A COMPARISON OF FOUR ROUGHNESS MEASURING SYSTEMS

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INTRODUCTION

Four different measuring devices for use in evaluating highway surface roughness were investigated in this study. Two, the CHLOE Profilometer (1), and the Bureau of Public Roads Roughometer with mechanical integrator (newer Bureau of Public Roads Roughometers are equipped with an electronic integrator) (2), are well known and have been compared previously (3). The others, the Portland Cement Association Roadmeter (4) and the Mays Road Meter* are recent developments which warrant some description, especially the latter, since no description of it has previously appeared in the literature.

The aims of our study of these instruments were:

1. To examine the field-worthiness of the several systems.
2. To determine the validity of their respective measurements.
3. To determine the effects on their results of such variables as operating speed, driver characteristics, operating temperatures, and other factors.

In conducting the tests and interpreting the results, we have adopted a viewpoint which should be explained. We regard all of these instruments as expedient tools which measure, possibly quite imperfectly, one or another aspect of the interaction between a complex irregular surface and an incompletely specified vehicle which traverses it. However, as imperfect as all may be, each may be employed usefully within its recognized limitations. It is our intent to provide comparative information

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*Patent applied for, Ivan K. Mays.

within this framework whereby, through a better understanding of the various instruments, a user or potential user may be aided in selecting the one best suited to his needs.

The following abbreviations will be used in this report:

(1) MAYS 40 = Mays Road Meter Roughness Index (inches per mile) determined at 40 mph.

(2) MAYS 50 = Mays Road Meter Roughness Index (inches per mile) determined at 50 mph.

(3) PCA 40 = Portland Cement Association Roadmeter Roughness Index determined at 40 mph.

(4) PCA 50 = Portland Cement Association Roadmeter Roughness Index determined at 50 mph.

(5) BPR = Bureau of Public Roads Roughometer Roughness Index (inches per mile) determined at 20 mph.

(6) CHLOE = Slope Variance determined by the CHLOE Profilometer at 3 mph.

EXPERIMENT

The road sections used in this evaluation were located in the Texas Highway Department's District 12. This district is located geographically on the east central Gulf Coast. The sections were divided into two groups; twenty-four sections which comprised the main experiment on which all four instruments were run and twenty-one additional sections on which only the Mays Road Meter and the Portland Cement Association Roadmeter were run. The sections had an average length of 0.155 miles. The sections in the main experiment were representative of the types of pavement surface found in Texas. There were 14 flexible pavement sections (8 asphaltic concrete and 6 with surface treatment), 7 concrete sections, and 3 concrete sections which had been overlaid with asphaltic concrete. The additional 21-section group had a similar distribution between concrete and flexible surfaces.

The data were taken during the summer of 1968. Replicate measurements were made approximately one week apart. The CHLOE Profilometer and the Bureau of Public Roads Roughometer were operated independently of the Mays Road Meter and the Portland Cement Association Roadmeter. The Mays Road Meter (Figure 1) and the Portland Cement Association Roadmeter (Figure 2) were installed in the same vehicle, a 1967 Ford custom sedan with 20,000 miles use. It is recommended that only vehicles with coil springs in the rear be used. The controls of the two instruments were situated so that it was possible to operate them simultaneously. Time limitations did not permit investigation of the effect of different vehicles on these instruments.

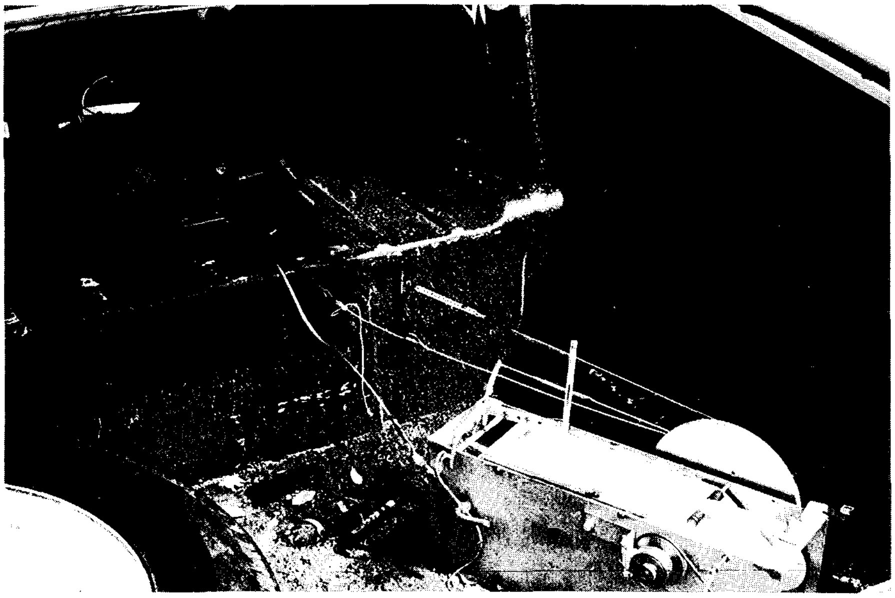

Figure 1 - The Mays Road Meter installed in trunk compartment of automobile. Note the three cables leading to the left. The top cable is connected to differential housing; the center cable leads to the front seat and is the on-off control; the lower cable, which also leads to the front seat, is the event marker control.

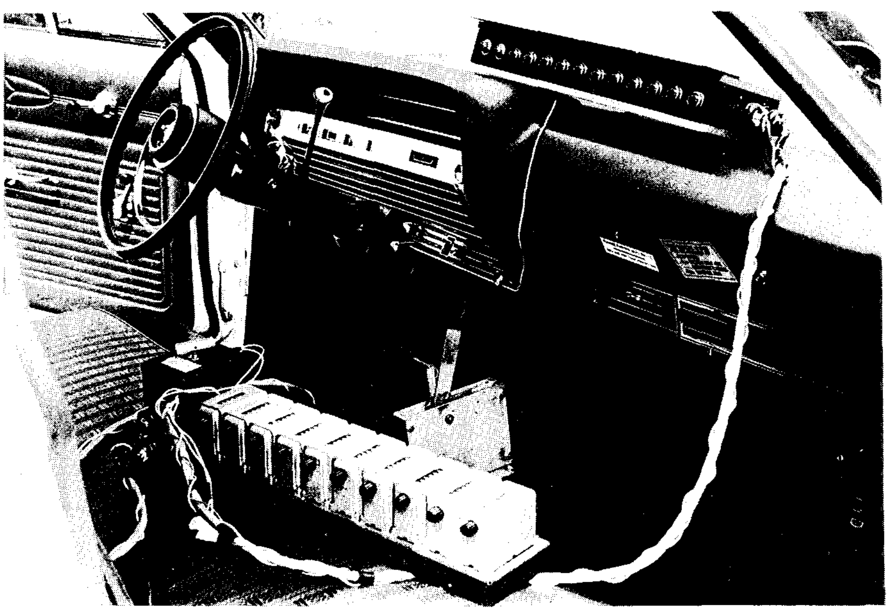

Figure 2 - View of the front seat of an automobile showing both the counters and indicator-light panel of the PCA Roadmeter and the two controls of the Mays Road Meter (two levers at center of photograph).

A 14-member panel, comprised of Texas Highway Department engineers, personnel from the Center for Highway Research, University of Texas, Austin, and non technical personnel rated the 24 sections in accordance with established procedures. The average of their ratings for each section was used in this report. Their examination of the sections was conducted during July, 1968.

The effect of different operators and the effect of varying operating speed on the Mays Road Meter measurements were also investigated. Three sections near College Station, Texas, each 1 mile in length, were run at speeds of 30, 40, 50, 60, and 70 mph with two operators, each making two runs through the section at each speed. Data taken on these tests indicated that there was negligible effect from changing operators, but that the higher operating speeds (60 and 70 mph) led to increased replication errors, while 30 mph was too slow for operation in freeway traffic (see Figure 3). From the above, the two speeds used in the remaining tests were selected at 40 and 50 mph. The slower speed (40 mph) was found to offer more precision with the Mays Meter, but the degree of impairment (as indicated in Table 1) does not prohibit use of this instrument at the higher speed (50 mph).

Early morning and late afternoon runs were made on successive days on a single flexible section for a period of 5 days using the Mays Road Meter and the Portland Cement Association Roadmeter with the object of determining the extent to which temperature influenced these instruments (see Appendix A for data). The average temperatures for these runs were 70°F. in the morning and 89°F. in the afternoon. The effect on the Mays

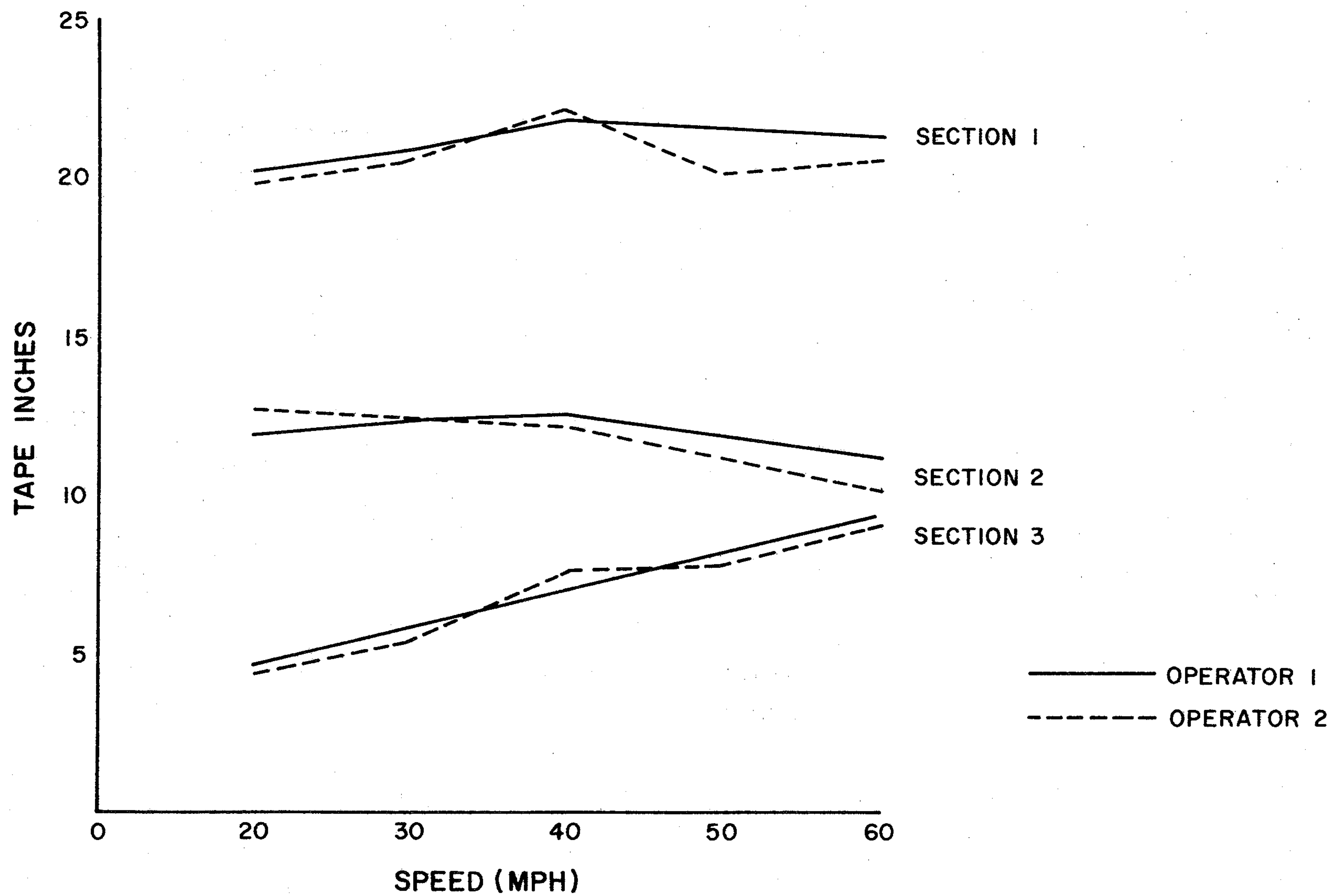

FIGURE 3 — EFFECT OF DIFFERENT SPEEDS AND OPERATORS ON MAYS ROAD METER.

Road Meter appeared to lie within the normal replication error associated with this instrument while the effect on the Portland Cement Association Roadmeter was an unexplained 15% increase in its roughness index with the 19°F. increase in temperature.

Six sections on a smooth textured road near Llano, Texas, were used to determine how much the Mays Road Meter output was influenced by the texture of the road surface. Four runs were made on each of these sections just prior to resurfacing with a surface treatment, and four runs were again made on each of these sections one week after the new surface was completed (see Appendix A for data). The aggregate used in the treatment had a maximum size of 3/8" and a mean size of 1/4". On the average, it was found that this surface change increased the Mays Road Meter readings by 10%. We believe the increase results from the texture rather than from any decrease in overall smoothness of these sections.

MAYS ROAD METER AND PORTLAND CEMENT ASSOCIATION ROADMETER DESCRIPTION

Both the Portland Cement Association Roadmeter and Mays Road Meter systems have been developed with the objective of providing a simple, low-cost instrument for installation in a passenger vehicle, capable of producing a reading acceptably representative of the surface roughness encountered while traversing highway sections at normal vehicle speeds. In one respect these two systems are alike: they both employ the vehicle chassis as their "reference plane" and respond to the variations of vertical distance between the chassis and the rear axle (differential housing) of the car. Since the Mays Road Meter is basically more similar to the familiar Bureau of Public Roads Roughometer, it will be described first. A flexible wire cable, attached to the differential housing, extends vertically upward through a small hole made in the floor of the trunk compartment. Passing over a fixed pulley, this cable is brought horizontally to the instrument where it wraps around a 7.5-inch diameter wheel and continues to an anchored tension spring. Accordingly, relative vertical motion between chassis and axle produces proportional rotation of this wheel; in one direction for upward axle movement, oppositely for downward movement. The resulting reciprocating motion is linked mechanically to a pen which produces a continuous record on adding machine tape. The same motion, but applied through a nonreversing clutch, is employed to advance the tape. The result is a graphic record on which the magnitude of the individual vertical excursions of the axle relative to the chassis are depicted as proportional excursions of the trace, while the length of the record represents the sum of all the upward movements of the axle which have occurred. A marking device controlled by the operator permits the beginning and end of each section to be indicated on the record. Figure 4 shows a typical example of the Mays Road Meter presentation.

The indicated roughness is obtained by measuring the length of the Mays Road Meter record in inches and multiplying by an appropriate constant. This constant is a function simply of the paper drive mechanism and the length of the section. The resulting Roughness Index is expressed in units of inches per mile, representing the total of the upward excursions (which is necessarily almost exactly one-half of all the vertical excursions) divided by the distance travelled. The basic similarity of this system to the Bureau of Public Roads Roughometer will be apparent. However, the additional feature of a pen trace which depicts the magnitude of the separate excursions, coupled with the simplicity of adding only a small recording device inside the car, instead of a trailer, makes it an attractive alternative system.

Likewise, the Portland Cement Association Roadmeter comprises a simple set of components added to a passenger vehicle. Its cable from the rear axle is attached to a switch or commutator so arranged that each successive 1/8 inch departure from a pre-selected "zero" or mid-position results in energizing a different contact of the switch. A series of electro-magnetic counters registers the number of times that the moving arm encounters each particular contact. Thus, in the course of driving over a given section, contacts near the mid-position will generally be reached frequently; and those farther away will be encountered seldom

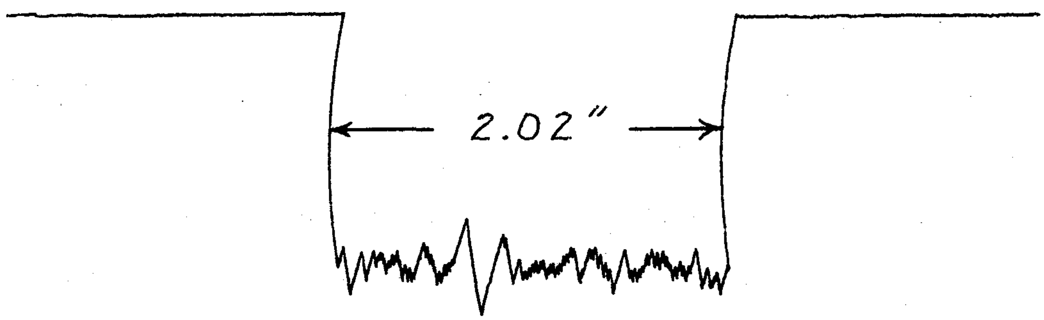

Figure 4 - Typical chart produced by the Mays Road Meter on a 0.2-mile section of flexible pavement. The distance between beginning mark and end mark, 2.02", when multiplied by 8 and divided by section length, gives a Roughness Index of 80.8 inches per mile.

since there are ordinarily many small surface irregularities, but only a few large ones. Accordingly, at the end of any traverse, the several counters indicate the number of times their respective contacts have been energized. The indication of surface roughness is obtained by multiplying the readings of the individual counters each by an appropriate constant, then summing the resulting numbers. It has been demonstrated (4), that this procedure, which gives greater weight to the larger excursions in proportion to their magnitudes, has a "square law" effect which renders the measurement closely akin to Slope Variance, the quantity derived by the CHLOE Profilometer. The summed Portland Cement Association Roadmeter count (divided by 64 times the section length) represents a measure of roughness in inches-squared per mile of section traversed.

RESULTS

The correlations shown in Figures 5, 6, and 7 demonstrate that each of the four instruments responds to much the same properties of the surface. As we expected, linear correlations were obtained among the measurements of all the instruments upon comparing the square root of the indicated slope variance against the direct readings of the "linear" instruments. Figure 4 indicates that a fixed offset of 52 units per mile exists in the data from our Bureau of Public Roads Roughometer. This we ascribe to tire or axle eccentricity, in the particular instrument which we used, which introduced an effective motion of the order of 0.07 inches at each revolution of its wheel. A similar effect, on the order of 0.02 inches, may exist in the vehicle in which we installed the Portland Cement Association and Mays devices.

Since all the instruments appear to measure substantially the same thing, the question naturally arises as to which instrument does the best job. If panel ratings could be accepted as perfect, the most precise instrument would be the one exhibiting the greatest correlation with these ratings. More realistically, however, the panel ratings must be subject to variation, thus the best correlation may merely indicate which particular instrument exhibits variations most similar to those of the panel. Accordingly, an independent check on instrument precision is very desirable.

A method (5) which can be used to rank each of the instruments in the order of its relative precision consists of comparing the variability of its measurements between sets with the variability of its measurements within

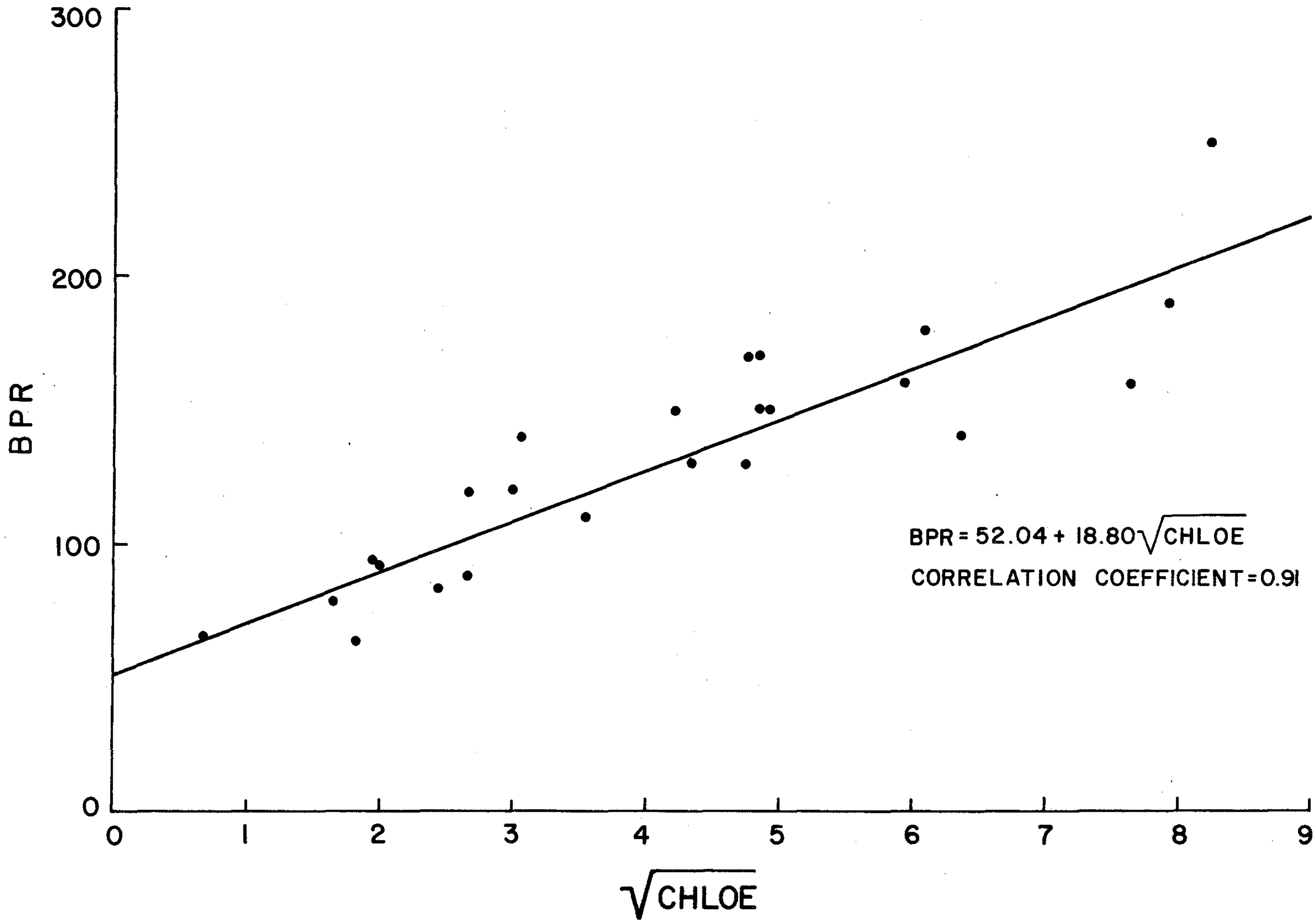

Figure 5 - Correlation between square root of CHLOE output and Bureau of Public Roads Roughometer output.

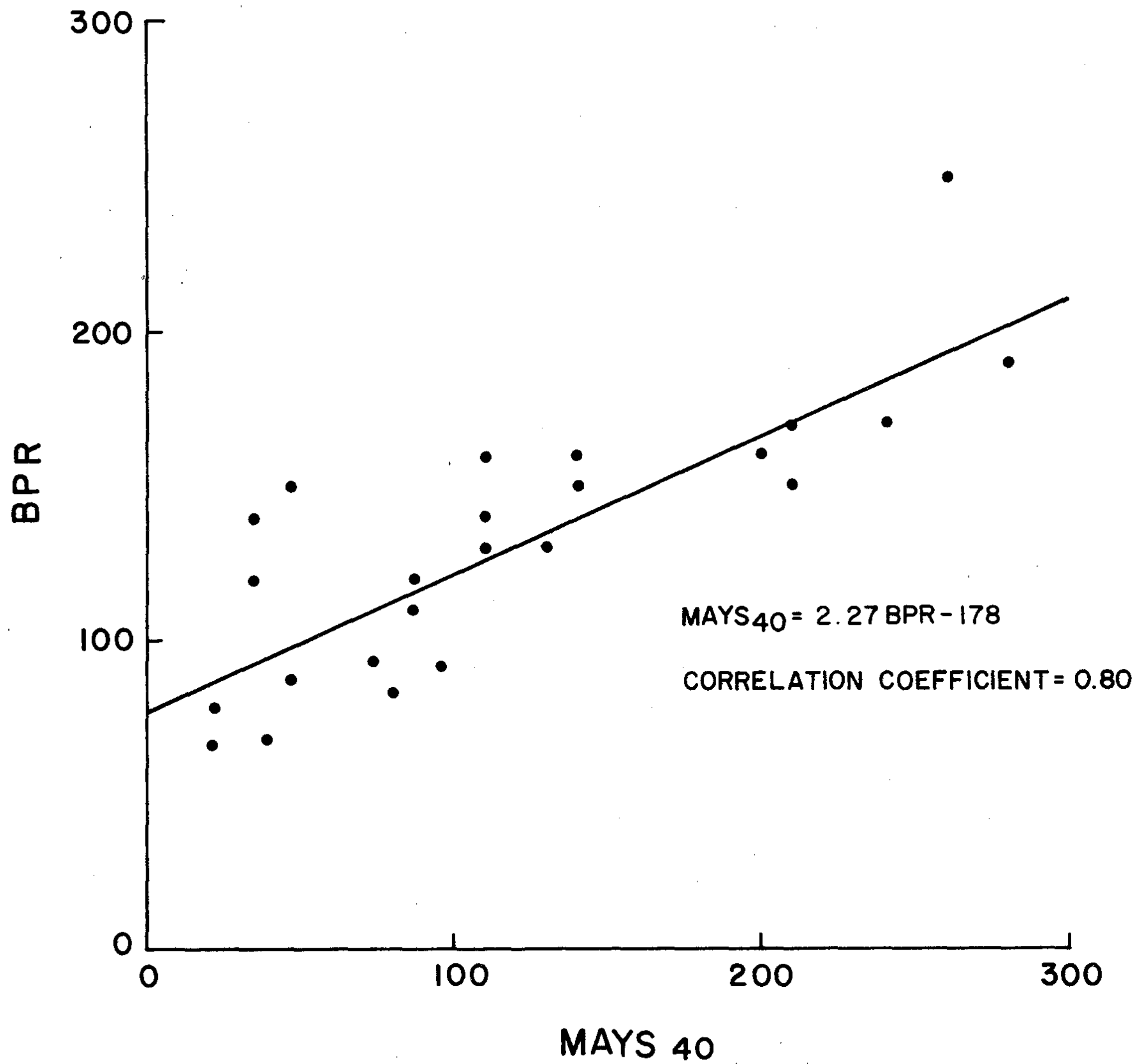

Figure 6 - Correlation between Mays Road Meter run at 40 mph and Bureau of Public Roads Roughometer.

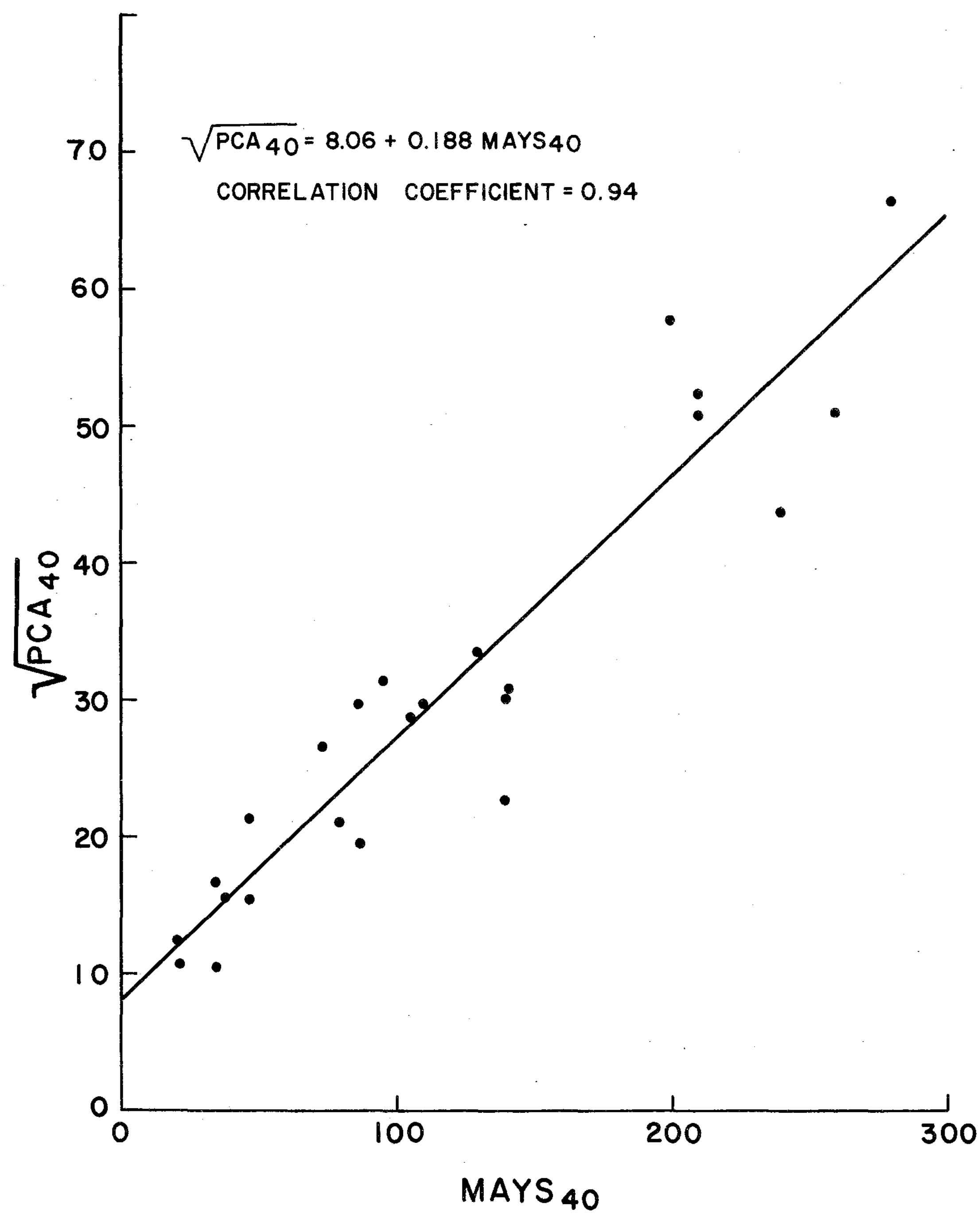

Figure 7 - Correlation between Mays Road Meter and Portland Cement Association Roadmeter, both run at 40 mph.

sets; here we use the word set to mean a pair of measurements one week apart on the same road section. If the variability between sets is large compared with the variability within sets, it can be said that the instrument is sensitive and precise, and the greater the ratio of these variabilities the greater its relative precision. The ratio of the between-set to the within-set variability is known as the "F-ratio."

Since the F-ratio depends upon the variabilities between and within sets--which, in turn, depend principally upon the physical differences between sections, and principally upon the instrument-operator-procedure within sections--it follows that a group of instruments can be ranked with complete fairness by their F-ratios provided all instruments were used on the same group of sections, and all were operated in a consistent manner at nearly the same time of day, and further, provided linear correlations exist between the data-sets representing each of the instruments. It can be seen from Table 1 and Figures 5, 6, and 7 that these criteria of fairness are satisfied for the four instruments. From the fact that the CHLOE Profilometer exhibits the largest F-ratio, while the Mays Road Meter (see Table 1 and Figure 8) exhibits the largest correlation coefficient with respect to panel ratings, we conclude that the CHLOE Profilometer's precision is greatest among the four instruments, but that the Mays Road Meter has characteristics which systematically follow departures of the Panel from agreement with the CHLOE Profilometer. From the reported standard deviations associated with the panel ratings, which averaged 0.66 PSR units, we also conclude that the panel ratings do not constitute a superior set of roughness measurements. In fact, they may, quite possibly,

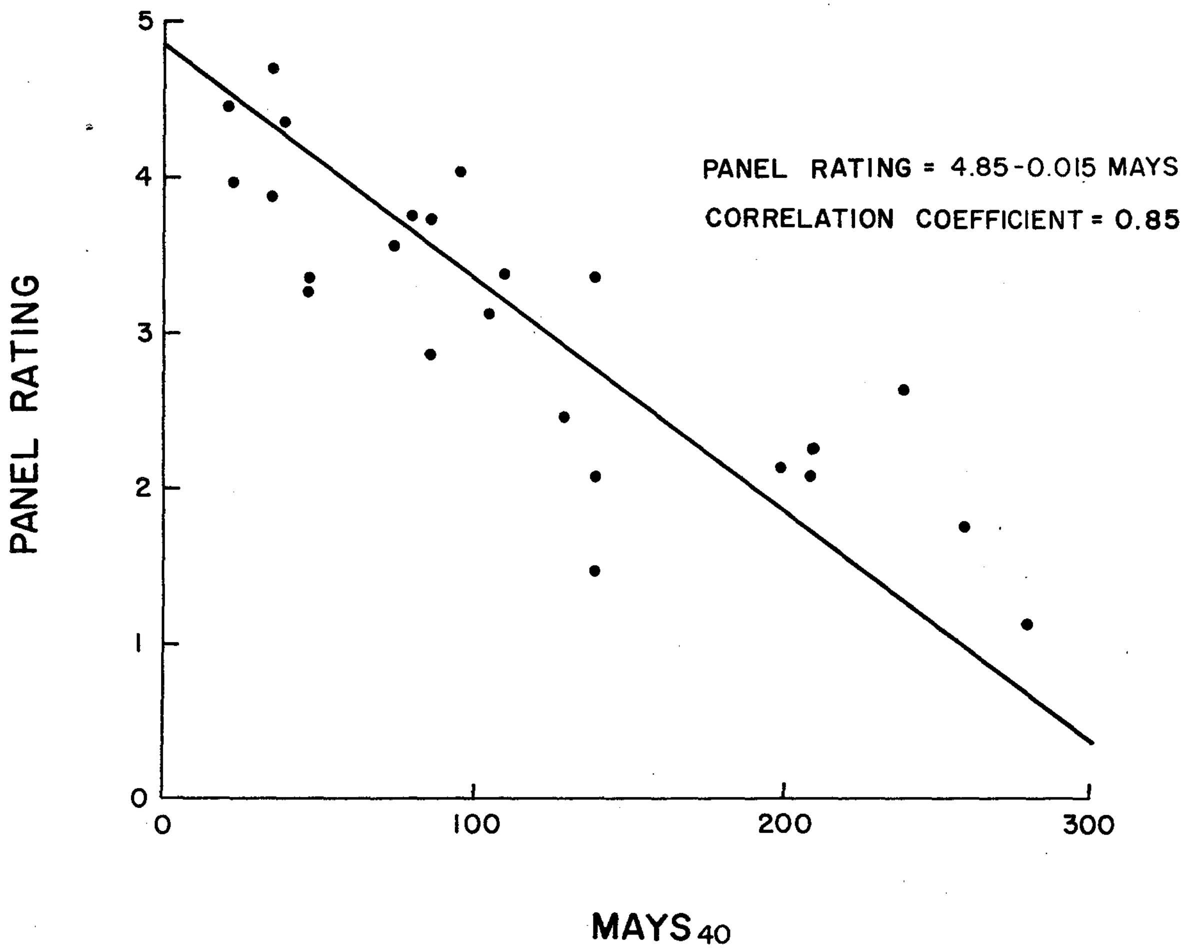

Figure 8 - Correlation between Mays Road Meter run at 40 mph and panel rating.

TABLE 1 - ANALYSES OF VARIANCE AND CORRELATION COEFFICIENTS

Instrument	Variable Analyzed	24 Section F-ratio	45 Section F-Ratio	Correlation Coefficient with Panel Ratings (24 Sections)
CHLOE Profilometer (3 mph)	Square Root of Slope Variance	416.7	--	0.80
Mays Road Meter (40 mph)	Roughness Index	192.2	172.2	0.85
Mays Road Meter (50 mph)	Roughness Index	82.4	100.0	0.82
PCA Roadmeter (40 mph)	Roughness Index	61.1	52.5	0.80
BPR Roughometer (20 mph)	Roughness Index	59.0	--	0.77
PCA Roadmeter (50 mph)	Roughness Index	27.5	28.9	0.71

be inferior in this respect to the measurements provided by several of the instruments. However, it is recognized that panel ratings do not depend exclusively on surface roughness. Hence their validity and general utility is not necessarily lessened by failure to correlate with a precise roughness instrument.

To confirm the relative ranking of the Mays Road Meter and Portland Cement Association Roadmeter, their respective F-ratios were determined from a larger number of tests embracing 45 sections. As shown in Table 1, the ranking was unchanged from that derived from the 24 section tests.

CONCLUSIONS

While the CHLOE Profilometer is best with respect to F-ratio, it is not necessarily the optimum choice for all applications. It is desirable, in making a choice among instruments, to consider numerous additional factors. These include initial cost, operating and maintenance costs, convenience and speed of operation, plus other less tangible factors; for example, the output data format and its compatability with the user's mental or physical data reduction scheme. Accordingly, each instrument, but most particularly the second most precise one, the Mays Road Meter, warrants careful consideration.

The Mays Road Meter offers several attractive advantages which, for many users, may more than offset its slightly diminished precision. Specifically, it can be obtained and installed for less than $750. It utilizes an ordinary sedan without trailer. Simple operation, low in maintenance, it measures while traveling at 40 or 50 miles per hour. In comparison, the CHLOE Profilometer may be characterized as precise, but complex, costly, very slow, and in the experience of these writers, difficult to maintain in operating condition. The Bureau of Public Roads Roughometer requires a trailer, is somewhat costly, and operates at intermediate speed. The Portland Cement Association Roadmeter matches the Mays Road Meter closely in several basic respects and would provide an attractive alternative if its precision were improved.

It should be understood that different makes and models of cars have different dynamic characteristics. This, coupled with the fact that there may be constructional differences among several Mays Meters and among several Portland Cement Association Roadmeters presently necessitates that each unit (vehicle with its Mays Road Meters and/or Portland Cement Association Roadmeter) be correlated with a known unit on a group of sections which have been rated by a panel. Further study may reveal that these differences among units are not of significant magnitude to require extensive correlation effort.

We have endeavored to provide a means, in Table 2, for choosing among these four instruments. The potential user may give weight to the various factors in the chart in accordance with his specific needs. Thus different users may arrive at different choices, but we consider the CHLOE Profilometer applicable where precision is paramount and the Mays Road Meter most appropriate for general field use.

TABLE 2 - COMPARISON OF ROAD ROUGHNESS DEVICES

DESCRIPTION	CHLOE PROFILOMETER	BPR ROUGHOMETER	PCA ROADMETER	MAYS ROAD METER
1. Apparatus	Trailer and car	Trailer and car	Car only	Car only
2. Basic response	Slope	Height	Height	Height
3. Proportionality	Square-law	Linear	Square-law	Linear
4. Accepted designation of measurement	Slope-variance	Roughness	$\Sigma(D^2)$, sum of road-car deviations sq.	Roughness index
5. Speed while measuring	3-5 mph	20 mph	40 or 50 mph	40 or 50 mph
6. Speed while traveling to and from sections	Legal limit	Legal limit	Legal limit	Legal limit
7. In-field set-up time	15 minutes	5 minutes	1 minute	None
8. In-field set-up requirements	Unload CHLOE from transport trailer, hook up cables, calibrate	Lower wheel; hook up roughness integrator and counters	Stop vehicle to set to zero	None
9. Maximum section length	Less than 0.5 mi.	Limited only by roughness exceeding counter capacity	Limited only by roughness exceeding counter capacity	Unlimited
10. Minimum section length	Not recommended for less than 0.1 mi.	Not recommended for less than 0.1 mi.	Not recommended for less than 0.1 mi.	Not recommended for less than 0.1 mi.

TABLE 2 - COMPARISON OF ROAD ROUGHNESS DEVICES (CONTINUED)

	DESCRIPTION	CHLOE PROFILOMETER	BPR ROUGHOMETER	PCA ROADMETER	MAYS ROAD METER
11.	Data presentation form	Number of 6" units traversed, counts, and counts^2	Single numerical counter	Plurality of numerical counters	Length of chart record
12.	Location of presentation	Adjacent to driver	Adjacent to driver	Adjacent to driver	Adjacent to driver or in trunk
13.	Determination of section length	Counter	Counter	Car odometer or roadside marker	Car odometer or roadside marker
14.	In-field data requirements (when measuring sections of known lengths	Record 3 readings	One reading at end of each section	8 counter readings at end of each section and reset counters	Merely keep track of the sequency in which the sections are traversed
15.	In-field adjustments	None required	Frequent check of dash pot fluid level	Frequent zero adjustment recommended. Requires vehicle halt.	None required
16.	At-home data processing to determine roughness	Calculating $\sqrt{SV}$ from 3 readings	Tabulating (may be done in-field)	Summing and tabulating	Measuring chart lengths and tabulating

TABLE 2 - COMPARISON OF ROAD ROUGHNESS DEVICES (CONTINUED)

DESCRIPTION	CHLOE PROFILOMETER	BPR ROUGHOMETER	PCA ROADMETER	MAYS ROAD METER
17. Additional data obtainable from record	None	None	Frequency distribution of roughness heights	Approximate location and heights of roughness within sections
18. Maintenance requirements	Frequent malfunction requiring repairs	Frequent servicing of grease fittings and dash pots	Frequent polishing of commutator to assure contact	Minimal

ACKNOWLEDGEMENTS

The authors are deeply grateful to Mr. Ivan K. Mays, Texas Highway Department, Austin, who developed the Mays Road Meter, for furnishing this instrument and valuable knowledge about its operating characteristics. The authors are also indebted to Mr. Phillip Brua of the Portland Cement Association for his assistance in the construction of the Portland Cement Association Roadmeter.

Special thanks are due Dr. W. Ronald Hudson and Mr. Freddy Roberts of the Center for Highway Research in Austin, who selected the test sections and provided panel ratings obtained in their Project 73,and Mr. James Bissett of District 12, Texas Highway Department, who provided traffic protection to the field crews. These data were furnished to this study at no cost.

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APPENDIX A

TABLE A-1
TEMPERATURE AND ROUGHNESS DATA
FOR MAYS ROAD METER

FM 60 - WESTBOUND LANE

Data Set No.	Date	Time	Temp.	Run	In./Mi.
1	May 31	AM	76	1	65.6
		9:00	76	2	57.6
			76	3	56.0
	June 6	7:00	70	4	58.0
			70	5	61.0
Mean			73.6		59.6
2	May 30	PM	87	1	60.0
		3:45	87	2	56.0
			87	3	56.8
			87	4	68.8
	June 5	4:30	82	5	57.6
			82	6	56.0
Mean			85.3		59.2

FM 60 - EASTBOUND LANE

Data Set No.	Date	Time	Temp.	Run	In./Mi.
3	May 31	AM	76	1	53.6
		9:00	76	2	51.2
			76	3	52.0
	June 6	7:00	75	4	52.4
			75	5	52.1
Mean			75.6		52.3
4	May 30	PM	87	1	51.2
		3:45	87	2	58.4
			87	3	51.2
			87	4	52.8
	June 5	4:30	82	5	57.6
			82	6	58.4
Mean			85.3		54.9

FM 2818 - WESTBOUND LANE

Data Set No.	Date	Time	Temp.	Run	In./Mi.
5	May 31	AM	76	1	160.8
		9:00	76	2	160.0
			76	3	162.4
			76	4	154.4
	June 6	7:00	70	5	153.7
			70	6	157.8
Mean			73.6		158.2
6	May 30	PM	87	1	156.0
		3:45	87	2	159.2
			87	3	163.2
			87	4	162.4
	June 5	4:30	82	5	160.8
			82	6	161.6
Mean			85.3		160.5

FM 2818 - EASTBOUND LANE

Data Set No.	Date	Time	Temp.	Run	In./Mi.
7	May 31	AM	76	1	158.4
		9:00	76	2	161.6
			76	3	158.4
			76	4	160.8
	June 6	7:00	70	5	162.4
			70	6	158.4
Mean			75.6		160.0
8	May 30	PM	87	1	161.6
		3:45	87	2	160.8
			87	3	159.2
			87	4	164.0
	June 5	4:30	82	5	159.2
			82	6	160.8
Mean			85.3		160.9

TABLE A-2 - EFFECT OF TEMPERATURE ON PCA ROADMETER
(Average of 5 runs shown)

Sec.	Date	Time	Travel W Avg	Travel E Avg	Temp °F
FM60	9/25/67	9:00 a.m.	262	261	72°
FM60	9/25/67	2:00 p.m.	456	382	86°
FM60	9/25/67	4:00 p.m.	489	447	85°
FM60	9/26/67	9:00 a.m.	269	242	74°
FM60	9/26/67	2:00 p.m.	328	369	84°
FM2818	9/26/67	9:00 a.m.	1514	1356	74°
FM2818	9/26/67	3:30 p.m.	1844	1754	83°
FM60	9/27/67	9:30 a.m.	231	225	66°
FM2818	9/25/67	4:30 p.m.	2107	2144	85°
FM2818	9/27/67	9:00 a.m.	1479	1578	68°

TABLE A-3 - LLANO SECTIONS
(Mays Road Meter Reading in Inches/Mi.)

	Before Surface Treatment					After Surface Treatment					Difference
Section	1st	2nd	3rd	4th	Avg	1st	2nd	3rd	4th	Avg	2nd - 1st
1	7.2	7.4	7.6	7.6	7.4	8.2	8.2	8.2	8.0	8.2	.8
2	9.7	8.7	9.3	8.7	9.0	11.0	10.7	10.7	9.7	10.3	1.3
3	9.8	10.4	10.2	10.8	10.4	13.0	11.6	12.0	11.6	12.0	1.6
1A	9.0	9.4	9.0	9.6	9.2	10.4	10.8	9.2	10.2	10.2	1.0
2A	8.3	9.0	8.7	9.7	9.0	9.7	9.3	9.3	10.0	9.7	.7
3A	10.6	10.4	10.6	11.0	10.6	12.0	11.6	10.8	12.0	11.6	1.0