Development of the PCA Road Meter: A Rapid Method for Measuring Slope Variance

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Results of the AASHO Road Test were determined in part by measurements of variations in longitudinal slope of pavement surfaces as made by the AASHO Profilometer. Later, a device known as the CHLOE Profilometer was developed by members of the Road Test staff to afford a less expensive method for measuring slope variance. Both profilometers operate at a speed well below that of traffic. Highway tests can be made only with extreme precautions that are costly to the operating agency and traveling public. Furthermore, the devices require multiple operating personnel, are expensive to acquire or construct, and neither is able to survey large mileages of pavement in a short time.

The PCA Road Meter was developed to afford a rapid method for measuring slope variance. The method uses a simple electromechanical device, installed in a conventional passenger automobile, which measures the number and magnitude of road-car deviations. These are statistically summed and correlated with slope variance measured by the CHLOE Profilometer. The test automobile can be operated at speeds consistent with traffic and without extra personnel.

The PCA Road Meter is not difficult to construct, is inexpensive, and has been tested and compared during the period from June 1965 to July 1966 in thousands of miles of highway use. At present, it is being used in extensive studies of pavement performance for the Portland Cement Association.

In this paper, the basic mechanical and electrical features are described, results of correlative tests with the CHLOE Profilometer are presented, and physical limitations are defined and discussed.

•MEASUREMENTS of the condition of pavements in the AASHO Road Test were made by a device known as the AASHO Profilometer. This instrument provided a continuous analog of longitudinal slope of pavement surface in each wheelpath. These data were reduced to observations taken at 1-ft intervals, and statistical variance of slope was calculated and used as a partial measure of pavement serviceability.

The Road Test staff also developed a simplified profilometer, now known as the CHLOE Profilometer. This device moved in one wheelpath and measured longitudinal slope of pavement surface at 6-in. intervals. Statistical variance of slopes was computed and used as a partial measure of pavement serviceability.

Because of the short length of pavement sections in the Road Test, both profilometers were designed to operate at a speed of 5 mph. While this speed is not objectionable in a research project, it seriously limits the utility of the profilometers when tests are needed in many miles of highway carrying high-speed, mixed traffic.

Paper sponsored by Committee on Surface Properties—Vehicle Interaction.

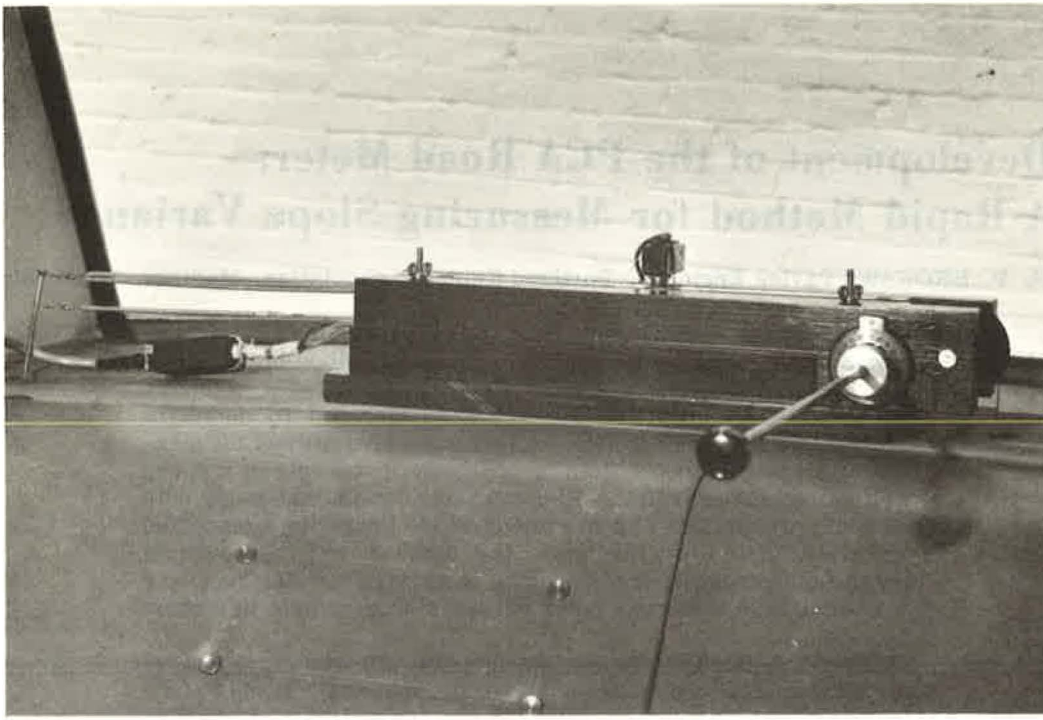

Figure 1. Switch assembly of Road Meter installed on rear package deck of automobile.

Recognizing this fact, the author has developed a simple, inexpensive device for installation in a conventional passenger automobile. The device measures the number and magnitude of vertical deviations per mile of road, between body of automobile and center of rear axle housing. From these measurements, sum of squares of road-car deviations can be calculated, and then correlated with slope variance from the CHLOE Profilometer.

The assumption was made that correlation coefficients include factors related to automobile suspension, shock absorbers, tires, speed of test, etc., and that while these factors remain reasonably constant, close estimates can be made of slope variance and serviceability. It was found that a satisfactory correlation with the CHLOE Profilometer can be achieved and that important variables can be evaluated.

Tests were conducted from June 1965 to July 1966. During this time, the Road Meter automobile was driven 40,000 miles and thousands of miles of highway were tested in Wisconsin and other areas. At the end of this period, the Road Meter was again compared with the CHLOE Profilometer with excellent results.

DESCRIPTION OF PCA ROAD METER

The Road Meter is a simple electromechanical device, of durable construction, which can perform consistently with extremely low maintenance. Tests are made by the automobile driver without the need for traffic protection or extra personnel, and at a speed of 50 mph or more if required by the traffic stream.

The device consists of a flexible, nylon-covered, braided steel strand connected to the top center of the rear axle housing in a 1965 Ford Galaxie four-door sedan. The steel strand extends vertically through the trunk compartment and then through a small hole in the package deck just back of the rear seat. At this point, the strand passes over a transverse-mounted pulley, and is restrained by a tension spring attached to a small post on the package deck at a point near the right side of the body shell. Thus,

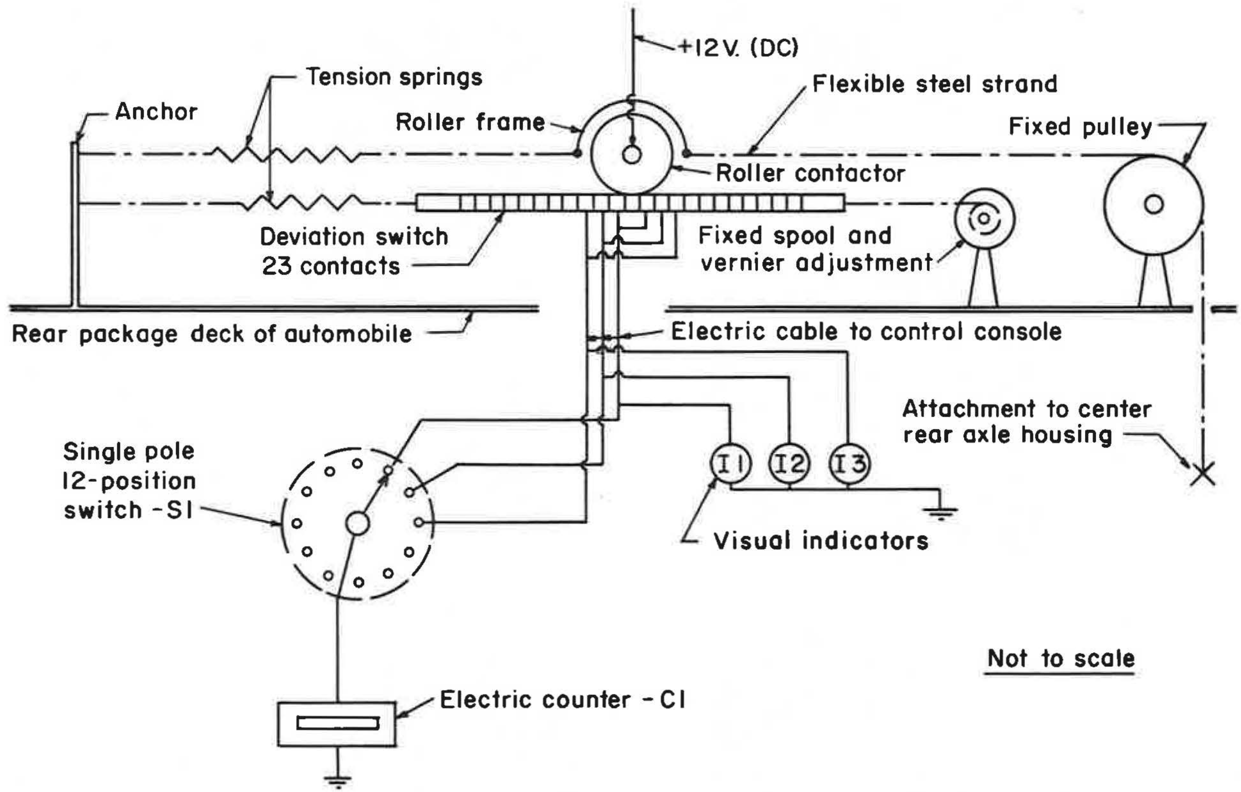

Figure 2. Diagram of mechanical and electrical features of the PCA Road Meter.

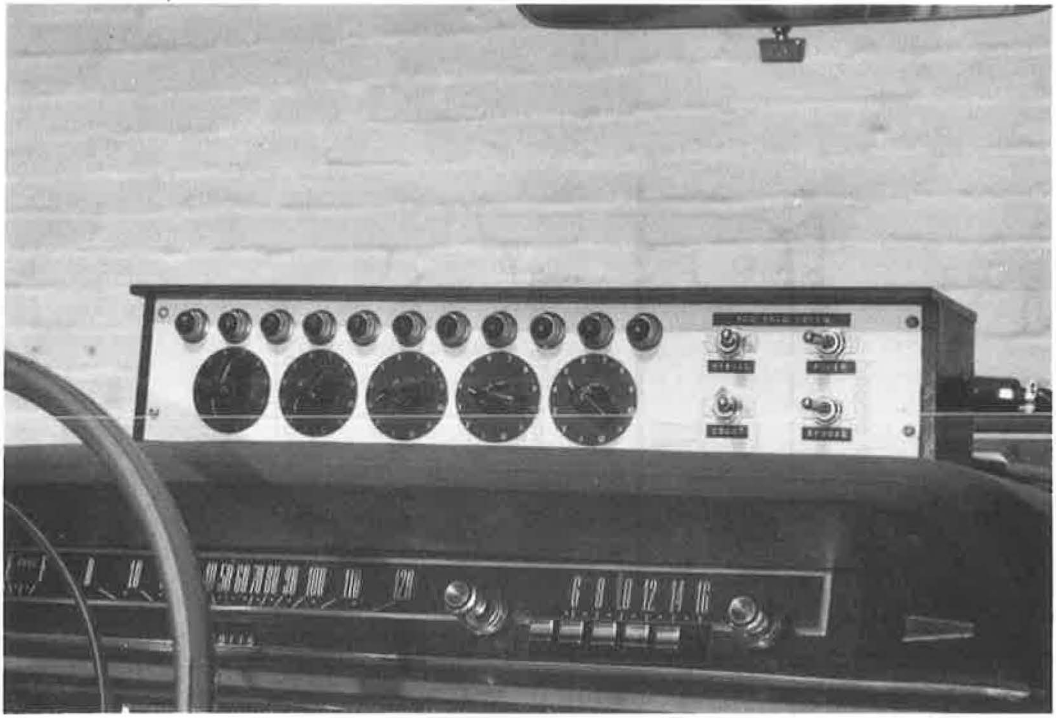

Figure 3. Road Meter control console, showing visual indicators and switches.

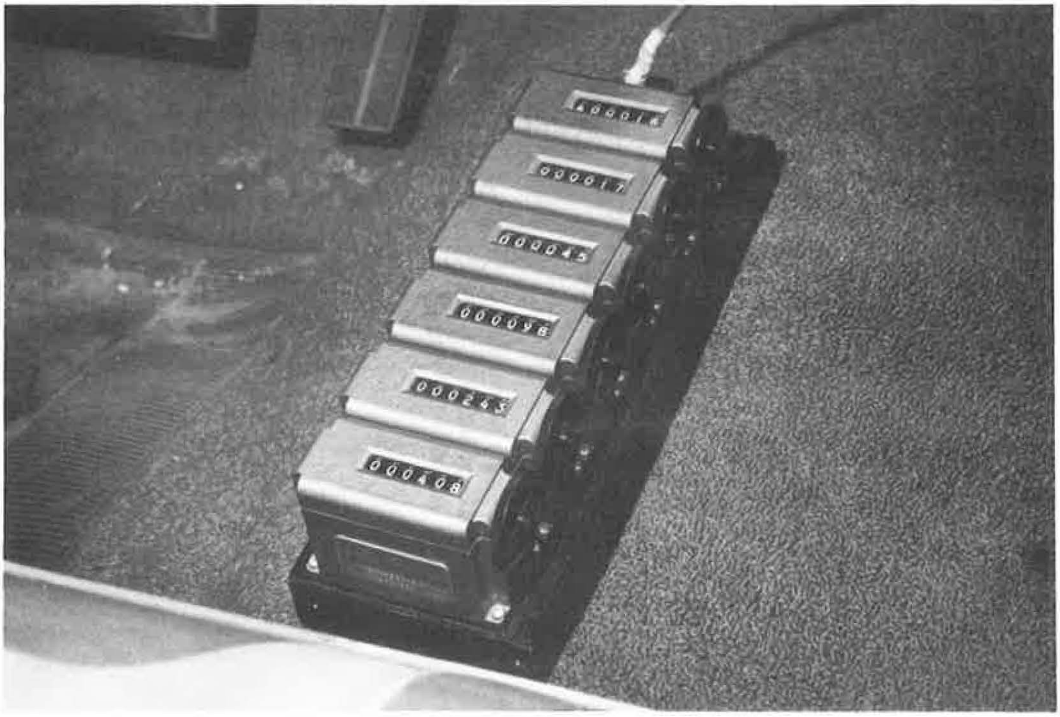

Figure 4. Electric counters mounted on separate chassis, resting on floor of automobile.

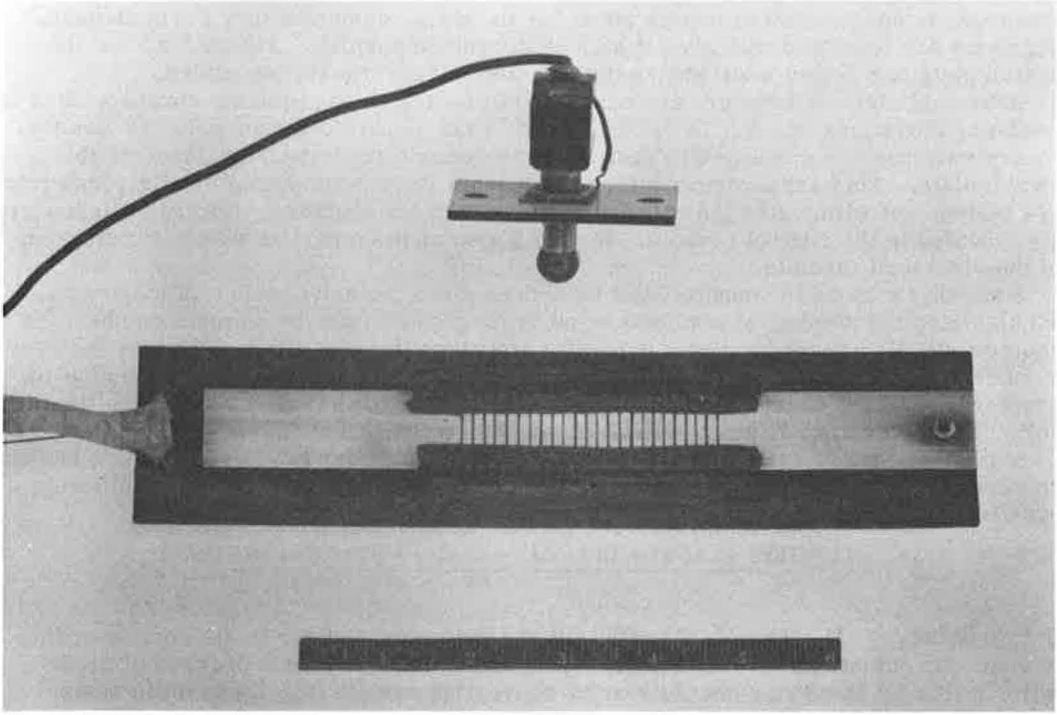

Figure 5. Disassembled switch plate and roller contactor.

vertical movement between the rear axle housing and the package deck is translated to horizontal movement of the strand.

Midway between the pulley and the tension spring, a roller microswitch (Minneapolis-Honeywell BZ-2RQ181-A2) is attached to the metal strand. The switch is mounted in a small rectangular Formica plate that slides in transverse metal guides. Figure 1 shows the switch assembly and tension spring installed on the package deck.

The microswitch roller impinges on a switch plate constructed so that transverse roller movements can be measured in ⅛-in. increments, either plus or minus from a reference standing position of the automobile. The switch plate is also mounted in transverse metal guides. The transverse reference position of the switch plate can be adjusted under the roller to accommodate various static loads in the automobile. This adjustment is made by a separate tension-spring attachment and vernier control. Figure 2 is a schematic diagram of the mechanical features.

Automotive electrical power of 12 volts is inserted in the roller and switch plate system. Output is directed to visual indicators of road-car deviations, mounted in a console placed just above the automobile instrument panel. Control console and indicators are shown in Figure 3.

Output is also wired to high-speed electric counters capable of recording impulses having a "make" time of 0.03 second (ITT-General Controls CE-600). These sum the impulses received from each of the segments of the switch plate, according to the magnitude relative to road-car deviations. Electric counters are mounted on a separate chassis resting on the floor of the automobile (Fig. 4).

A roller microswitch is used because of its rugged construction and availability, and because it has an internal compression spring to force the roller against the switch plate. The switch is always in a partial compressed state, and electrical impulses are conducted through the roller and not by microswitch contacts.

The switch plate is divided into 23, ⅛-in. segments. The center segment, used for initial static reference, has no electrical connection. The plate, which has never been replaced, is constructed of copper about $\frac{1}{32}$ in. thick, cemented to a Formica base. Segments are insulated with glyptal high-temperature varnish. Figure 5 shows the switch plate and roller microswitch disassembled from transverse guides.

Individual electric counters are connected to switch plate segments corresponding to road-car deviations of $\pm\frac{1}{8}$, $\frac{2}{8}$, $\frac{3}{8}$, $\frac{4}{8}$, $\frac{5}{8}$ and $\frac{6}{8}$ in. Separate single-pole, 12-position rotary switches are connected to each electric counter and to each segment of the switch plate. This arrangement affords additional range when exceptionally rough roads are tested, and eliminates the expense of more than six counters. Rotary switches are also located in the control console. Figure 2 also shows a partial schematic diagram of the electrical circuits.

Methods for reducing counter data have been given intensive study. Each counter accumulates the number of impulses equal to or greater than its segment number. A counter will also record a double-count for impulses that are greater than its segment number. For example, a maximum road-car deviation of $\frac{4}{8}$ in. will record twice on counters 1, 2, and 3, and once on counter 4. This is true because most of the time the roller will return to, or pass, its initial reference position at the end of a single impulse.

Mathematical deductions have shown that double-counts and total of impulses in each counter can be reduced to the sum of squares of road-car deviations by the following equation:

$$\Sigma(D^2) = \frac{(1 \times C1) + (2 \times C2) + (3 \times C3) + (4 \times C4) + (5 \times C5) + (6 \times C6) + \ldots}{64}$$

In this equation, C1, C2, C3, C4, C5, C6 are individual counter totals corresponding to road-car deviations of $\pm\frac{1}{8}$, $\frac{2}{8}$, $\frac{3}{8}$, $\frac{4}{8}$, $\frac{5}{8}$ and $\frac{6}{8}$ in.; $\Sigma(D^2)$ is expressed per unit-mile, either by surveying one mile or by converting results to a single-mile basis. Development of the sum-of-squares equation is shown in the Appendix.

CORRELATION OF CHLOE PROFILOMETER AND PCA ROAD METER

The sum of squares of road-car deviations measured by the Road Meter should be related in some way to slope variance measured by the CHLOE Profilometer. This is true because the CHLOE device detects incremental vertical deviations in longitudinal road profile in a 9-in. gage length, this being the distance between detecting wheels.

It can be shown (see Appendix) that the sum of squares of incremental vertical deviation per mile, measured by the CHLOE Profilometer, is related to slope variance. The equation for this relationship is CHLOE slope variance = $1.17\ \Sigma(d^2)$.

If passengers in an automobile can judge serviceability of a road, and serviceability rating can be partially related to slope variance, then there should be some mathematical connection between CHLOE slope variance, $\Sigma(d^2)$ and $\Sigma(D^2)$. A correlation of CHLOE slope variance and $\Sigma(D^2)$ should have the mathematical form

$$\text{CHLOE slope variance} = A \times \Sigma(D^2) \pm B$$

With the cooperation of the State Highway Commission of Wisconsin, correlative tests were made during June 1965. A wide variety of highways was tested. These included portland cement concrete, with and without granular subbase, bituminous pavements resting on granular base, and old resurfaced pavements of the two types.

The CHLOE Profilometer was operated according to instructions supplied by the U. S. Bureau of Public Roads. The PCA Road Meter was operated at 50 mph over the same road sections.

The regression equation, derived from results of 24 tests, is:

$$\text{CHLOE slope variance} = 0.68\ \Sigma(D^2) + 0.8$$

The practical significance of this regression is shown in Figure 6, where serviceability index of each pavement section, calculated with CHLOE slope variance, is compared with the serviceability index calculated with the slope variance given by the equation containing $\Sigma(D^2)$. Standard deviation of regression is 0.16.

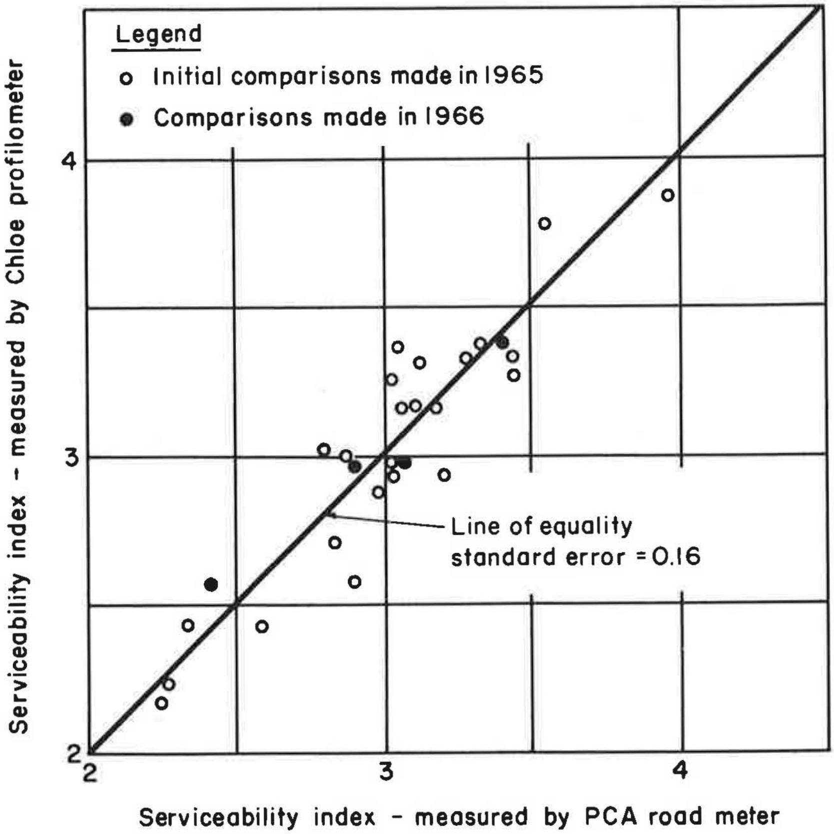

Figure 6. Comparison of serviceability index measured by the CHLOE Profilometer and by the PCA Road Meter.

Investigation of Factors Affecting Road Meter Results

Soon after initial correlation tests were completed, the PCA Road Meter was used in five different road sites for the purpose of establishing references for future Road Meter performance and for immediate experimentation. These sites included substantially faulted undoweled rigid pavement having a 20-ft transverse joint spacing, undulating roadmix bituminous pavement on stage-constructed base, bituminous plant-mix pavement on crushed-stone base affected by sunken transverse sewer laterals, new portland cement concrete pavement, and frost-free pavement represented by the surface of structures spanning the Wisconsin river on I-90-94.

Experiments were made to assess the effects of changes in conditions that existed at the time of initial CHLOE-Road Meter tests. They are described in the following.

Type of Tire and Tire Pressure—Initial tests were made with standard 2-ply 7.7 × 15 tires inflated at a pressure of 25 psi. Later, rear tires were replaced by 4-ply nylon snow tires inflated at 25 psi. Tests in the experimental sites showed that snow tires did not significantly affect serviceability index. The mean difference for all sites was nearly zero.

Other tests with standard tires showed that pressure within the range of 24-26 psi (cool, static) had no significant effect on serviceability index.

Speed of Test Automobile—Initial tests were made with the Road Meter automobile operating at 50 mph. Additional tests in the experimental sites indicated that $\Sigma(D^2)$ varies with the speed of the automobile.

When tests must be made at a speed other than 50 mph, the following equation for CHLOE slope variance can be used with reasonable confidence, within the range of 30-65 mph:

$$\text{CHLOE slope variance} = (1.18 - 0.01\ \text{mph})\ \Sigma(D^2) + 0.8$$

Load in Test Automobile—Initial tests were made with one person in the Road Meter automobile. Other tests of limited scope were made to determine the effect of additional weight of passengers. The driver and one passenger occupied the front seat and another passenger occupied the left rear seat. Results of this one test in six different roads showed that the serviceability index was increased 0.16. Other tests showed that a passenger in the front seat did not affect results.

These experiments were not continued because the purpose of the Road Meter is to make serviceability ratings with minimum personnel and expense.

Variable Air Temperature—One of the advantages of the Road Meter is that it can be operated throughout the year, provided roads are not covered by ice, snow, or water in wheelpath grooves. Effects of low temperature on mechanical and electrical components could be of concern.

Tests were made to evaluate this variable. It was found that the automobile should be driven for a period of time needed to warm electric counters and other components.

At air temperatures below 10 F, significant changes take place in road-car deviations. This is probably a result of changes in operating characteristics of shock absorbers and other automobile components, including tires. Therefore, tests are made only when the air temperature is above 10 to 15 F.

Variable Wind Velocity and Direction—Initial tests were made when wind velocity was low and not a matter of concern. Other tests have shown that wind velocity is not an important factor until it reaches about 15 mph. Crosswinds of that velocity create aerodynamic effects that disturb the automobile in motion and change the static reference position of the Road Meter roller contactor.

Tests should be made when wind velocity is less than the tolerable limit. Velocities are usually estimated from weather reports issued by local radio stations. Headwinds and tailwinds can be tolerated more than crosswinds. Data have not been collected to establish limits.

Deterioration of Automobile—Initial correlation of the PCA Road Meter and CHLOE Profilometer was made when the automobile had been driven about 20,000 miles. After that, the automobile was driven an additional 40,000 miles.

In July 1966, new comparisons were made with the CHLOE Profilometer to determine if wear in the automobile had affected the initial correlation made in June 1965. Tests were made in projects of portland cement concrete and bituminous-flexible pavement. Results were in agreement with the initial correlation (Fig. 6).

Type of Test Automobile—Another Road Meter, installed in a 1966 Ford 4-door sedan, has been operated about 8,000 miles. Comparison of test results between this and the original Road Meter showed no need to change the equation relating CHLOE slope variance and $\Sigma(D^2)$.

When a test automobile must be replaced, new comparisons should be made with the CHLOE Profilometer, or with ratings made of roads while using the old automobile.

Application of the PCA Road Meter

During the first year of operation of the PCA Road Meter, the author completed an extensive design and serviceability study of 500 miles of non-reinforced concrete pavement. In an effort to assess resistance to frost and winter damage, work is under way to evaluate serviceability in 125 projects of rigid and bituminous pavement resting on treated and untreated base and subgrade soils. In addition, a large number of projects have been selected and tested in a continuing program to establish serviceability trends with weight of traffic and incremental age of pavement.

CONCLUSIONS

The PCA Road Meter is a simple, durable, and economical device that can be constructed by anyone having ordinary mechanical aptitude and simple tools. Cost of the components is not excessive, and should not exceed \$180, including electric counters and microswitch.

Results of tests have shown that the CHLOE Profilometer and PCA Road Meter can be correlated with satisfactory precision. The Road Meter affords a rapid method for measuring serviceability with minimum personnel, cost, and inconvenience to traffic. Where a CHLOE Profilometer is not available for comparison, locally acceptable estimates of serviceability rating can be correlated with $\Sigma(D^2)$.

ACKNOWLEDGMENTS

For their cooperation in making possible the correlations with the CHLOE Profilometer, appreciation is expressed to the State Highway Commission of Wisconsin, and in particular to Karl Dunn, materials research engineer.

REFERENCES

1. The AASHO Road Test: Report 5—Pavement Research. HRB Spec. Rept. 61E, 1962.
2. Carey, W. N., Jr., Huckins, H. C., and Leathers, R. C. Slope Variance as a Measure of Roughness and the CHLOE Profilometer. HRB Spec. Rept. 73, pp. 126-137, 1962.

Appendix

ROAD METER THEORY

The PCA Road Meter measures the number of road-car deviations in $\pm 1/8$-in. increments referenced to the standing position of the automobile. Numbers are accumulated in electric counters. Sum of squares of deviations, $\Sigma(D^2)$, has been correlated with slope variance from the CHLOE Profilometer. The method for reducing Road Meter data is shown in the following.

1. Basic Data for Sum of Squares

Let a, b, c, d, e, f, ... = number of road-car deviations corresponding to ±1, 2, 3, 4, 5, 6, ... eighths of an inch, respectively. Then,

$$\Sigma(D^2) = (1a + 4b + 9c + 16d + 25e + 36f + \ldots)/64 \tag{1}$$

2. Composition of Road Meter Counts

Because electric counters record once for a maximum deviation and twice for segment numbers less than the maximum, total recorded counts are

$$\begin{aligned}
\text{Counter 1 } (1/8 \text{ in.}) &= a + 2b + 2c + 2d + 2e + 2f + \ldots \\
\text{Counter 2 } (2/8 \text{ in.}) &= b + 2c + 2d + 2e + 2f + \ldots \\
\text{Counter 3 } (3/8 \text{ in.}) &= c + 2d + 2e + 2f + \ldots \\
\text{Counter 4 } (4/8 \text{ in.}) &= d + 2e + 2f + \ldots \\
\text{Counter 5 } (5/8 \text{ in.}) &= e + 2f + \ldots \\
\text{Counter 6 } (6/8 \text{ in.}) &= f + \ldots
\end{aligned}$$

3. Reduction of Road Meter Counts to $\Sigma(D^2)$

If recordings shown in Road Meter counters 1, 2, 3, 4, 5, 6, ... are multiplied by the integers 1, 2, 3, 4, 5, 6, ..., respectively, the following reduction and summation can be made:

$$\begin{aligned}
\text{Counter 1} &= a + 2b + 2c + 2d + 2e + 2f + \ldots \\
\text{Counter 2} &= \quad\; 2b + 4c + 4d + 4e + 4f + \ldots \\
\text{Counter 3} &= \qquad\quad 3c + 6d + 6e + 6f + \ldots \\
\text{Counter 4} &= \qquad\qquad 4d + 8e + 8f + \ldots \\
\text{Counter 5} &= \qquad\qquad\quad 5e + 10f + \ldots \\
\text{Counter 6} &= \qquad\qquad\qquad 6f + \ldots \\
\hline
\Sigma(D^2) &= (a + 4b + 9c + 16d + 25e + 36f + \ldots)/64 \qquad (2)
\end{aligned}$$

Eq. 2 = Eq. 1.

4. Sample Calculation

Road Meter count from one-mile survey of rigid pavement:

Counter 1 = 348
Counter 2 = 180
Counter 3 = 40
Counter 4 = 14
Counter 5 = 7
Counter 6 = 2
Counter 7 = 0 (extrapolated)

Composition of Road Meter count:

$\Sigma 7/8$ in. deviations = 0
$\Sigma 6/8$ in. deviations = 2 - (2 × 0) = 2
$\Sigma 5/8$ in. deviations = 7 - (2 × 2) = 3
$\Sigma 4/8$ in. deviations = 14 - (2 × 2) - (2 × 3) = 4
$\Sigma 3/8$ in. deviations = 40 - (2 × 2) - (2 × 3) - (2 × 4) = 22
$\Sigma 2/8$ in. deviations = 180 - (2 × 2) - (2 × 3) - (2 × 4) - (2 × 22) = 118
$\Sigma 1/8$ in. deviations = 348 - (2 × 2) - (2 × 3) - (2 × 4) - (2 × 22) - (2 × 118) = 50

Sum of squares of deviations:

$$\begin{aligned}
\Sigma(6/8)^2 &= 2 \times 36 = 72/64 \\
\Sigma(5/8)^2 &= 3 \times 25 = 75/64 \\
\Sigma(4/8)^2 &= 4 \times 16 = 64/64 \\
\Sigma(3/8)^2 &= 22 \times 9 = 198/64 \\
\Sigma(2/8)^2 &= 118 \times 4 = 472/64 \\
\Sigma(1/8)^2 &= 50 \times 1 = 50/64 \\
\hline
\Sigma(D^2) &= 931/64 = 14.6 \qquad (1)
\end{aligned}$$

Direct reduction of Road Meter counts:

$$\begin{aligned}
\text{Counter } 1 &= 348 \times 1 = 348 \\
\text{Counter } 2 &= 180 \times 2 = 360 \\
\text{Counter } 3 &= 40 \times 3 = 120 \\
\text{Counter } 4 &= 14 \times 4 = 56 \\
\text{Counter } 5 &= 7 \times 5 = 35 \\
\text{Counter } 6 &= 2 \times 6 = 12
\end{aligned}$$

$$\Sigma(D^2) = 931/64 = 14.6 \qquad (2)$$

5. Typical Results From Road Meter Surveys

The following table shows a comparison of road-car deviations obtained from surveys in several different highways:

Type of Pavement	Description	Road-Car Deviations/Mile (1/8 in.)						$\Sigma(D^2)$
		1	2	3	4	5	6	
Rigid	In service for one year	68	70	9	0	0	0	6.7
Flexible	In service for one week	90	56	8	1	0	0	6.2
Rigid	Cracked and patched	84	133	28	28	7	5	26.1
Rigid	Undoweled joints (20 ft) faulted 1/4 in.	1	119	52	47	25	6	39.5
Flexible	Scheduled for resurface	31	104	37	20	23	2	27.3

STATISTICAL SIMPLIFICATIONS IN THE ROAD METER

The unique Road Meter switch plate is the key to construction economy and ease of calculation of $\Sigma(D^2)$.

It was presumed that plus and minus road-car deviations, measured from a standing reference position of the automobile, are about equally distributed so that $\Sigma(\pm D) = 0$; or that the difference can be neglected in the calculation of variance and correct sum of squares.

Therefore, equivalent plus and minus segments are electrically interconnected within the switch plate, and outputs are summed in one counter instead of two (Fig. 2). The unconnected center segment serves as a reference for adjustment of plate under the roller contactor before tests are started.

This hypothesis was verified by tests in four different roads. Tests were made with a modified Road Meter switch plate capable of recording both plus and minus deviations. Results of the tests are given below.

1. New Rigid Pavement

Deviations per mile = 228
$\Sigma(D^2) = 5.8$
$\Sigma(D) = -6.8$

Simplified method:

CHLOE slope variance = $0.68 \times 5.8 + 0.8 = 4.7$
Serviceability index = 4.63

Correct method:

CHLOE slope variance = $0.68 \times 228 \times (5.8/228 - 6.8^2/228^2) + 0.8 = 4.6$
Serviceability index = 4.66

2. Rigid Pavement With Faulted Undoweled Joints at 20-foot Intervals

Deviations per mile = 348
$\Sigma(D^2)$ = 25.3
$\Sigma(D)$ = -16.4

Simplified method:

CHLOE slope variance = 0.68 × 25.3 + 0.8 = 18.0
Serviceability index = 3.23

Correct method:

CHLOE slope variance = $0.68 \times 348 \times (25.3/348 - 16.4^2/348^2) + 0.8 = 17.5$
Serviceability index = 3.27

3. Flexible Pavement Containing Sunken Transverse Sewers

Deviations per mile = 279
$\Sigma(D^2)$ = 23.0
$\Sigma(D)$ = +8.0

Simplified method:

CHLOE slope variance = 0.68 × 23.0 + 0.8 = 16.4
Serviceability index = 2.82

Correct method:

CHLOE slope variance = $0.68 \times 279 \times (23.0/279 - 8.0^2/279^2) + 0.8 = 16.3$
Serviceability index = 2.83

4. Flexible Pavement With Undulating Surface

Deviations per mile = 375
$\Sigma(D^2)$ = 11.1
$\Sigma(D)$ = -11.9

Simplified method:

CHLOE slope variance = 0.68 × 11.1 + 0.8 = 8.4
Serviceability index = 3.49

Correct method:

CHLOE slope variance = $0.68 \times 375 \times (11.1/375 - 11.9^2/375^2) + 0.8 = 8.1$
Serviceability index = 3.53

INVESTIGATION OF REITERATIVE RESPONSE OF THE ROAD METER

Ability of the Road Meter to repeat measurements of $\Sigma(D^2)$, CHLOE slope variance, and serviceability index in a single test section was determined by multiple runs in two roads with widely different ratings. One was a new rigid pavement having a very good rating, and the other an old rigid pavement, severely cracked and patched, having a poor rating. Results of tests in the two roads were as follows:

Site	Rating	Length of Test	No. of Tests	Average PSI	Standard Deviation	Range
New rigid	Very good	0.90 mi	8	4.56	0.07	4.45-4.64
New rigid	Very good	0.90 mi	8	4.27	0.06	4.19-4.37
Old rigid	Poor	0.37 mi	8	2.03	0.01	2.00-2.04

(Note: Pavement serviceability index does not include reductions for cracking and patching.)

DERIVATION AND MODIFICATION OF CHLOE COMPUTING FORMULA SHOWING THE RELATION OF SLOPE VARIANCE AND SUM OF SQUARES OF CHLOE VERTICAL DEVIATIONS

Derivation of the CHLOE computing formula is outlined on page 136 of Highway Research Board Special Report 73. From it, Eq. 4b is restated as follows:

$$\text{CHLOE slope variance}/10^6 = (\tan 10')^2 \times \left[\frac{\Sigma Y^2}{N} - \left(\frac{\Sigma Y}{N} \right)^2 \right]$$

Instead of computing slope variance of pavement surface, it is possible to calculate variance of vertical deviations (d) in a 9-in. gage length. Gage length is the distance between detecting wheels of the CHLOE Profilometer.

Then Eq. 4b can be modified:

$$\text{Variance of vertical deviations} = 81 \times \text{CHLOE slope variance}/10^6$$

Sum of squares of CHLOE vertical deviations per mile is equal to variance multiplied by the number (N) of observations taken at 6-in. intervals. Then,

$$\Sigma(d^2) = 10,560 \times 81 \times \text{CHLOE slope variance}/10^6$$

$$\Sigma(d^2) = 0.855 \times \text{CHLOE slope variance}$$

Therefore,

$$\text{CHLOE slope variance} = 1.17\ \Sigma(d^2)$$