

ROADMETER ROUGHNESS TESTING IN VIRGINIA

by

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SUMMARY

A passenger car mounted PCA roadmeter has been correlated with the BPR roughometer used for road roughness testing in Virginia for many years. The results showed a good correlation and that the roadmeter is capable of excellent reproducibility. Roadmeter (R_m) and roughometer (R) roughness are related by the equation

$$R = 1.14 R_m + 25.$$

A temperature correction is necessary if precise roadmeter results are to be obtained.

Spectra analysis using the roadmeter is useful in more completely describing roughness characteristics and in defining the most objectionable types of roughness.

The roadmeter is recommended for use by the operating divisions of the Highway Department for all future road roughness testing.

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INTRODUCTION

For many years the familiar trailer type BPR roughometer was used for road roughness testing in Virginia. This device served well for both construction testing and research purposes. However, a two-man crew was required under ideal conditions, while under heavy traffic the low speed of operation (20 mph) resulted in dangerous testing conditions and in the need for traffic control personnel at increased testing cost.

The constantly increasing rate of construction activity and increasing traffic volumes led to an informal study of other safer and more efficient methods of measuring roughness. Several publications^(1, 2, 3), and personal contacts with other highway agencies led eventually to consideration being given to the device developed by Brokaw⁽¹⁾ and referred to as the PCA roadmeter (hereinafter referred to as simply the roadmeter). Inherent advantages foreseen for the device were:

1. The roadmeter is used in a passenger car and therefore measures roughness of the same nature as that experienced by the traveling public.
2. roughness tests are conducted at 50 mph by a one-man crew (the driver) so that the roadmeter appeared both safer and more efficient than the roughometer.
3. the mechanical principles used in the roadmeter are similar to those used in the roughometer. Thus, there was a good probability of a satisfactory correlation between the two devices. This feature was considered desirable in order to make valid comparisons between roadmeter test results and the large backlog of previous roughness data on hand.

Late in 1969 plans for the roadmeter were secured from the Portland Cement Association. The device was assembled at a cost of approximately \$1,000 and placed in a 1970 Ford station wagon. Studies of the operating characteristics and of the correlation with the BPR roughometer were begun in early 1970. These studies were reasonably successful so that the first routine roughness tests were run with the device during the 1970 construction season. Later studies showed that the device gave more reproducible results when used in a passenger car. Currently, tests are run with the roadmeter mounted in a 1967 Ford four-door sedan.

The above mentioned studies and an outline of the testing procedures are discussed in the following pages.

ROADMETER DESCRIPTION

The roadmeter measures and accumulates the sum of vertical movements between the passenger compartment and the rear axle of an automobile induced by pavement roughness. One horizontal plane of reference is through the center of the differential housing, the other is the surface of the rear package deck. A braided steel cable connected to the center of the differential housing extends vertically through the trunk and through a hole in the package deck. The cable then traverses a pulley and is finally connected to a spring-loaded roller switch positioned to move transversely whenever the package deck moves vertically with respect to the rear axle. A view of the switch and pulley assembly is shown in Figure 1.

The roller switch impinges on a transverse copper switch plate having 23 contact points spaced at 1/8-inch center-to-center. A schematic diagram of these mechanical features is shown in Figure 2.

Automotive electrical power is fed to the roller switch and to all but the center contact point on the switch plate. This center contact point, electrically inactive, is the neutral position for the measuring system. Thus, vertical deviations of the package deck, either up or down, cause the roller switch to make electrical contact with one or more of the active contact points. Each of these active points is electrically connected to one of a series of eleven indicator lights mounted on the dash in front of the driver (see Figure 3). Contact points located equal distances on either side of the neutral position are connected to the same indicator light (Figure 2). The switch plate is designed to permit the driver to adjust its transverse position so that the neutral position (no indicator light) can be maintained if the loading of the automobile is changed. Gasoline usage is one factor making adjustments necessary.

Each of the active contact points also is connected through a twelve position switch assembly to a bank of electrical impulse counters (Figure 4). Through the appropriate selection of switch positions, the sensitivity and range of the measuring system can be altered. Under normal operating conditions, vertical movements of $\pm 1/8$, $2/8$, $3/8$, $4/8$, $5/8$, and $6/8$ inch register on the counters. Through the use of other switch settings, deviations of up to $\pm 1 \frac{1}{8}$ inch can be measured.

To reach an extreme position, the roller switch twice contacts all contact points except the extreme. For example, to register a $3/8$ inch deviation, the roller switch leaves the neutral position, travels through the $1/8$ and $2/8$ inch points, makes contact with the $3/8$ inch point, then returns to neutral (or beyond) through the $1/8$ and $2/8$ inch points. Thus, the $3/8$ inch deviation causes a minimum of 2, 2, and 1 registered impulses of $1/8$, $2/8$, and $3/8$ inch, respectively.

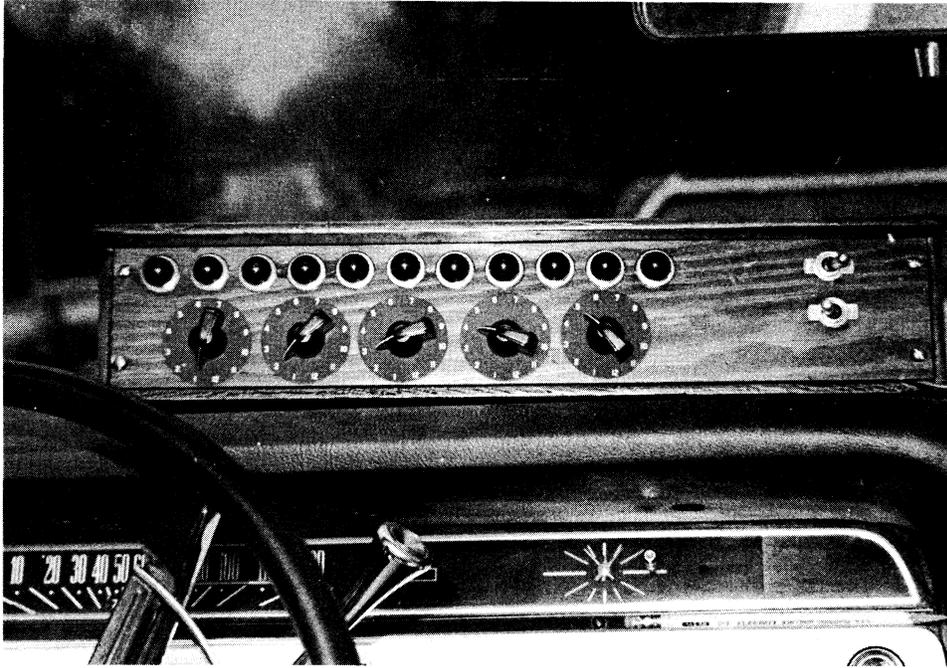


Figure 3. Indicator light and selector switch assembly mounted on the dashboard.

An additional electrical counter, shown in Figure 4, is used for distance measurements. This counter is activated by a rolling microswitch mounted inside a rear wheel. The switch makes contact with an eccentric on the brake drum and is activated once for each wheel revolution. The distance measuring mechanism is unique to the Virginia roadmeter and must be calibrated for the specific vehicle in which it is used. An exact distance calibration course is used to determine the number of revolutions per mile of roadway traversed.

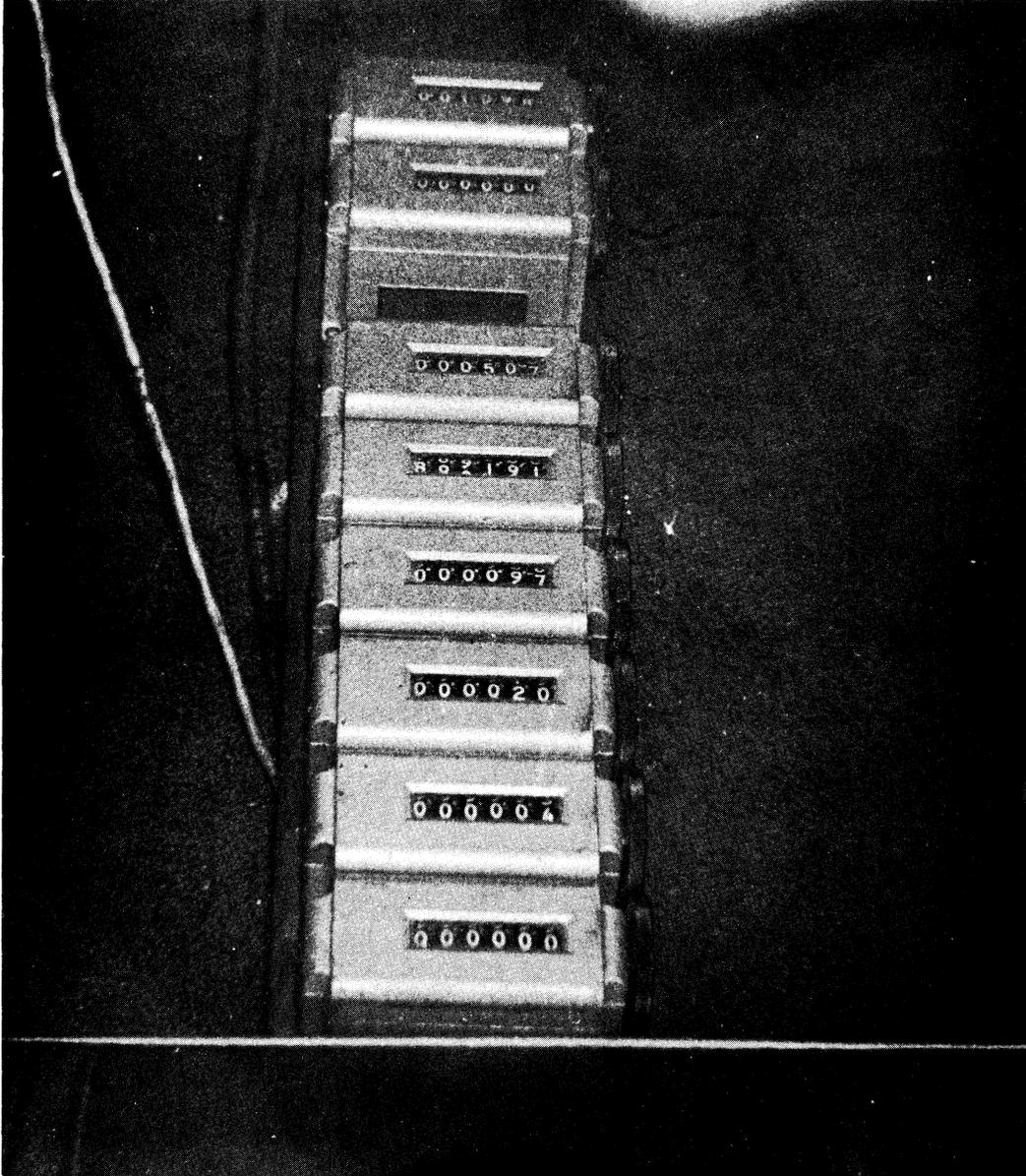


Figure 4. Electrical counter mounted on the drive shaft "hump".

OPERATIONS PROCEDURES

The roadmeter is designed so as to be simply operated by one man. Operation consists essentially of five steps: (1) Establishing the center or neutral position on the switch plate, (2) setting the electrical counters to zero, (3) maintaining a constant speed when the test section is traversed, (4) manipulating the on-off switches at each end of the test section, and (5) recording the electrical counter readings at the end of the test section. Certain features of operation are discussed further below.

Centering the Switch Plate

Maintaining the switch plate precisely on center is essential to the accurate operation of the roadmeter and is by far the most difficult part of the test. The switch plate assembly (Figures 1 and 2) is provided with a vernier dial which is used to accurately establish the neutral position. For the Virginia meter, changing the vernier reading by one unit was found to correspond to approximately 1/64 inch movement of the switch plate. The accurate positioning of the vernier is made easier by the provision of an extension control rod magnetically attached to the vernier and by the use of a lighted vernier dial (the light is unique to the Virginia unit). Thus, the driver is able to position the vernier from his normal driving position without disturbing the load balance of the automobile. For the unit now in use, it was found that the use of the indicator lights was the most convenient centering method. It was determined that with the roadmeter switched "on", movement of the vernier four units in either direction from the switch plate neutral position brought the roller switch in contact with an active contact point and caused the 1/8 inch indicator light to glow. Thus, precise centering was found to be the vernier reading corresponding to midway between the + 1/8 inch and - 1/8 inch contact points on the switch plate.

Centering must be done frequently during a day's operation and the authors have found it most convenient just prior to each run on a test section. Centering is done while stopped at a location having a transverse slope similar to that of the roadway to be tested, or on the roadway if conditions permit. The automobile must be in "drive" with the foot-brake depressed. Otherwise, torque transmitted through an automatic transmission causes a shift in the switch plate position when the automobile begins to move. This facet of the operation was discovered by the authors accidentally when centering problems were first encountered. Brokaw⁽⁴⁾ has since reported that he uses the opposite approach and centers with the transmission locked.

The most important factor influencing switch plate centering is a load shift within the automobile. Vehicle response to roughness also is influenced by load shifts so that tests should be run under standard conditions which are not permitted to vary much. One agency⁽²⁾ chooses to use two operators to balance the loading on the front seat. The authors have chosen to use a sandbag ballast on the passenger side of the front seat. Gasoline usage causes a significant balance shift so that some users⁽²⁾ recommend that the fuel tank be kept at least half full. A rough rule of thumb for the Virginia unit is that the vernier will require one unit of movement for each gallon of gasoline used (approximately 15 miles of travel).

Vehicle Speed

Tests with the roadmeter are conducted at a nominal 50 mph by almost all users. However, exact speed is not critical to the test results. Phillips and Swift⁽²⁾ found little difference between tests conducted at 50 mph and those at 40 mph. The authors agreed, but found that reducing the speed to 30 mph had a substantial effect on the roughness. All test results, correlations, etc., discussed later in this report are for 50 mph tests. If it is deemed necessary to conduct tests at lower speeds in congested areas, there is little doubt that satisfactory correlations can be developed.

OTHER FACTORS INFLUENCING TEST RESULTS

Two principal external factors have been identified as influencing the results of roadmeter tests. These are air temperature and wind velocity as discussed below.

Air Temperature

The mechanical suspension system of an automobile is affected by changes in air temperature. Depressed temperatures cause shock absorber, tire, and spring stiffness to the extent that Brokaw⁽¹⁾ recommended that the roadmeter not be used at temperatures below 10°F, but recommended no temperature correction. Others,^(2,3) however, found that much variation in temperature from an established standard (usually taken as 70°F) could significantly influence test results. Appropriate temperature corrections were developed for the types of tests conducted by these agencies.

Correction Factor

Tests were conducted with the Virginia roadmeter on numerous projects at air temperatures ranging from 25°F to 85°F. These tests showed that the correction factor was dependent upon the degree of roughness as well as the temperature. The equation developed from these studies and to be applied to subsequent tests with the roadmeter is:

$$R_m = R_o \left[1 + 0.005(70 - T) \right] \quad (1)$$

where; R_m = corrected roadmeter roughness, as discussed later,

R_o = measured roadmeter roughness,

T = temperature at which R_o is measured.

The above equation was developed with the roadmeter mounted in a 1970 Ford station wagon. Later testing with a 1967 Ford sedan showed that the same equation was applicable.

Wind Velocity

Tests by the roadmeter developer⁽¹⁾ indicated that crosswinds in excess of 15 mph should be avoided because they exert enough side pressure on the vehicle to cause the switch plate to shift off center. Other users have accepted this limitation and the authors concur that tests should not be conducted under heavy wind conditions.

CORRELATION WITH BPR ROUGHOMETER

As indicated earlier, the backlog of roughness data in Virginia was developed with the BPR roughometer, so a satisfactory correlation with the roadmeter was desirable. Yet, other users of the roadmeter have developed correlations with either the Chloe profilometer or with the Mays road meter.^(1, 2, 3) On the other hand, other users were primarily interested in using the roadmeter within the framework of the present servicibility rating system (PSI) devised from the AASHO Road Test.⁽⁵⁾ In such a system Brokaw⁽¹⁾ showed that the sum of squares $\sum (D^2)$ of road car deviations measured by the roadmeter is directly related to the slope variance measured by the Chloe profilometer. A thorough discussion of this concept can be found in Brokaw's report.

In Virginia, however, the PSI system has proven inadequate as a means of evaluating pavement performance.⁽⁶⁾ For this reason, the authors were interested in measuring roughness per se without regard to PSI or other performance equations. The thinking was that the roadmeter would be used primarily as a tool to measure the initial roughness of new construction projects.

Calculation of Roadmeter Roughness

Roughness measured by the BPR roughometer is in terms of inches per mile of roadway, no square law is involved. In order to express the roadmeter output in similar terms, the analysis outlined in the Appendix was performed. This analysis showed that roughness (in./mi.) can be determined from the electrical counter readings, (where six counters are used), by use of the equation

$$R_o = \frac{N_1 + N_3 + N_5}{8} \quad (2)$$

where: R_o = measured roughness (in./mi.),

N = counter reading (odd numbered counters only).

If more than six counters are used on very rough roads only the odd numbered counters need be used to determine the roughness. However, as will be discussed later, all counters are needed to define the nature of the roughness.

As indicated earlier, equation (1) is used to correct the roughness measurements to a standard 70°F air temperature.

Tests Conducted

The test sections selected for the correlation studies are listed according to descending BPR roughness in Table I. The first eleven were projects on which a great deal of previous BPR roughness data had been collected. Selections also were based on the desire to obtain a good spread of roughness from smooth to rough. While BPR and roadmeter tests were not conducted simultaneously, several of the projects were tested both ways within a few days of each other. Projects 12 and 13 were added in order to develop data on smoother projects. These projects were tested with both devices on successive days.

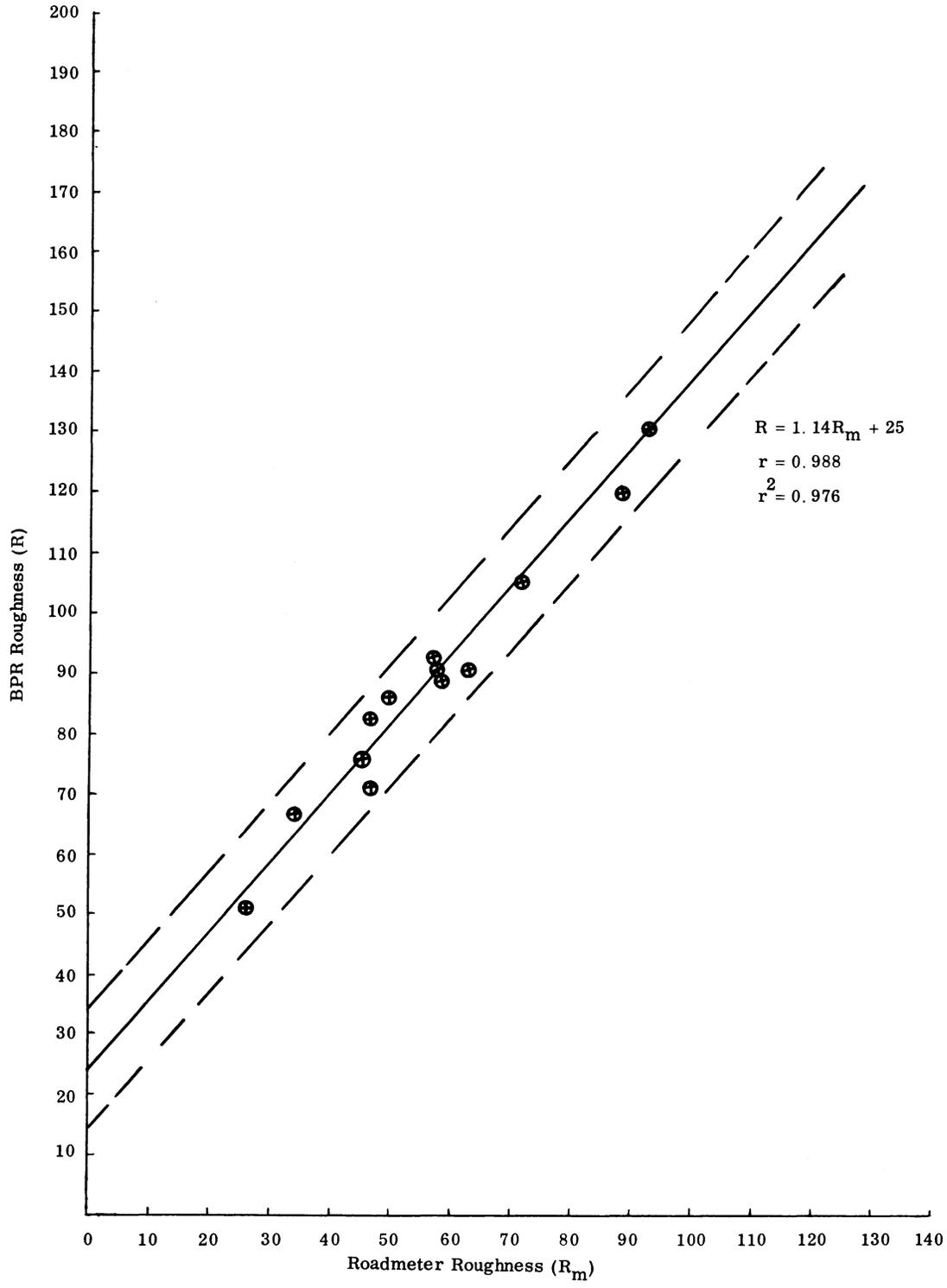
TABLE I

BRP ROUGHOMETER TO ROADMETER CORRELATION PROJECTS

No.	BPR Roughness (R)	Roadmeter Roughness (R _m)
1	131	92
2	120	88
3	105	71
4	93	57
5	91	58
6	91	63
7	89	58
8	86	50
9	83	46
10	76	45
11	71	46
12	67	34
13	51	26

All test sections were a minimum of one mile in length. All were tested at moderate temperatures and the roadmeter results corrected to 70°F. Ten 50 mph repetitive roadmeter tests were run on each section. The results shown in Table I are average roughnesses as determined by both test methods.

The results of the correlation tests also are shown graphically in Figure 5, where the regression line has been plotted through the points. Note that a very



satisfactory correlation is indicated by the correlation coefficient (r) of 0.988 ($r^2 = 0.976$). There is, however, a good deal of spread in the data as shown by the confidence limits plotted parallel to the regression line. This spread was not altogether unexpected for two reasons:

- (1) While both instruments indicate roughness in terms of inches per mile, there is a fundamental difference in that the roadmeter measures vehicle response to roughness while the roughometer measures vertical movement of one wheel in direct contact with the pavement.
- (2) As will be discussed below, there is a significant variability between the replicate roadmeter tests on a given section so that the exact averages plotted in Figure 5 could be subject to some error.

Nevertheless, the authors feel that the roadmeter is directly indicative of the roughness felt by the traveling public and that the correlation is completely satisfactory. Thus, the regression equation,

$$R = 1.14 R_m + 25 \quad (3)$$

is recommended to estimate the roughometer roughness (R).

As can be seen in Figure 5, a fixed roughness of 25 units per mile is found in the BPR roughometer data. This is not uncommon in similar correlations of roughness measuring equipment. Texas researchers,⁽²⁾ for example, found a 52-unit per mile offset in this correlation of the roughometer and the Chloe profilometer. The offset was attributed to tire or axle eccentricity causing an inherent BPR roughness. Since this offset could be different for each roughometer, the regression equation developed herein would not be recommended to relate instruments other than those tested in this study.

REPRODUCIBILITY OF TEST RESULTS

During the correlation studies each section of roadway was represented by ten replicate roadmeter tests. While a good correlation was developed, the researchers still were concerned about the apparent lack of repeatability of the roadmeter test results. Statistical analysis of the 13 correlation projects yielded an average coefficient of variation of 7.7 percent. Allowing a 5 percent tolerance (i. e., one is satisfied to know the true roughness within 5 percent), statistical tables show that these values indicate an acceptable 95 percent confidence level. Ten tests, however, are too many for routine roughness testing since twice as much time would be required as with the roughometer (2 roughometer tests at 20 mph has been the norm for many years). Thus, the authors made many futile attempts to reduce the variability and finally concluded that there was a built-in poor repeatability due to difficulties in centering the switch plate.

Conversations with other roadmeter users indicated that test results would be more satisfactory if the roadmeter was mounted in a sedan rather than a station wagon. The roadmeter was placed in a 1967 Ford four-door sedan and the calibration checked against the station wagon correlation. The repeatability was found to be markedly improved and the previously given regression equation and temperature corrections were found to be applicable. A total of 200 tests on 40 new construction projects (5 tests on each project) showed an average variation coefficient of 3.1 percent, corresponding to virtually a 100 percent confidence level for a 5 percent tolerance. Three tests represent a 99.7 percent confidence level, with a 5 percent tolerance and thus are recommended for future testing with the device. The repeatability test data are summarized in Table II.

TABLE II
REPEATABILITY DATA

	<u>Station Wagon</u>	<u>Sedan</u>
Number of Tests	80	200
Average R_o	54 in./mi.	42 in./mi.
Average Standard Deviation	4.2 in./mi.	1.3 in./mi.
Average Variation Coefficient	7.7%	3.1%

No satisfactory explanation can be offered for the difference in repeatability between the station wagon and the sedan. One possibility that has not been examined is that there is an anti-sway mechanism on the station wagon but not on the sedan.

ROUGHNESS SPECTRAL ANALYSIS

The roadmeter's ability to measure vehicle deviations in 1/8 inch increments makes possible a more detailed roughness study than with the roughometer. The contribution of each size deviation and the total number of such deviations to the total roughness can be studied through the use of a bar chart such as is shown in Figure 6. Note that the D values are computed from equations 2A through 7A of the Appendix and that the roadmeter roughness for each increment is the weighted area under the bar chart. For example, the roughness attributable to a 1/8 inch deviation is $1/8 \times D_1$, while that attributable to a 2/8 inch deviation is $1/4 \times D_2$, etc.

The five projects shown in Figure 6 represent examples of typical roughness results determined by the roadmeter. A more detailed description of these data are given in Table III. No temperature corrections have been applied to these data because all tests were made at temperatures near 70°F. It has been observed that at low testing

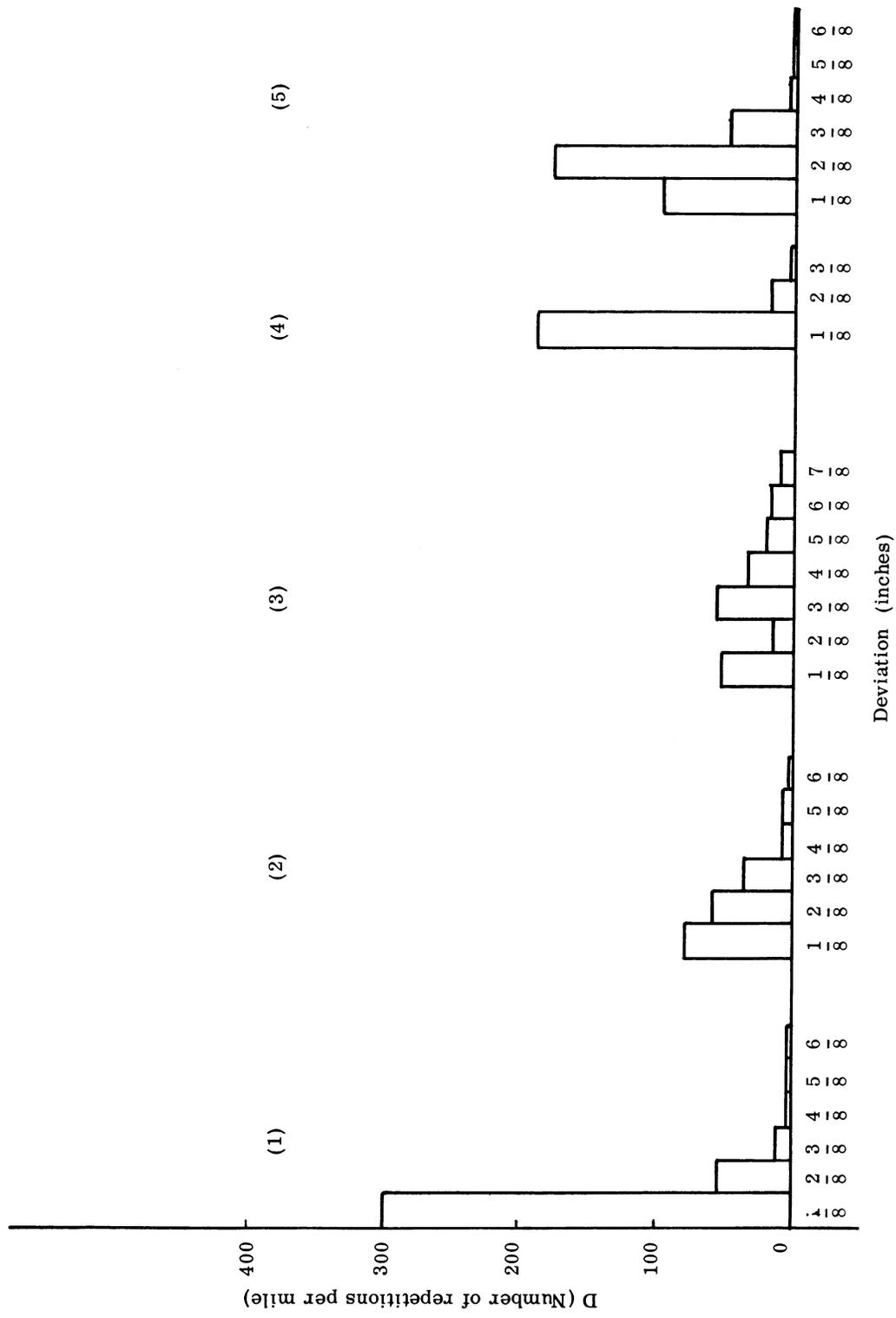


Figure 6. Typical roadmeter roughness spectra.

temperatures the number of larger deviations is significantly reduced. For this reason, when spectral analysis is contemplated, it seems desirable to restrict testing to a temperature of from 60 to 80°F. The temperature correction given earlier is applicable only to the gross roughness.

TABLE III
TYPICAL ROADMETER SPECTRA

Project No.	Description (Pavement Type)	Roadmeter Roughness (in./mi.)	Total Deviations (per mi.)	Average Deviations (in.)	Predicted Roughometer Roughness (in./mi.)
1	New concrete continuously reinforced	56	366	0.15	89
2	Old flexible	48	187	0.26	76
3	Old flexible	86	228	0.38	123
4	New flexible	30	214	0.14	59
5	Old concrete jointed, reinforced	81	346	0.23	117

Several comments are pertinent to the data shown in Table III and Figure 6. Project No. 1 is a moderately heavily textured concrete pavement with good riding quality. It is likely that the texture contributes significantly to the large number of 1/8 inch deviations (300 per mile as contrasted with 100 per mile for the old concrete pavement, Project 5). Project No. 2 has a lower computed roadmeter roughness than Project No. 1 (48 and 56 inches per mile, respectively). However, Project 1 provides a more comfortable ride, probably because of the few deviations larger than 3/8 inch. Data of this type have led the authors to conclude that the computed average deviation (Equation 10A) is a better index of riding quality than is the gross roughness. Note the average deviations of 0.15 and 0.26 inch for Projects 1 and 2, respectively.

A similar comparison can be made between Projects 3 and 4, where the number of deviations per mile are nearly the same. The riding quality, however, is vastly different because of the larger deviations found on Project 3. The average deviation for Project 3 is more than twice that for Project 4 (0.38 inch as opposed to 0.14 inch). In this case, the measured roughness for Project 3 also is twice that for Project 4. Project 3 is one of the courses used for a check on both the roadmeter and roughometer calibrations. It has numerous large distortions of the pavement surface and is considered to be very rough.

Finally, Project 5 is a jointed concrete pavement having a roughometer roughness typical of that type pavement. No efforts have been made to analyze the pavement at different temperatures where thermal distortions would doubtlessly influence the roughness results. Note that for the case shown, most of the deviations are 1/2 inch or smaller with the preponderance being 1/4 inch. While this unusual distribution of deviations really cannot be explained, it is surmised that the cause may be traced to the many faulted joints observed on the project.

CONCLUSIONS

The studies of the PCA roadmeter as a roughness measuring device have led to the following conclusions:

1. The roadmeter is useful for roughness measurements either on its own merits or as an expedient to predict BPR roughometer values.
2. The roadmeter is capable of excellent repeatability of test results when care is taken to maintain exact centering of the switch plate.
3. The roadmeter may be correlated with the BPR roughometer, but differences in mechanical reactions between vehicles suggest that a general equation may not be applicable to all roadmeter-roughometer pairings, and that a regression equation should be developed for the two devices being compared.
4. Roadmeter spectral analysis can provide clues to the causes of pavement roughness and to the types of roughness most objectionable to the driver.
5. The magnitude of the average vehicle deviation caused by the pavement may be a better index of riding quality than is the gross roughness.
6. The roadmeter is simple to operate and lends itself to more rapid, less expensive roughness testing than with the roughometer.
7. Temperature variations can significantly affect roadmeter roughness results and should be accounted for if precise results are desired.

RECOMMENDATIONS

1. The PCA roadmeter is recommended to the Virginia Department of Highways for all future roughness testing of new construction. Since mechanical behavior is subject to change, the establishment of calibration courses is recommended for use in periodically checking roadmeter results.

2. Gross roughness measurement with the roadmeter is no longer considered a researchable area. Thus, it is recommended that future testing be undertaken by the operating divisions of the Highway Department. The low cost of equipment may make the purchase of a device for each of the eight highway districts feasible.
3. Further research on roadmeter spectral analysis is recommended only to the extent that such analysis would be of interest and value to the Highway Department. Since the authors are unable to make a judgment of this value, no further research will be undertaken except at the request of the Department.

ACKNOWLEDGEMENTS

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APPENDIX

100

The following definitions are necessary to a discussion of the mathematics of the roadmeter (six counters and a one mile test section are assumed):

- $N_1, N_2, N_3 \dots N_6$ Counter readings for counters number 1, 2, 3 ... 6, respectively.
- $D_1, D_2, D_3 \dots D_6$ Number of deviations of 1/8, 2/8, 3/8, ... 6/8 inch, respectively.
- $R_1, R_2, R_3 \dots R_6$ Roughness corresponding to $D_1, D_2, D_3 \dots D_6$, respectively.

Then, the total roughness (R) is:

$$\begin{aligned}
 R_o &= R_1 + R_2 + R_3 + R_4 + R_5 + R_6 \\
 &= 1/8 D_1 + 2/8 D_2 + 3/8 D_3 + 4/8 D_4 + 5/8 D_5 + 6/8 D_6 \\
 8R_o &= D_1 + 2 D_2 + 3 D_3 + 4 D_4 + 5 D_5 + 6 D_6 \qquad (1A)
 \end{aligned}$$

Brokaw⁽¹⁾ shows that the number of deviations of a given size may be determined as follows:

$$D_6 = N_6 \qquad (2A)$$

$$D_5 = N_5 - 2 N_6 \qquad (3A)$$

$$D_4 = N_4 - 2 N_5 + 2 N_6 \qquad (4A)$$

$$D_3 = N_3 - 2 N_4 + 2 N_5 - 2 N_6 \qquad (5A)$$

$$D_2 = N_2 - 2 N_3 + 2 N_4 - 2 N_5 + 2 N_6 \qquad (6A)$$

$$D_1 = N_1 - 2 N_2 + 2 N_3 - 2 N_4 + 2 N_5 - 2 N_6 \qquad (7A)$$

substituting in equation (1A):

$$\begin{aligned}
 8 R_o &= N_1 + N_3 + N_5 \\
 R_o &= \frac{N_1 + N_3 + N_5}{8} \text{ in./mi.} \qquad (8A)
 \end{aligned}$$

Similarly, the total number of deviations per mile (D) is determined by adding:

$$D_1 + D_2 + D_3 + \dots + D_6 = N_1 - N_2 + N_3 - N_4 + N_5 - N_6 \quad (9A)$$

The average deviation (\bar{Y}) is then:

$$\bar{Y} = \frac{R_0}{D} \text{ (in.)} \quad (10A)$$