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DEPARTMENT OF HIGHWAYS  
FRANKFORT

HENRY WARD  
COMMISSIONER OF HIGHWAYS

March 30, 1965

ADDRESS REPLY TO  
DEPARTMENT OF HIGHWAYS  
DIVISION OF RESEARCH  
132 GRAHAM AVENUE  
LEXINGTON, KENTUCKY 40506

H.2.25

MEMORANDUM

TO: W. B. Drake, Assistant State Highway Engineer;  
Chairman, Kentucky Highway Research Committee

SUBJECT: Research Report; "Accelerometer Method of  
Riding-Quality Testing"; KYHPR-64-25; Part II,  
HPS-HPR-1(26).

At a meeting of Highway Research Board Committee D-B4 last January, R. L. Rizenbergs presented an oral discription of our development of the accelerometer method of measuring road roughness; and representatives from several state highway departments expressed an interest in duplicating our instrumentation. It became incumbent upon us then to prepare a more formal discription for distribution to the Committee and other interested parties. The report submitted herewith is intended to fulfill that purpose. No specific action is requested. Copies are furnished for information only.

Respectfully Submitted,

Jas. H. Havens  
Director of Research;  
Secretary, Kentucky Highway  
Research Committee

JHH:skb

Attachment

cc: Research Committee  
A. O. Neiser  
T. J. Hopgood  
R. L. Campbell  
R. O. Beauchamp

Research Report

ACCELEROMETER METHOD OF RIDING-QUALITY TESTING

AN INTERIM REPORT  
KYHPR-64-25; HPS-HPR-1(26)

by

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in cooperation with the  
BUREAU OF PUBLIC ROADS  
U. S. Department of Commerce

132 Graham Avenue  
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## INTRODUCTION

In 1949, some exploratory research was initiated in Kentucky on the measurement of road-surface irregularities. At that time, emphasis was placed on localized irregularities in pavement profiles detectable by a roller-type straight-edge, template, and level (1)\*. It was soon realized that these methods were too tedious and that such measurements were not direct indicators of the riding quality of the surface. Effort was then directed toward the development of a method that would portray the roughness of a road in a more realistic manner. It was thought that the response of a vehicle traversing a highway at a normal driving speed would provide a better criterion of roughness than the measurement of the road surface geometry. Various parameters associated with a vehicle in motion were investigated. Both acceleration and rate of change of acceleration, commonly referred to as "jerk", have a bearing on riding quality. Certainly, acceleration is the force which a passenger senses and would therefore enter into his judgement of riding quality. According to some authorities (2,3), however, "jerk" is a more prominent indicator of riding quality in the range of some frequencies associated with an automobile in motion. This

\* The number in parentheses refers to the list of references at the end of the report.

kind of thinking led to the adoption of a triaxial arrangement of accelerometers and multi-channel recording equipment which were mounted in an ordinary automobile. At first, the accelerometers were positioned in various places within the body of the car; but, invariably, stray vibrations originating within the mechanical system were picked up; and they obscured the fundamental reaction of the car to irregularities in the pavement surface. After several vain attempts to find a suitable damping medium on which to mount the accelerometers, it was realized that the reaction of a passenger would provide a more realistic approach to the measurement of riding quality. Fortunately too, when the accelerometers were mounted on the passenger's chest, it was found that his body was an ideal damping medium. The triaxial accelerations monitored then were evaluated in terms of "jerk", but the manual analysis of the acceleration trace proved to be too time consuming to be applied in any meaningful extent to pavement evaluation. A report (4) presented to the 34th Annual Meeting of the Highway Research Board in 1955 discussed some of the relationships with respect to riding quality and described the equipment and the method of measurement. This earlier method of analysis and testing has been revised from time to time (5,6,7). A number of approaches to the analysis of the acceleration recordings were tried. Finally, it was decided that the only practical alternative was to summate the area under the vertical acceleration trace only and to

express this measurement in terms of a roughness index. The manual analysis of the acceleration trace, while providing much needed information as to riding quality, was also tedious; and the results were not readily forthcoming. Recent advancements in electronics, however, have made it possible to acquire and adapt the necessary equipment to automatically summate the passenger's vertical accelerations. The measurement of riding quality has implemented the judgement of workmanship employed in pavement construction. Moreover, it has provided meaningful information regarding the rate of pavement deterioration. Objective measurements of roughness combined with other complementing factors have been correlated with subjective, scalar ratings of pavement serviceability. The serviceability concept, first introduced by Carey and Irick (8), has found wide acceptance as a scalar expression of pavement condition. Various methods of measuring roughness are being employed by the several state highway departments and other research groups. NCHRP Project 1-2 (9), provided an opportunity for each agency to participate in a correlation study involving a series of roads - for which the subjective serviceability rating had been independently determined. Appendix C presents the resulting equations correlating the Kentucky roughness index with the serviceability ratings.

## INSTRUMENTATION

The instrumentation used for detecting, measuring, and recording acceleration was installed in a 1962 Ford, 4-door sedan, as shown in Figure 1. Resistive-type,  $\pm 2G$ , Statham accelerometers (Figure 2) were used as sensing devices and were mounted on an aluminum plate which was designed to rest on the test passenger's chest. A circular, bubble-type level was affixed to the mounting base of the accelerometers to facilitate leveling.

### Automatic Roughness-Measuring System

The roughness-measuring system was designed to automatically summate the vertical accelerations experienced by the test passenger (Figure 3,4). The accelerometer is powered and balanced by circuits in the bridge balance unit. The output signal from the accelerometer is then amplified, rectified by a selenium bridge rectifier, and integrated by a solion cell-type integrator. The integrator output is read accurately on a D.C. digital voltmeter. A Sanborn Model 320 recorder provides a chart for in-field or laboratory inspection of acceleration impulses and the accumulated accelerations. The recorder, however, is not an essential component of the automatic system. A detailed description of the system may be found in Appendix A.

### Triaxial Acceleration Recording

Vertical, transverse and longitudinal accelerometer,

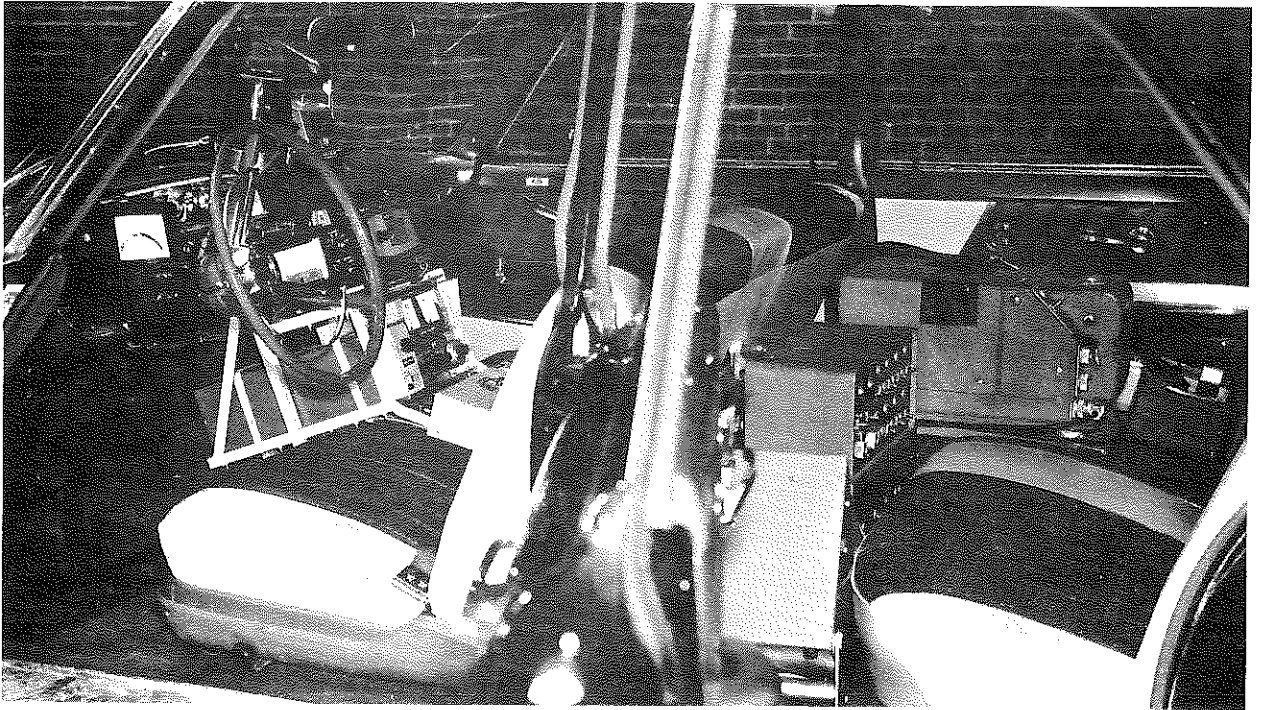


Figure 1. Photograph Showing Accomodation of Equipment in the Test Vehicle. Front: Automatic Roughness-Measuring System. Back: C.E. Bridge Balance, Recording Oscillograph, Sanborn Recorder and Accelerometers in Safety Box.

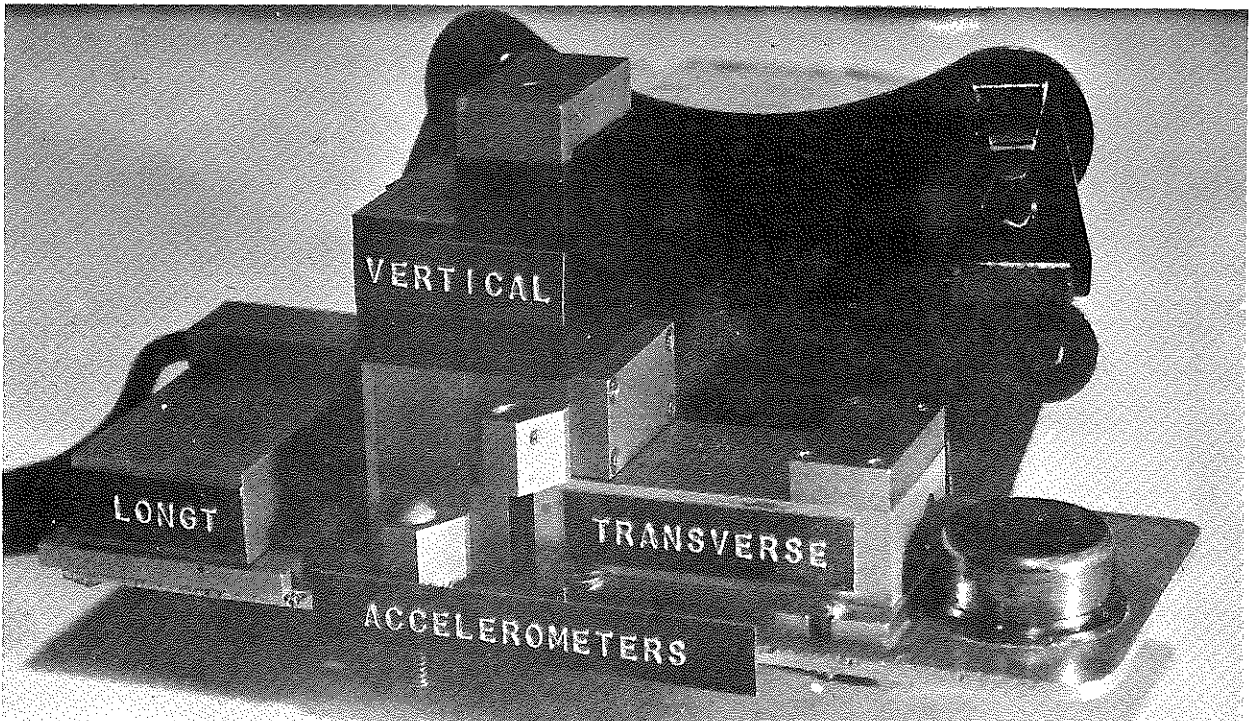


Figure 2. Linear Accelerometers and Level Mounted on a Base Plate.



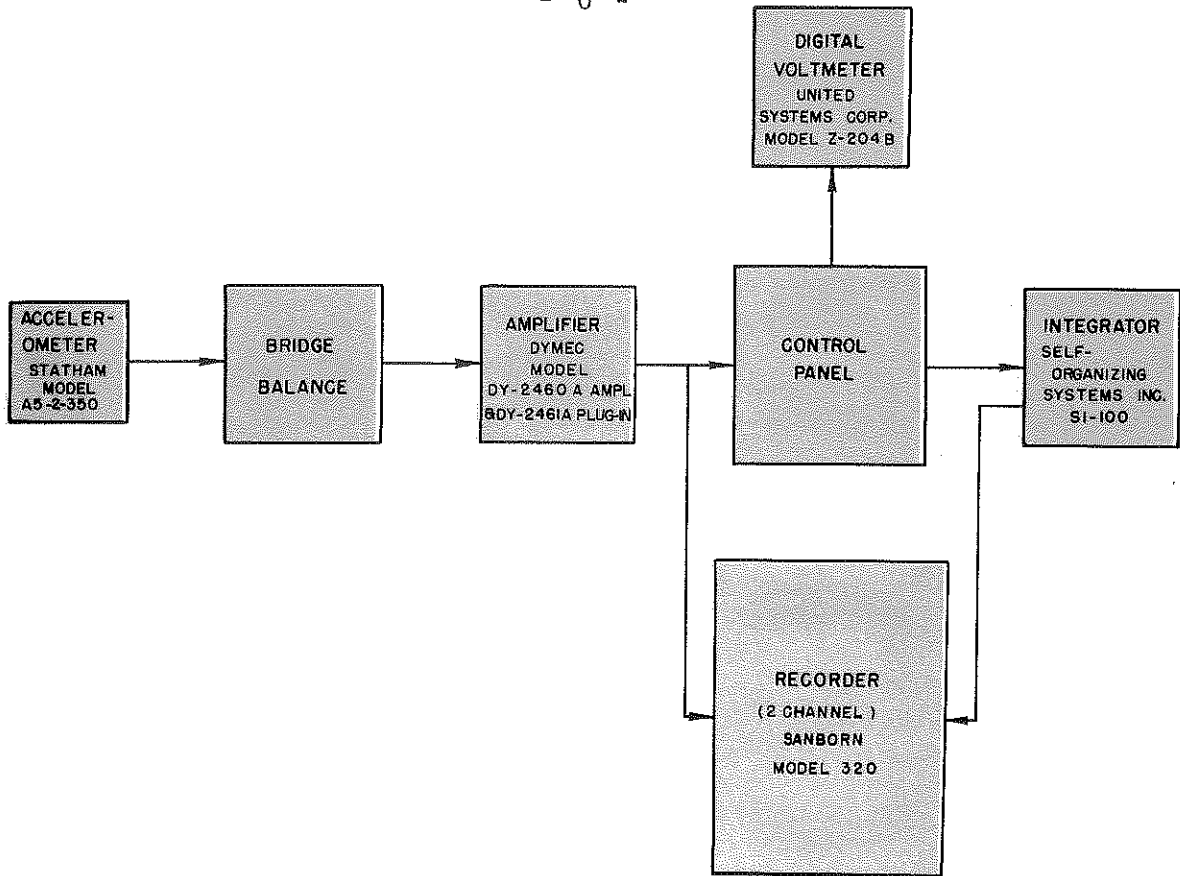


Figure 3. Block Diagram of Automatic Roughness-Measuring System.

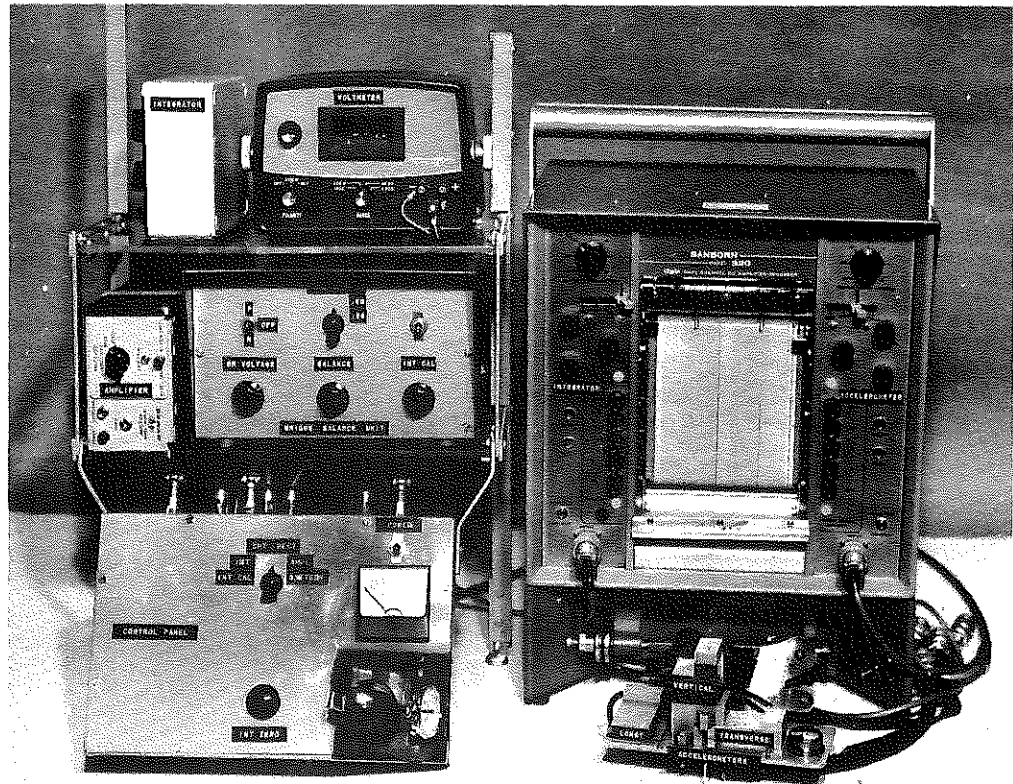


Figure 4. Photograph Showing Components of Automatic Roughness-Measuring System Mounted in Instrument Rack. Sanborn, Model 320 Recorder, and Accelerometers are shown at the Right.

Figure 2, sense the accelerations in the three principal directions. A Consolidated Engineering Corporation bridge balance, Figure 5, provides a means by which to balance the

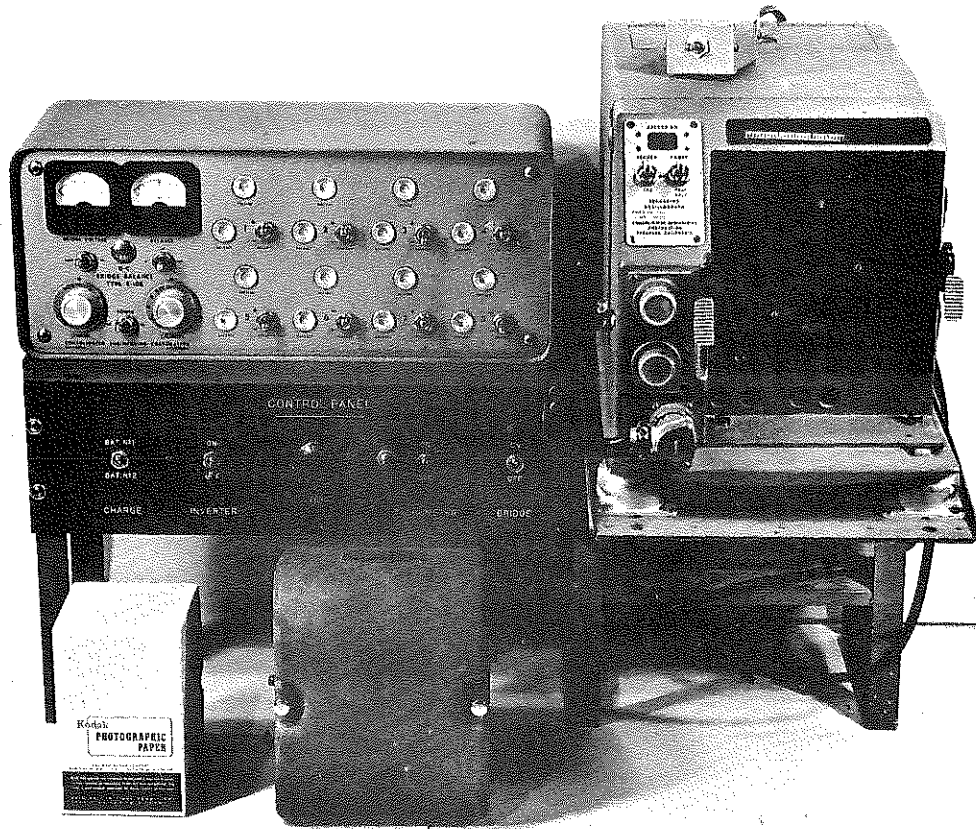


Figure 5. Consolidated Engineering Corporation Bridge Balance (left) and Recording Oscillograph (right). Chart Magazine is detached (lower center); control panel is at left center.

accelerometer circuits and calibrate their outputs. Bridge voltages are monitored and recorded on a C.E. oscillograph. Normally, 17.5 inches of the acceleration chart represents one mile of roadway -- thereby permitting visual inspection of the distribution of roughness within any section of road.

Of course, manual analyses of the acceleration traces may be performed if they are desired. Triaxial acceleration recordings of the two sections of pavement shown in Figure 6 illustrate a difference in their riding quality.

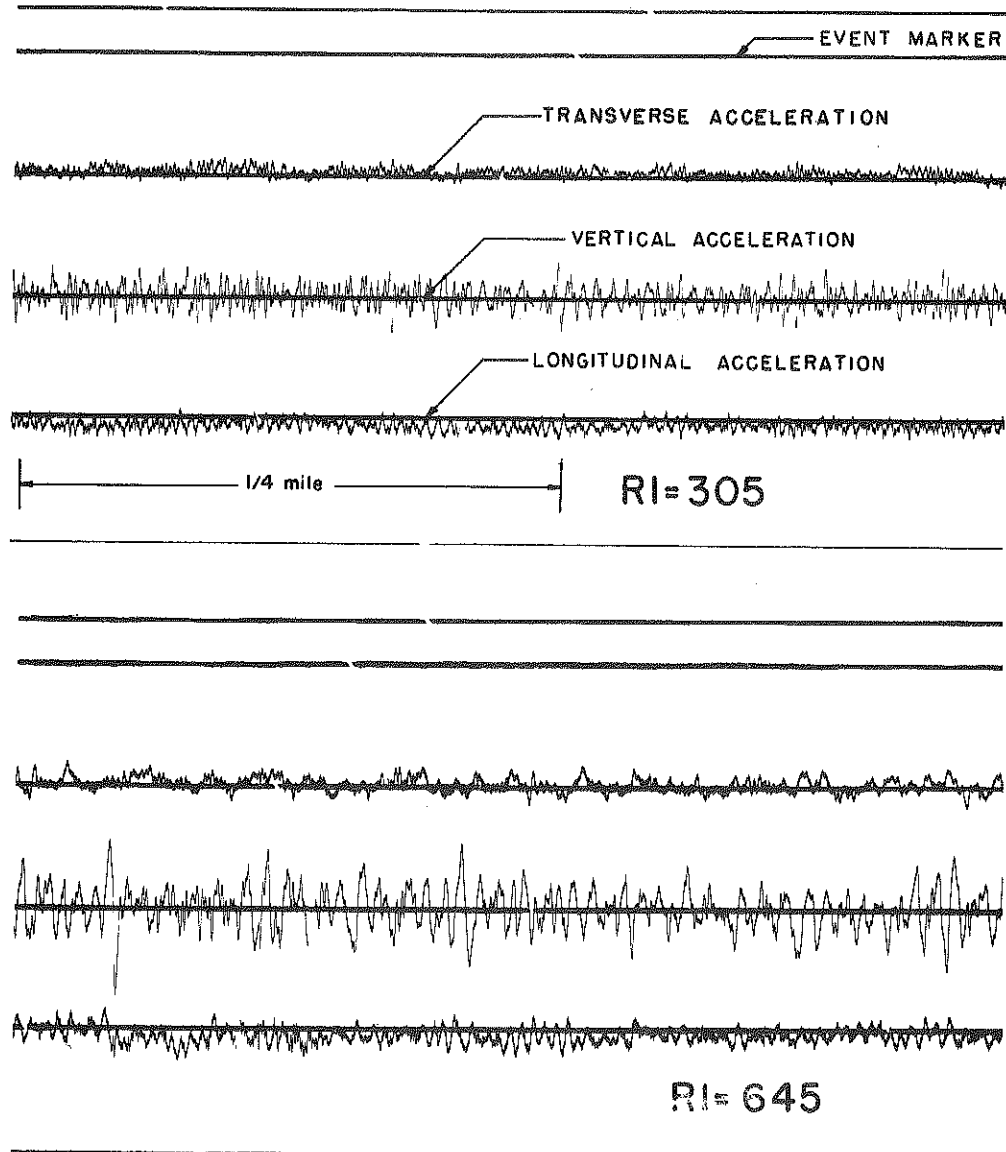


Figure 6. Oscillographic Charts Illustrating the Difference Between a Smooth (upper) and a Rough (lower) Pavement.

## PROCEDURES

### Recording Excursions

The test passenger is seated erectly, but relaxed, in the front seat of the test vehicle; his arms are resting in his lap as shown in Figure 7. The accelerometers are suspended

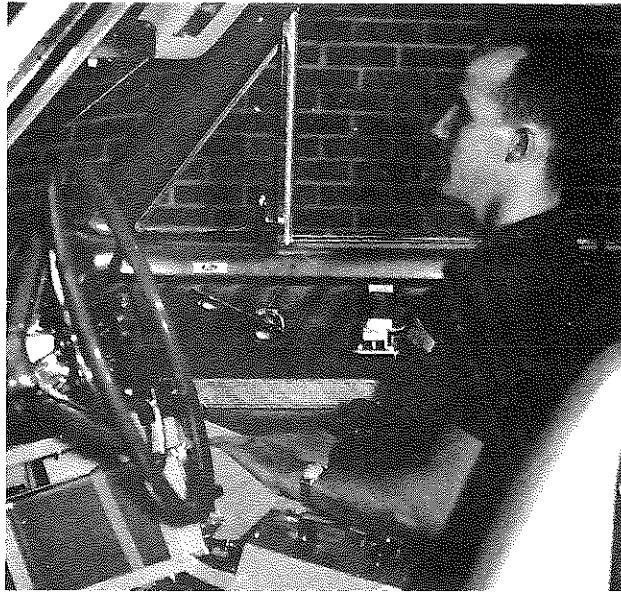


Figure 7. Test Passenger, with Sensing Mechanism on his Chest.

from a cloth strap looping over his shoulders and behind his neck and rests against his chest. A mirror mounted on the right sunvisor permits the test passenger to view the level at all times and, therefore, to maintain the proper position of the accelerometers.

The test vehicle tire pressure is adjusted to 24 psi, + 2 psi, and the gas tank is checked to insure that it is at least one-half full.

summation of acceleration with respect to time  $[\int_0^t |a(t)| dt]$  and time elapsed during the test. By substituting the integrator output, integration time, the selected integrator range and its full-scale calibration; a roughness index is computed using an appropriate system equation - the derivation of which is given in Appendix B. The indexes range from 180 for a very smooth pavement to above 1,000 for a very rough pavement.

## AFFECTING FACTORS

The magnitude of the roughness index depends not only on the road profile, but also on the dynamic characteristics of the vehicle and the speed at which the traverse is made. Extraneous variables must be controlled so that comparisons among various surfaces may be made. Several variables affecting the magnitude of the roughness index were investigated to provide information on how closely these variables must be controlled.

### Test Passenger

The test passengers are required to be of medium build and frame and to weight 150 to 170 pounds. Limited investigation concerning the use of passengers having different body structures and weights yielded inconclusive results. However, the results obtained suggest that the governing factor may be the weight per unit area the passenger exerts on the vehicle seat.

### Instrumentation

The commercially manufactured equipment used in the system conformed to 1% accuracy, and calibrations of all components in the system were within 1% tolerance.

### Vehicle

The influence of the dynamic characteristics of the test vehicle was well demonstrated during a change-over from a 1957 Ford to a 1962 Ford. Even though an excellent corre-

lation was established between the two vehicles, the roughness indexes for any given test section differed; and a distinction had to be made between the types of pavement involved. The use of reference or "standard" test surfaces, while providing some indication of vehicle condition, is not entirely satisfactory because most pavements tend to deteriorate with age and also experience seasonal changes. Therefore, it would be desirable to develop laboratory procedures for checking the test vehicle's springs, shock absorbers, and seat, to insure a reasonably constant suspension system performance.

### Tires

To insure reproducible test results, some thought should be given to the selection of test tires. A limited investigation of the influence of tires suggests the roughness index of bituminous pavements may not be affected by tires. However, significant variations in the roughness index were observed on concrete surfaces. Only tires which are free of shake and roughness should be used.

Inflation pressure was found to have little effect on the magnitude of the roughness index; the tires respond to shorter wave-length irregularities, i.e., higher frequencies which are significantly above the resonant frequency of the suspension system. A tire pressure variation of  $\pm 2$  psi. from the normal test pressure of 24 psi. was deemed acceptable.

A large number of tests were made on several pavements in a given day and under varying weather conditions. These tests suggest that the temperature of the vehicle tires may influence test results. Tire temperature should be sufficiently high to feel warm to the touch. For this reason, roughness testing was not conducted under rainy or wet conditions or at temperatures below 45°F.

#### Vehicle Load

The variation in vehicle load greatly influenced the test results. Of particular concern was the change in load accompanying gasoline consumption. It was found that a difference of 8% in roughness index resulted between tests ran with a full and a nearly empty gas tank. This represented a difference of 130 pounds. Subsequently, it became standard practice to discontinue testing when the tank was half full. A similar increase in roughness index was obtained when an extra passenger was riding in the back seat of the test vehicle. Care is always taken to insure that the test vehicle load remains constant.

#### Vehicle Speed

The speed at which the test is conducted profoundly influences the test results. Several pavements were tested at various speeds, and somewhat characteristic curves resulted for each type of pavement. Figure 8 shows two interstate projects which have identical roughness indexes at the



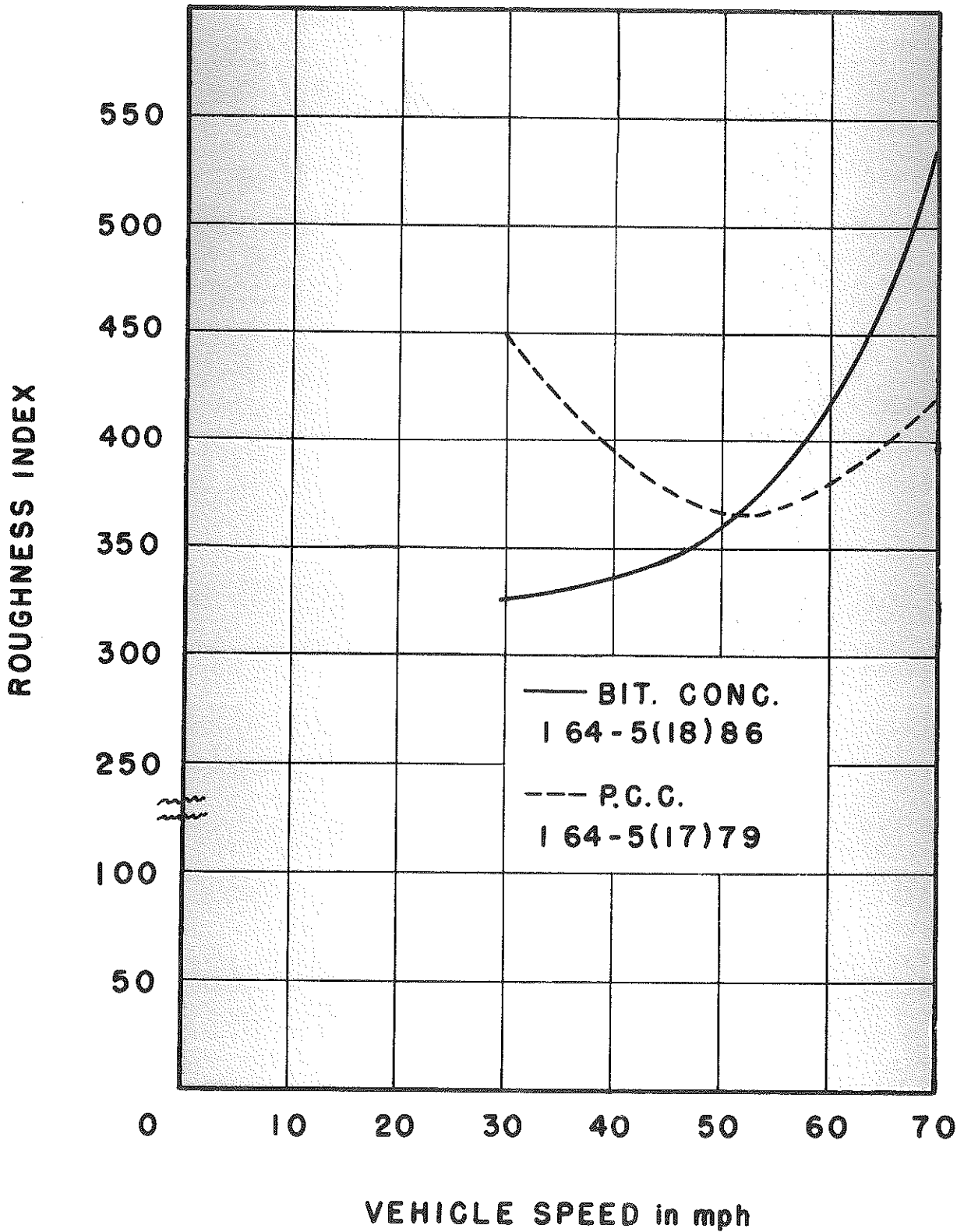


Figure 8. A Plot of Roughness Index vs. Vehicle Speed for a Bituminous and a Portland Cement Concrete Pavement.

normal testing speed of 51.5 mph. Certainly, the average driving speed on these facilities is considerably higher than the test speed. If the two projects are rated as having identical riding qualities, a fallacy becomes obvious; the bituminous pavement exhibited a higher roughness index at 70 mph than the concrete. Ideally, it would be desirable to test a roadway at a speed in the range which the road is normally traveled. If direct comparisons are to be made, it becomes imperative to make the tests at a common speed. It would be difficult, if not impossible, to test all roads at several increments in speeds from 50 to 70 mph.

A tachometer generator driven by a trailing "fifth wheel" proved to be quite useful in maintaining test speed, but an accurately calibrated vehicle speedometer is adequate.

#### Repeatability of Test Results

Two to three repeat runs are necessary to insure reliability of the test. Repeated tests were made on several stretches of highways, and the means were taken as the true roughness index of each respective section. The first two runs differing by less than 4% were taken as normal test runs. A statistical analysis on repeatability of test runs revealed an average error of 2% and a standard deviation of 1.98. This gave a 95% confidence interval of

of the mean error being less than 3.8%. The greatest errors occur on short lengths of pavements and on sections having very low roughness indexes.

## RESULTS

Approximately 6,000 lane-miles of pavements have been tested and rated according to numerical roughness indexes. These include primary and secondary roads of various ages and 2,100 lane-miles of new primary, interstate, and turn-pike highways. The automatic measuring system was used extensively during 1964 in testing a wide variety of roads. Currently some 180 projects are under study; some have been tested periodically since 1957; these and others will be retested from time to time to determine their condition and rate of deterioration. Effects of resurfacing and construction workmanship, as well as distinctions in the type of pavements, are well noted.

## CONCLUSIONS

1. This method of measuring road roughness facilitates evaluation of road surfaces in terms which are closely associated with riding comfort.
2. The test excursion may be made at a speed that is compatible with the normal flow of traffic and, therefore, can be carried out with maximum safety to testing personnel.
3. The test results are available immediately and are closely repeatable.
4. The automatic roughness-measuring system may be duplicated at moderate cost, and large scale testing may be conducted at minimum expense.

## APPENDIX A

### DETAILED DESCRIPTION OF THE AUTOMATIC ROUGHNESS-MEASURING SYSTEM

#### Accelerometer

The acceleration is detected by a resistive-type,  $\pm 2$  G, Statham Model A5-2-350, vertical accelerometer. The construction of a platform on which the accelerometers are mounted is shown in Figure 9.

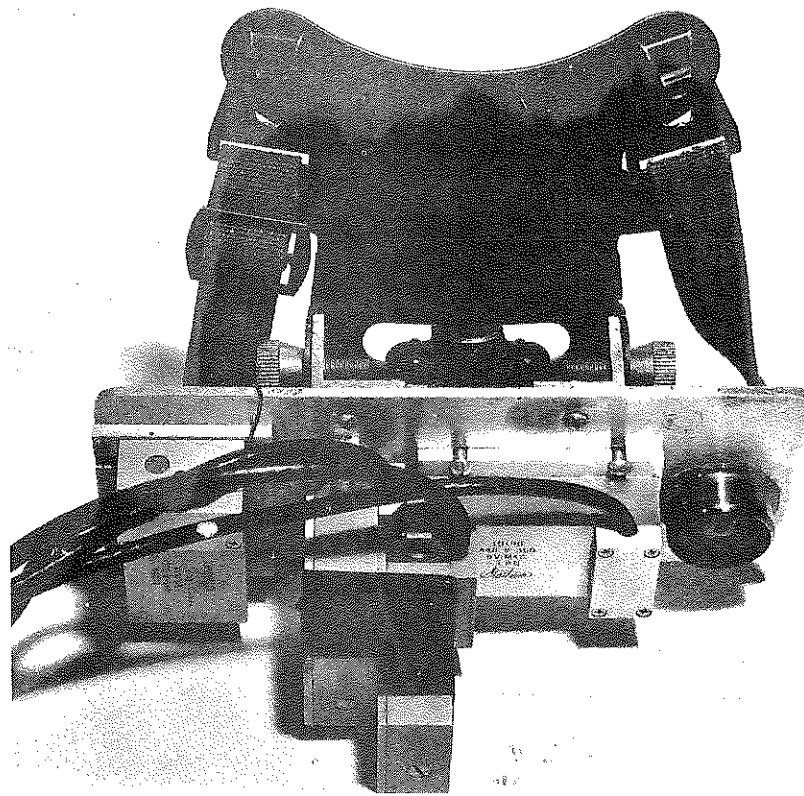


Figure 9. Construction Details of Accelerometer Mounting-Platform and Strap Attachment.

#### Bridge Balance Unit

The bridge balance unit contains a 12.6-volt, mercury-cell, power source. Mercury batteries were chosen because they provide a relatively constant voltage. A 250-ohm

10-turn potentiometer was connected in series with the accelerometer in order to control the applied voltage as the batteries discharged. A double-pole, double-throw, center-position-off, toggle switch was added to the power circuit to prevent drain on the batteries when the accelerometer was not in use, and to provide the desired polarity on the bridge.

The bridge balance circuit was designed for close balancing so there would be near zero output voltage at zero acceleration. It was decided that  $\pm 1$  volt maximum control would be sufficient. By experimental substitution, it was found that a 10-turn, 100-ohm potentiometer, together with 6.98K and 8.66K resistors, provided stable operation and enabled the bridge to be easily balanced within 1 millivolt after amplification.

Although it is necessary to maintain constant voltage on the bridge, it is more useful to monitor the output voltage at some specific acceleration input. This could be accomplished by rotating the accelerometer 90 degrees for 1 G, or 180 degrees for 2 Gs calibration; but errors are introduced in the tedious positioning of the accelerometers. This calibration can also be performed electrically by producing a bridge unbalance equal to some known acceleration input. For this purpose, 0.5 G and 0.2 G were selected as two convenient calibration

levels. The calibration resistances were experimentally determined by first inverting the accelerometer, equivalent to 2 G input, and then multiplying the output voltage by 0.25 and 0.10. From a level position of zero G input, the resistors were substituted until unbalances of the desired magnitudes were obtained. Only  $\pm 1\%$  tolerance resistors were used. It is important to determine the calibration resistors with an otherwise complete bridge balance circuit. A good supply of precision resistors and a decade resistance substitution box are desirable and useful in building the circuit.

The 12.6 volt power source also provides, with a proper voltage dividing circuit, a convenient e.m.f. for calibrating the integrator.

The bridge balance schematic is shown in Figure 10 and a complete parts list is given in Table I.

#### Amplifier

The accelerometer output signal is amplified by a DYMEC, Model MY 2460A-M1, high-gain, transistorized D.C. amplifier. This is an operational amplifier with a multiplier plug-in unit. The amplifier has a maximum output of  $\pm 10$  volts and is utilized at its maximum gain of 1,000. The DYMEC amplifier was chosen because of its high gain, compactness and low power requirement (4 watts).



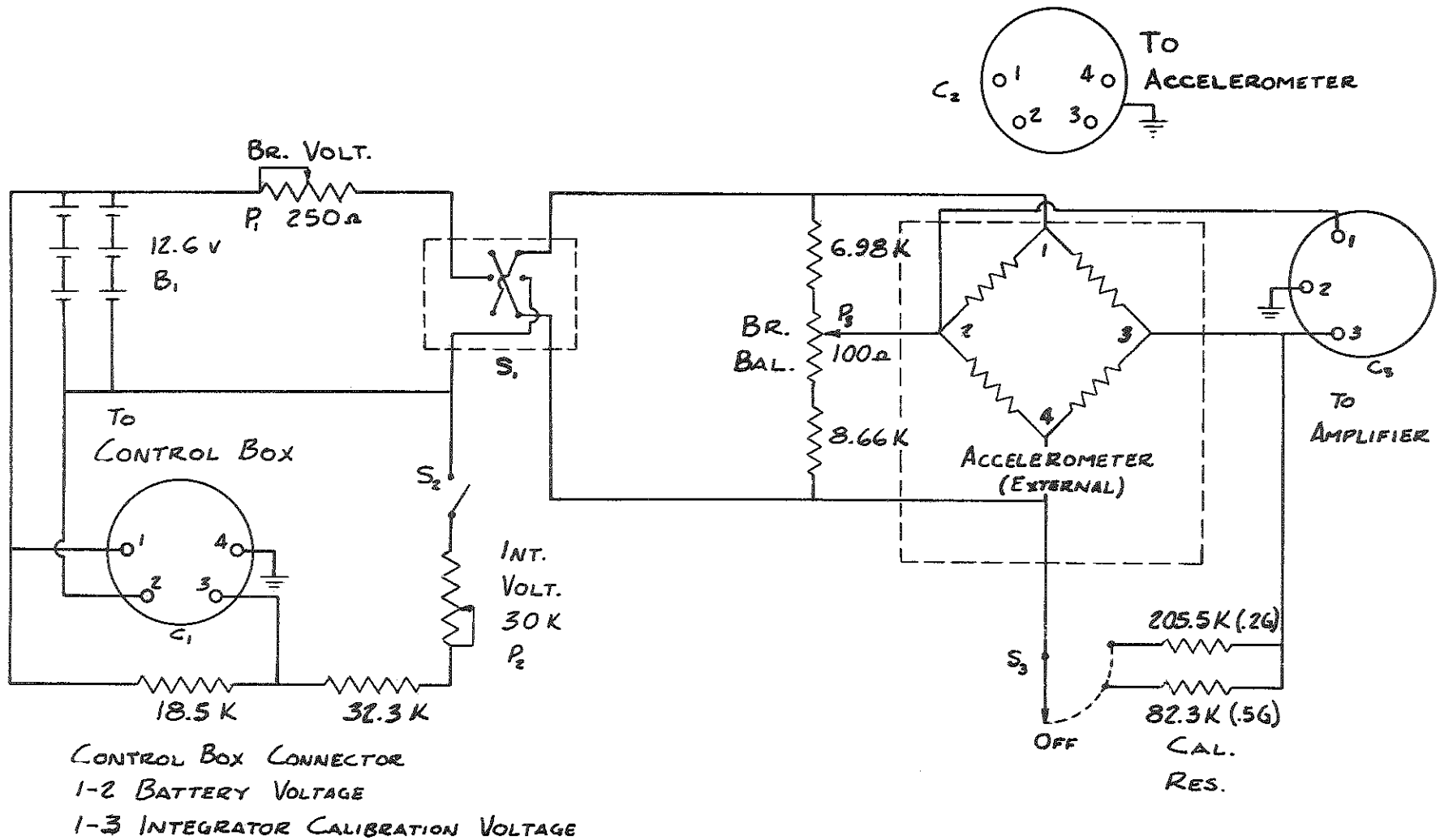


Figure 10. Bridge Balance Schematic.

TABLE I  
PARTS LIST FOR BRIDGE BALANCE

DIAGRAM NO.	DESCRIPTION	PART
B <sub>1</sub>	6-4.2 volt Mercury Batteries for Bridge Power	BURGESS Type H-233
C <sub>1</sub> , C <sub>2</sub>	Control Box Connector and Accelerometer Connector	4 Terminal, CANNON XLR-4-14N, mates with CANNON XLR-4-11SC
C <sub>3</sub>	Amplifier Connector	3 Terminal, CANNON XLR-3-14N, mates with CANNON XLR-3-11SC
P <sub>1</sub>	Bridge Voltage	CLAROSTAT Series 62JA-250, 10 Turn Potentiometer
P <sub>2</sub>	Integrator Voltage	CLAROSTAT Series 62JA-30K, 10 Turn Potentiometer
P <sub>3</sub>	Bridge Balance	CLAROSTAT Series 62JA-100, 10 Turn Potentiometer
S <sub>1</sub>	Bridge Voltage On, Polarity	Double-Throw, Double Pole, Center Position Off, Toggle Switch
S <sub>2</sub>	Integrator Calibration Voltage On-Off	Single-Pole, Single-Throw, Toggle Switch
S <sub>3</sub>	Accelerometer	Single-Pole, 3 Position, Rotary Switch
	Instrument Cabinet	BUD, Cowl Type Minibox, 6"x10"x7", Type SC-2130

Rectifier

A selenium bridge rectifier is used to rectify the amplifier output. This is essential since the integration of the unrectified signal would result in a near zero value. After extensive testing of several rectifiers, the International, J29B5 rectifier was chosen because it had the best low voltage rectification characteristics, as shown in Figures 11 and 12. Several of the rectifiers had a large difference in output voltage when input voltage was reversed, others had poor linearity. The output voltage of an ideal rectifier would be linearly proportional to negative and positive voltages ( $E_o = |KE_{in}|$ ). By looking at the general linear equation of the rectifier curves:

$$E_o = |K_1 E_{in}| - K_2$$

where

$$\begin{aligned} K_1 &= \text{slope} \\ K_2 &= E_{in} \text{ intercept} \end{aligned}$$

or

$$|E_{in}| = K_3 E_o + K_4$$

it is easily seen that  $K_2$  should be as small as possible to detect small impulses of acceleration, and  $K_1$  should be as near to unity as possible. Although silicon and germanium rectifiers had good linearity, the intercept was too large, in excess of 0.6 volts. As shown in Figures 11 and 12, the

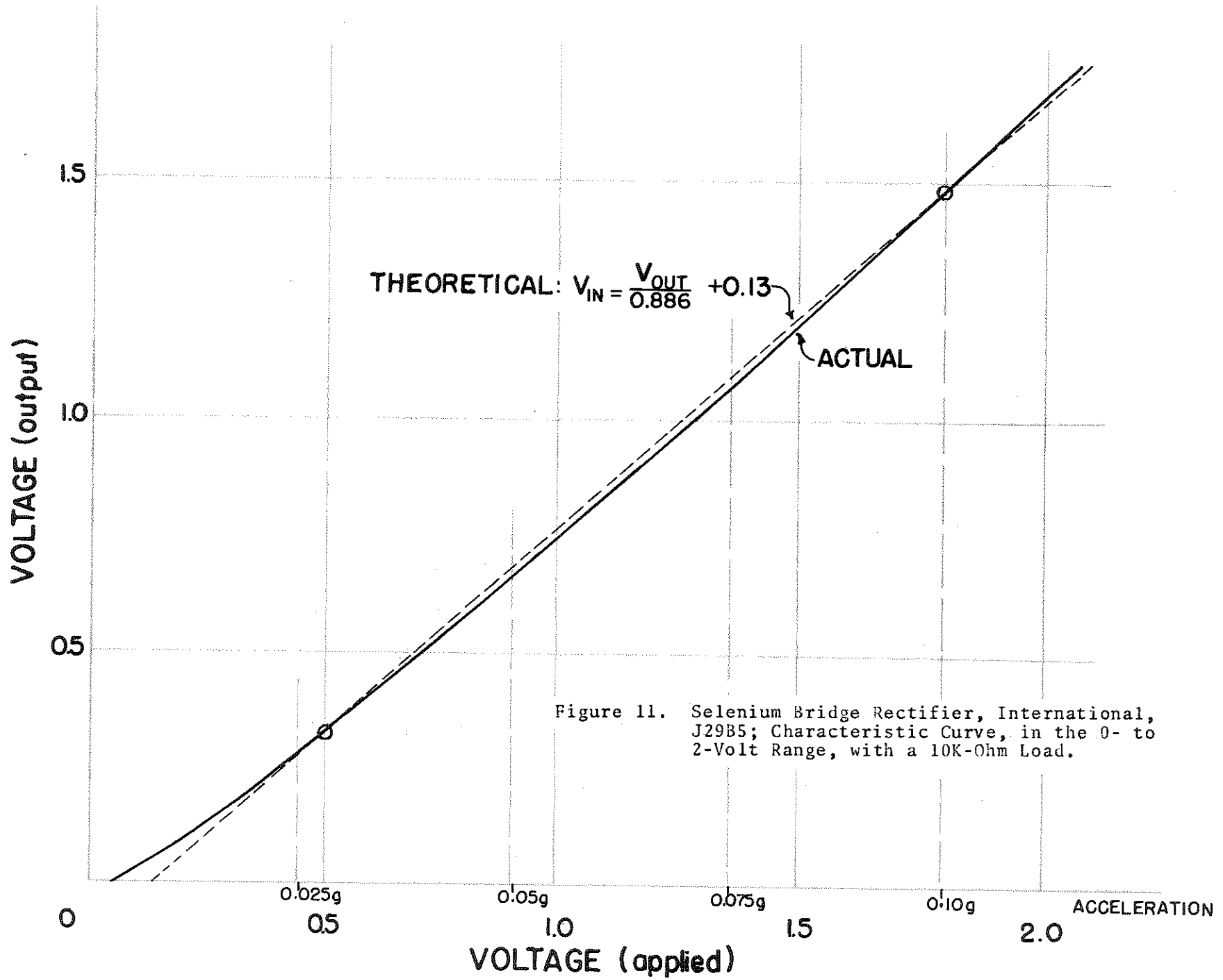


Figure 11. Selenium Bridge Rectifier, International, J29B5; Characteristic Curve, in the 0- to 2-Volt Range, with a 10K-Ohm Load.

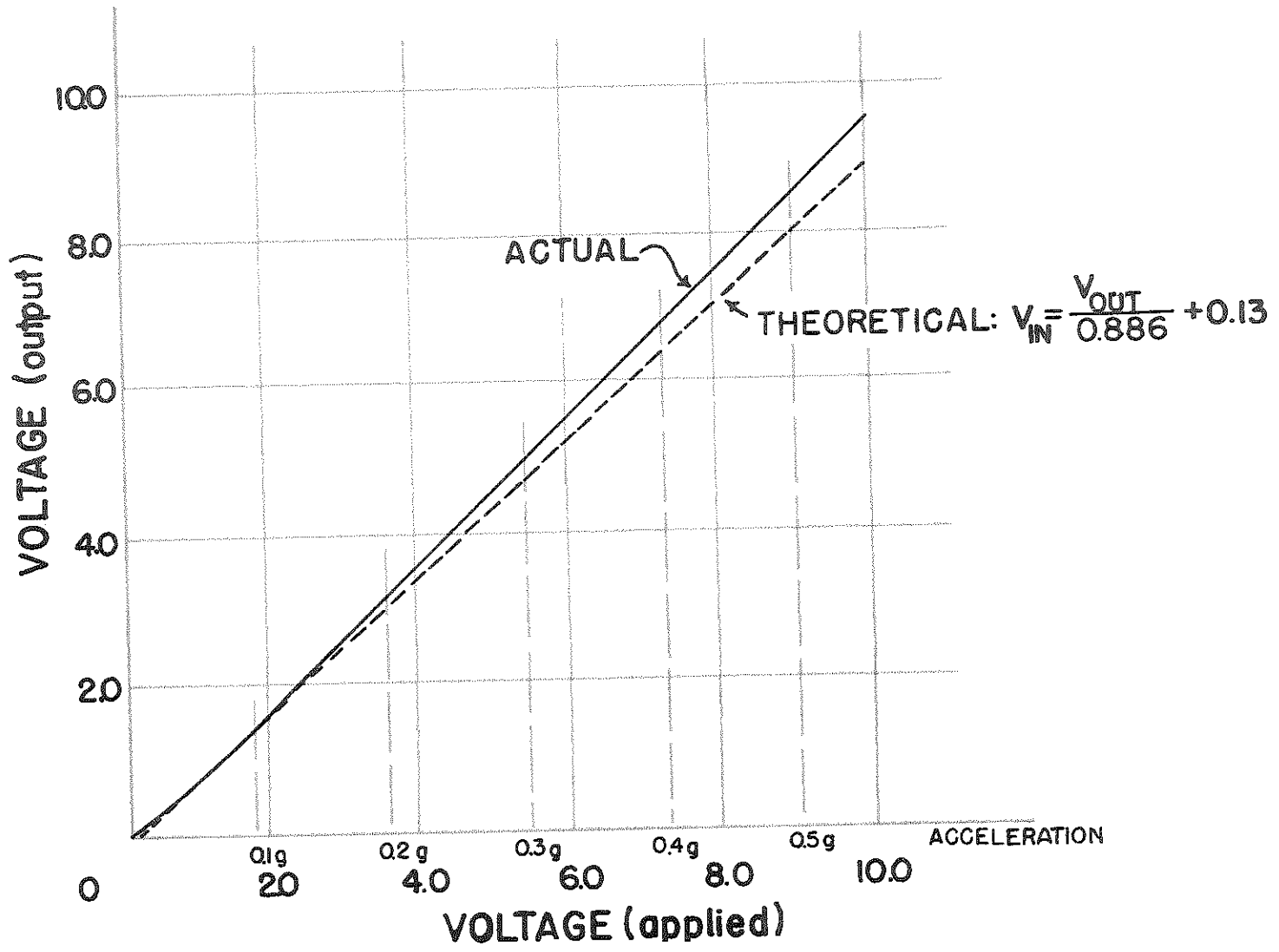


Figure 12. Selenium Bridge Rectifier, International, J29B5; Characteristic Curve, in the 0- to 10-Volt Range, with a 10K-Ohm Load.

theoretical line was drawn to intercept the actual curve at 1.8 volts (0.1 G) and 0.5 volts (0.0278 G). The resulting equation,

$$V_{in} = \frac{V_{out}}{0.886} + 0.13,$$

had a small intercept; and it closely matched the actual curve in the range of accelerations which were deemed significant in roughness testing. A medium-rough pavement has an average acceleration of about 0.06 G which is equivalent to an amplifier output of 1.08 volts. Several J29B5 rectifiers were tested in order to select those having the most desirable characteristics. The rectifier was mounted in the control box.

### Integrator

The output of the rectifier is summated, or integrated, on a time basis by a Self-Organizing Systems, SI-100, Integrator. The heart of this instrument is a solion cell, an electrochemical device, which produces an output voltage as an exact integral of the input current.

The integrator is a compact, versatile instrument which can be reset within five seconds. It has several integration ranges, making it adaptable to any length of traverse or roughness of pavement. The instrument output can be monitored on the integrator meter, but the accuracy is limited to the meter readability. The integrator output voltage, a maximum of 0.5 volts, is therefore read on a digital voltmeter.

An integrator output of 0.020 volts at zero volt-seconds had to be nulled by using a circuit which provided a negative bias of the same magnitude.

The integrating characteristics of the instrument were dependent upon the ambient temperature. Normally, the full-scale output voltage varied as much as 2% over the range of operating temperatures. A much greater variation was encountered when direct sunshine on the integrator heated the instrument above its specified operating temperature. The integrator was then painted white to minimize the heating effect due to sunshine, and the instrument was provided with higher temperature compensation. To gain accuracy, the full-scale integration voltage was checked frequently. A high-resistance voltage-dividing circuit in the bridge balance unit was connected across the 12.6 volt accelerometer supply. It was designed so the 18.5K resistor could always have a 3.0 volt drop, and this voltage was integrated 100 seconds to calibrate the output voltage of the frequently used 300-volt-second range. The accuracy of integration was increased to above 99%.

#### Stopwatch

The time of integration is measured by a cumulative-action stopwatch mounted on a stopwatch holder in the

control box. A UNIMAX DAP push-on, push-off switch (Figure 13) was used to turn the integrator on and off.

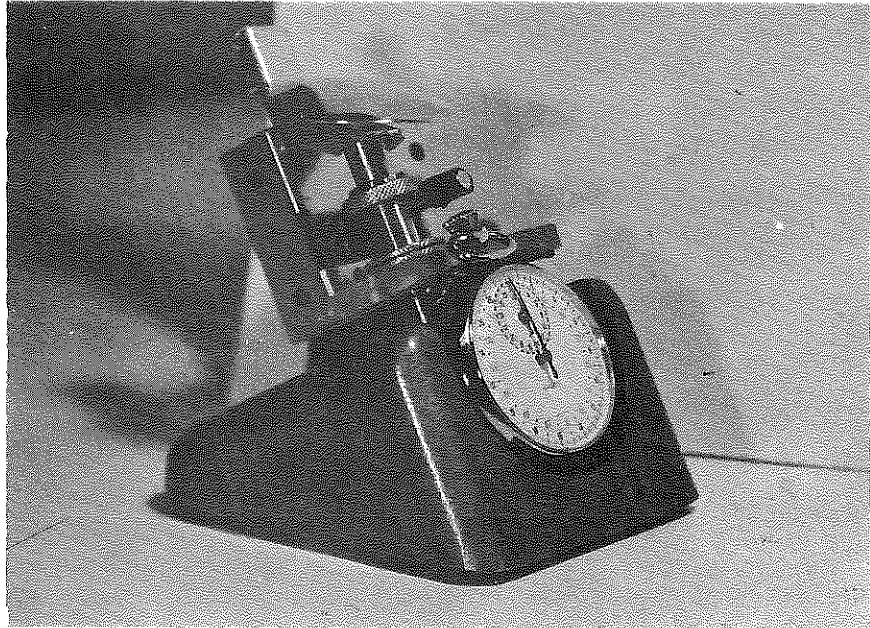


Figure 13. Stopwatch Assembly

It was fastened to the stopwatch stand and synchronized with the stopwatch.

#### Control Box

A 4-pole, 6-position, rotary switch is located in the control box facilitating selection of any of the six inputs to be monitored by a digital voltmeter. They are: 1) integrator calibration voltage, 2) integrator output voltage, 3) short for zeroing the digital voltmeter, 4) rectifier output voltage, 5) amplifier output voltage, and 6) the battery voltage in the bridge balance unit. The switch



also controls the integrator input. On the position to view the integrator calibration voltage, the integrator will summate the calibration voltage. On all other positions, the integrator will summate the rectifier output.

A power switch and A.C. voltmeter are mounted on the panel to control and monitor the A.C. power to the digital voltmeter and amplifier.

The control box schematic is shown in Figure 14, and the parts list is given in Table II.

#### Digital Voltmeter

A United Systems Corporation Model Z-204B, D.C., digital voltmeter is used to monitor the system's voltages as selected by the rotary switch in the control box. The meter permits voltage readings from 0.001 to 4.000 volts, 0.01 to 40.00 volts, etc.

#### Power

During 1964, the power to all equipment was supplied by a Carter, D.C.-to-A.C., rotary inverter located between the front and rear seats of the car. A variable transformer was installed to limit the voltage between 115 to 125 volts, as specified by the manufacturers of the instruments. A Terado, 40-watt, transistorized inverter, operating from the cigarette lighter, was later incorporated as a substitute for the rotary inverter -- making the system self-sufficient.

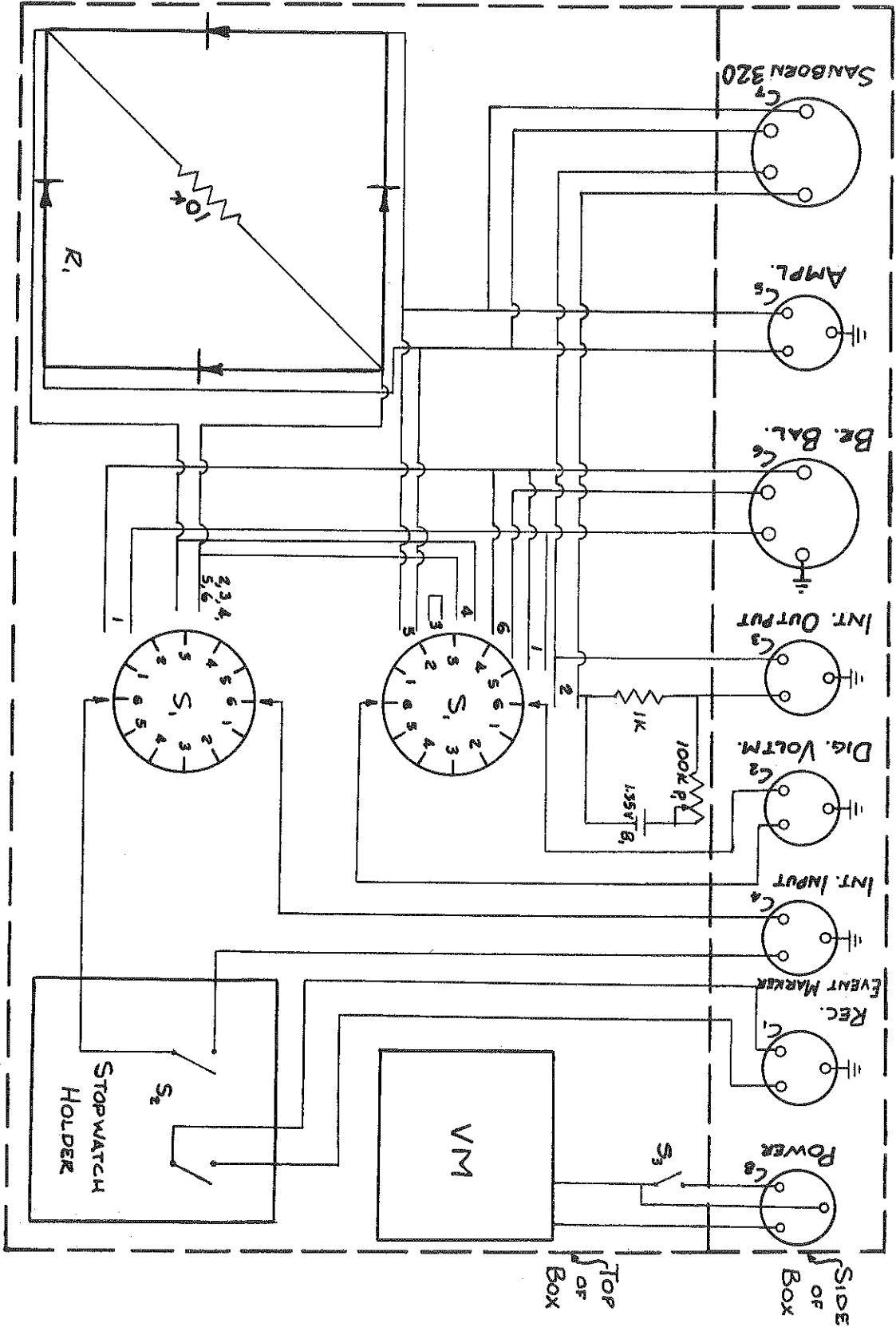


Figure 14. Control Box Assembly

TABLE II  
PARTS LIST FOR CONTROL BOX

DIAGRAM NO.	DESCRIPTION	PART
B <sub>1</sub>	Integrator Output Zero Circuit Battery	1.35-volt Mercury Battery
C <sub>1</sub> , C <sub>2</sub> , C <sub>3</sub> , C <sub>4</sub> , C <sub>5</sub>	Input Connectors	SWITCHCRAFT JAX 3-Position Phone Plug
C <sub>6</sub> , C <sub>7</sub>	Bridge Balance Connector and Sanborn 320 Connector	4-Terminal, CANNON XLR-4-14N, mates with CANNON XLR-4-11SC
C <sub>8</sub>	Power Connector	3-Terminal, CANNON XLR-3-14N, mates with CANNON XLR-3-11SC
P <sub>1</sub>	Integrator Output Zero Circuit Potentiometer	100K, 1 Turn Potentiometer
R <sub>1</sub>	Acceleration Rectifier	INTERNATIONAL RECTIFIER, Selenium Rectifier J29B5
S <sub>1</sub>	Digital Voltmeter and Integrator Input Selector Switch	4-Pole, 6-Position Rotary Switch
S <sub>2</sub>	Integrator Input and Event Marker Switch, Operating Simultaneously with Cumulative Stopwatch	UNIMAX DAP, Double-Pole, Double-Throw, Push-On, Push-Off Switch
S <sub>3</sub>	Power Switch	Single-Pole, Single-Throw, Toggle Switch
	Instrument Cabinet	BUD, Cowl-Type Minibox, 6"x10"x7", Type SC-2130
VM	Voltmeter	SIMPSON, "Wide-Vue", AC Panel Voltmeter, 0-150 volts

A-14

### Instrument Rack

The instrument rack was custom built of aluminum stock to fit the 1962 Ford sedan (Figure 15). The front seat was adjusted to accommodate the test passenger and driver and to still allow the recorders to be placed between the front and rear seats. Two hoods in the legs of the rack were fastened to eyelets mounted in the floor of the car. The rack rested on rubber pads, and was tilted against the dashboard of the automobile. Tension was applied to the rack to hold it in place by attaching an adjustable strap between the rear of the rack and a heater duct under the dashboard. The rack was quite stable and vibrationless. The instruments were mounted on Plexiglass shelves in the rack. The control panel pivots on the rack extension arms and lies flatly on the seat. The main supports are L-shaped, and the braces are bar-shaped. The rack construction details and instrument accommodation are shown in Figures 16 and 17.

### Cabling

All cabling between the various units was shielded to minimize electrical noise. Each instrument can be unplugged to facilitate its removal from the instrument rack.

### Grounding

All the instruments, cables, and the rack were commonly grounded to the chassis of the vehicle.

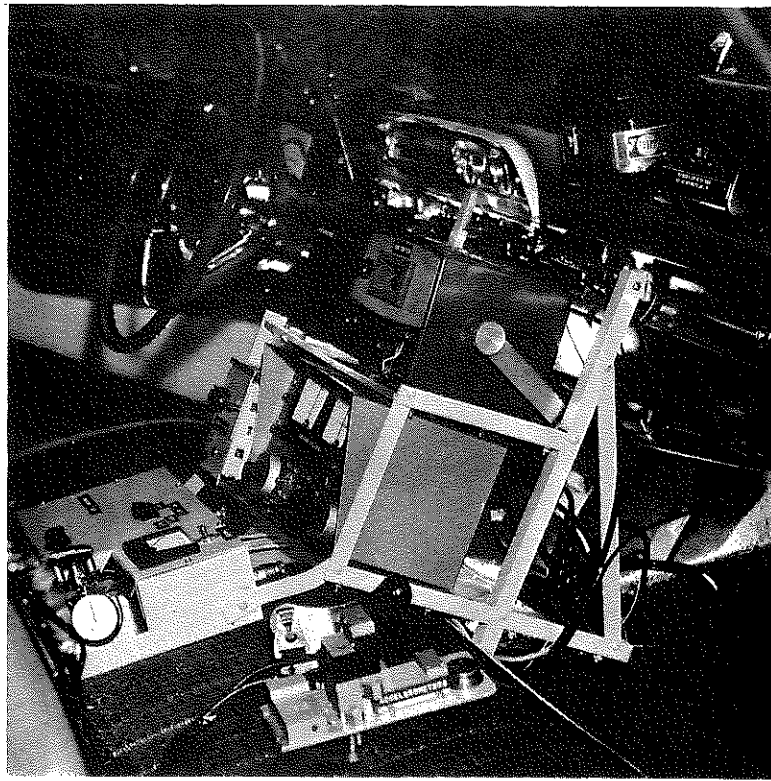


Figure 15. Automatic Roughness-Measuring System Mounted in the Test Vehicle.

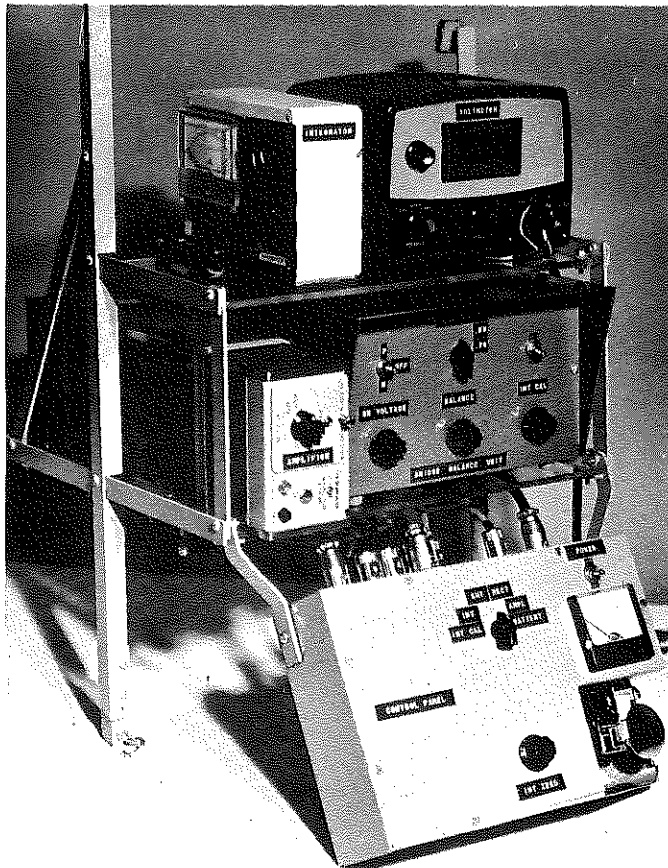


Figure 16. Left-Side View of System Components and Instrument Rack.

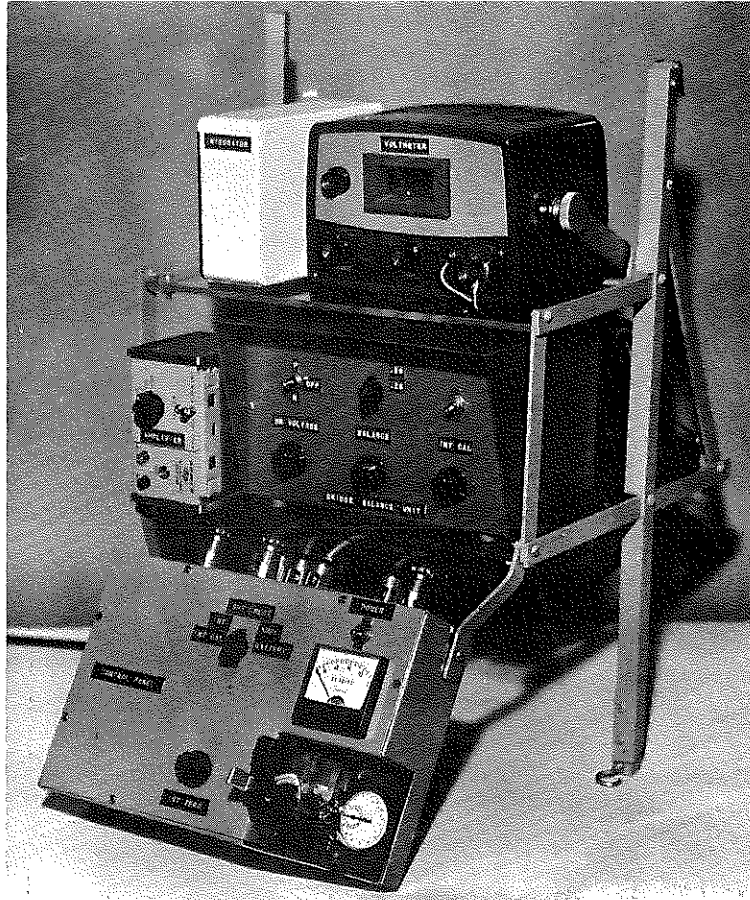


Figure 17. Right-Side View of System Components and Instrument Rack.

Equipment Cost

The automatic roughness measuring system can be acquired at an approximate cost of \$1,450.00. This does not include labor costs for constructing the bridge balance unit, control box, and the equipment rack. A complete list of equipment cost and manufacturers is given in Table III.

Recorder (Optional)

A Sanborn Model 320, dual-channel, D.C., strip-chart recorder was used as an auxiliary unit. The accumulated acceleration, or the output of the integrator, and the actual acceleration signal at the output of the amplifier were recorded at a chart speed of 1 millimeter per second. At this speed, several miles of tested roadway can be inspected at a glance. An event marker was activated by the Unimax Dap switch mounted on the stopwatch holder. The event marker distinguished between the sections integrated and those omitted, such as passing other vehicles and crossing bridges.

Speedometer (Optional)

A Tracktest, Model 5101, Trackmeter, a trailing "fifth wheel", was utilized to accurately measure the test vehicle speed. A Weston Model 901, double-range, indicating meter displays the output from a Weston, Model 750, Type J-2 tachometer connected to the fifth wheel.

TABLE III  
EQUIPMENT COST

Accelerometer

Model A5-2-350 \$330.00  
Alternate Model: A73TC-1-350 (Temperature  
Compensated)  
Alternate Model: A73TC-2-350 (Temperature  
Compensated)

Statham Instruments, Inc.  
12401 West Olympic Blvd.  
Los Angeles 64, California

Amplifier

DY-2460A Amplifier \$395.00  
DY-2461A Plug-in Unit 85.00 480.00

DYMEC  
Division of Hewlett-Packard Co.  
395 Page Mill Road  
Palo Alto, California

Integrator

Model SI-100 99.50

Self-Organizing Systems, Inc.  
6612 Denton Drive  
Dallas 35, Texas

Digital Voltmeter

Digitec Model Z-204-B 357.50

United Systems Corp.  
918 Woodley Road  
Dayton 3, Ohio



TABLE III (Cont.)

Stopwatch

Model 55460 Timer-stopwatch, 7-jewels,  
single action, 30 minutes, 1/10  
seconds, cumulative 27.50

Chicago Apparatus Co.  
1735 North Ashland Avenue  
Chicago 22, Illinois

Stopwatch Holder

Model 22-3655 Stopwatch holder, Eberbach  
safety model 12.50

The Chemical Rubber Co.  
2310 Superior Avenue  
Cleveland 14, Ohio

Alternate-Action Switch

Type DAP Push-on, Push-off switch 3.95

Unimax Switch Division  
Maxon Electronics Corp.  
Wallingford, Connecticut

Bridge-Balance Unit

Materials (approximate) 70.00

Control Box

Materials (approximate) 50.00

Allied Electronics or Newark Electronic Corp.  
100 N. Western Ave. 223 West Madison Street  
Chicago 80, Illinois Chicago 6, Illinois

Instrument Rack

Materials (approximate) 20.00

Total \$1450.00

APPENDIX B

DERIVATION OF AUTOMATIC  
ROUGHNESS-MEASURING SYSTEM EQUATIONS

- K - proportionality constant (volt-sec./volt)  
 $V_r$  - integrator input voltage (volts)  
 T - integration time (seconds)  
 $V_{dvm}$  - integrator output voltage (volts)  
 R - integrator range (volt-sec.)  
 $V_c$  - integrator full scale output voltage (volts)  
 $V_a$  - amplifier output (volts)  
 G - acceleration (G's)  
 RI - roughness index (G's x  $10^4$ )

Basic Equation:

$$RI = \frac{\int_0^t |a(t)| dt}{T} \times 10^4 \text{ G's} \quad (\text{Eq. 1})$$

$$V_r T = K V_{dvm}$$

where

$$K = \frac{R}{V_c}$$

then  $V_r T = \frac{R V_{dvm}}{V_c}$

$$\frac{V_r T}{T} = V_r = \frac{R V_{dvm}}{V_c T} \quad (\text{Eq. 2})$$

Rectifier Characteristic Equation:

$$V_a = \frac{V_r}{0.886} + 0.13 \quad (\text{Eq. 3})$$

then

$$V_a = \frac{RV_{dvm}}{0.886 V_c T} + 0.13 \quad (\text{Eq. 4})$$

The calibration at the output of the amplifier is 9 volts = 0.5 G, but the assumed rectifier characteristics curve does not intersect the rectifier characteristics curve at this point. We can take a point of intersection, such as 0.1 G, where  $V_a = 1.8$  volts, and, by proportion, we can find any other value of G for a given  $V_a$ .

then

$$\frac{G}{0.1} = \frac{V_a}{1.8}$$

$$G = \frac{0.1}{1.8} V_a = 0.0555 V_a$$

substituting for  $V_a$

$$G = 0.0555 \frac{1.13 RV_{dvm}}{V_c T} + 0.13$$

$$G = 0.0627 \frac{RV_{dvm}}{V_c T} + 0.00722 \quad (\text{Eq. 5})$$

$$RI = G_{ave} \times 10^4$$

$$= \frac{627 RV_{dvm}^{cT}}{V^{cT}} + 72.2$$

(Eq. 6)

APPENDIX C

PRESENT SERVICEABILITY INDEX EQUATIONS  
IN TERMS OF THE KENTUCKY ROUGHNESS INDEX

- PSI - present serviceability index
- RI - Kentucky roughness index at 40 mph for rigid pavements and at 51.5 mph for flexible and overlay pavements
- C - major cracking in ft. per 1,000 sq. ft. of area
- P - bituminous patching in sq. ft. per 1,000 sq. ft. of area
- RD - average rut depth of both wheelpaths in inches measured at the center of a 4-ft. span in the most deeply rutted part of the wheelpath

Equations Derived From Purdue Test Data (Table 4\*):

Pavement	Equations	Standard Error	Correlation Coefficient
Rigid	$PSI = 6.89 - 0.0068RI - 0.084\sqrt{C+P}$	0.45	0.90
Overlay	$PSI = 5.38 - 0.0042RI - 0.04\sqrt{C+P} - 13.87RD^2$	0.44	0.89
Flexible	$PSI = 4.71 - 0.0027RI - 0.009\sqrt{C+P} - 2.34RD^2$	0.32	0.90

Equations Derived from AASHO Road Test and Purdue Test Data (Table 10\*):

Pavement	Equations
Rigid	$PSI = 6.39 - 0.0056RI - 0.08\sqrt{C+P}$
Overlay	$PSI = 5.39 - 0.0055RI - 0.01\sqrt{C+P} - 1.34RD^2$
Flexible	$PSI = 4.42 - 0.0018RI - 0.01\sqrt{C+P} - 1.34RD^2$

PSI Determination From Roughness Index Only  
(Table 12\*):

Pavement	Equations	Standard Error	Correlation Coefficient
Rigid	$PSI = 6.65 - 0.007RI$	0.47	0.88
Overlay	$PSI = 5.53 - 0.006RI$	0.46	0.85
Flexible	$PSI = 4.65 - 0.003RI$	0.32	0.88

\* Derived from Tables given in Reference No. 9.

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