5.41 - 1.80 \log(1 + \overline{SV}) - 0.09 \sqrt{C + P} \quad (7)$$

to obtain

$$\text{PSI 225} = 5.41 - 1.80 \log(1 + 0.40 \overline{AR}_{10} - 34) - 0.09 \sqrt{C + P} \quad (8)$$

or

$$\text{PSI 225} = 5.41 - 1.80 \log(0.40 \overline{AR}_{10} - 33) - 0.09 \sqrt{C + P} \quad (9)$$

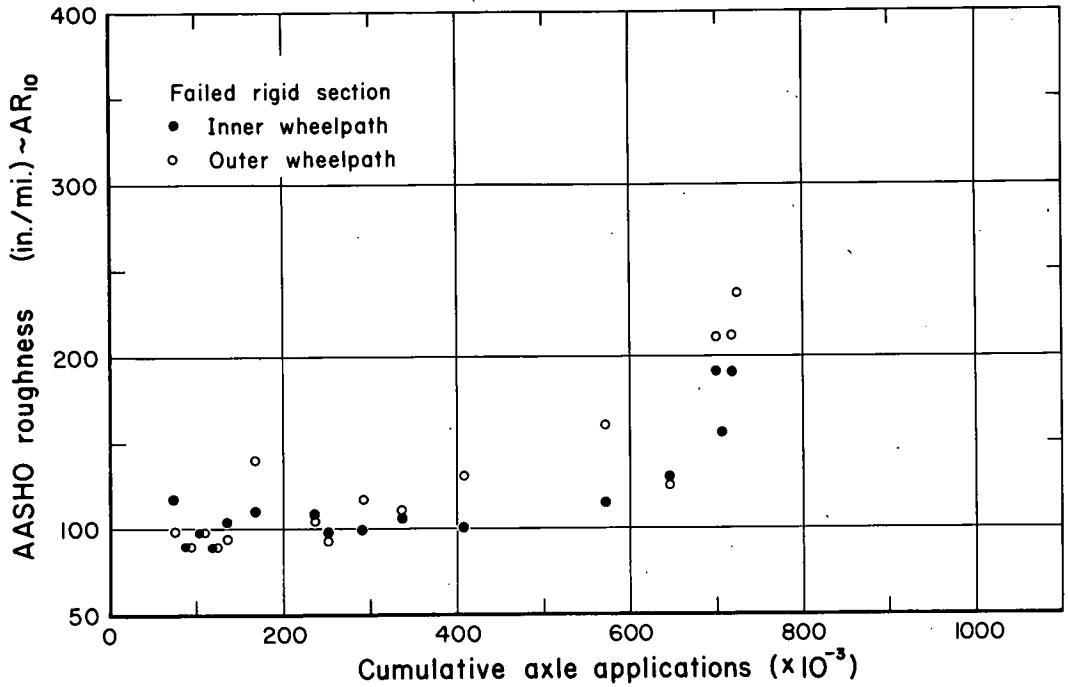


Figure 12. Roughness history, failed rigid section.

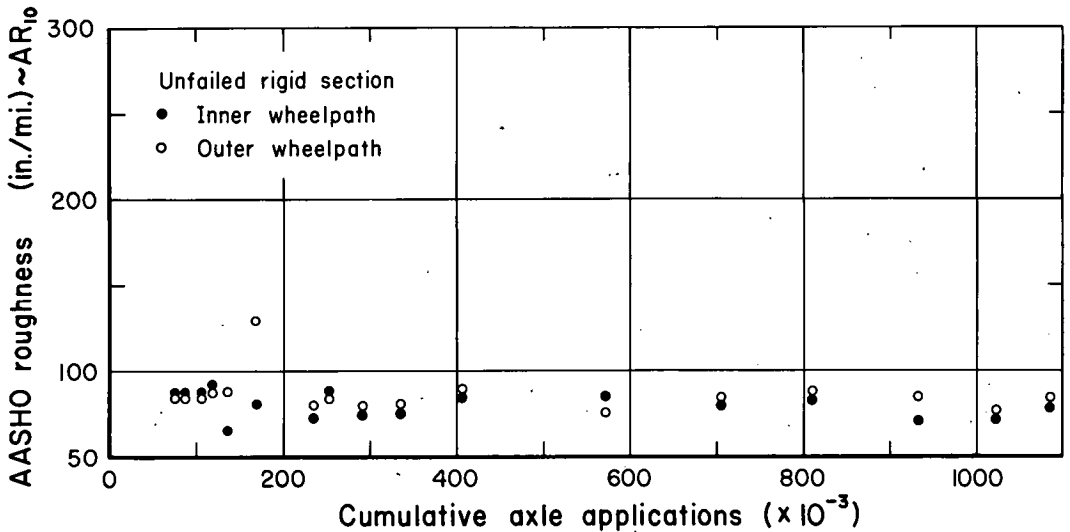


Figure 13. Roughness history, unfailed rigid section.

Eq. 9, which was used to determine serviceability indexes for sections as needed, has the advantage of giving, through use of the calibration concept, an unbiased estimate of serviceability—thus correcting all three discrepancies previously described.

This analysis assumes that the relationship between SV and corrected  $AR_{10}$  does not change significantly. However, this must be checked periodically. The results of several such checks on  $\frac{1}{4}$ -mi sections of highway pavements are given in Table 3.

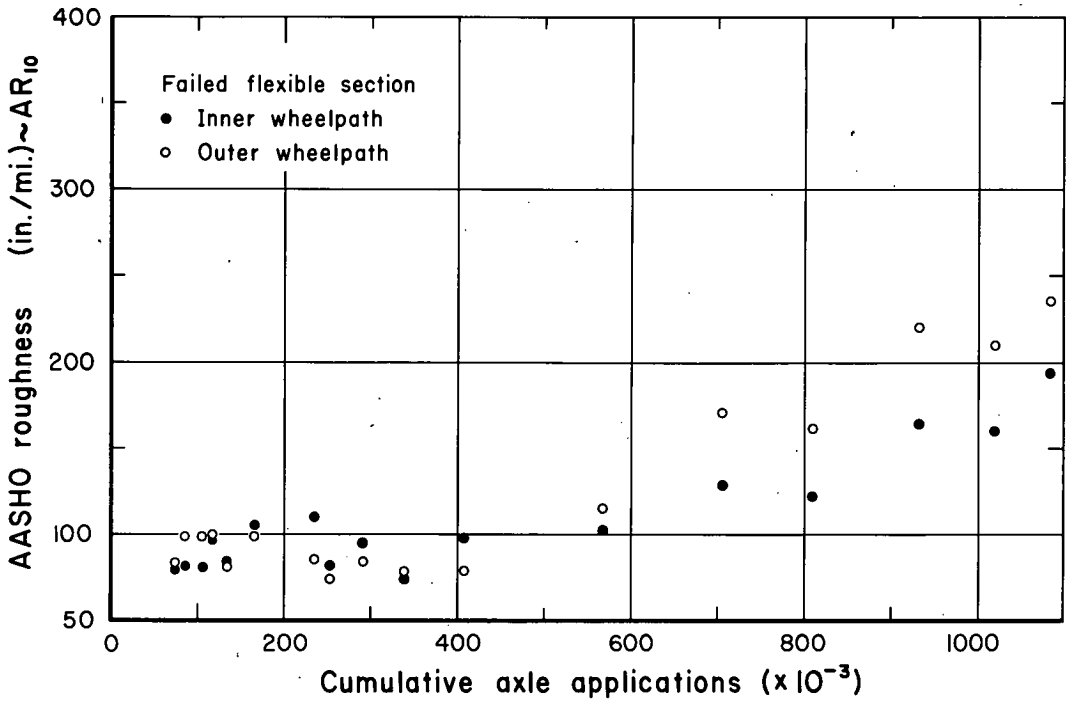


Figure 14. Roughness history, failed flexible section.

TABLE 2

## DATA FOR 40 SELECTED RIGID PAVEMENT WHEELPATHS

Section Number	Section Length (ft)	Inner Wheelpath		Outer Wheelpath	
		Roughness (AR <sub>10</sub> )	Slope Variance	Roughness (AR <sub>10</sub> )	Slope Variance
226	120	106	4	114	14
384	120	97	1	99	5
402	120	117	15	154	26
490	120	136	17	224	56
506	120	96	4	141	31
643	120	123	24	134	31
Osage A	240	264	41	276	52
Osage B	240	286	87	262	85
490-a	120	158	22	229	100
494	120	132	17	174	39
506-a	120	95	3	161	26
226-a	120	117	4	180	28
234	240	109	3	183	28
643-a	120	117	25	132	24
650	120	139	21	152	20
704	120	108	4	200	87
Osage C	240	267	99	330	117
Osage D	240	262	45	237	46
Osage E	240	271	51	262	37
Osage F	240	267	99	266	82

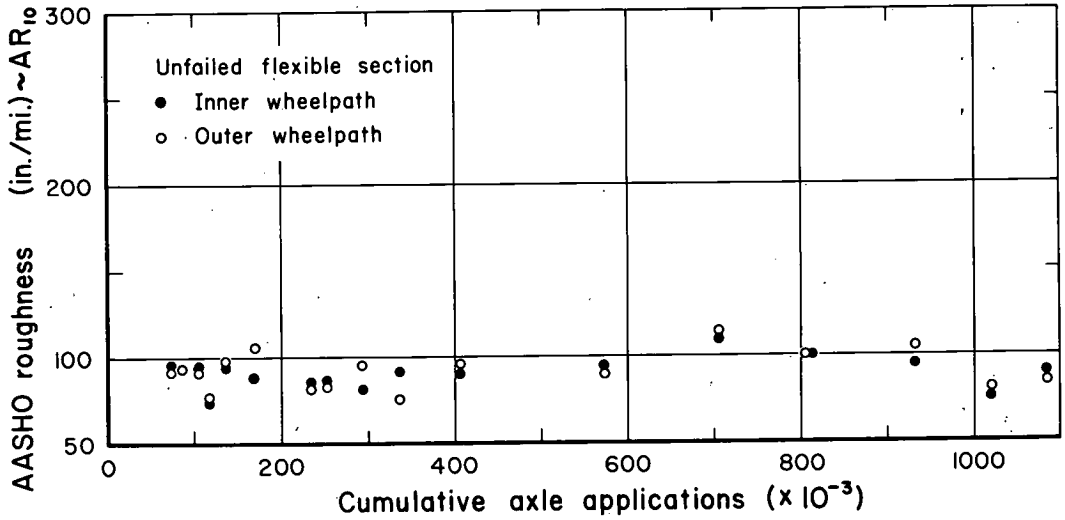


Figure 15. Roughness history, unfailed flexible section.

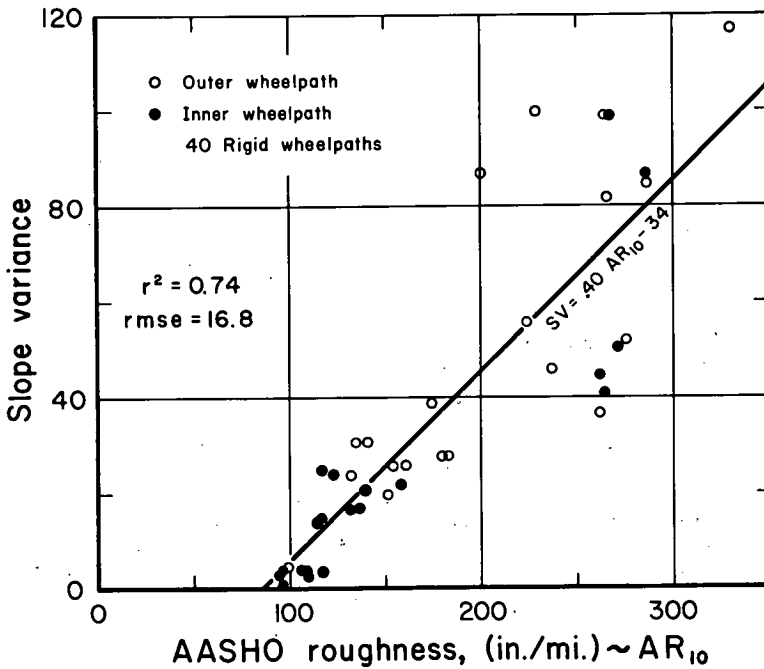


Figure 16. Slope variance vs AASHO roughness.

It should be noted that there are at least two reasons why slope variance and  $AR_{10}$  will never be perfectly correlated. These are:

1. The profilometer and roughometer probably do not measure the same elements of pavement roughness. The roughometer runs faster than the profilometer and has an entirely different tire and suspension system.



- The instruments have different frequency response characteristics.

## EVIDENCE OF VARIATION WITHIN THE ROUGHOMETER AND BETWEEN ROUGHOMETERS

### Statistical Concepts

The roughometer may be used to estimate two variables—present serviceability rating and slope variance—associated with roughness. In such an estimating procedure two sources of variation, or effects, are encountered and estimated, as follows:

- The amount of change in PSR or slope variance explained by or associated with a change in roughometer reading. In other words, this tells how well the rating of a pavement can be predicted with the roughometer.

- Residual Variation.** The amount of change in PSR or slope variance which cannot be explained by a change in roughometer reading. It can also be thought of as the deviations observed when a straight line is passed through a plot of PSR vs  $\log \bar{AR}_{10}$ .

TABLE 3  
EQUATIONS FOR UNCORRECTED AND CORRECTED ROUGHOMETER OUTPUT

Pavement Type	Date of Correlation	Uncorrected			Corrected		
		Equation	$r^2$	rmse	Equation	$r^2$	rmse
Rigid	May 5, 1960	$SV = 0.34 \text{ UAR}_{10} - 33.0$	0.97	6	$SV = 0.34 \text{ AR}_{10} - 33.0$	0.97	6
	Oct. 13, 1960	$SV = 0.40 \text{ UAR}_{10} - 38.9$	0.91	8	$SV = 0.35 \text{ AR}_{10} - 33.2$	0.91	8
	Nov. 16, 1960	$SV = 0.36 \text{ UAR}_{10} - 37.5$	0.92	7	$SV = 0.33 \text{ AR}_{10} - 32.5$	0.91	8

Residual variation, in addition, is made up of the following two different types of variation:

- Inherent Variation.** This variation is analogous to variation encountered when a coin is flipped and lands heads or tails. Inherent variation is caused by climatic conditions, chance physical changes in the instrument, and chance changes in the operation of the instrument. Chance errors in processing the data may also, for the current purposes, be classified as inherent variation.

- Assignable Variation.** That variation which is statistically significant compared to inherent variation. It may be caused by a physical change in the instrument (changing a tire, breaking a spring, etc.) or it may show up as an "out-of-control" point on a control chart with no detectable change in the instrument.

Inherent variation in indicated roughness may be estimated by measuring the roughness of an unchanging pavement. Assignable variation may also be detected with this technique. A control chart is a method of picturing these variations. A control chart uses the variation (e.g., range) between runs which are close together (15 min in this case) as a yardstick to discover excessive variation (out of control) between runs made hours or days apart. The control charts for four pavements of unchanging roughness are shown in Figure 17.

### Physical Aspects

A major problem in estimating variation is to find an acceptable standard against which to check. At the Road Test two such "standards" were available: (a) mean panel rating and (b) output of the profilometer (SV). Through continuous comparison of the roughometer with these two "standards," it became apparent that the magnitude of the assignable variation in the roughometer could be great. For example, the early plots of roughometer history of some test sections might show wide fluctuation from smooth to rough and back to smooth in four to six weeks. In reality these changes did not occur, as was seen by comparison with the profilometer. This is best illustrated by the control charts in Figure 17, where out-of-control points occur many times.

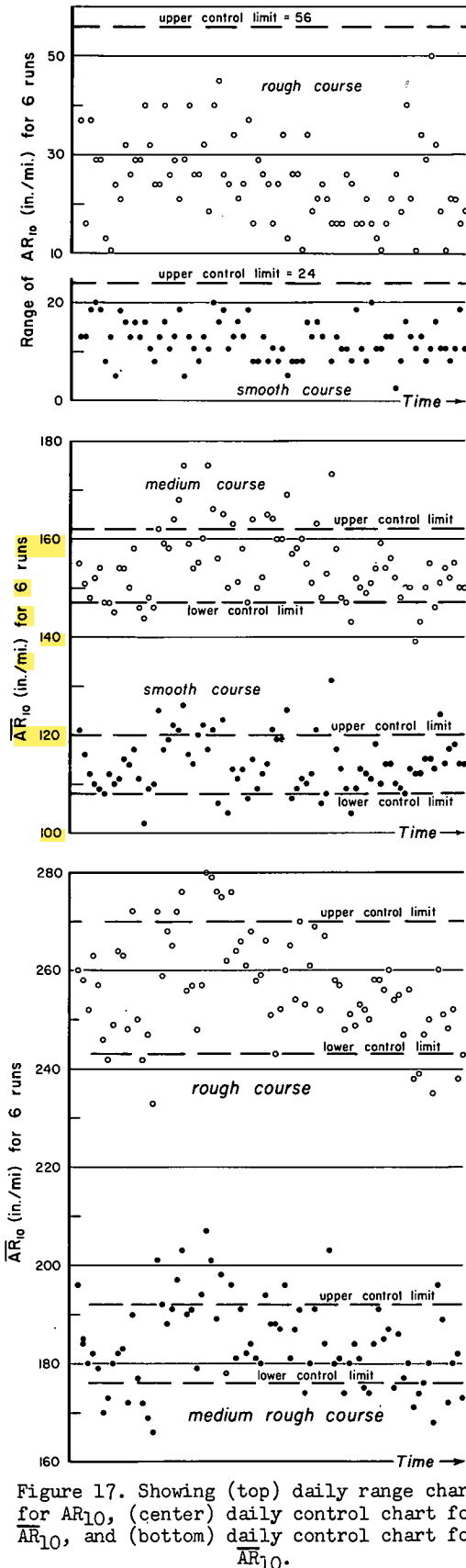


Figure 17. Showing (top) daily range chart for  $AR_{10}$ , (center) daily control chart for  $AR_{10}$ , and (bottom) daily control chart for  $AR_{10}$ .

In other words the apparent roughness of a section was significantly different from its true roughness.

Actual physical changes in the roughometer can result in radical changes in its output (e.g., the change from a treaded to a smooth tire resulted in a detectable change in indicated roughness, as did the introduction of the new counter system). General wear and tear on the instrument causes a gradual change in the output because the response of the instrument to roughness is an integral part of the output.

### Variations Among Instruments

Standard plans for the BPR roughometer do exist (10); however, many organizations have made modifications, either major or minor, which affect the output of their device. Some example modifications include: (a) those made on the Road Test roughometer; (b) the Illinois Department of Highways transports and operates its device from a specially constructed trailer and records the results electrically through a potentiometer circuit; (c) Minnesota has made several modifications, including the addition of an electronic integrator (12). Comparison runs have been made with the AASHO, Illinois, Indiana, Michigan, and Missouri roughometers. These comparisons were run as part of correlation studies with the profilometer. In every case a formula was generated for determining the PSI with the various State instruments. A correlation equation was also generated comparing each instrument to the AASHO roughometer. These equations (Table 4) adequately illustrate the variation between roughometers.

### CALIBRATION PROCEDURE TO MINIMIZE EFFECT OF ASSIGNABLE VARIATION IN THE ROUGHOMETER

#### Fundamental Calibration Concepts

One normally applied calibration procedure consists of checking a measuring device against a standard and then adjusting the device either mechanically or electrically until the output is equal to the standard by definition. A second common type of calibration is that applied to a device such as a proving ring. Several known loads are applied to the ring and the corresponding deflections are recorded. This procedure is repeated several times and the mean deflection for a given load is established. A best

fitting line is passed through the points and a calibration curve results. From this curve it is then possible to predict an unknown load from a known deflection of the ring. In this type of calibration, an accurate loading platen, such as a Universal testing machine, is used as the standard.

### Dynamic Calibration

This applies to static measuring devices. Some instruments, however, are used to record dynamically, and their output depends not only on the accuracy of the static calibration, but also on the method and speed with which the devices react to dynamic excitation. For example, the leaf springs and the integrator of the roughometer can be calibrated separately for a known input of deflection or displacement. It is impossible from this static calibration, however, to predict the response under dynamic conditions. This situation is borne out by the variation in roughometers previously reported.

TABLE 4  
EXAMPLES OF VARIATIONS BETWEEN ROUGHOMETERS

Instrument	Pav't. Type	Date	Correlation with AR <sub>10</sub>			Correlation with AR <sub>30</sub>			Slope Variance		
			Equation	r <sup>2</sup>	rmse	Equation	r <sup>2</sup>	rmse	Equation	r <sup>2</sup>	rmse
Ind.	Rigid	5/22/59	AR <sub>10</sub> = 1.591NR <sub>30</sub> - 18.6	0.95	17	AR <sub>30</sub> = 1.591NR <sub>10</sub> - 39.7	0.96	15	SV = 0.441NR <sub>30</sub> - 33	0.87	7
	Flex.		AR <sub>10</sub> = 1.731NR <sub>30</sub> - 27.1	0.92	22	AR <sub>30</sub> = 1.361NR <sub>10</sub> - 23.3	0.93	16	SV = 0.541NR <sub>30</sub> - 38	0.76	13
Mo.	Rigid	5/5/60	AR <sub>10</sub> = 1.45MR <sub>30</sub> - 12.9	0.99	13	AR <sub>30</sub> = 1.45MR <sub>10</sub> - 35.0	0.98	12	SV = 0.46MR <sub>30</sub> - 38	0.92	8
	Flex.		Insufficient data			AR <sub>30</sub> = 0.96MR <sub>10</sub> + 11.9	0.89	5	SV = 0.44MR <sub>30</sub> - 30	0.70	4
Ill.	Rigid	10/13/60	AR <sub>10</sub> = 1.43DR <sub>30</sub> - 4.1	0.98	12	AR <sub>30</sub> = 1.191R <sub>10</sub> + 2.2	0.95	15	SV = 0.501R <sub>30</sub> - 34	0.88	10
	Flex.		AR <sub>10</sub> = 1.45DR <sub>30</sub> - 15.2	0.92	28	AR <sub>30</sub> = 0.941R <sub>10</sub> + 17.7	0.88	23	SV = 0.181R <sub>30</sub> - 6	0.70	8
Mich.	Rigid	11/16/60	AR <sub>10</sub> = 0.90MR <sub>30</sub> - 9.4	0.98	15	AR <sub>30</sub> = 0.67MR <sub>10</sub> + 6.1	0.98	7	SV = 0.29MR <sub>30</sub> - 36.0	0.89	9
	Flex.		AR <sub>10</sub> = 0.65MR <sub>30</sub> + 22.0	0.77	26	AR <sub>30</sub> = 0.73MR <sub>10</sub> - 1.8	0.90	18	SV = 0.20MR <sub>30</sub> - 19.7	0.82	7

### Road Test Calibration

As the roughometer was used it became more apparent that the variability in indicated roughness made it impossible to record the actual roughness history of test sections with the desired degree of accuracy. It was clear that a method of dynamic calibration had to be developed if the roughometer was to become a useful tool at the Road Test.

Theoretically it is possible to calibrate the roughometer directly against the profilometer every day. This, however, would defeat the purpose of using the roughometer in the first place. It was decided instead to establish standard sections which presumably did not change during the two years of the Road Test. The true or "constant" roughness of these standard sections could be established through correlation between the roughometer, the profilometer and the rating panel. After that, it was possible to recalibrate the roughometer through another correlation on the standard section. Any time the results appeared questionable, a recorrelation with the profilometer could be run.

If the control charts show the roughometer to be out of control, the output must be adjusted to bring it into control. By trial and error, tire pressure, travel speed or mechanical parts can be adjusted until the roughometer reads the calibration course correctly. This would be a time consuming technique and concomitant changes in several parts would be unwise. In lieu of physical change, it is possible that mathematical correction of the output can be employed as in the case of the proving ring, which is calibrated periodically to insure against change due to material adjustment or fatigue. The principle is the same; the difference is merely one of time. The proving ring needs checking only every three or four months, whereas the roughometer should be checked daily.

Experimentation with the roughometer indicated that the variation on any one day might not be constant throughout the entire range of roughness. This indication, plus common sense, dictated that any calibration should investigate the entire range of interest (i.e., interpolation is normally more accurate than extrapolation). With this in mind, four calibration sections were set up: smooth (80 to 100 in. per mi), medium



(100 to 160 in. per mi), medium rough (180 to 200 in. per mi) and rough (230 to 250 in. per mi). The primary factor involved is that the course must remain constant in roughness. Secondly, the four sections should be adjacent for convenience. It was felt that these two conditions could not be met by utilizing naturally rough pavements with cracks, patches and faults. A pavement with bumps and potholes could be cast out of steel, but this is impractical. Instead a new, heavy-duty portland cement concrete pavement was chosen, over which no heavy traffic and minimum of light traffic was allowed to travel.

To simulate roughness, a series of artificial bumps were installed which could be standardized for use elsewhere. Bars of tempered aluminum were chosen as readily available and corrosion resistant. Bars of varying width and height were used to simulate various types and severity of bumps, and the proper number of bumps required to produce the range of roughness desired was installed (Figs. 18 and 19). A layout of the course as used is shown in Figure 20. It is understood that this type of course may not indicate the exact response of the roughometer to all types of roughness, particularly flexible pavements. However, the results thus far indicate that it does an acceptable job, because the amount of roughness is more critical than the character of the bumps. The mean or constant roughness for the calibration sections was established by averaging  $AR_{10}$  for 50 roughometer runs per section made within a period of five days. At the same time a correlation was made between  $AR_{10}$  and SV on 40 rigid pavement sections. Thus the constant values were obtained for a correlation between the profilometer and the roughometer.

#### Steps in Calibration Procedure:

1. Run the roughometer at least 1 mi to get the whole system warmed up and eliminate any flat spot developed in the tire.
2. Run the four calibration sections, which are laid out in random order, three times in each direction for a total of six readings on each course. (Using both directions is a convenience).
3. Average the six runs for each course and convert the four averages to  $AR_{10}$  (in. per mile).
4. Plot the average indicated roughness for each section against the constant roughness for that section (Fig. 21).
5. The least squares regression line for these points becomes a calibration or correction factor from which the output on any test section can be corrected to the standard (Fig. 21).



Figure 18. General view of calibration course.

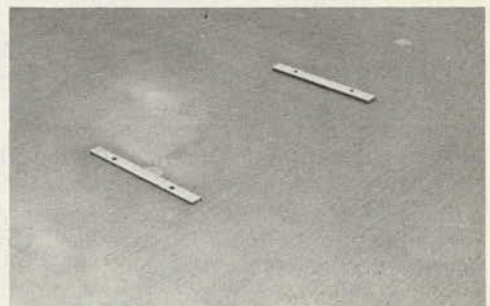


Figure 19. Aluminum Calibration Bar (1/2 x 2 x 24").

#### Validity of the Calibration Procedure

The calibration procedure makes use of a well-known, well-defined statistical concept, regression analysis. This technique is such that the sum of squares of the observed points from the regression line is a minimum. Two assumptions are that the independent variable is fixed (that is, measured without error) and that the dependent variable is random (that is, measured with error). The slope variance and  $AR_{10}$  are both measured with error, so two regressions are possible.

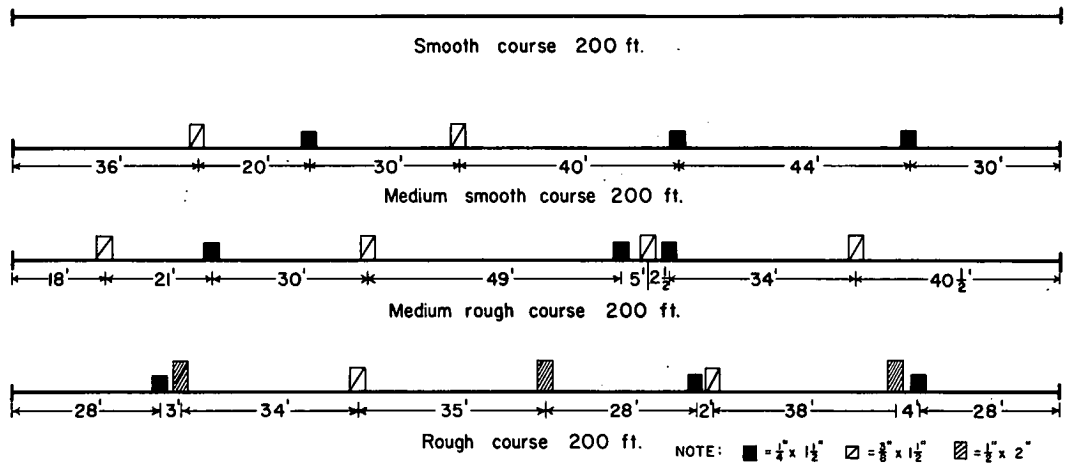


Figure 20. AASHTO roughometer calibration course.

Only one was chosen, the regression of SV on  $AR_{10}$ , because this is the way the equation is used.

An assumption about the calibration course is that its roughness is not changing. This can be true by definition, as in the case of a meter bar in the Bureau of Standards, or the variation in roughness can be acceptably small. Any change in roughness could be measured only by an instrument whose variation is less than the variation in roughness of the calibration course. With a suitable calibration course, it should be possible over any period of years to correct any changes in the roughometer back to an initial condition when the actual roughness of the course was established. This technique gives a solid foundation for discriminating between changes in roughness of a pavement in service and changes in the roughometer.

If it is desired to estimate PSR or SV, the roughometer can be calibrated against the profilometer or rating panel each time it is run. However, as long as it can be assumed that the relationship between the original corrected roughness and PSR or SV still holds, this need not be done.

Setting up a Permanent Calibration Course

There are certain problems involved in setting up a calibration course for use outside the Road Test (e.g., the long life required). There is no previous experience to indicate exactly how to establish such a course. Possibly a continuously reinforced concrete pavement would do the job successfully. It would probably be helpful to locate the calibration course on a residential street, which would have some continuous traffic of low magnitude to serve as conditioning traffic. On the other hand, it may be that a specially constructed course not on any normal thoroughfare would best do the job. In any event, some detailed thought must be given to developing a permanent standard calibration course.

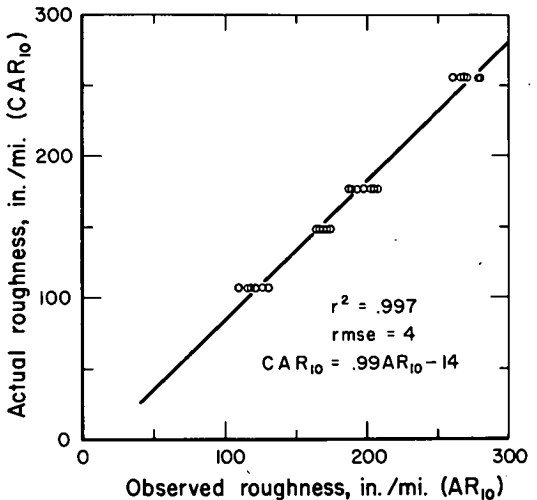


Figure 21. Sample roughometer calibration curve.



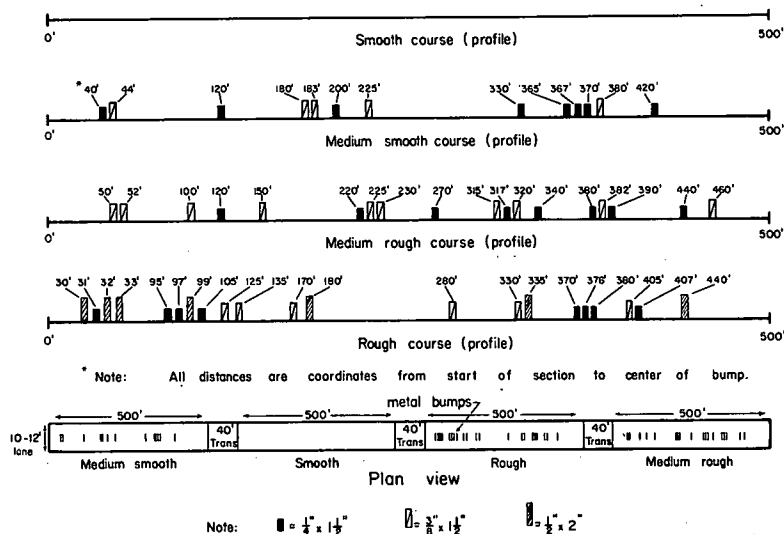


Figure 22. Proposed layout for permanent calibration course.

It would be necessary to check the roughness of the course periodically. A rod and level survey could be used to detect any general changes. Use of the present AASHO profilometer would be more precise. If the profilometer could be used every year or two to check the calibration course, the uniformity of the course could be assured or the calibration could be adjusted to the new level of roughness. A rating session could and should be held periodically to check the results of the roughometer output against an actual rating panel.

For setting up a calibration course, it is hoped that some standard set of bumps can be established in order to make it possible to standardize measurements between agencies without actually transporting the equipment. One possible layout for such a course is shown in Figure 22.

### SUMMARY

Four roughometers have been used to establish PSI equations, either by direct correlation with the rating panel or by cross-correlation with the profilometer. These correlations all indicate a high degree of success in predicting PSI with reasonable accuracy, as shown in Table 4. The data were obtained in a relatively short time and thus were not affected greatly by long-term variation of the indicator. Table 3, however, shows the variation of the Road Test roughometer in predicting slope variance before and after application of the calibration-correction procedure. It can be seen that correcting  $AR_{10}$  results in more stable coefficients. Sufficient data are not available for a comparison on flexible pavements. More data will be obtained.

The roughometer is one answer to the problem of measuring roughness or performance. The Road Test profilometer, however, does a better job of predicting PSR as judged by correlation coefficients and residuals. This system is costly and requires detailed summary work. Other instruments are also being used, such as the California and Michigan profilographs. At present, development work is being done at the Road Test on a profilometer using a summary recording device which eliminates the necessity for reading charts. Such a development would greatly decrease the cost.

It is sincerely hoped that continued development will soon place at the disposal of the highway departments a more perfect means of measuring roughness. Until such devices become generally available, the BPR roughometer with a calibration procedure can do an acceptable job of estimating roughness or serviceability within a

reasonable budget. It is hoped that the roughometer will help expand the use of the pavement serviceability performance concept.

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