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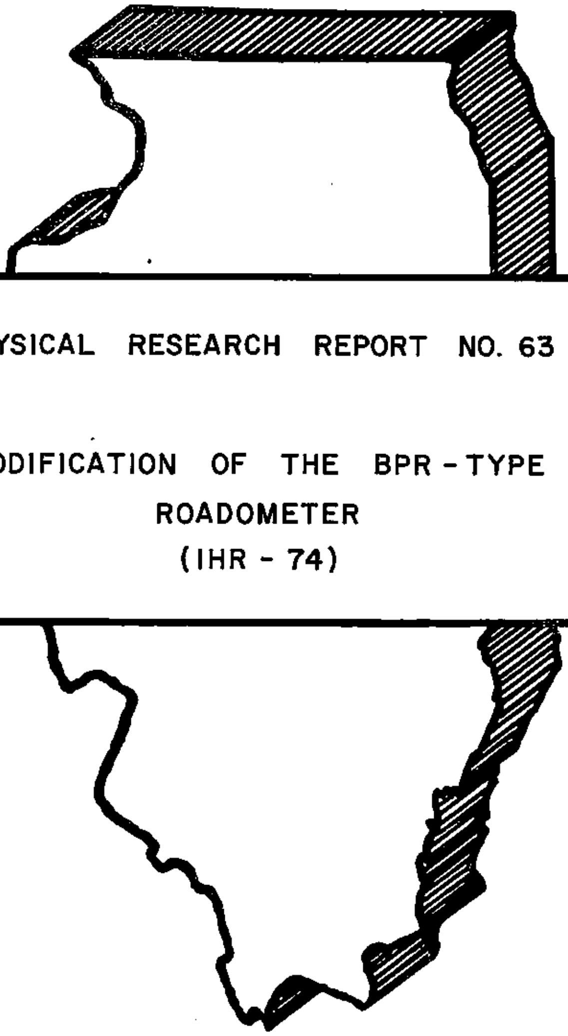

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MODIFICATION OF THE BPR-TYPE ROADOMETER

(IHR - 74)

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16. Abstract

Modifications were made in the horizontal distance and vertical displacement sensing devices of a BPR-Type Roadometer to improve the capabilities of this device for measuring pavement segments as short as 100 feet in length, and to increase the operating speed. Test results show that the modified system can be operated at test speeds ranging to 50 mph, and strongly suggest that the limiting speed may be in excess of 60 mph. Preliminary tests indicate that the device is capable of measuring pavement segments as short as 100 feet with sufficient accuracy to obtain RI values that are meaningful and usable. Roughness measurements obtained at 30, 40, and 50 mph correlated very well with those obtained at 20 mph.

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MODIFICATION OF THE BPR-TYPE ROADOMETER

By

J. E. LaCroix and E. J. Kubiak

Interim Report
IHR-74
Road Smoothness

A Research Project Conducted by
Illinois Division of Highways
in Cooperation with
U. S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Illinois Division of Highways or the U. S. Department of Transportation. This report does not constitute a standard, specification, or regulation.

June 1975

SUMMARY

The horizontal distance and vertical displacement sensing devices of a BPR-Type Roadometer were modified. The purposes of the modifications were to make the device capable of measuring pavement sections as short as 100 ft in length and to increase the operating speed capabilities.

A new integrator was constructed, and this integrator has the capability of measuring vertical displacements as small as 0.01 of an inch. In the new integrator, the double-acting ball clutch and 6-lobe cam were replaced with a commercially available uni-directional photoelectric encoder. The new integrator produces a pulse for each 0.01 in. of vertical displacement as compared to one pulse per inch of displacement in the original integrator.

The original horizontal distance accumulator produces one count for every wheel revolution (approximately 7 ft of travel). This was modified so that one pulse would be generated for approximately one in. of travel. An 82-tooth commercially available gear was attached to the hub of the test tire and a proximity switch was located above the gear. One electrical pulse is generated every time a gear tooth passes under the switch.

A digital printout feature was incorporated in the modified system to accommodate the high-speed operation capabilities, and to eliminate the need for the roadometer operator to copy field data during the field test operations.

A minor modification included the use of commercially available rod ends instead of ball and socket joints on the damper units. This modification was made because the old joints were found to affect the damping factor.

Test results show a very high degree of correlation between the roughness obtained at 20 mph with Illinois' original Roadometer No. 1 and the roughness obtained at 20 mph with the roadometer with the new sensing devices (Roadometer No. 3).

Frequency response curves show that there were only slight differences in the damping factors for the two instruments.

The new roadometer is capable of producing RI on pavements one mi. in length with the same degree of accuracy as obtained with the original devices. Although the data scatter was somewhat greater on the 100-ft long sections, the results were considered to be meaningful and usable.

The modified system can be operated at 50 mph, the present speed for vehicles owned by the State of Illinois. However, the results suggest that the limiting speed is in excess of 60 mph. The roughness recorded at 30, 40, and 50 mph were highly correlated with the roughness recorded at 20 mph. The correlation coefficients were .998, .996, and .994, respectively.

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INTRODUCTION

Two BPR-Type Road Roughness Indicators, Roadometers No. 1 and No. 2, have been used for several years to measure the as-constructed riding quality of newly constructed pavements in Illinois. This type of device has been proven to be very dependable and easy to operate, and a high degree of confidence is associated with the results obtained on pavement segments 1/2 mile or more in length. However, two specific limitations of the Illinois BPR-Type Roadometers are that the systems are not capable of providing reliable results for pavement segments much shorter than 1/4 to 1/2 mile in length, and that the operating test speed of the equipment is limited to 20 mph.

These limitations are of significant importance for several reasons. First, the roadometer ideally should be capable of testing at speeds close to the normal flow of traffic for obvious safety reasons. Second, by increasing the test speed, the volume of tests that could be made each season would be increased. Third, the Roadometer would be a much-improved research and test tool if the device were capable of measuring short segments of pavement with a high degree of confidence in the accuracy of the results.

To eliminate these constraints, a third roadometer, designated Roadometer No. 3, was constructed using completely new sensing devices. The basic design of the BPR instrument was maintained because, as previously mentioned, this type of device has many proven qualities. New electronic devices were used in place of the old mechanical devices for measuring horizontal distance and vertical displacement to improve the capabilities of the new roadometer to measure relatively short segments of pavement and to operate at test speeds in excess of 20 mph. It was the goal that the new device would be capable of measuring segments of pavement as short as 100 feet with the same degree of accuracy and repeatability as the present device in measuring a one-mile segment, and that it would be capable of testing at speeds at least up to 45 mph.

The purpose of this report is to describe the equipment modifications made on the new Roadometer No. 3, and discuss the field test results. The work described in this report was conducted as Phase II of Illinois Highway Research Project IHR-74, "Road Smoothness."

BACKGROUND

During testing, BPR-Type Roadometers obtain two types of information: (1) the horizontal distance traveled and (2) the accumulated vertical displacement between the axle and the frame of the test equipment. The ratio of vertical displacement to horizontal distance is expressed as inches per mile, which is commonly referred to as the "Roughness Index" (RI) and is related to the riding quality of the pavement tested.

Horizontal distance data are being obtained by Roadometers No. 1 and No. 2 from a "Micro-Switch" which is activated by a cam mounted on the axle of the test wheel. One count is generated for each wheel revolution, and each count represents approximately 7 ft of travel.

In the original system, vertical displacement is obtained through the use of a mechanical integrator. Differential movement between the axle and frame is transmitted to the integrator mounted on the frame by means of a small-diameter cable attached to the axle at one end and looped around and attached to the integrator drum at the other end. The integrator drum is spring-loaded to keep the cable taut. When changes in displacement occur between the roadometer axle and the roadometer frame, the cable causes the integrator input shaft to rotate. Inside the integrator a double-acting ball clutch converts the upward displacement into uni-directional rotary motion. This uni-directional motion rotates a 6-lobe cam and activates a "Micro-Switch" which generates one count every time a lobe passes. Each count represent one inch of vertical displacement.

A major disadvantage in the use of a 6-lobe cam is that error of as much as ±1 inch can occur in a field test cycle because the cam does not automatically return to zero after each cycle. The cam lobes can be in any position when the test cycle is initiated even though the counters are zeroed; therefore, two counts can be generated for the first one inch of vertical displacement. Similarly, almost one inch vertical displacement can be lost at the end of the test cycle because the counters only count in inches.

When the field tests are made on pavement sections one mile or more in length, the inherent equipment error of ± 1 inch does not significantly affect the results. However, errors in measurements are magnified on pavement sections shorter than one mile in length by the ratio of 5,280 feet to the length of the section being tested. For example, the resolution of the vertical displacement counter from testing a 100-foot segment of pavement would be multiplied by 52.8 to compute the RI in inches per mile. The ±1 inch error in the existing equipment would then result in a ±52.8 in./mi variation in the RI for the 100-foot section.

Improved results can be obtained by interpreting the recordings on the oscillograph that is included on Roadometer No. 1. The oscillograph recordings include vertical displacement, horizontal distance, and event marks which indicate the beginning and ending of the test section. In the recording, vertical displacement is represented by a series of sloping lines, each of which represents 6 inches of roughness regardless of the length of line. Horizontal distance is recorded as crude sine waves equaling one test-wheel revolution per wave, and the event marks are single pips representing the beginning and ending points of the selected locations as desired. Interpretation of the recording permits the vertical displacement to be determined to the nearest 0.2 inch rather than to the nearest full inch as obtained from the counters.

Although the RI results can be improved by interpreting the oscillograph recordings, the reduction of data is rather difficult and very time consuming. Also, the accuracy is still not sufficient for testing short segments of pavement. The variation in RI of a 100-foot section would be ±52.8 x 0.2, or about ±11 in./mi.

The mechanical inertia of the "Micro-Switches" used in the test system is one of the primary factors in limiting the test speed to 20 mph.

The above comments relative to the inherent equipment error for vertical displacement also applies to the horizontal distance measurement. In this case, the error is ± one plus, which is equal to ± approximately 7 feet.

MODIFICATIONS

In an attempt to alleviate the above-mentioned restrictions, new electronic sensing devices were constructed for use in conjunction with the basic BPR-Type Roadometer to permit more precise measurements of vertical displacement and horizontal distance.

A new integrator was constructed in which a commercially available unidirectional photoelectric encoder was used to replace the mechanical double-acting ball clutch and the 6-lobe cam. In the new integrator, a plastic disk with 600 small windows is attached to the integrator shaft. The windows are arranged similar to the spokes on a wheel. A small light source is focused on the disk, and as the disk rotates the light is interrupted. On the opposite side of the light source is a photocell which picks up the interruptions and generates electrical pulses. One hundred pulses are generated for each inch of cable movement. The new integrator generates a pulse for each 0.01-inch of vertical displacement as compared to one pulse per inch for the original mechanical integrator.

The integrator could have been constructed with output capabilities of 0.1-, 0.01-, or 0.001-inch output per pulse. The 0.01-inch output per pulse was chosen because the systems resolution should be sufficient for measuring short segments of pavement and a moderately priced, commercially marketed photoelectric encoder was readily available. The 0.1-inch output per pulse would not be sufficient for measuring short segments of pavement. The 0.001-inch output per pulse would greatly exceed the resolution needed and would have resulted in a high cost of constructing a compatible recording system.

The frequency response of the new integrator is in excess of any operating rate needed during field tests regardless of the test speed. The encoder used was rated at 30,000 counts/sec. This rating is more than 40 times greater than would be needed to test a pavement with an RI of 360 in./mi roughness at a test speed of 70 mph.

The new integrator is attached near the top of the rear member of the "A" frame supporting device of the roadometer (see Figure 1). A steel cable rotates the integrator shaft in the same manner as the original integrator.

Horizontal distance accumulation was modified so that one pulse would be generated for approximately one inch of travel. An 82-tooth gear was attached to the hub of the test tire, and a proximity switch (magnetic switch) was positioned above the gear (see Figure 2). One electrical pulse is produced every time a gear tooth passes under the switch. Laboratory tests indicate that the proximity switch can operate in excess of 1400 counts per second which, theoretically, would be sufficient to allow roadometer testing at speeds of more than 80 mph.

One count per inch of travel results in a sample length of considerably greater resolution than the original distance accumulation which recorded one count per

Figure 1. New electronic integrator and new rod end on the damper unit

Figure 2. Horizontal distance measuring device

wheel revolution, or one count per approximately 7 ft. Also, one count per inch of travel far exceeds the shortest sample length which will be needed in the foreseeable future.

The 82-tooth gear was selected for use because the ratio of inches of tire circumference versus number of gear teeth was nearly one in. per one tooth; and the gear was readily available.

A functional drawing of the modified roadometer is shown in Figure 3. Two input transducers are shown which include the vertical displacement transducer (integrator) and the horizontal distance transducer (mileage indicator). Both transducers produce crude sine waves which are fed into signal-conditioning circuits.

The signal-conditioning circuits reshape the crude sine wave inputs into square waves. The resultant square wave voltages are fed into the accumulators. The signal-conditioning circuit for the vertical displacement transducer also halves the frequency of the incoming signal. The halving function is needed because the integrator shaft rotates back and forth, which doubles the displacement input.

Information stored in the accumulators is fed through latching circuits and a print command into the mechanical digital printer. The latching circuits and print command circuit are included to compensate for the differences between the operating speeds of the accumulators (10 to 20 micro-seconds) and the mechanical digital printer (750,000 micro-seconds per printout).

The digital printout feature was incorporated in the modified system to eliminate the need for the operator to copy field data during the field test operations. The printer can be operated either automatically or manually. Functional coding is also included and a letter of the alphabet between A and I is original drawings of

FIGURE 3

USED FOR R&D REPORT

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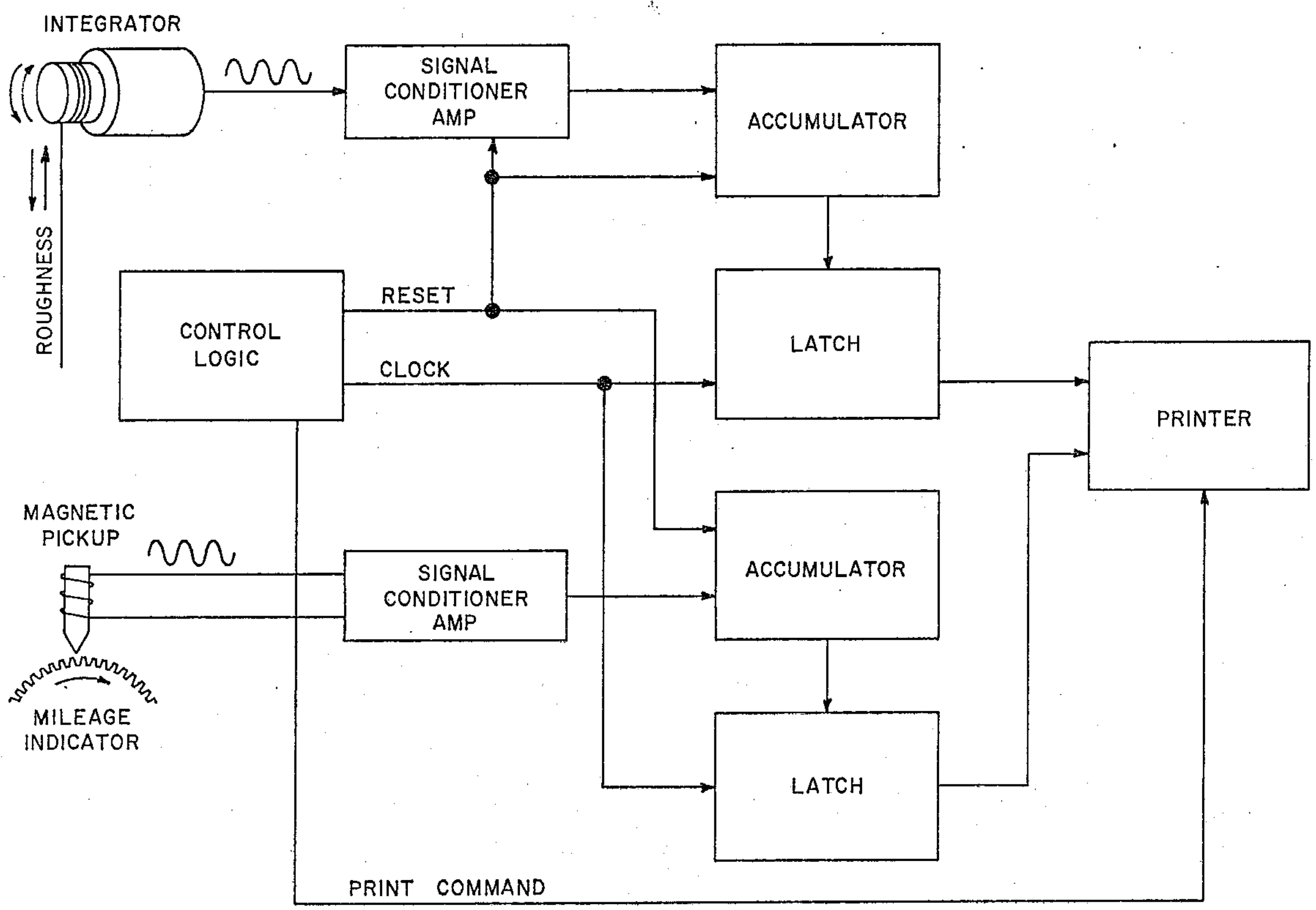

Figure 3. Functional Drawing Of The Roadometer Recording System.

printed each time the printer is activated. This function can be used to identify pavement features such as patches, intersections, bridges, etc.

The instrument console and printer are presently mounted on the tow truck floor between the driver and the operator, and can be activated by either person (see Figure 4). The package is shock-mounted to the floor of the tow truck. Further consideration is being given to the possibility of densifying the instrument console so that it can be mounted on the dash or possibly hand carried by the operator. Also, a visual display may be developed to replace the digital printer.

The entire system is operated by the 12-volt D.C. power supply of the towing vehicle.

A minor modification includes the use of commercially available ball joint rod ends on the damper units instead of the ball and socket joints included on the original equipment (see Figure 1). The new rod ends are designed and constructed so that elongation or compression of the body head does not bind or interfere with ball movement, which is an advantage not associated with the original ball and socket joints. This modification overcame the problems of variation in damping caused by wear and improper adjustment of the ball and socket joints. A final advantage associated with this modification is that the purchase price of the ball joint rod ends is considerably less than the in-house construction cost of the ball and socket joints.

TYPICAL FIELD TEST

When field testing, the equipment is operated in the following manner: As the roadometer approaches the test site, pulses are being generated but are not being accepted because the "Record Switch" is in the off position. In the off position, the accumulators are automatically zeroed. Upon reaching the beginning

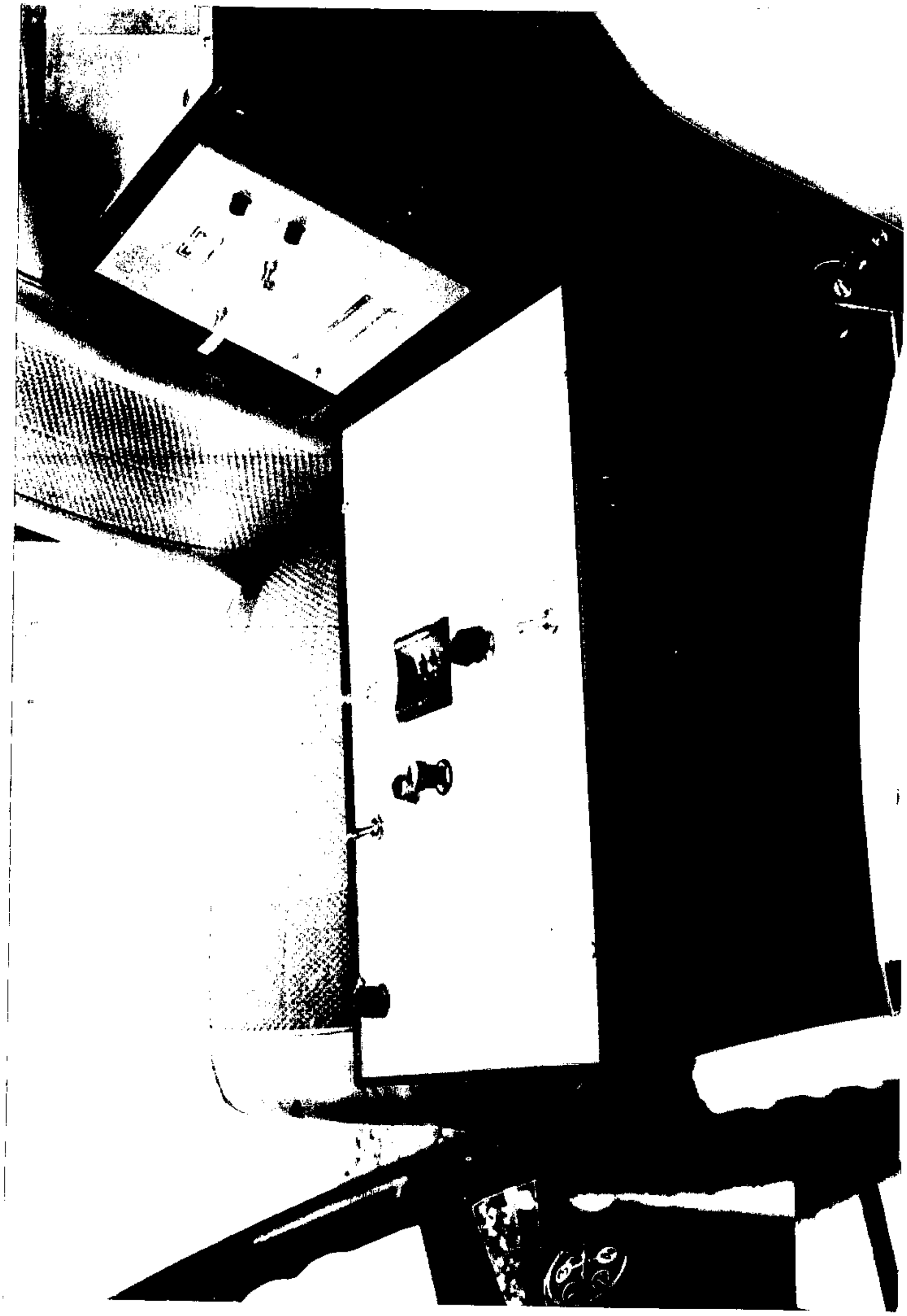

Figure 4. Instrument console and printer

of the test site, the "Record Switch" is activated by cycling to the "on" position. At this point, both accumulators begin to accept data. Simultaneously, the control logic circuit gives a read command to the latching circuit and then generates a print command. The printout generated is:

B 00000 00000

From left to right, "B" indicates the beginning test reading, vertical displacement is recorded in the first 5-digit group, and horizontal displacement in the next 5-digit group.

Later in the test, when the distance accumulator collects the number of pulses equal to the number of pulses programmed in the preset counters for a pre-determined pavement length, the control logic circuit will generate a print command. The printout could be as follows:

A 00773 05940

The "A" indicates an automatic printout, the vertical displacement is 7.73 inches (773 counts at 0.01 in./count) and the horizontal distance is 5,999 inches, or 500 feet (5,940 counts at 1.01 in./count). The length per count was calculated using actual field data.

The automatic printout feature is controlled by a 4-digit set of counters which can be programmed to activate the printer at any number of counts between 10 and 99990. No significant advantage could be seen in programming 5 digits, although a 5-digit counter could have been used.

The output capability of the mechanical printer is physically limited to printouts at not less than 1 sec. per printout. Therefore, as the test speed increases, the programmed automatic printout interval must also be increased. Mathematically, at 20 mph the minimum interval is 264 inches (22 ft) and at 70 mph the minimum interval is 964 inches (77 ft). When using the automatic printout feature, a printout will be generated each time the number of inches in the horizontal distance accumulators equals the number of inches programmed into the preset counters. The accumulators "zero" automatically with each printout.

The printer can also be operated manually so that portions of the pavement surface can be evaluated separately. The six remaining function codes (C, D, E, G, H, and I) are assigned to designate specific pavement identifications. For example, "C" represents a railroad crossing. When field testing, the operator preselects function code "C" and activates the print command switch at the beginning and the end of the railroad crossing to be evaluated separately. Two printouts would then be generated such as:

```
C  00231  01696  (Second printout)
C  00135  01156  (First printout)
```

Vertical displacement for the railroad crossing equals 2.31 inches (231 x 0.01 from second printout) and the horizontal distance recorded for the crossing equals 1713 inches (1696 x 1.01 from second reading). The first "C" printout represents the data stored in the accumulators since the previous printout. The accumulators "zero" automatically each time the print command is activated.

The system will continue to print automatically, as programmed, unless interrupted by the print command or until the "Record Switch" is cycled to the "off" position. When the "Record Switch" is cycled to the "off" position, a printout will be generated such as:

```
F  00173  01079
```

The "F" indicates the end of the test. The vertical displacement of 1.73 inches and the horizontal distance of 1,092 inches represent the data stored in the accumulators since the previous printout.

For routine field test purposes, the function codes have been tentatively assigned as follows:

C - Railroad Crossing

D - Bridge

E - Unassigned, describe in Field

G - PCC Deep patch

H - Bituminous skin patch

I - Intersection

As previously indicated, function codes A, B, and F are permanently assigned.

A typical field test printout is shown in Figure 5. The far right column contains the horizontal distance in counts per 1.01-in. of travel, the center column contains vertical displacement in 0.01 inches, and the far left column contains the function code.

Figure 6 contains a straight line diagram of the pavement developed from the field test printout shown in Figure 5. The 1.77-miles of measurements were made in the eastbound lane of US 6, between LaSalle, Illinois and the intersection of US 6 and Ill. 178. The test speed was 50 mph and the measurements were made in the center of the eastbound lane. The vertical inches are actual data. Although several function codes are shown, only the "dirt on pavement" omission between stations 42+87 and 45+94 was real.

DATA COLLECTION

The modified roadometer was subjected to the following field tests:

(1) The modified roadometer (Roadometer No. 3) was correlated with the original roadometer (Roadometer No. 1) at 20 mph to determine the relationship between the output of the two systems.

```
F    0 0 0 0 0    0 0 0 0 0
F    0 0 1 7 3    0 1 0 7 9
A    0 0 9 0 3    0 5 9 4 0
A    0 0 8 2 7    0 5 9 4 0
A    0 0 7 1 5    0 5 9 4 0
H    0 0 2 7 2    0 2 5 5 9
H    0 0 2 2 0    0 1 0 7 4
A    0 0 6 1 7    0 5 9 4 0
A    0 0 6 0 8    0 5 9 4 0
D    0 0 2 9 7    0 2 4 4 1
D    0 0 1 6 9    0 1 7 3 5
A    0 0 7 0 8    0 5 9 4 0
G    0 0 2 6 4    0 2 2 3 9
G    0 0 6 8 9    0 3 4 8 6
A    0 0 8 1 9    0 5 9 4 0
E    0 0 5 6 1    0 3 6 4 4
E    0 0 6 9 3    0 3 3 5 6
A    0 0 8 9 7    0 5 9 4 0
I    0 0 7 2 0    0 5 1 2 4
I    0 0 5 6 9    0 3 9 6 4
A    0 0 6 9 6    0 5 9 4 0
A    0 0 9 6 5    0 5 9 4 0
A    0 0 8 2 9    0 5 9 4 0
C    0 0 2 3 1    0 1 6 9 6
C    0 0 1 3 5    0 1 1 5 6
A    0 0 6 7 7    0 5 9 4 0
A    0 0 7 7 3    0 5 9 4 0
B    0 0 0 0 0    0 0 0 0 0
```

Figure 5. Typical field test results

Station	Printout Code	Section Length (ft)	Vertical Inches	Type of Omission
END				
93 + 22	F	91	1.73	
92 + 31	A			
		500	9.03	
87 + 31	A			
		500	8.27	
82 + 31	A			
		500	7.15	
77 + 31	H	215	2.72	Bit. Skin Patch
75 + 16	H	90	2.20	
74 + 26	A			
		500	6.17	
69 + 26	A			
		500	6.08	
64 + 26	D	205	2.97	Bridge
62 + 21	D	146	1.69	
60 + 75	A			
		500	7.08	
55 + 75	G	188	2.64	PCC Deep Patch
53 + 87	G	293	6.89	
50 + 94	A			
		500	8.19	
45 + 94	E	307	5.61	Misc. (Dirt on Pavement)
42 + 87	E	282	6.93	
40 + 05	A			
		500	8.97	
35 + 05	I			
		431	7.20	Intersection
30 + 74	I	334	5.69	
27 + 40	A			
		500	6.96	
22 + 40	A			
		500	9.65	
17 + 40	A			
		500	8.29	
12 + 40	C	143	2.31	R. R. Crossing
10 + 97	C	97	1.35	
10 + 00	A			
		500	6.77	
5 + 00	A			
		500	7.73	
0 + 00	B			
BEGIN				

INTERSECTION OF ILL. 178 and U. S. 6

Figure 6. Straight-line diagram of the pavement for which the results are shown in Figure 5.

(2) The frequency response characteristics of the two instruments were compared.

(3) Replicate readings were made at 20 mph on three 5000-ft long segments of pavements, with printouts at 100-, 500-, and 5000-ft, to check the repeatability of the modified system and to determine whether the modified system was capable of measuring cumulative roughness of pavements as short as 100 ft with sufficient accuracy to obtain Roughness Index values that are meaningful.

(4) Replicate passes were made at test speeds of 20, 40, and 60 mph on a measured mile of pavement to determine whether the horizontal distance accumulators were capable of functioning at test speeds greater than the National speed limit.

(5) Replicate passes were made at test velocities of 20, 30, 40, and 50 mph on three one-mile pavement sections to determine whether the new vertical displacement sensing device was capable of operating at test speeds greater than 20 mph and to compare the RI obtained at the higher test speeds with the RI obtained at 20 mph.

DATA ANALYSIS

Correlation

The output of the modified roadometer was correlated to the output of the original roadometer at 20 mph. Data for this correlation were collected from measured one-mile lengths of four bituminous and three portland cement concrete pavement sections. The pavement sections are 2-lane, low-traffic volume, rural pavements. Eight readings were made on each section; four each on the center of each lane of each section. A total of 56 readings were taken with each instrument.

The analysis consisted of least squares regression of the output data from the two roadometers.

Figure 7 contains the relationship developed for the two roadometers. Included in the figure are the regression equation, standard error of estimate, a plot of the regression line, and a plot of the actual data points. In the equation, RI_1 and RI_3 are the Roughness Index values obtained from Roadometers No. 1 and No. 3, respectively. A high degree of correlation exists, indicating that the modified roadometer, when operating at 20 mph, is essentially responding to the pavement roughness in the same manner as the original Illinois roadometer.

Frequency Response

Frequency response curves were obtained by subjecting the instruments to sinusoidal forces over a moderate frequency range. Previous test results (1) have shown that the roadometer output closely follows that of a system having linear damping with one degree of freedom. The equation for the curve is:

$$\frac{Z}{\delta} = \frac{\left(\frac{W}{W_n}\right)^2}{\sqrt{\left[1-\left(\frac{W}{W_n}\right)^2\right]^2 + \left[2D\frac{W}{W_n}\right]^2}}$$

where $\frac{Z}{\delta}$ = the magnification factor

$\frac{W}{W_n}$ = frequency ratio

D = the damping factor

The frequency response curves for the two instruments computed from the above model are shown in Figure 8. Included in the figure are a plot of the actual data points and the computed frequency response curves.

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(1) LaCroix, J. E., "Correlation of Illinois Roadometer," Illinois Department of Transportation Research Report No. , 1975.

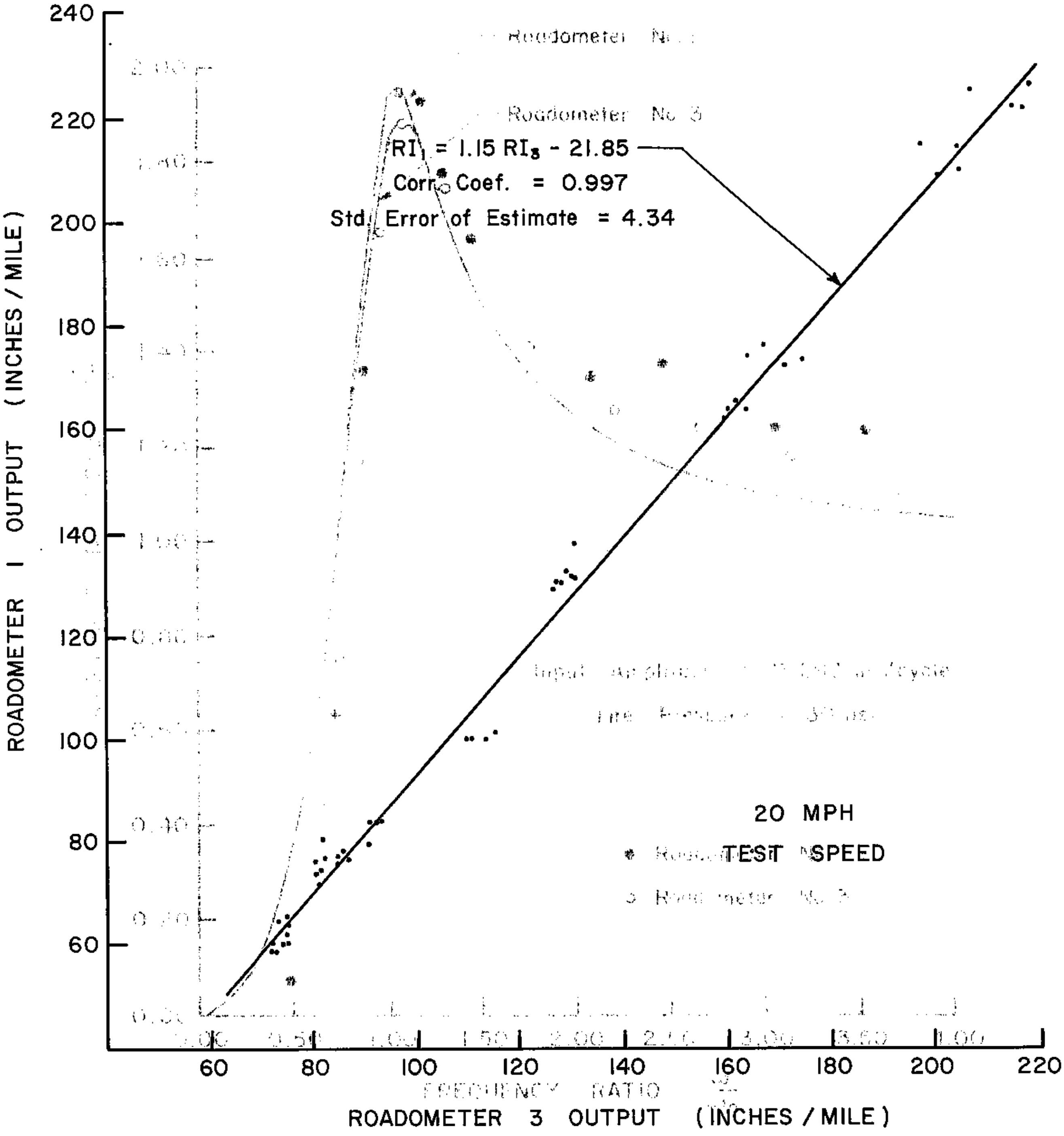

Figure 7. Roadometer 1 Output vs Roadometer 3 Output.

As can be seen in the figure, the computed response curves nearly coincide. Analysis of the data shows that there were slight differences in the damping factors for the two instruments (D for Roadometer No. 1 = 0.27 and D for Roadometer No. 3 = 0.28), which resulted in a slightly higher magnification factor for Roadometer No. 1 at a frequency ratio of about 1.1. Also, as the frequency ratios increase from 1.5 to 3.5, the data points for Roadometer No. 3 show less divergency from the computed curves than the data points for Roadometer No. 1.

Vertical Displacement

Thirty-six roadometer readings were made at 20 mph on each lane of three measured 5000-ft pavement sections to check the repeatability of Roadometer No. 3, to determine whether Roadometer No. 3 is capable of measuring cumulative roughness of pavement sections as short as 100 ft, and to determine whether the extrapolated RI for a 100-ft test section is usable and meaningful. The readings were made in the center of each lane of pavement at each test site and were made in sets of three. The output from the first of each set of three was in 100-ft increments, the output of the second was in 500-ft increments, and the third reading was a single printout which included the roughness for the entire 5000-ft section. The roadometer printer was activated manually at the beginning of each test, but the intermediate printouts and conclusion of each test were controlled automatically by the preset counters. The tests for each set of three were repeated twelve times.

The Roughness Index was computed for each 5000-ft section separately for the entire length, for the sum of the 50 readings for 100-ft segments, and for the sum of the 10 readings for the 500-ft segments. Separate calculations were made for each of the twelve repeat tests.

A summary of the repeatability test program results is given in Table 1. Included in the table are the numerical range which is the difference between the maximum and minimum RI's, the mean RI, and the Standard Deviation.

As is shown in the table, the results obtained with Roadometer No. 3 were very consistent. Also, no significant difference exists in the results obtained using the different printout lengths. This strongly suggests that usable RI values can be obtained when using Roadometer No. 3 to measure pavement segments as short as 100 ft. The vertical displacement and resultant RI obtained for a test section by summing the 50 individual 100-ft printouts was the same as that obtained from the single 5000-ft printout.

A more detailed presentation of the results obtained from the 100- and 500-ft printouts is shown in Tables 2 and 3, respectively. Included in the tables are the results from the first printout only for each test section for each of the 12 repeat measurements. Also included are the numerical ranges, the mean RI, and the Standard Deviation for each test section. The first printout from each test section was chosen for ease in data reduction.

In comparing the results in Tables 1, 2, and 3, it can be seen that the data scatter tends to decrease as the length of pavement segment increases, and that the data scatter tends to be less on the smoother pavements. The Standard Deviation was greatest for the 100-ft segments (3.7 to 8.4), next for the 500-ft segments (1.9 to 8.1), and least for the 5000-ft sections (0.4 to 4.2).

Although the data scatter for the 100-ft segments was greater than for the 5000-ft test sections, the results obtained in the repeatability test program are considered very encouraging that with more precise field testing procedures the new roadometer can be used to determine the Roughness Index of pavement segments as short as 100 ft in length with a high degree of confidence in the results.

TABLE 1. Summary of repeatability test program results for Roadometer No. 3 at 20 mph test speed.

Length of Printout*	CO. HWY. 15			U. S. 51 SPUR			ILL. 71		
	Numerical Range in./mi	Mean RI in./mi	Standard Deviation	Numerical Range in./mi	Mean RI in./mi	Standard Deviation	Numerical Range in./mi	Mean RI in./mi	Standard Deviation
	Northbound Lane			Eastbound Lane			Eastbound Lane		
5000-ft Section	5	85	1.4	2	104	0.4	12	233	4.0
Sum of Ten 500-ft Sections	6	85	1.3	5	104	1.4	9	231	3.2
Sum of Fifty 100-ft Sections	5	85	1.6	4	105	1.2	13	229	4.1
	Southbound Lane			Westbound Lane			Westbound Lane		
5000-ft Section	5	120	1.5	2	100	0.4	9	235	2.9
Sum of Ten 500-ft Sections	5	120	1.7	2	99	0.7	10	235	3.2
Sum of Fifty 100-ft Sections	6	121	1.7	3	100	0.7	14	232	4.2

*Twelve readings were made on each lane of each pavement section at each printout length.

TABLE 2. Results for the first 100-ft printout of each test.

Test Number	CO. HWY. 15 (PCC)				U. S. 51 SPUR (PCC)				ILL. 71 (BIT.)			
	Northbound Lane		Southbound Lane		Eastbound Lane		Westbound Lane		Eastbound Lane		Westbound Lane	
	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)
1	2.05	108	2.79	147	2.03	107	1.92	101	3.43	181	3.54	187
2	2.27	120	2.74	145	1.85	98	1.73	91	3.69	195	3.38	178
3	2.19	116	2.80	148	1.97	104	1.82	96	3.39	179	3.51	185
4	2.26	119	2.86	151	1.98	105	1.78	94	3.28	173	3.56	188
5	2.18	115	2.58	136	1.95	103	1.70	90	3.45	182	3.40	180
6	2.19	116	2.81	148	1.87	99	1.88	98	3.29	174	3.31	175
7	2.23	118	2.63	139	1.77	93	1.87	99	3.32	175	3.44	182
8	2.23	118	2.75	145	1.93	102	1.90	100	3.58	189	3.52	186
9	2.16	114	2.79	147	1.77	93	1.94	102	3.18	167	3.68	194
10	2.07	109	2.77	146	2.01	106	1.94	102	3.19	168	3.26	172
11	2.26	119	2.76	146	2.04	108	1.70	90	3.23	171	3.48	184
12	2.18	115	2.79	147	1.93	102	1.97	104	3.55	187	3.52	186
Numerical Range	0.22	12	0.28	15	0.27	15	0.27	14	0.51	28	0.42	22
Mean	--	115	--	146	--	102	--	97	--	179	--	183
Standard Dev.	--	3.7	--	4.1	--	4.9	--	5.1	--	8.4	--	6.1

TABLE 3. Results for the first 500-ft printout of each test.

	CO. HWY. 15 (PCC)				U. S. 51 SPUR (PCC)				ILL. 71 (BIT.)			
	Northbound Lane		Southbound Lane		Eastbound Lane		Westbound Lane		Eastbound Lane		Westbound Lane	
Test Number	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)	Vertical Displacement (in.)	Extrapolated RI (in./mi)
1	9.15	97	12.42	131	10.14	107	8.41	89	18.90	200	21.72	229
2	9.00	95	12.33	130	10.32	109	8.38	88	19.80	209	22.57	238
3	9.26	98	12.81	135	10.23	108	8.21	87	19.54	206	22.63	239
4	9.04	95	13.01	137	10.13	107	8.44	89	19.29	204	22.38	236
5	9.15	97	12.83	135	10.40	110	8.33	88	18.55	196	22.35	236
6	8.78	93	12.45	131	10.61	112	8.39	89	19.79	209	22.45	237
7	8.92	94	12.67	134	10.35	109	8.68	92	20.05	212	22.48	237
8	8.95	95	12.83	135	10.41	110	8.90	94	19.83	209	22.55	238
9	8.71	92	13.09	138	10.32	109	8.49	90	18.44	195	21.09	223
10	8.97	95	12.81	135	10.36	109	8.68	92	17.50	185	22.09	233
11	8.69	92	12.80	135	10.73	113	8.76	93	18.87	199	21.56	228
12	8.82	93	12.74	135	10.72	113	8.68	92	18.42	195	22.16	234
Numerical Range	0.57	6	0.76	8	0.60	6	0.69	7	2.55	27	1.54	16
Mean	--	95	--	134	--	110	--	90	--	202	--	234
Standard Dev.	--	1.9	--	2.4	--	2.1	--	2.2	--	8.1	--	5.1

Much of the data scatter in testing for short segments is believed to be due to operator error in manually starting the recording at the beginning of each test. Even at 20 mph, manually starting the recording could result in a variation of plus or minus several feet from the true beginning point on repeat tests. While this would have only a minor effect on the 5000-ft sections, the percent error could be considerable on a segment as short as 100 ft. This belief is further supported by the information in Table 1, which shows that no data were lost in testing the 5000-ft test sections even when testing in 100-ft intervals. The results strongly suggest that the need for a photo-electric cell or other device to automatically turn the recording on at the precise beginning of a test when testing short pavement segments.

Horizontal Distance

Eight roadometer readings were made on US 51 spur (4 on each lane of pavement at each test speed of 20, 40, and 60 mph. Prior to making the test runs, the truck speedometer was calibrated using radar, and during the actual test program the driver regulated the tow vehicle's speed using the truck accelerator pedal. The roadometer recording equipment was operated manually in starting and stopping at the beginning and ending of the course. The particular location on the US 51 spur was selected for this testing since it was a previously established and measured 1-mi calibration course.

The results of the horizontal distance testing are summarized in Table 4.

At 20 mph test speed, the average number of counts per mile was equal to one count per 1.01 inches distance travelled, while at 60 mph the average number of counts per mile is equal to one count per 1.02 inches of distance. The total difference in length of the measured mile between maximum and minimum counts for each set of eight repeat tests was 12.2 feet at 20 mph, 14.8 feet at 40 mph, and

TABLE 4. Summary of horizontal distance measurements.

Velocity	Range of Counts Per Measured Mile			Average Counts Per Measured Mile	Change From 20 MPH	Difference From 63360 in./mi	
MPH	Max.	Min.	Diff.		%	Counts	%
20	62816	62682	134	62757	-	503	0.8
40	62631	62453	178	62552	0.3	808	1.3
60	62359	62076	283	62198	0.9	1162	1.8

23.6 feet at 60 mph. The number of counts per mile decreased as the test speed increased, and the variability in repeat testing tended to increase with test speed. Even at 60 mph, however, the total difference in the length of the measured mile was only 23.y feet in eight repeat tests.

As with the vertical displacement tests, the range in counts obtained during repeat tests at each test speed is attributed in large part to operator error resulting from manually activating and deactivating the test equipment at the beginning and ending of the test section. Precise calibration will require automatic activation and deactivation of the test equipment. Also, experience and other research indicate that as the test velocity increases, the number of the revolutions per mile, or counts per mile in this case, will decrease. For example, as the test speed increases, the radius of the test tire increases because of greater centrifugal force. The increase in velocity (20 to 60 mph) can cause as much as 0.25-in. increase in the standing height of a bias ply tire for a given load, which would result in a decrease of several wheel revolutions per mile.

The results show that horizontal distance can be accumulated at test speeds ranging to 60 mph, which is in excess of the present National speed limit of 55 mph, and that the resolution of the new horizontal distance measuring equipment is significantly better than that of the original Illinois device. For all practical purposes, one count is being generated for each 1-in. of horizontal distance travelled.

Roughness Index vs Speed

The objectives of this last phase of the test program were to determine whether the new vertical displacement sensing device was capable of operating at test speeds greater than 20 mph and to compare the RI obtained at the higher test speeds with the RI obtained at 20 mph.

Data were collected at 20, 30, 40, and 50 mph on three 1-mi. test sections which ranged in roughness from "smooth" to "unsatisfactory" by Illinois standards. Eight roadometer readings, four in the center of each lane of pavement, were taken on each test section at each test speed. The upper test speed of 50 mph was used because prior to completing this phase of the test program the State of Illinois lowered the speed limit of all State-owned vehicles from 55 to 50 mph.

The Roughness Index was determined for each individual test at each test speed and the results are listed in Table 5.

The RI obtained at 20 mph was compared with the RI obtained at other test velocities through the use of least squares regression analysis with the following results:

Correlation Equations	Correlation Coeffidient	Standard Error of Estimate
$RI_{20\ mph} = 1.09\ RI_{30\ mph} - 3.14$	0.998	3.73
$RI_{20\ mph} = 1.09\ RI_{40\ mph} + 8.65$	0.996	5.57
$RI_{20\ mph} = 1.14\ RI_{50\ mph} + 9.65$	0.994	6.61

The analyses show that the roughness recorded at 30, 40, and 50 mph correlates well with the roughness recorded at 20 mph. The correlation coefficients are quite high but decrease slightly as the test velocities increase. Also, the standard error of estimate increased as the test speed was increased, but stayed within what is considered acceptable limits.

The above correlation equations are considered only as tentative equations. They were developed from limited data and on the basis of a linear relationship only. Referring to the data in Table 5, it can be seen that the scatter was quite small in each series of four repeat tests at each test speed, and that the measured

TABLE 5. Roughness Index determinations at various testing speeds.

	CO. HWY. 15				U. S. 51 SPUR				ILL. 71			
Test	Velocity (MPH)				Velocity (MPH)				Velocity (MPH)			
Number	20	30	40	50	20	30	40	50	20	30	40	50
	Northbound Lane				Eastbound Lane				Eastbound Lane			
1	85	85	76	72	104	94	85	81	226	207	206	195
2	86	87	75	72	104	94	85	81	229	214	210	202
3	87	86	75	72	104	95	85	82	231	216	210	203
4	85	84	74	71	103	94	86	82	227	220	210	195
Avg.	86	86	75	72	104	94	85	82	228	214	209	199
	Southbound Lane				Westbound Lane				Westbound Lane			
1	117	108	95	88	99	94	84	80	231	208	196	180
2	117	110	96	88	99	93	85	80	235	215	198	190
3	116	110	96	88	99	95	84	80	232	216	197	192
4	117	108	97	87	99	94	85	81	230	214	201	187
Avg.	117	109	96	88	99	94	85	80	232	213	198	187

RI of a section decreased as the test speed was increased. Further, the reduction in RI with increase in test speed appears to be greater for the test sections that are rougher. This suggests that the development of correlation equations from an expanded data base utilizing non-linear as well as linear relationships could result in a set of equations providing even better fit and lower standard errors of estimate. The analyses as performed, however, certainly show that the potential of the new roadometer for testing at speeds considerably in excess of 20 mph is excellent.

CONCLUSIONS

The modifications that were made to the new Roadometer No. 3 were intended to expand the capability of the BPR-Type Road Roughness Indicator for use in measuring relatively short segments of pavement and for testing at higher operating speeds. The field test program carried out on the new machine was to provide a measure of its capability relative to meeting its intended use, and to compare its operation with that of the original Roadometer No. 1 relative to reliability, repeatability, and accuracy. The following conclusions have been drawn from the findings of the field test program.

(1) The roughness recorded at 20 mph with the new Roadometer No. 3 correlated well with the roughness recorded at 20 mph with the original Illinois Roadometer No. 1.

(2) The frequency response curves for both roadometers nearly coincide.

(3) The capabilities of the horizontal and vertical sensing devices of new Roadometer No. 3 relative to accuracy, sensitivity and speed far exceed those of the existing Roadometer No. 1.

(4) The test results show that Roadometer No. 3 is capable of operating in test mode at speeds up to at least 50 mph, and further indicates that

the limiting test speed could be in excess of 60 mph. Roughness measurements recorded at test speeds up to 50 mph correlated well with those obtained at 20 mph. The correlation equations were developed from limited test data, however, and new equations should be developed from an expanded data base using more precise testing procedures before the new roadometer is pressed into service for testing at higher speeds.

(5) The modified roadometer has the capability of measuring both horizontal distance and vertical displacement of pavements as short as 100 ft in length with sufficient accuracy to obtain RI that are meaningful and useful. The variations that occurred in the limited repeat testing, although greater than for longer segments of pavement, are considered to be within acceptable limits. The field testing indicated the need for an additional modification to the new roadometer to permit automatic activation and deactivation of the recording equipment at the precise beginning and ending of a pavement being tested. This modification will eliminate operator error in manually starting and stopping the recording, and improve the accuracy of results from tests of short segments of pavement. It also should improve the preciseness of equipment calibration and correlation for different testing speeds.

(6) With the modification discussed above in conclusion 5, it is believed that the modified roadometer has good potential for use in quality control testing for acceptance of the as-constructed riding quality of new pavement surfaces. Additional work is needed to determine whether the machine actually possesses this capability and to develop the necessary specifications and test procedures.