COMMONWEALTH OF KENTUCKY
DEPARTMENT OF TRANSPORTATION
BUREAU OF HIGHWAYS
JOHN C. ROBERTS
COMMISSIONER
Division of Research
533 South Limestone
Lexington, KY 40508

JOHN C. ROBERTS
SECRETARY

JULIAN M. CARROLL
GOVERNOR

H-2-25

January 31, 1977

MEMO TO: G. F. Kemper
State Highway Engineer
Chairman, Research Committee

SUBJECT: Research Report No. 465, "Surface Dynamics Profilometer and Quarter-Car Simulator: Description Evaluation and Adaptation;" KYHPR-64-25; HPR-PL-1(11), Part II.

The report enclosed pertains to the mechanics of measuring roughness of pavements. A companion report, which will follow, will relate data and interpretations in meaningful terms of riding comfort and performance of pavements. The importance of roughness histories was made evident recently in the R-R-R study requested by FHWA -- which was completed in approximately one month. "Pavement management" encompasses measurement of condition and renewals or extensions of service life. The ensuing report will be the final one issuing from Study 25. Surveys will continue under KYHPR-76-79 and KYP-74-61.

The present report fulfills some principal objectives in the work plan for the study -- that is, to evaluate the measuring equipment. A power spectrum analyzer (a playback analog tape, loop, scanner input) was abandoned in the course of the study. Further explanation will be given in the later report.

Respectfully submitted,

Jas. H. Havens

Jas. H. Havens
Director of Research

gd
Enc.
cc's: Research Committee

Technical Report Documentation Page

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Surface Dynamics Profilometer and Quarter-Car Simulator: Description, Evaluation, and Adaptation

5. Report Date

January 1977

6. Performing Organization Code

7. Author(s)

8. Performing Organization Report No.

465

9. Performing Organization Name and Address

Division of Research
Kentucky Bureau of Highways
533 South Limestone
Lexington, Kentucky 40508

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

KYHPR-64-25

12. Sponsoring Agency Name and Address

13. Type of Report and Period Covered

Interim

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the US Department of Transportation, Federal Highway Administration
Study Title: Road Roughness and Serviceability Investigation

16. Abstract

A Surface Dynamics Profilometer was acquired in December 1968. The SD Profilometer was designed to rapidly and accurately measure the profile of the surface over which it is driven. A Quarter-Car Simulator was obtained in 1970. The simulator, a special purpose analog computer, was designed to process road profiles measured with the SD Profilometer. This processing involves analog simulation of a simplified vehicle. Factors and variables associated with the devices and calibration and test procedures were investigated and standardized. The Automatic Roughness-Measuring System using an automobile (Kentucky interim standard method of test for roughness) was correlated with the SD Profilometer - QC Simulator system to permit continued assessment of pavements previously tested with the automobile.

Precision of the SD Profilometer and QC Simulator was demonstrated by repeated testing of several pavements. Pavements with the higher roughness indices exhibited about the same standard deviation as pavements with lower roughness indices. On a percentage basis, therefore, the measurement precision was better for a rougher pavement than for a smoother pavement. A single measurement was within three percent of the sample mean 95 percent of the time. The roughness index obtained by simulating the Bureau of Public Roads Roughometer within the QC Simulator system was selected as the best expression of road roughness.

17. Key Words

Road Roughness
Roughness Index
Riding Quality
Profilometer
Quarter-Car Simulator
Road Profile

18. Distribution Statement

19. Security Classif. (of this report)

Unclassified

20. Security Classif. (of this page)

Unclassified

21. No. of Pages

22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

Research Report
465

SURFACE DYNAMICS PROFILOMETER AND QUARTER-CAR SIMULATOR: DESCRIPTION, EVALUATION, AND ADAPTATION

INTERIM REPORT
KYHPR-64-25; HPR-PL-1(11), Part II

by

James L. Burchett
Research Engineer Chief

Rolands L. Rizenbergs
Assistant Director

and

Thomas A. Moore
Research Engineer Senior

Division of Research
Bureau of Highways
DEPARTMENT OF TRANSPORTATION
Commonwealth of Kentucky

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

January 1977

INTRODUCTION

Accelerometer measurements of a passenger's torso, utilizing the Automatic Roughness-Measuring System *(1)*, has been used by the Kentucky Department of Transportation for several years. The resultant roughness index denotes riding quality of the pavement, and it was used to judge construction practices, paving and grading equipment, and general workmanship of the contractors. However, a roller-type straight edge continues to be used for control of construction. Thousands of lane-miles (lane-kilometers) of newly constructed and older roads have been tested and periodically retested. Correlations between the roughness index and service period, cumulative traffic (volumes), and EAL's were performed *(2)*. The rate at which roughness increases has been found to be different for each type of pavement and to vary according to the original or as-constructed roughness of the pavement, structural number, and type of highway. The automobile as a testing device does present inherent deficiencies and limitations; long-term reproducibility, of course, is a major concern.

The Surface Dynamics Profilometer, a profile-measuring device provides useful information in analog form when recorded on a strip chart. Visual inspection of the recording quickly pinpoints localized roughness and permits the engineer to (1) locate the pavement area in question, (2) measure the amplitude and wavelength of the surface irregularities, and (3) make judgements concerning possible remedial action. The profile analog on magnetic tape enables further evaluation in the laboratory.

A special purpose, analog computer, known as the Quarter-Car Simulator and developed for the Surface Dynamics Profilometer, was fabricated for the Department. The QC Simulator (Model 1088) is an electrical analogy of a vehicle suspension, which includes the tire, wheel mass, suspension spring, shock absorber, and vehicle mass. Two vehicle simulations are available -- the Bureau of Public Roads Roughometer (BPR Roughometer) and a 1969 Chevrolet Impala. The electrical analogs representing the pavement profile, taken directly from the SD Profilometer computer or the magnetic tape recorder, can be processed through the QC Simulator to yield deflection of the spring in analog or digital form; the velocity, acceleration, and jerk of the vehicle body; and the force of the tire on the pavement. Also, the device can be used as a peak signal detector, and it can simulate any driving speed regardless of the speed at which the profile record was made.

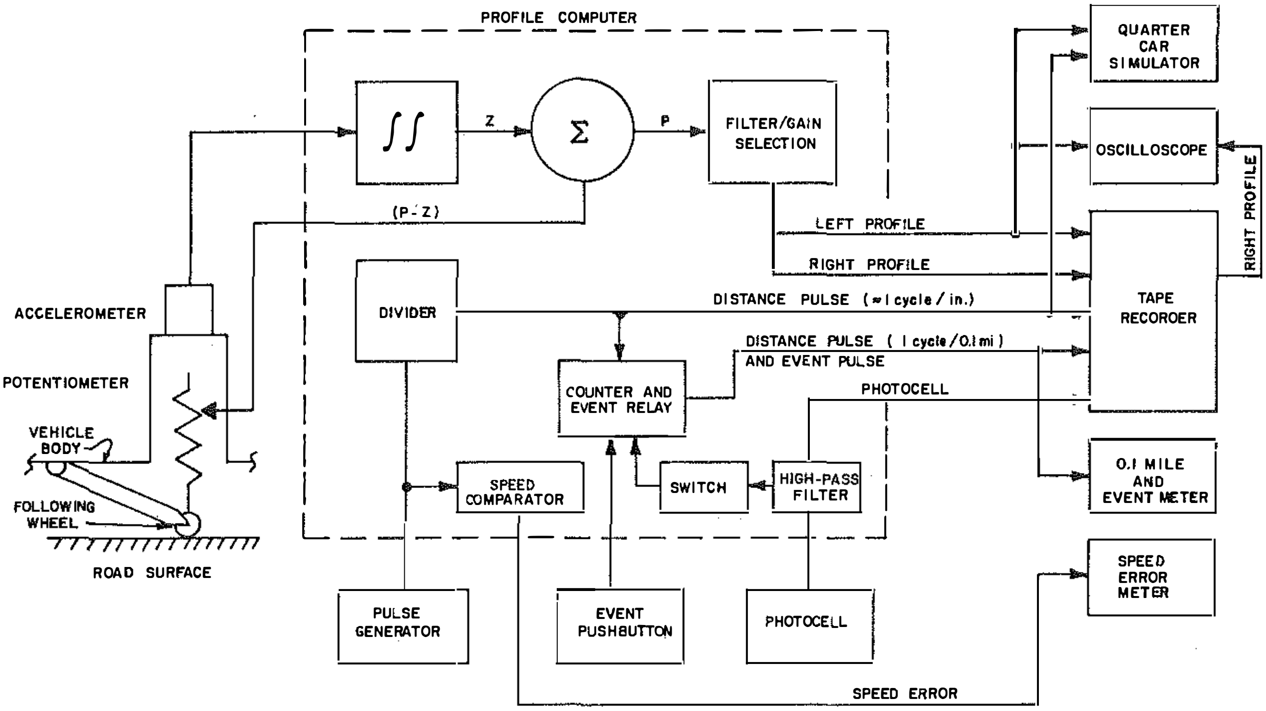
This report describes the SD Profilometer and QC Simulator and presents the evaluation and adaptation of the systems. The precision and dependability of the devices were determined. Calibration and test procedures were developed and standardized. The Automatic Roughness-Measuring System using an automobile (Kentucky interim method of test for road roughness) was correlated with all indices obtainable from the QC Simulator. The roughness index obtained with the simulated BPR Roughometer incorporated within the QC Simulator was selected as the best expression of road roughness.

The SD Profilometer (Model 690) was developed by the Research Laboratories of the General Motors Corporation *(3)* and was fabricated by K. J. Law Engineers, Inc., Detroit, Michigan, under a licensing agreement with General Motors Corporation. It consists of a carryall truck equipped with road-following devices, transducers, recorder(s), oscilloscope, and profile computer. The diagram in Figure 1 shows the measurement system. The profile in each wheel path is tracked separately by a small, rubber-tired wheel held firmly in contact with the surface by a spring-loaded arm. A linear potentiometer measures the displacement between the road surface and the vehicle body. An accelerometer, mounted above the potentiometer, senses the vertical acceleration of the body of the vehicle. The computer integrates the acceleration signal twice to yield a displacement which is then added algebraically to the displacement indicated by the potentiometer. The combined signal represents the road surface profile in the respective wheel paths.

The computer also provides internal checks on the condition of the transducers. The operator may select the desired amplitude and wavelength content of the measured profile. The analog of the road profile is recorded on magnetic tape for subsequent analysis and, when desired, channeled to the QC Simulator or a strip-chart recorder for a scaled, visual record. Signals representing distance traveled and reflectivity of the pavement surface are also processed by the computer for recording.

A detailed description of the SD Profilometer is presented in APPENDIX A. A schematic of the QC Simulator is shown in Figure 2, and a detailed description is given in APPENDIX B.

Figure 1. Block Diagram of Measurement System.



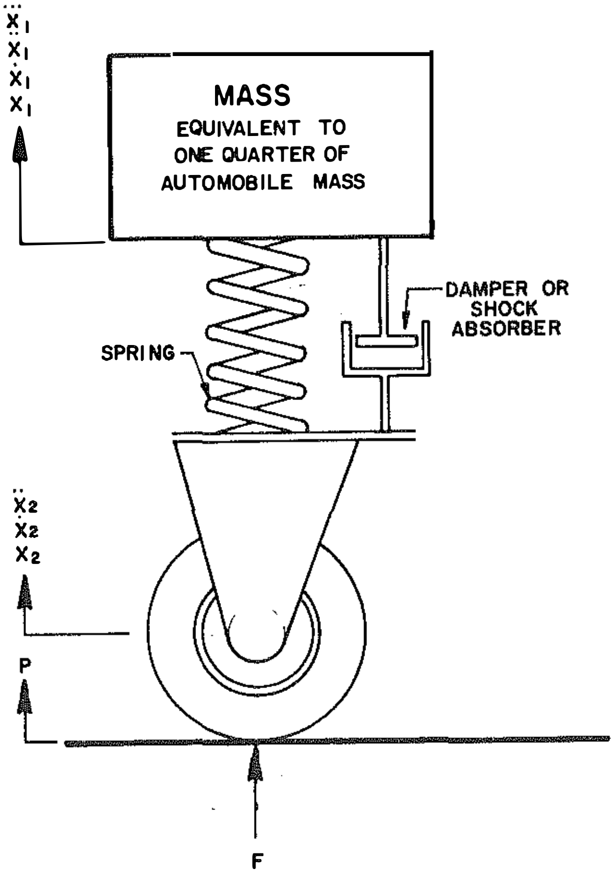


Figure 2. Quarter-Car Suspension Configuration.

PROCEDURES

CALIBRATION

The equipment was calibrated quarterly during the first year and semi-annually during the next 2 years. Based on this experience, calibration has been performed semi-annually during periods of limited testing but more often during periods of extensive testing. Calibration procedures are presented in APPENDIX C.

Two calibrations are required for the QC Simulator. These are the calibration of the vehicle simulation circuitry and the calibration of the summary statistics circuitry. Procedures are presented in APPENDIX C.

MEASUREMENT

Filter Selection. Very low frequency signals (long wavelength), induced by hills and grade changes, are filtered from the profile measurement to prevent overloading of the profile computer and the recorder with high-amplitude features of the roadway. The profile does not resemble the actual terrain. A true elevation map of the terrain can be produced by restoring long-wave features through the process of tipping *(3)*. This requires elevation measurements at predetermined intervals, such as every 100 feet (30 meters). For ride and roughness evaluations, however, the profile, as measured with the SD Profilometer, is adequate *(4, 5)*.

To allow some versatility in obtaining desired wavelength information, four filter selections are provided. The four filter natural frequencies of the four filters are sufficent to cover the expected range of road surface characteristics. The frequency response through each filter section is shown in Figure 3 (left side) and Figure 4 (right side). Since computations for each of the wheel paths are performed independently of each other, it is not necessary that the same filter band be used for both wheel paths. Selection of the proper filter depends on the speed and the road characteristics to be measured.

Filter 1. The 0.3-radian-per-second filter is for general purposes; above 20 mph (9 m/s), this filter admits all wavelength information necessary to evaluate the quality of road for all vehicle speeds.

Filter 2. The 0.6-radian-per-second filter, when used with speeds of 40 mph (18 m/s) or higher, admits wavelength information needed. When the recording speed is 40 mph (18 m/s) or higher, the 0.6-radian-per-second filter provides better selection than the 0.3-radian filter because scaling in the profile computer offers better resolution.

Filter 3. The 1.0-radian-per-second filter does not admit enough information to evaluate the quality of the higher-speed roads for all frequencies important to automobiles. This filter is useful to measuring roads where the recording speed and the speed of normal traffic are about the same. This filter allows better resolution of short wavelengths than Filter 1 and Filter 2.

Filter 4. The 3.0-radians-per-second filter is useful for evaluating the high frequency content of the road profile. This filter tends to attenuate the longer wavelengths and, in effect, amplify the shorter wavelengths which cause automobile shake.

Initially, a test speed of 34 mph (15.2 m/s) was selected for normal recording. Filter 2 was used for the left wheel path and Filter 3 for the right wheel path. More recently, a test speed of 40 mph (17.9 m/s) was adopted, and Filter 2 was used for both wheel paths.

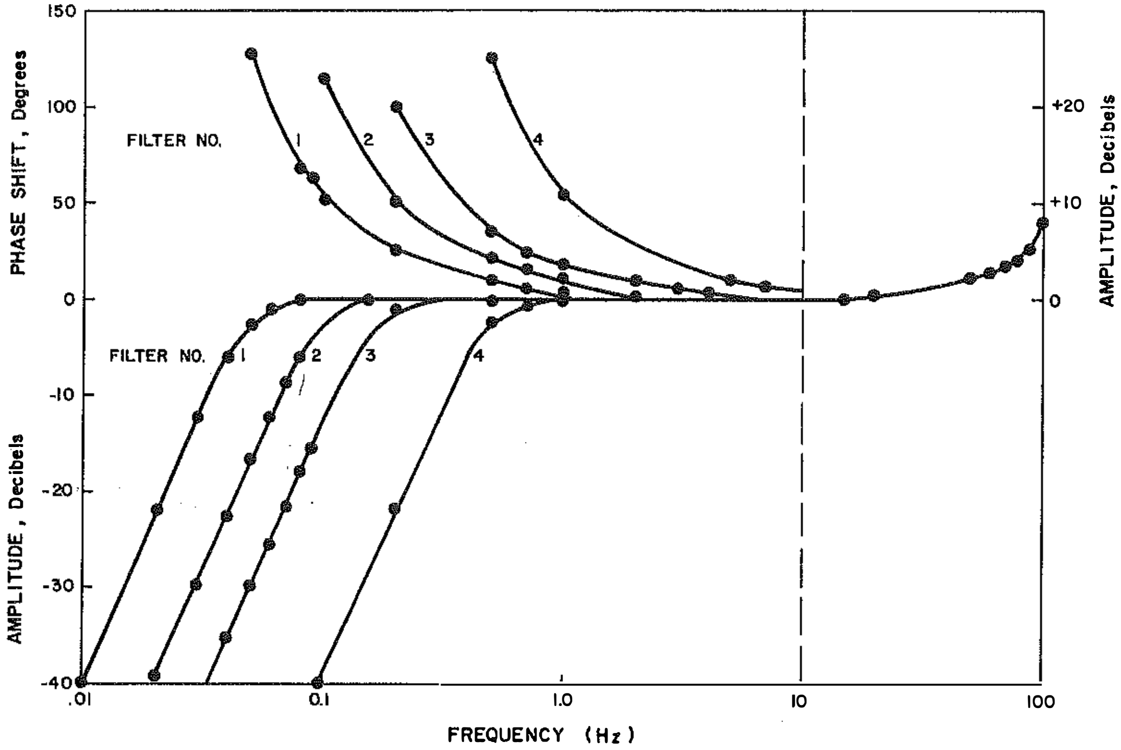
Gain. The highest gain setting which will not cause an overload of the computer is selected. If the roughness of the road can be estimated, the following gain settings would be used:

	Road Profile Rating		
Filter	Rough	Normal	Smooth
1	0.2	0.5	1
2	0.5	1	1
3	1	1	2
4	1	2	2

If the roadway roughness is not known, a trial run may be necessary. The road-following wheels may be left in the up position for the trial run.

QC Simulator Settings. As a result of correlations with the automobile method of test (discussed later), the Roughness Index, using the BPR Roughometer simulator, was selected for routine measurement. Three signals -- the road profile for the left wheel path, distance pulses, and system ground -- from the profile computer are connected to the QC Simulator. Switch or dial settings to be made are distance interval at 1/16 mile (101 meters), velocity at 20 mph (8.9 m/s), gain to match the profile computer gain setting, and the output switches to "RI" and "INTEG".

Figure 3. SD Profilometer System Frequency Response and Phase Shift – Left Side.



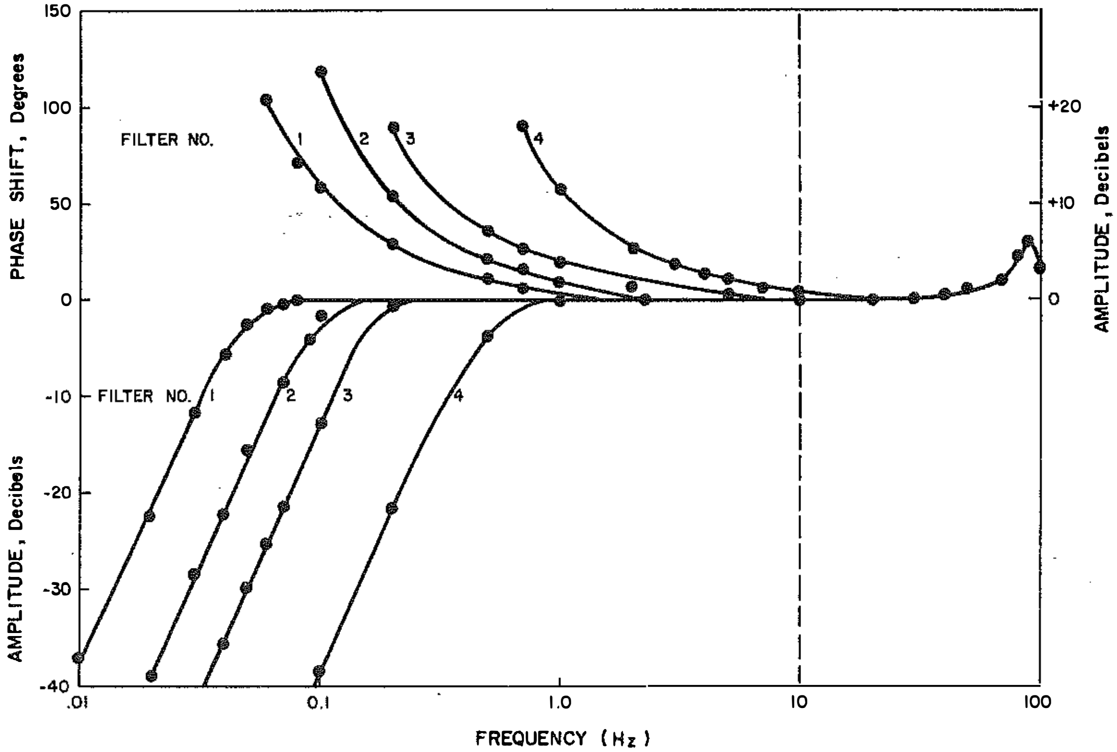


Figure 4. SD Profilometer System Frequency Response and Phase Shift – Right Side.

Test Run. Allow 15 to 20 minutes for warm up. The vehicle is stopped a sufficient distance from the test section to allow transients, introduced in the vehicle once it begins to move, to subside before entering the test section. The minimum approach distance can be approximated from

$$D = 10\ V/f \text{ (in International Units } D = 6.8\ V/f\text{)}$$

where D = minimum approach distance in feet (meters),
V = test speed in mph (m/s), and
f = natural frequency of the selected filter in rad/sec.

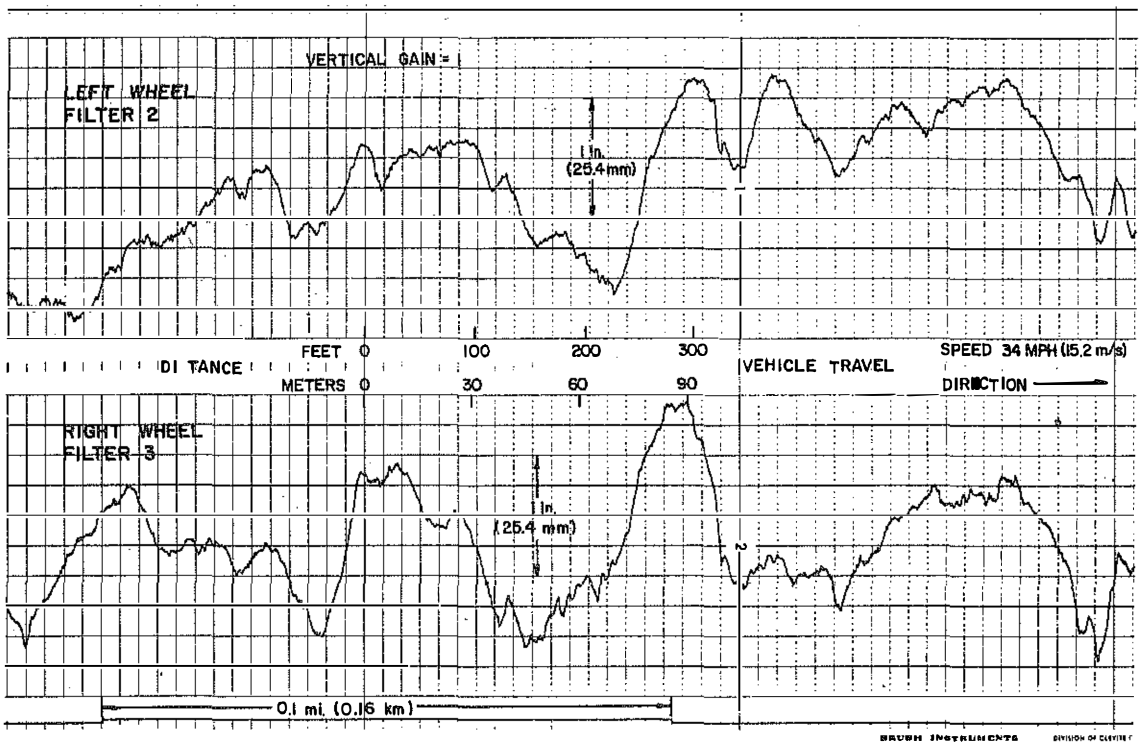
The following wheels are then lowered to the ground and the "STEP" and "TRANSIENT" calibration signals are recorded on magnetic tape.

The driver accelerates as rapidly and smoothly as possible to the selected speed. The tape recorder and QC Simulator printer are started before entering the test section. Upon entering the test section, an event mark is inserted and the QC Simulator reset button is released. During the test, the driver maintains the selected speed as closely as possible and minimizes steering corrections. The operator observes the profile on the oscilloscope, triggers event marks where necessary, and records oral descriptions of test conditions on tape. A typical road profile obtained with the profilometer is shown in Figure 5.

QC Simulator Output. Upon completion of each 1/16 mile (101 meters) traversed, the roughness index for that interval is printed. In the office, the incremental roughness indices are punched on computer cards. Increments containing bridges or overpasses are omitted. A computer program then determines the average index for the test section and determines the distribution of roughness in terms of 1/16-mile (101-meter) increments. Figure 6 is a typical computer printout from one run.

Other simulations are obtained in the laboratory as needed by replaying the magnetic tape and inputing the signals to the QC Simulator. The magnetic tape is replayed at the same speed as when recorded. The reproduce electronics are adjusted to the same output voltage as was inputed. The voltage equivalent to 1.0 inch (25.4 mm) of upward displacement ("Step Calibration Switch"), applied at the beginning of the test section, is used for this purpose. The appropriate gain, simulation variable, and speed are selected on the QC Simulator. The printer is energized and the reset button depressed. The reset button is released when the tape event signal indicates the start of the test section. Other events, such as bridges, are marked on the printout. The printer is turned off at the end of the test section.

Figure 5. Typical Road Profile Obtained with SD Profilometer.



```
ROUTE NO.    PROJECT NO.    LANE    TEST DATE    SHEET NO.
   I75       I75-2(24)35     NBO     1/21/74        14

                    CONCRETE   PAVEMENT

     NO. OF INCREMENTS    TOTAL SUM    AVERAGE BPR RI
           90              7505.94         83.45

*****************************************************

         DISTRIBUTION OF BPR ROUGHNESS INDEX

   GREATER THAN        LESS THAN          PERCENT OF
    OR EQUAL                              INCREMENTS

        0                  5                 0.0
        5                 10                 0.0
       10                 15                 0.0
       15                 20                 0.0
       20                 25                 0.0
       25                 30                 0.0
       30                 35                 0.0
       35                 40                 0.0
       40                 45                 0.0
       45                 50                 0.0
       50                 55                 1.11
       55                 60                 0.0
       60                 65                 1.11
       65                 70                 7.78
       70                 75                14.44
       75                 80                12.22
       80                 85                24.44
       85                 90                10.00
       90                 95                12.22
       95                100                 8.89
      100                105                 4.44
      105                110                 1.11
      110                115                 1.11
      115                120                 1.11
      120                125                 0.0
      125                130                 0.0
      130                135                 0.0
      135                140                 0.0
      140                145                 0.0
      145                150                 0.0
```

Figure 6. **Test Section Summary of BPR Roughometer Roughness Index.**

PERFORMANCE

PRECISION

Test Run. A bituminous and a portland cement concrete pavement were selected and repeatedly tested at 34 mph (15.2 m/s) with the SD Profilometer-QC Simulator measuring system. Roughness indices were obtained by simulating the BPR Roughometer. Seven test runs were made on each pavement utilizing Filter 3. Data and standard deviations are presented in Table 1. The standard deviations were 1.0 in. per mi for the bituminous section and 0.8 in. per mi for the portland cement concrete section. The standard deviations indicated that, for bituminous pavements, one measurement will be within 2.7 percent of the sample mean 95 percent of the time; and, for the portland cement concrete pavement, one measurement will be within 2.1 percent of the sample mean 95 percent of the time. Precision may be improved by making two runs. The average of each combination of the seven measurements (Table 1) and the standard deviation of these averages were determined. The standard deviations were 0.6 in. per mi for bituminous pavement and 0.5 in. per mi for portland cement concrete pavement. For the bituminous pavement, the average of two measurements will be within 1.6 percent of the sample mean 95 percent of the time and 1.3 percent for portland cement concrete pavement.

To determine if the various levels of roughness affected the precision differently, repeated test runs were made on 12 bituminous sections. RI (X_1 - X_2) and displacement (X_1) of the simulated BPR Roughometer at 20 mph (8.9 m/s) were obtained for the left wheel path using Filter 2 and a test speed of 34 mph (15.2 m/s). Four runs were made; the standard deviations from the mean are presented in Table 2. The standard deviations were comparable to those determined previously for the single, bituminous section (seven test runs). The standard deviations appear to be independent of roughness. The test section having the lower RI exhibited the same standard deviation as the test section with the higher RI. Thus, as a percentage, the test precision is better on a rougher pavement than on a smoother pavement.

To determine if filter selection would affect precision, two pavements were profiled three times at 34 mph (15.2 m/s) with each filter. The results are presented in Table 3. Standard deviations ranged from 0.7 to 1.2 in. per mi for the bituminous pavement and 0.3 to 0.8 in. per mi for the portland cement concrete pavement. Thus, standard deviations were not significantly different for the various filter selections and were comparable to those cited in Table 1.

Tape Replay. Table 4 illustrates the excellent reproducibility obtainable from repeated playback (Filter 3) into the QC Simulator. The simulated vehicle in this case was the BPR Roughometer, and the variable was displacement (X_1) at 20 mph (8.9 m/s). Standard deviations averaged less than 0.2 in. per mi.

Table 5 presents BPR RI output from playback of the same runs from which the field values, shown in Table 3, were obtained. Unfortunately, all test runs were made using a gain of 1.0. This gain was too high for Filter 1 measurements. The profile signal (Filter 1) exceeded the record-level capability of the tape recorder. The recorded profile measurement, therefore, was distorted. For other filters, standard deviations ranged from 0.6 to 1.1 in. per mi for the bituminous pavement and 0.1 to 0.7 in. per mi for the portland cement concrete pavement. These standard deviations are essentially the same as those obtained in the field and indicated that playback of recorded profiles into the QC Simulator does not create any additional impreciseness.

Other QC Simulator Outputs (Variables). The preceding sections indicated excellent precision of field measurements using the SD Profilometer-QC Simulator system and demonstrated almost perfect reproducibility when recorded on magnetic tape. Field measurements, however, were largely confined to determination of RI in terms of the simulated BPR Roughometer. Available time did not permit repeated field measurements for the many combinations of other QC Simulator outputs and simulated speeds. Since very little variability was attributed to tape replay, values of other QC Simulator outputs, obtained by tape replay, may portray reasonably well the precision obtainable from field measurements.

Replay values for selected variables of the QC Simulator are presented in Tables 6 and 7. Test sections and profile measurements (Filter 2) were the same as for the data shown in Tables 3 and 5. The precision, as indicated by standard deviation, ranged from excellent to fair and primarily reflects reproducibility of field measurements. In most cases, the reproducibility of the left wheel path was better than that of the right wheel path.

TABLE 1. ROUGHNESS INDEX ($x_1 - x_2$) (in./mi) FOR SIMULATED BPR ROUGHOMETER FROM REPEATED TESTS ON SAME TEST SECTION, FILTER 3

PAVEMENT	TEST NUMBER 1	2	3	4	5	6	7	AVERAGE	STANDARD DEVIATION
Bituminous	74.2	75.2	75.7	74.1	72.8	73.9	74.1	74.3	1.0
Concrete	76.4	76.0	75.3	75.0	74.0	74.7	75.7	75.3	0.8

TABLE 2. ROUGHNESS INDEX ($x_1 - x_2$) AND DISPLACEMENT (x_1) AT 20 MPH (8.9 m/s) FOR SIMULATED BPR ROUGHOMETER FROM REPEATED TESTS OF SEVERAL TEST SECTIONS (BITUMINOUS PAVEMENTS), FILTER 2

	ROUGHNESS INDEX (in./mi)						DISPLACEMENT (in./mi)					
	TEST NUMBER						TEST NUMBER					
TEST SECTION	1	2	3	4	AVERAGE	STANDARD DEVIATION	1	2	3	4	AVERAGE	STANDARD DEVIATION
1	58.1	56.1	57.9	56.2	57.2	1.1	50.8	50.2	49.8	50.2	50.2	0.4
2	83.4	83.4	81.2	83.2	82.8	1.1	88.7	91.0	88.9	86.3	88.7	2.0
3	64.9	63.6	66.0	66.4	65.2	1.3	73.8	75.3	75.3	77.2	75.4	1.4
4	69.6	72.8	69.6	70.4	70.6	1.5	66.6	66.0	65.4	65.8	66.0	0.5
5	78.0	75.2	72.8	75.1	75.3	2.1	75.9	74.8	75.2	73.9	75.0	0.8
6	75.7	77.6	77.1	78.5	77.2	1.2	89.6	89.5	89.3	90.0	89.6	0.3
7	66.6	67.7	67.3	65.6	66.8	0.9	71.8	70.5	72.4	72.4	71.8	0.9
8	68.2	68.5	71.0	66.7	68.6	1.8	66.6	70.9	69.1	69.3	69.0	1.8
9	71.0	70.2	71.1	69.2	70.4	0.9	80.8	82.6	81.0	80.2	81.2	1.0
10	65.9	64.7	65.3	66.0	65.5	0.3	66.3	67.7	65.6	62.6	65.6	2.2
11	65.6	68.2	66.4	67.5	66.9	1.2	70.4	72.5	73.7	68.1	71.2	2.5
12	71.4	72.3	72.9	72.7	72.3	0.6						

TABLE 3. ROUGHNESS INDEX ($x_1 - x_2$) (in./mi) FOR SIMULATED BPR ROUGHOMETER FROM REPEATED TESTS ON SAME TEST SECTION

	BITUMINOUS PAVEMENT					CONCRETE PAVEMENT				
	TEST NUMBER					TEST NUMBER				
FILTER	1	2	3	AVERAGE	STANDARD DEVIATION	1	2	3	AVERAGE	STANDARD DEVIATION
1	72.0	74.2	72.5	72.9	1.2	74.7	74.8	74.3	74.6	0.3
2	73.0	72.3	70.6	72.0	1.2	75.5	74.1	74.5	74.7	0.7
3	73.4	72.9	72.1	72.8	0.7	77.0	75.9	76.6	76.5	0.6
4	71.3	73.4	73.5	72.7	1.2	74.5	75.7	76.0	75.4	0.8

TABLE 4. DISPLACEMENT (x_1) (in./mi) AT 20 MPH (8.9 m/s) FOR SIMULATED BPR ROUGHOMETER FROM REPEATED TAPE REPLAY (BITUMINOUS PAVEMENTS)

TEST SECTION	REPLAY NUMBER 1	2	3	4	AVERAGE	STANDARD DEVIATION
1	52.3	52.2	52.3	52.2	52.2	0.1
2	83.9	84.1	84.1	84.0	84.0	0.1
3	77.3	77.7	77.6	77.6	77.6	0.2
4	63.8	63.5	63.4	63.4	63.5	0.2
5	73.5	74.0	73.9	73.8	73.8	0.2
6	89.2	89.1	89.1	89.0	89.1	0.1
7	73.4	72.9	73.0	73.2	73.1	0.2
8	67.2	67.6	67.6	67.4	67.5	0.2
9	82.2	82.1	81.8	81.9	82.0	0.2
10	63.1	63.2	63.3	63.4	63.3	0.1
11	69.5	69.7	69.7	69.7	69.6	0.1

TABLE 5. ROUGHNESS INDEX (x_1 - x_2) (in./mi) FOR SIMULATED BPR ROUGHOMETER FROM TAPE PLAYBACK OF REPEATED TESTS ON SAME TEST SECTION

FILTER	BITUMINOUS PAVEMENT TEST NUMBER 1	2	3	AVERAGE	STANDARD DEVIATION	CONCRETE PAVEMENT TEST NUMBER 1	2	3	AVERAGE	STANDARD DEVIATION
1	110.5	116.2	115.7	114.1	3.2	83.8	78.3	82.3	82.3	3.0
2	73.3	72.7	71.4	72.5	1.0	75.7	74.7	75.0	75.1	0.5
3	73.9	72.8	73.6	73.4	0.6	77.2	77.0		77.1	0.1
4	71.7	73.4	73.7	72.9	1.1	74.8	75.8	76.1	75.6	0.7

TABLE 6. INDICES FOR SEVERAL VARIABLES OF THE QUARTER CAR SIMULATOR FROM TAPE PLAYBACK OF REPEATED TESTS (FILTER 2) ON SAME TEST SECTION (BITUMINOUS PAVEMENT)

VARIABLE*	TEST NO.	BPR ROUGHOMETER SIMULATED SPEED 20 MPH (9 m/s) WHEEL PATH LEFT	BPR ROUGHOMETER SIMULATED SPEED 20 MPH (9 m/s) WHEEL PATH RIGHT	1969 CHEVROLET IMPALA SIMULATED SPEED 55 MPH (25 m/s) WHEEL PATH LEFT	1969 CHEVROLET IMPALA SIMULATED SPEED 55 MPH (25 m/s) WHEEL PATH RIGHT	1969 CHEVROLET IMPALA SIMULATED SPEED 70 MPH (31 m/s) WHEEL PATH LEFT	1969 CHEVROLET IMPALA SIMULATED SPEED 70 MPH (31 m/s) WHEEL PATH RIGHT
Load	1	86.6	88.2	101.0	103.4	105.3	100.1
	2	86.9	90.6	103.2	107.6	106.1	103.5
	3	84.6	96.0	101.5	107.8	104.1	109.5
	Average	86.0	91.6	101.9	106.3	105.2	104.4
	SD**	1.3	4.0	1.2	2.5	1.0	4.8
Displacement	1	86.3	75.1	72.9	65.0	69.4	63.8
	2	87.4	73.9	72.9	64.4	69.9	64.1
	3	85.8	70.0	72.5	64.3	68.8	62.6
	Average	86.5	73.0	72.8	64.6	69.4	63.5
	SD	0.8	2.7	0.2	0.4	0.6	0.8
Velocity	1	76.2	74.0	39.8	35.4	38.9	36.3
	2	70.3	65.1	39.8	36.7	38.9	36.8
	3	74.4	70.3	39.5	37.3	40.3	36.3
	Average	73.6	69.8	39.7	36.5	39.4	36.5
	SD	3.0	4.5	0.2	1.0	0.8	0.3
Acceleration	1	159.5	151.3	67.6	63.5	68.7	65.3
	2	154.9	154.4	68.0	67.2	63.4	65.3
	3	154.9	161.1	67.7	68.6	68.6	67.4
	Average	156.6	155.6	67.8	66.4	66.9	66.0
	SD	2.9	5.0	0.2	2.6	3.0	1.2
Jerk	1	322.4	279.5	236.8	234.1	210.1	201.3
	2	275.1	289.7	236.3	233.9	209.8	202.3
	3	295.6	300.4	235.3	238.1	208.5	205.8
	Average	297.7	289.9	236.1	235.4	209.5	203.1
	SD	23.7	10.4	0.8	2.4	0.9	2.4

*See Table 3 for scaling

**Standard Deviation of the average

TABLE 7. INDICES FOR SEVERAL VARIABLES OF THE QUARTER CAR SIMULATOR FROM TAPE PLAYBACK OF REPEATED TESTS (FILTER 2) ON SAME TEST SECTION (CONCRETE PAVEMENT)

		BPR ROUGHOMETER		1969 CHEVROLET IMPALA			
VARIABLE*	TEST NO.	SIMULATED SPEED 20 MPH (9 m/s) WHEEL PATH		SIMULATED SPEED 20 MPH (9 m/s) WHEEL PATH		SIMULATED SPEED 70 MPH (31 m/s) WHEEL PATH	
		LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
Load	1	106.5	101.7	115.5	108.9	114.0	110.6
	2	105.9	102.6	114.5	108.7	112.8	112.3
	3	105.0	101.9	115.0	107.4	112.8	111.7
	Average	105.8	102.1	115.0	108.3	113.2	111.5
	SD**	0.8	0.5	0.5	0.8	0.7	0.9
Displacement	1	63.5	64.7	36.8	38.6	34.3	34.6
	2	63.0	64.2	36.7	38.7	33.9	35.0
	3	62.8	66.0	36.7	38.2	34.0	34.4
	Average	63.1	65.0	36.7	38.5	34.1	34.7
	SD	0.4	0.9	0.1	0.3	0.2	0.3
Velocity	1	63.9	65.4	22.1	23.5	20.8	21.9
	2	63.4	63.7	21.9	24.7	20.6	22.6
	3	63.4	65.5	22.1	25.4	20.3	20.4
	Average	63.6	64.9	22.0	24.5	20.6	21.6
	SD	0.3	1.0	0.1	1.0	0.3	1.1
Acceleration	1	187.8	172.8	58.9	58.3	59.0	56.6
	2	179.6	174.9	58.6	59.7	57.8	61.2
	3	181.3	174.7	60.0	61.0	53.8	59.0
	Average	182.9	174.1	59.2	59.7	56.9	58.9
	SD	4.1	1.2	0.7	1.0	2.7	2.3
Jerk	1	282.9	258.6	246.7	234.6	212.1	205.6
	2	249.9	262.6	247.2	237.7	212.4	208.6
	3	262.4	275.7	248.9	232.9	212.4	207.1
	Average	265.1	265.6	247.6	235.1	212.3	207.1
	SD	16.7	8.9	1.2	2.4	0.2	1.5

*See Table 3 for scaling

**Standard Deviation of the average

COMPARISONS

Filter Selections. Results from three test runs at 34 mph (15.2 m/s) with each filter on the two types of pavements, as presented in Table 3, were previously evaluated for precision. Even though test runs with the different filters were not made on the same day (within a 10-day period), mean RI values for the three runs were numerically in close agreement. In fact, the standard deviation of the means for the four filters was 0.4 in. per mi for bituminous pavement and 0.9 in. per mi for portland cement concrete pavement. A more realistic determination of the variability was obtained by combining the 12 individual values for each pavement to obtain an overall average and standard deviation. Standard deviations were 1.0 in. per mi for both the bituminous pavement and the portland cement concrete pavement. These standard deviations were comparable to those in Table 1 and indicated that the numerical variability between RI values obtained with different filters were within the limits of precision of the SD Profilometer-QC Simulator system.

Distance Intervals. The summary statistics from the QC Simulator can be obtained over distance intervals of 1/6, 1/8, and 1/4 mile (101, 201, and 402 meters). The circuit differences for the three selections are a distance pulse-rate divider and a summation-count multiplier. To verify that the summary-statistics output is not affected by the distance selection, average RI for the test sections at three distance intervals (from tape replay) were averaged and compared. Average RI of the simulated BPR Roughometer were obtained for each distance selection from tape replay of the profile measurements on both bituminous and portland cement concrete pavements. The length of sections were between 1 1/2 miles (2.4 km) and 3 miles (4.8 km). Results are presented in Table 8. As indicated by the standard deviations, variations between the RI values were very small. About one-half of the variations may be attributable to errors associated with tape replay (see Table 4). The remaining variation indicated that average BPR Roughometer RI's obtained for different distance selections on a given test section will differ by less than 0.3 percent.

TABLE 8. ROUGHNESS INDEX (x_1 - x_2) (in./mi) FOR SIMULATED BPR ROUGHOMETER OBTAINED AT DIFFERENT DISTANCE INTERVALS

DISTANCE INTERVAL		BITUMINOUS PAVEMENT TEST SECTION			CONCRETE PAVEMENT TEST SECTION		
MILES	METERS	1	2	3	1	2	3
1/16	101	32.2	49.9	61.4	77.4	80.1	81.4
1/8	201	32.1	49.8	60.8	76.8	80.7	81.2
1/4	402	32.0	50.0	61.1	77.1	80.2	81.8
Standard Deviation		0.1	0.1	0.3	0.3	0.3	0.3

Field and Playback Values. A comparison of Table 5 with Table 3 provides an indication of the accuracy of BPR Roughometer RI's obtained from tape playback and those obtained in the field. The averages and the percent differences between playback and field values are presented in Table 9. As indicated previously, playback values through Filter 1 measurements were invalid. For the other filters, the differences were less than one percent. Playback's for bituminous pavements had about the same precision as those for portland cement concrete pavements. The playback values were slightly higher than the field values.

Wheel Path. Differences between the Roughness Indices (simulated BPR Roughometer) of the left wheel path and the right wheel path were investigated by playback of repeat measurements (see Table 3) to obtain a RI for each wheel path. The average values of the three replayed measurements and the percent differences are presented as the August measurements in Table 10. Differences were about 13 percent for bituminous pavements and 6 to 8 percent for portland cement concrete pavement. However, one month later (September), retests (two measurements on each section) of the same pavements indicated different percentages (Table 10).

Results from both wheel path tests (tape replay) on other pavements are presented in Table 11. Differences between the wheel paths were not consistent amongst test sections. Values for the left wheel path were not consistently larger than those for the right wheel path.

Single Wheel Testing. The profilometer senses each wheel path independently. Occasionally, the following-wheel assembly or electronics of one side malfunctioned. In instances where the left side remained operational, or could be made operational by substituting right-side components, testing was continued with only the left following wheel in the down position. To determine if any differences resulted from testing with a single wheel, several test sections that had been profiled with both wheels down and sensing (see Table 10) were also profiled with only the left following wheel in the down position. The test data are compared in Table 12. Differences were small and within the precision limits of the SD Profilometer-QC Simulator system.

TEST SPEED

The QC Simulator values compared heretofore were obtained from profiles measured at a test speed of 34 mph (15.2 m/s). To determine the influence of test speed on simulation results, five test sections of each pavement type were measured at three speeds. The results are presented in Table 13. The average difference between RI's obtained at 34 mph (15.2 m/s) and 40 mph (17.9 m/s) was 2.0 percent for bituminous pavements and 1.5 percent for portland cement concrete pavements. The 40-mph (17.9-m/s) values were lower on both pavement types. The average difference between values obtained at 40 mph (17.9 m/s) and 50 mph (22.4 m/s) was 3.9 percent for bituminous pavement and 3.7 percent for portland cement concrete pavement. The 50-mph (22.4-m/s) values were lower.

The difference between the two lower speeds was within the reproducibility of the system. However, the difference between 40 mph (17.9 m/s) and 50 mph (22.4 m/s) values was larger than expected. An investigation was made to determine contributing influences.

Frequency Response. Response of the SD Profilometer to the low frequencies (long wavelength) (see Figures 3 and 4) is different for each of the four filters. As mentioned before, the BPR Roughometer RI at 34 mph (15.2 m/s) was not influenced by filtering. This indicated that long waves attenuated by Filter 4 did not significantly influence QC Simulator values. Since increase in test speed shifts the measurement range to longer wavelengths, the resulting RI will not be different. As a cursory check of filter comparison at a higher speed, measurements were made at 50 mph (22.4 m/s) on two pavements using Filter 2 and Filter 4. Results are presented in Table 14. Measurements on the portland cement concrete pavement yielded almost identical results, and on the bituminous pavement there was only a slight difference (Filter 4 value larger). Since any attenuation by Filter 4 should result in smaller values, the difference cannot be attributed to attenuation of the long waves.

Frequency response of the SD Profilometer is also dependent upon the mechanical response of the measuring system. As shown in Figure 3, response greater than 3 decibels occurs for frequencies above 60 Hz. This corresponds to wavelengths of about 0.8 foot (0.24 meter) at 34 mph (15.2 m/s) and 1.2 feet (0.37 meter) at 50 mph (22.4 m/s). Increase in speed changes the response to the short wavelengths. For example, at 34 mph (15.2 m/s), the response to wavelengths of 1.2 feet (0.37 meter) is 2 decibels; at 50 mph (22.4 m/s), the response is 3 decibels. However, parameters in the QC Simulator (except for tire force) are not significantly affected by the higher frequencies (see Figure C2), and any change in the SD Profilometer response should not significantly change outputs of the QC Simulator.

TABLE 9. ROUGHNESS INDEX ($x_1 - x_2$) (in./mi) FOR SIMULATED BPR ROUGHOMETER: COMPARISON BETWEEN FIELD AND PLAYBACK VALUES

	BITUMINOUS PAVEMENT			CONCRETE PAVEMENT		
FILTER	FIELD	PLAYBACK	PERCENT DIFFERENCE	FIELD	PLAYBACK	PERCENT DIFFERENCE
1	72.9	114.1	56.5	74.6	82.3	10.3
2	72.0	72.5	0.7	74.7	75.1	0.5
3	72.8	73.4	0.8	76.5	77.1	0.8
4	72.7	72.9	0.3	75.4	75.6	0.3

TABLE 10. ROUGHNESS INDEX ($x_1 - x_2$) (in./mi) FOR SIMULATED BPR ROUGHOMETER FROM TAPE REPLAY: COMPARISON BETWEEN LEFT WHEEL PATH AND RIGHT WHEEL PATH ON SAME TEST SECTION

	BITUMINOUS PAVEMENT			CONCRETE PAVEMENT		
	WHEEL PATH			WHEEL PATH		
FILTER	LEFT	RIGHT	PERCENT DIFFERENCE	LEFT	RIGHT	PERCENT DIFFERENCE
			August Measurements			
2	72.5	63.1	13.0	75.1	70.3	6.4
3	73.4	64.0	12.8	77.1	70.8	8.2
4	72.9	63.3	13.2	75.6	71.4	5.6
			September Measurements			
3	73.5	67.0	8.8	75.3	75.3	0.0

TABLE 11. ROUGHNESS INDEX (x_1 - x_2) (in./mi) FOR SIMULATED BPR ROUGHOMETER FROM TAPE REPLAY: COMPARISON BETWEEN LEFT WHEEL PATH AND RIGHT WHEEL PATH ON SEVERAL TEST SECTIONS (FILTER 2)

TEST SECTION	BITUMINOUS PAVEMENT			CONCRETE PAVEMENT		
	WHEEL PATH		PERCENT DIFFERENCE	WHEEL PATH		PERCENT DIFFERENCE
	LEFT	RIGHT		LEFT	RIGHT	
1	69.6	67.5	3.0	150.4	151.3	0.6
2	67.9	72.1	6.2	79.6	84.2	5.8
3*	44.5	51.2	15.1	97.0	96.6	0.4
4	54.8	52.3	4.6	67.3	75.6	12.3
5	46.6	50.8	9.0	77.5	80.6	4.0
6	45.7	43.8	4.2	87.5	86.3	1.4

*Inner Lane (all other test sections were in the outer lane)

TABLE 12. ROUGHNESS INDEX (x_1 - x_2) (in./mi) FOR SIMULATED BPR ROUGHOMETER -- LEFT WHEEL PATH, 40 MPH (17.9 m/s), FILTER 2: WITH BOTH FOLLOWING WHEELS DOWN AND WITH ONLY LEFT FOLLOWING WHEEL DOWN

TEST SECTION	BITUMINOUS PAVEMENT			CONCRETE PAVEMENT		
	WHEEL DOWN		PERCENT DIFFERENCE	WHEEL DOWN		PERCENT DIFFERENCE
	BOTH	LEFT		BOTH	LEFT	
1	42.1	41.3	1.9	66.0	65.8	0.3
2	43.9	44.3	0.9	58.8	59.2	0.7
3	48.8	49.3	1.0	82.8	83.9	1.3
4	53.3	53.1	0.4	132.5	135.2	2.0
5	57.2	58.6	2.4	137.2	136.2	0.7

TABLE 13. ROUGHNESS INDEX (x_1 - x_2) (in./mi) FOR SIMULATED BPR ROUGHOMETER: COMPARISON OF MEASUREMENTS AT THREE SPEEDS (FILTER 2)

TEST SECTION	BITUMINOUS PAVEMENT TEST SPEED, MPH (m/s) 34 (15.2)	40 (17.9)	50 (22.4)	CONCRETE PAVEMENT TEST SPEED, MPH (m/s) 34 (15.2)	40 (17.9)	50 (22.4)
1	42.7	42.1	40.2	66.7	66.0	64.7
2	44.6	43.9	43.7	58.6	58.8	57.9
3	47.1	48.8	45.7	82.1	82.8	80.6
4	53.2	53.3	51.6	135.3	132.5	123.7
5	59.1	57.2	54.3	141.8	137.2	129.6

TABLE 14. ROUGHNESS INDEX (x_1 - x_2) (in./mi) FOR SIMULATED BPR ROUGHOMETER -- SAME TEST SECTION, 50 MPH (22.4 m/s) TEST SPEED: COMPARISON BETWEEN FILTER 2 AND FILTER 4

FILTER	PAVEMENT BITUMINOUS	CONCRETE
2	62.4	70.2
4	63.4	70.0

Pulse Rate Error. The distance-pulse count for calibration was obtained at 40 mph (17.9 m/s). The count was used in setting the null in the speed-meter comparison circuit. The pulse rate was found not to be directly proportional to speed. Test speeds below or above 40 mph (17.9 m/s) were found to be slightly lower or higher, respectively, than the selected speed. For instance, the speed for a 50-mph (22.4-m/s) selection was 50.2 mph (22.5 m/s).

The speed error causes a corresponding error in the QC Simulator summary statistics. The QC Simulator sampled only a percentage of the input signal (see APPENDIX B). This percentage depends upon both test and simulated speeds. For a simulated speed of 20 mph (8.94 m/s) and a test speed of 40 mph (17.9 m/s), 40 percent of the signal is sampled. The percentage should increase in direct proportion to the increase in test speed (50 percent at 50 mph (22.4 m/s), 60 percent at 60 mph (26.8 m/s), etc.). Due to the pulse rate error, however, the sampling percentage for a test speed of 50.2 mph (22.5 m/s) was found to be 50 percent rather than 50.2 percent. Therefore, the resulting QC Simulator summary statistics at the indicated test speed of 50 mph (22.4 m/s) would be 0.4 percent smaller than at 40 mph (17.9 m/s).

BREAKDOWNS AND REPAIRS

Repairs often involved extensive loss in time and were expensive. Major problems were associated with the road-following wheel system; these and other problems are enumerated:

1. The road-following wheels lasted between 500 to 1,000 lane-miles (800 to 1,600 lane-kilometers) of testing. Usually the tread became pitted and out-of-round. In some instances, structural damage occurred to the wheels. Worn wheels were returned to the manufacturer for retreading. Damaged wheels were replaced. Considerable delays occurred in the repair and delivery of the wheels.

2. The hydraulic system used in raising and lowering the road-following wheels failed several times. The electrical motor was overhauled once. The hydraulic pistons which raises the wheels were replaced. All relays and valves required replacement. Adjustments of the raising and lowering controls are critical and periodic readjustments have been required.

3. The slider shafts on which the linear potentiometers are mounted were occasionally bent. Four became unserviceable. Pins connecting the slider

shafts to the following-wheel assembly frequently broke. The cause of these failures remains uncertain. Damage has resulted when the following-arm centering springs broke, and the shafts struck the body of the vehicle during raising or lowering maneuvers. The pins also seem to be subject to fatigue failure caused by vibration. Another cause might be improper tracking, due to longitudinal cracks or severe turning movements, which may cause the shaft to bind against the vehicle body.

4. Yolks holding the following wheels to the arms cracked alongside the weld. They were rewelded.

5. Transmission fluid leaked into the Veedor Root Pulse Generator. The assembly was removed, cleaned, and reinstalled. Fluid leakage occurred about every 6 months and normally required 2 to 3 days for repairs.

6. The tape recorder tracking changes due to component looseness resulting from vehicle-induced vibrations. Since an additional tape recorder was needed for other purposes, a sturdier but otherwise identical recorder was obtained to replace the recorder in the vehicle. These problems and other minor ones associated with the three alternators, six pulley belts, two inverters, and various instrumentation components have been frustrating. A stock of spare parts, frequent preventive maintenance, and proper operating precautions were essential to assure continued operation of the SD Profilometer. The development and manufacture of a noncontacting probe is envisioned for the future. A probe to replace the road-following wheel will surely improve the dependability of the SD Profilometer.

CORRELATION BETWEEN AUTOMOBILE AND SD PROFILOMETER--QC SIMULATOR SYSTEM

Since 1957, pavement roughness has been measured with an automobile *(1, 2, 6, 7)*. Vertical accelerations of a passenger riding in the automobile were automatically summed while traveling a section of road at 51.5 mph (23.0 m/s). A roughness index was obtained by summing the accelerations and dividing by the time elapsed during the test. The resulting roughness index was used to judge construction practices, paving and grading equipment, and general workmanship of the contractor. Many thousands of lane-miles (lane-kilometers) of newly constructed and older roads were tested and periodically retested.

Measurements obtained with SD Profilometer-QC Simulator system, of course, differs from the automobile method of test. Correlation of the two methods, therefore, was necessary to enable continued assessment of pavements previously tested with the automobile. A roughness index of only one variable of the QC Simulator could be obtained from a single profile measurement in the field. The selected index should be one which correlates well with the automobile method of test.

Test sections, ranging from smooth to rough, were tested with both devices at the same time. The left wheel-path profile signal was processed during the test run utilizing the simulated BPR Roughometer to obtain RI. Variables associated with the car simulation were obtained from later replay of the left wheel-path recording. Velocity ($\dot{X}_1$) output was also obtained from replay of the right wheel-path profile. Resulting indices are presented in Table 15.

A separate correlation was warranted for each pavement type. Data for pavements composed of a bituminous surface and a portland cement-concrete base (Sites 15B-20B) did not fit the relationship for bituminous pavements. Data from continuously reinforced (Sites 15C and 16C) and older pavements (Sites 17C-20C) with closely spaced construction joints did not fit the relationships for the newer portland cement concrete pavements.

Results from linear regression analysis between the automobile and variables of the QC Simulator are presented in Table 16. On bituminous pavements, the best correlation was obtained with the Roughness Index of the BPR Roughometer. For the car simulation at a 20-mph (8.9-m/s) simulated speed, the best correlations were obtained for displacement and velocity. At the higher simulated speed (70 mph (31.3 m/s)), acceleration and jerk provided the best correlations. On portland cement concrete pavements, the highest coefficients of correlation were obtained for displacement and velocity at the simulated speed of 20 mph (8.9 m/s). At higher simulated speeds, correlations generally were not as good. Unfortunately, the correlation between the automobile method of test and the BPR Roughometer RI yielded a coefficient of correlation of only 0.851.

Displacement and velocity indices (car simulation) at the simulated speed of 20 mph (8.94 m/s) correlated well with the automobile method of test for both pavement types, and in this respect, either would be a good choice as the roughness index to be obtained routinely during field measurements. The velocity index, however, had a very limited range of values for portland cement concrete pavements and was judged not be be adequate as a standard measure of roughness. Even though the BPR Roughometer RI's on portland cement concrete pavements did not correlate as well with the automobile method of test as did displacement (car simulation), the BPR Roughometer RI's had the added advantage of being a widely understood measure of roughness. For this reason, the index obtained by simulating the BPR Roughometer was selected as the

TABLE 15. RESULTS FROM THE AUTOMOBILE METHOD OF TEST AND SEVERAL VARIABLES* OF THE QUARTER CAR SIMULATOR

	AUTOMOBILE METHOD OF TESTING	BPR ROUGHOMETER SIMULATED SPEED 20 MPH	1969 CHEVROLET IMPALA SIMULATED SPEED 20 MPH					1969 CHEVROLET IMPALA SIMULATED SPEED 70 MPH				
SITE NO	ROUGHNESS INDEX (RI)	ROUGHNESS INDEX (BPR RI)	DISP	VELOCITY LEFT	VELOCITY RIGHT	ACCEL	JERK	DISP	VELOCITY LEFT	VELOCITY RIGHT	ACCEL	JERK
			BITUMINOUS PAVEMENTS									
1B	370	57.5	60.5	29.1	27.8	69.1	349.6	52.2	28.7	29.8	50.4	183.0
2B	275	49.8	54.0	24.9	20.0	64.4	337.9	52.0	27.4	22.8	41.8	162.6
3B	450	60.3	65.6	29.4	29.3	73.3	349.8	63.4	32.3	35.0	57.2	191.2
4B	350	47.4	62.2	27.1	23.2	64.6	338.0	68.7	34.7	31.3	46.7	163.2
5B	740	89.8	131.0	55.1	56.9	101.9	333.8	102.7	58.2	62.7	75.5	239.7
6B	800	95.3	122.8	57.5	59.1	109.3	336.6	101.6	53.3	64.0	85.9	245.0
7B	520	67.9	74.8	36.9	45.6	72.6	324.2	74.1	38.5	42.6	70.5	222.5
8B	410	55.1	63.5	28.7	36.5	67.0	330.7	73.5	38.8	43.9	60.3	188.6
9B	430	62.4	70.6	35.6	32.4	75.6	352.8	44.9	24.5	24.6	44.1	184.2
10B	455	63.7	70.0	33.8	34.8	72.5	379.6	41.9	23.7	28.9	55.0	194.6
11B	460	59.7	70.3	38.0	37.6	71.9	367.6	56.9	31.0	33.9	55.3	190.8
12B	590	74.7	97.9	48.5	41.4	71.3	361.6	70.3	39.9	36.0	70.7	216.0
13B	405	55.6	62.0	29.0	28.6	71.2	353.6	60.4	31.3	33.9	53.7	185.4
14B	445	55.2	71.7	32.7	32.6	56.3	339.9	71.2	36.6	39.0	57.4	188.6
15B	730	138.2	111.7	63.1	58.9	71.4	339.7	111.6	59.1	59.2	105.3	262.3
16B	770	133.3	110.1	63.7	63.0	70.4	348.3	129.5	68.3	59.8	99.8	248.0
17B	555	96.8	77.2	43.0	47.7	133.3	365.4	52.3	30.7	33.4	92.3	257.0
18B	560	94.5	75.5	41.0	44.5	135.4	368.3	50.0	29.4	33.3	90.0	246.6
			PORTLAND CEMENT CONCRETE PAVEMENTS									
1C	495	88.0	72.7	39.5	45.7	94.0	323.7	39.5	23.2	27.4	70.5	234.5
2C	465	101.3	69.4	39.1	42.2	109.6	321.7	36.9	24.1	25.7	85.0	260.0
3C	445	87.7	69.5	37.5	35.2	100.4	377.5	34.5	22.3	22.9	65.4	234.6
4C	410	83.9	65.4	35.9	35.8	97.4	376.0	35.5	21.3	21.4	60.2	223.3
5C	460	87.3	66.6	34.8	39.0	99.7	334.9	53.0	30.6	30.0	69.7	236.6
6C	410	76.8	62.6	32.1	31.2	87.1	341.2	52.1	29.1	29.5	63.8	219.7
7C	295	66.1	46.9	24.7	21.5	86.4	350.7	33.2	17.9	16.3	47.2	198.8
8C	275	54.3	40.5	21.3	20.9	76.1	360.9	36.8	19.7	19.6	45.3	186.0
9C	340	73.9	50.4	27.1	29.7	89.0	353.4	36.0	22.0	20.9	62.7	223.0
10C	385	83.3	56.8	29.9	34.4	98.2	352.7	39.3	23.8	26.6	69.3	238.8
11C	320	73.3	45.5	27.0	25.5	88.6	362.8	26.0	16.9	14.8	58.7	220.5
12C	260	59.6	42.1	22.1	21.0	69.2	369.2	24.7	14.1	13.9	45.1	186.9
13C	310	73.4	45.1	26.3	25.3	88.6	343.3	34.4	20.2	18.8	59.9	218.4
14C	285	79.9	42.4	25.9	26.1	83.6	344.8	32.6	21.2	21.8	78.0	240.8
15C	330	57.9	38.4	22.0	21.6	65.9	345.6	29.5	15.7	15.0	52.8	193.3
16C	330	46.1	39.1	20.7	21.5	53.8	318.8	28.7	15.7	16.0	47.1	173.6
17C	495	142.1	70.6	47.2	48.7	148.0	259.7	38.6	26.9	28.1	118.0	306.0
18C	515	136.1	72.3	51.3	49.8	159.5	263.7	43.9	31.0	32.0	125.0	306.2
19C	635	144.3	92.8	56.3	58.6	150.9	312.2	47.9	31.5	30.8	102.8	288.8
20C	620	139.8	105.2	58.5	58.0	145.8	311.7	49.9	32.7	35.1	102.4	283.0

* SEE TABLE 3 FOR SCALING OF SIMULATOR VARIABLES

TABLE 16. RESULTS FROM CORRELATION BETWEEN AUTOMOBILE AND SD PROFILOMETER - QC SIMULATOR SYSTEM

		BITUMINOUS PAVEMENT			CONCRETE PAVEMENT		
QC SIMULATOR OUTPUT (x)**	SIMULATED SPEED	EQUATION*	STANDARD ERROR (E_s)	COEFFICIENT OF CORRELATION (r)	EQUATION*	STANDARD ERROR (E_s)	COEFFICIENT OF CORRELATION (r)
BPR Roughometer RI	20 mph (8.9 m/s)	$Y = 10.05x - 163$	33	0.976	$Y = 5.49x - 58$	44	0.851
Displacement		$Y = 5.93x + 22$	22	0.966	$Y = 6.59x + 3$	15	0.984
Velocity Left		$Y = 13.46x - 8$	38	0.967	$Y = 12.42x - 7$	20	0.970
Velocity Right		$Y = 12.11x + 41$	41	0.961	$Y = 9.58x + 72$	22	0.964
Acceleration		$Y = 8.90x - 183$	73	0.874	$Y = 6.33x - 205$	47	0.827
Jerk		$Y = 1.31x + 933$	149	0.140	$Y = -1.92x + 1043$	75	0.421
Displacement	70 mph (31.3 m/s)	$Y = 6.35x + 55$	90	0.802	$Y = 5.99x + 148$	67	0.595
Velocity Left		$Y = 12.21x + 43$	81	0.844	$Y = 13.10x + 82$	58	0.718
Velocity Right		$Y = 10.29x + 90$	71	0.833	$Y = 12.23x + 98$	50	0.798
Acceleration		$Y = 10.64x - 148$	55	0.930	$Y = 4.39x + 92$	64	0.643
Jerk		$Y = 5.54x - 612$	41	0.963	$Y = 2.70x - 234$	59	0.708

*Y = Automobile Roughness Index
** Except for BPR Roughometer RI, the simulated vehicle was the 1969 Chevrolet Impala

standard measurement of road roughness. Results of correlation between the automobile method of test and the BPR Roughometer RI are presented in Figure 7.

Regression lines in Figure 7 show a large difference between the two pavement types for the same roughness index obtained with the automobile. Apparently, the shorter wavelength irregularities on portland cement concrete pavements influenced the roughness measurements. As described previously, the BPR Roughometer RI is a summation of the displacement differences between the sprung and unsprung masses. The unsprung mass reacts more readily to the shorter wavelengths, and therefore, contributes greatly to the BPR Roughometer RI. On the other hand, the automobile method of test measures the response of the entire vehicle system and the passenger to the road profile. Shorter wavelengths are filtered by the automobile suspension and seat, and to some extent by the passenger, and will contribute little to the automobile roughness index. If the index obtained from the automobile method of test were the same on both pavement types, the portland cement concrete pavement will yield a larger BPR Roughometer RI. This difference has been recognized by others *(8)* in assigning adjective ratings for riding quality of newly constructed interstate pavements. Similar differences also exist between the BPR RI and the indices determined from the sprung mass of the simulated car (discussed later).

CROSS CORRELATIONS OF QC SIMULATOR OUTPUT VARIABLES

As indicated previously, only a single set of summary statistics is obtained from the QC Simulator during a test run. Others must be obtained from tape replay. Fortunately, several of the sets, obtained from correlation with the automobile roughness index (see Table 16), correlated well with each other. Coefficients of correlation for all combinations are presented in Table 17. Disregarding the comparisons involving jerk at 20 mph (8.9 m/s) on bituminous pavements, almost one-half of the combinations resulted in coefficients of correlation greater than 0.866 (75 percent of the variations explained). On portland cement concrete pavements, about one-fourth of the combinations correlated as well. On portland cement concrete pavement, displacement and velocity at 70 mph (31.3 m/s) did not correlate well with the other variables. Even on bituminous pavement, combinations involving these two variables resulted in coefficients of correlation of only 0.700 to 0.800.

Combinations of variables involving BPR Roughometer RI correlated well. More than one-half of the coefficients of correlation were greater than 0.866. Thus, several different indices can be predicted, with a reasonable degree of certainty, from a known BPR Roughometer RI. Lines of best fit between BPR Roughometer RI and several other sets of variables are shown in Figure 8. Plots for displacement and velocity show some of the same differences in response between the two types of pavement caused by unlike wavelength characteristics (discussed previously). That is, for the same BPR Roughometer RI, larger values were obtained on bituminous pavement than on portland cement concrete pavement. The same difference, but to a lesser extent, was also evident for the acceleration variable at the simulated speed of 70 mph (31.3 m/s). Acceleration at 20 mph (8.9 m/s) and jerk at 70 mph (31.3 m/s) exhibited very little difference between pavement types.

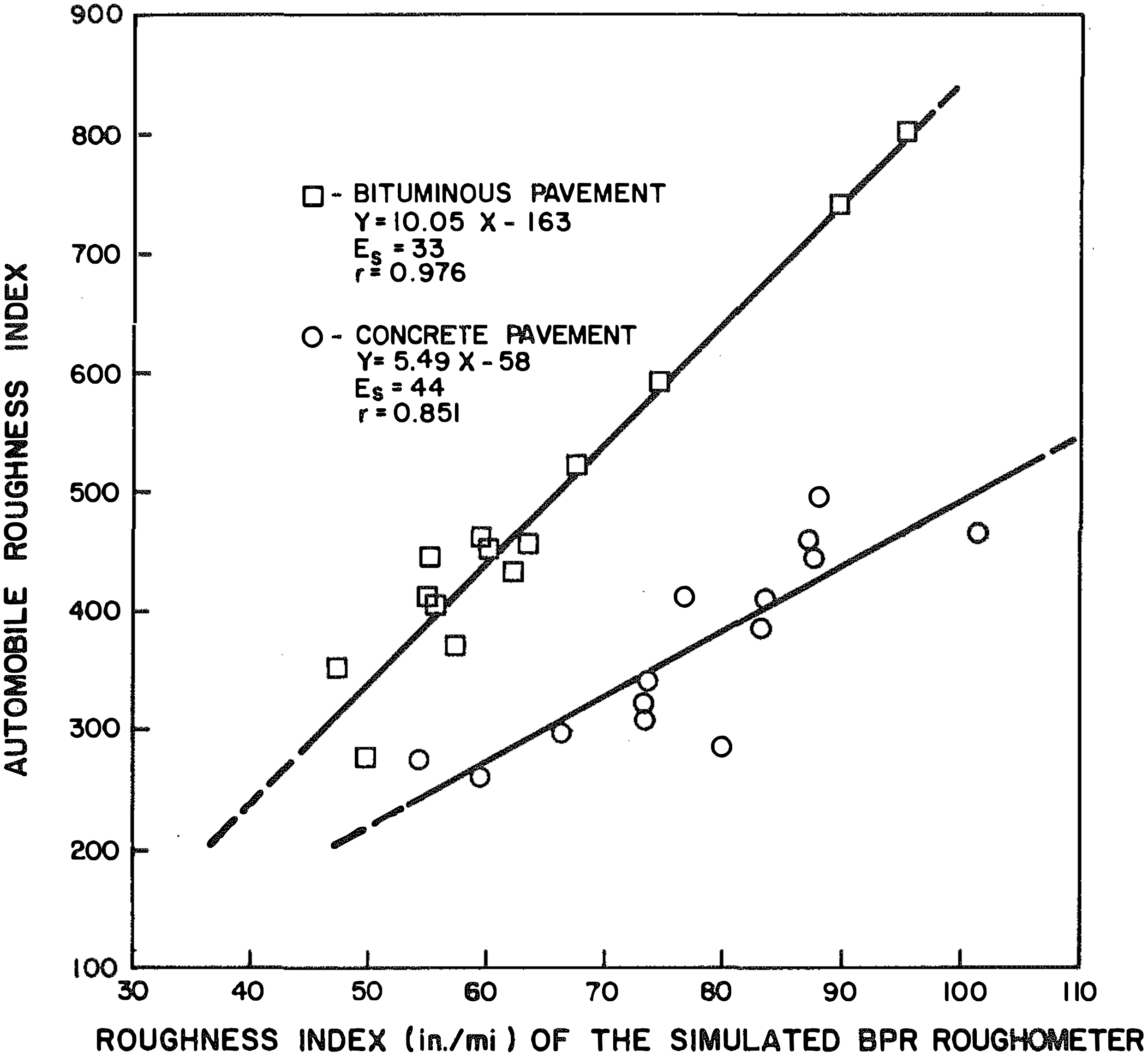


Figure 7. Correlation between Automobile and Simulated BPR Rougbometer.

TABLE 17. CROSS CORRELATION (COEFFICIENTS OF CORRELATION) OF QC SIMULATOR OUTPUT VARIABLES

VARIABLE	SIMULATED SPEED	BPR Rougho-meter RI	Displacement	Velocity Left	Velocity Right	Acceleration	Jerk	Displacement	Velocity Left	Velocity Right	Acceleration	Jerk
		20 mph (8.9 m/s)						70 mph (31.3 m/s)				
BPR Rougho-meter RI	20 mph (8.9 m/s)		0.828	0.904	0.892	0.918	- 0.458	0.366	0.597	0.671	0.898	0.951
Displacement		0.957		0.975	0.935	0.802	- 0.320	0.554	0.667	0.752	0.581	0.653
Velocity Left		0.964	0.971		0.951	0.851	- 0.349	0.447	0.606	0.697	0.686	0.755
Velocity Right		0.939	0.912	0.926		0.821	- 0.492	0.503	0.655	0.777	0.741	0.785
Acceleration		0.915	0.869	0.843	0.832		- 0.346	0.394	0.588	0.611	0.739	0.852
Jerk		- 0.108	- 0.173	- 0.051	- 0.216	- 0.157		- 0.490	- 0.520	- 0.569	- 0.595	- 0.498
Displacement	70 mph (31.3 m/s)	0.725	0.817	0.724	0.784	0.692	- 0.606		0.953	0.886	0.350	0.327
Velocity Left		0.783	0.876	0.789	0.828	0.731	- 0.534	0.988		0.950	0.595	0.583
Velocity Right		0.821	0.858	0.787	0.894	0.793	- 0.465	0.951	0.955		0.670	0.646
Acceleration		0.885	0.856	0.858	0.932	0.734	- 0.272	0.841	0.858	0.902		0.973
Jerk		0.954	0.902	0.915	0.973	0.812	- 0.192	0.759	0.803	0.860	0.956	

CONCRETE PAVEMENT

BITUMINOUS PAVEMENT

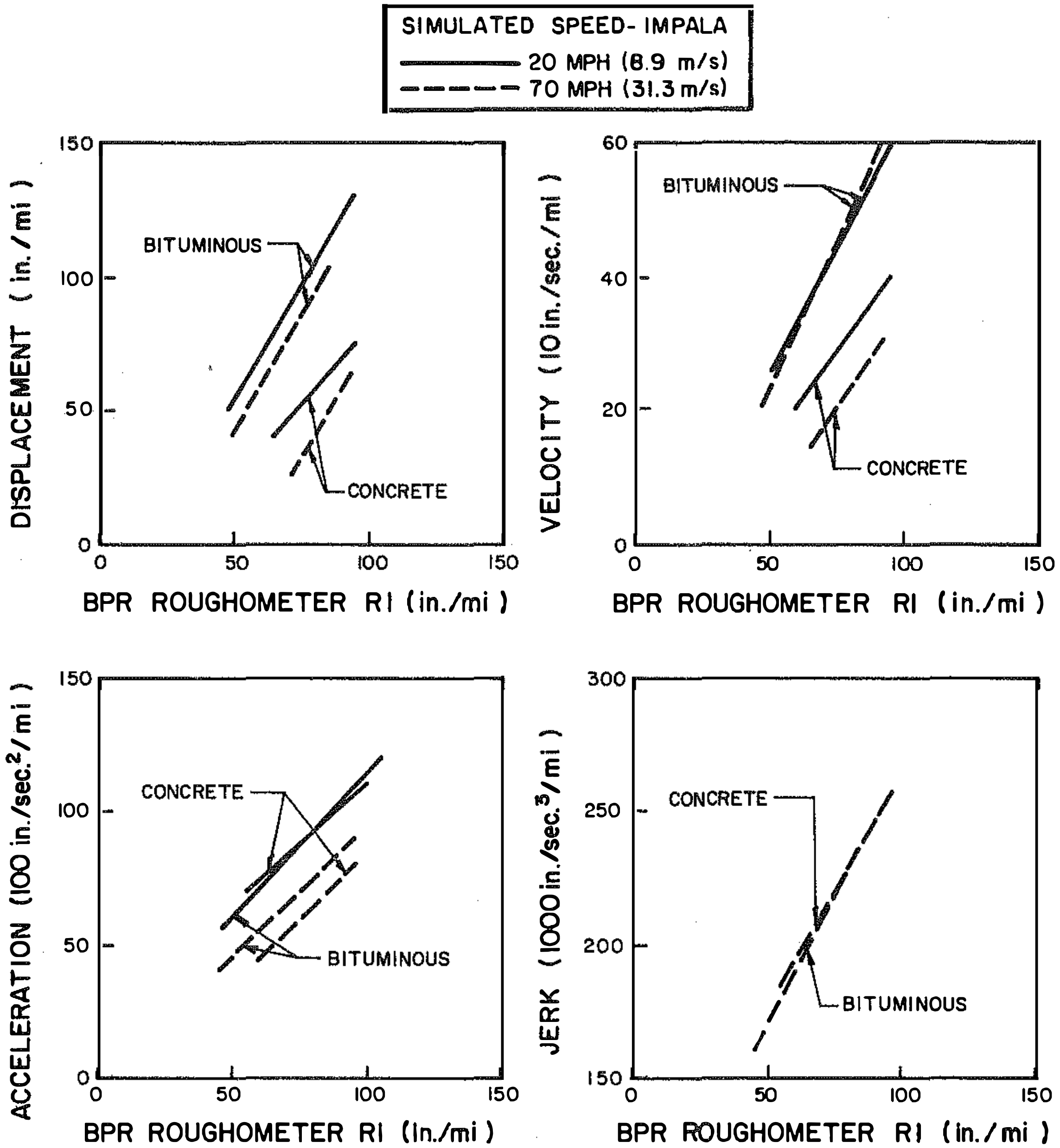


Figure 8. Correlation between Roughness Index of Simulated BPR Roughometer and Several Variables of Simulated Quarter-Car.

As before, the phenomenon may be explained by wavelength characteristics of the two pavement types. Assume throughout the following discussion that a test section of each pavement has the same BPR Roughometer RI. The displacement and velocity variables of the simulated quarter-car were relatively insensitive to the higher frequencies (short wavelengths). The values were, therefore, less for the portland cement concrete section. Increasing the simulated speed has the affect of increasing the frequency, thus, resulting in smaller values. The acceleration variable was more responsive to higher frequency. In fact, at 20 mph (8.9 m/s), the sections exhibited about the same values. However, increasing the test speed caused a greater decrease for the portland cement concrete section. Finally, jerk was the most responsive to high frequencies. At 70 mph (31.3 m/s), the two types of pavements having the same BPR RI yielded about the same jerk.

SUMMARY AND CONCLUSIONS

The precision of the Surface Dynamics Profilometer-Quarter Car Simulator system was demonstrated by repeated testing of several pavements. Roughness indices (RI) of the simulated BPR Roughometer were obtained. Standard deviations of the BPR RI's were 1.0 in. per mi for bituminous pavement and 0.8 in. per mi for portland cement concrete pavement. Standard deviations were not affected significantly by filters. Also, pavements with the higher roughness indices had about the same standard deviation as pavements with lower roughness indices. On a percentage basis, therefore, the measurement precision was better for a rougher pavement than for a smoother pavement. For example, on a smooth pavement -- BPR RI of about 50 in./mi -- a single measurement was within four percent of the sample mean 95 percent of the time; on a rougher pavement -- BPR RI of about 100 in./mi -- a single measurement was within two percent of the sample mean 95 percent of the time.

The excellent reproducibility of QC Simulator values, determined from playback of recorded profiles, was demonstrated. The average standard deviation of values (displacement at 20 mph (8.9 m/s) of the simulated BPR Roughometer), resulting from repeated playback of the same profile recording, was less than 0.2 in. per mi. Standard deviations obtained for BPR Roughometer RI values resulting from playback of repeated runs ranged, for the various filter selections, from 0.6 to 1.1 in. per mi for the bituminous pavement and 0.1 to 0.7 in. per mi for the portland cement concrete pavement. Thus, playback of recorded profiles into the QC Simulator does not create any additional impreciseness. However, playback values were generally larger (average of about one-half percent) than corresponding field values.

The SD Profilometer permits measurements of each wheel path independently. As expected, the BPR Roughometer RI of the left wheel path differed from the right wheel path. The differences were not consistent amongst test sections. Routinely, only the left wheel path was profiled while the right-side following wheel remained in the up position. Test results indicated the RI of the left wheel path was not affected when the right-side following wheel remained in the up position.

The QC Simulator permits vehicle simulation at any speed. However, tests at three speeds indicated that RI at 50 mph (22.4 m/s) was almost four percent less than at 40 mph (17.9 m/s). Part of the difference was attributed to a pulse-rate error -- the pulse generator produces fewer pulses per mile (kilometer) at higher speeds. To avoid test speed errors, a test speed of 40 mph (17.9 m/s) was selected as a standard.

The SD Profilometer has experienced numerous breakdowns. The major problems were associated with the road-following wheel system. Experience showed, however, that with an adequate stock of spare parts, frequent preventative maintenance, and proper operating precautions, satisfactory performance can be achieved in all measurement applications.

Several variables of the QC Simulator correlated well with the Kentucky automobile method of test. The Roughness Index of the simulated BPR Roughometer was selected for routine measurements of road roughness. The BPR Roughometer RI is a widely understood measure of road roughness. A separate correlation was warranted for each pavement type. On bituminous and portland cement concrete pavement with equal automobile roughness index, the BPR Roughometer RI will be significantly higher for the portland cement concrete than for bituminous pavement. This is in agreement with adjective ratings developed by others that allow a larger RI on portland cement concrete pavement for the same rating.

The SD Profilometer and the QC Simulator permit evaluation of pavement roughness to a higher degree of confidence than heretofore has been possible with other measuring devices. Pavement profiles and roughness indices have been obtained since 1970 on many paving projects. Measurements of major roadways constructed since 1972 will indicate as-built roughness. A third of the 250 paving projects being evaluated are tested each year. The measurements will be used to assess pavement performance and aid in the establishment of priorities for pavement maintenance. These and other applications of the SD Profilometer and QC Simulator are described in more detail in the following section.

APPLICATIONS

Chart recorders provide a visual record for locating and analyzing problem areas such as patches, rough areas, and distressed areas. The recording also allows for the evaluation of such construction methods and procedures as joints, mesh placement, bridge approaches, and bridge deck treatments.

The SD Profilometer-QC Simulator system provides an immediately available roughness index of the pavement. The roughness index pertains to increments of the pavement as short as 1/16 mile (101 meters). The index is useful for comparing amongst paving projects and segments in the same project. It does not relate directly to the amplitudes and wavelengths of the profile. However, a tabular representation of road roughness, such as an amplitude-frequency distribution (AFD), has been developed by others *(9)*. The AFD calculations require tape-recorded profile signals obtained from the SD Profilometer. The analysis shows a distribution of equivalent amplitudes for a particular frequency band. In contrast, the more commonly employed power spectral density analysis shows only a single mean value for each frequency band.

All projects involving interstate and parkway routes (about 150 projects) and selected projects on rural primary and secondary routes (100 projects) have been profiled and recorded on magnetic tape. A simulated BPR Roughometer index was obtained for each 1/16-mile (101-meter) increment of roadway. One-third of the projects are being reprofiled each year. The data available from these measurements will enable assessment of pavement performance and provide input for continued assessments of riding quality. The results will also aid in the establishment of priorities for major maintenance reconstruction and relocation.

Profile measurements with the SD Profilometer have been used by others in obtaining a true elevation map of the roadway through a process called "tipping" *(3, 4, 5)*. Several uses of the resulting elevation map were found *(5)*, including determining airport runway profiles and estimating bituminous material needed in resurfacing.

Several types of meters or roughness measuring devices have become commonplace. A roughness index with many of these devices is obtained from the displacement measurement of vertical movement of the rear axle of an automobile with respect to its chassis. Measurements are affected by changes in vehicle components. Road roughness measurements obtained with the Kentucky automobile method of test and the Mays Ride Meter, used by the Divisions of Research and Maintenance, respectively, are also affected by the condition of the test vehicles. These devices, therefore, must be periodically correlated with a more precise measurement system, such as the SD Profilometer-QC Simulator System, to assure long-term reproduceability of measurements.

REFERENCES

1. Rizenbergs, R. L., *Accelerometer Method of Riding-Quality Testing,* Kentucky Department of Highways, February 1965.
2. Rizenbergs, R. L., Burchett, J. L. and Davis, L. E., *Pavement Roughness: Measurement and Evaluation,* **Record No. 471,** Highway Research Board, 1973.
3. Spangler, E. B. and Kelly, W. J., *GMR Road Profilometer -- A Method for Measuring Road Profile,* **Record No. 121,** Highway Research Board, 1966.
4. Darlington, J. R. and Milliman, P., *A Progress Report on the Evaluation and Application Study of the General Motors Rapid Travel Road Profilometer,* **Record No. 214,** Highway Research Board, 1968.
5. Darlington, J. R., *High-Speed Profilometry,* **Record No. 362,** Highway Research Board, 1971.
6. Rizenbergs, R. L., *Analysis of Pavement Roughness,* Kentucky Department of Highways, March 1961.
7. Rizenbergs, R. L. and Havens, J. H., *Pavement Roughness Studies,* Kentucky Department Of Highways, April 1962.
8. Balmer, G. G., *Road Roughness Technology, State of the Art,* **Report No. FHWA-RD-73-54,** Federal Highway Administration, December 1973.
9. Brickman, A. D., Wambold, J. C., and Zimmerman, J. R., *An Amplitude-Frequency Description of Road Roughness,* **Special Report 116,** Highway Research Board, 1971.

APPENDIX A

DESCRIPTION OF MODEL 690 SURFACE DYNAMICS PROFILOMETER

DESCRIPTION OF SURFACE DYNAMICS PROFILOMETER

VEHICLE

The vehicle (Figure A1) is a 1968 Chevrolet, Series 10, Carryall truck equipped with automatic transmission, power steering, power brakes, air conditioning, and tinted windows. It has a 396-cubic inch (6490-cm^3), 310-horsepower (231-kW) engine. An automatic speed control allows the driver to more easily maintain speed. An amber warning flasher is mounted on top of the vehicle. Much of the interior of the vehicle is acoustically lined or carpeted to reduce noise created by the road-following wheels. Acoustical ceiling reduces drumming of the vehicle roof. The operator's console and seat are located near the center of the vehicle (Figure A2). The profile computer is mounted on the console directly in front of the operator. The QC Simulator is mounted on top of the profile computer and can be quickly disconnected for laboratory use. An oscilloscope or, if a visual recording is desired, an incremental drive, strip-chart recorder is mounted to the left of the computer. A magnetic tape recorder is at the left of the oscilloscope. A pulse amplifier for the strip-chart recorder is located on the floor under the tape recorder. Other equipment in the vehicle includes a speed error and events meter on the dash above the steering wheel and duplicate controls to the right of the steering wheel (Figure A3). The 110-volt power supply, batteries, and hydraulic pump are located in the rear of the vehicle, as shown in Figure A4.

ROAD FOLLOWING DEVICES

The road surface profile is traced by a small rubber-tired wheel assembly (Figure A5) in each of the two wheel paths. The wheels are about 6 inches (150 mm) in diameter and 58 inches (1.47 m) apart. Each wheel is mounted on a spring-loaded, stainless steel arm which maintains the tracking of the wheel in the proper path. The spring loading is provided by a torsion bar which applies a hold-down force of about 300 lb (1.3 kN). The spring rate at the wheel is about 10 lb per inch (2 kN/m). The torsion-bar springs and bearing are housed in a rectangular steel tube which is transversely bolted to the underside of the vehicle frame. A bracket mechanically holds each road-following wheel arm in the up position when not in use.

A hydraulic piston and lever arrangement is provided to rapidly raise the road-following wheel off the ground to avoid damage to the wheel and potentiometer shaft by unusually severe road surface conditions. As an added precaution, a skid is mounted on the trailing arm to prevent the wheel from dropping into a pot hole. The wheels are also raised for traveling from one test site to another. Pushbutton switches are provided on the operator's and driver's control panel to raise and lower both wheels and, on the operator's panel, a switch is provided to enable either wheel to be raised or lowered independently.

TRANSDUCERS

The displacement between the road-following wheel and the vehicle body is measured with a Markite linear potentiometer (Type 9045) at each wheel. One end of the potentiometer is connected to the following arm -- directly above the wheel -- and the other end to the vehicle body. The potentiometer measures up to 12 inches (300 mm) of vertical displacement. Its output signal is scaled in the profile computer to 1.0 volt per inch (25.4 mm). The motion (acceleration) of the vehicle body is measured with a Systron-Donner Model 4310 servo accelerometer mounted on the vehicle body directly above each road-following wheel (Figure A6). The resulting output signal is integrated twice in the profile computer to yield displacement of the vehicle body from an inertia plane of reference. The accelerometers have a range of ± 2 g with an unamplified output of 3.75 volts per g.

Road distance measurement is obtained with a Veeder-Root pulse generator coupled to the speedometer drive take-off near the transmission. The device contains an internal light source, a rotary light gate, a photocell, and an electronic pulse-shaping circuit. It produces about 250,000 pulses per mile (155 pulses per meter). The pulse rate is reduced by a factor of four in the profile computer. The resulting signal is used to drive the strip-chart recorder for direct distance scaling of the chart and to generate a 0.1-mile (0.16-kilometer) distance pulse (also recorded). The pulse is recorded on magnetic tape for later use in either driving the strip-chart recorder or to operate the QC Simulator.

A phototube is provided to detect identifying marks on the road surface for precisely marking the beginning, ending, or other events during a test run. A 30-watt spot light, housed in the photocell transducer box, is directed to the road surface transversely in line with the road-following wheel. The phototube is pointed toward the illuminated spot and changes its electrical resistance in relation to the reflectivity of the road surface. An abrupt change in the resistance triggers the profile computer to generate a signal for event-marking purposes. Such a change may be caused by painted lines, reflective metal strips, reflective tape, or changes in material such as bituminous to portland cement concrete pavement. The phototube is packaged in a sealed box attached to the underside of the vehicle.

PROFILE COMPUTER

The main function of the profile computer (Figure A7) is to admit the accelerometer and potentiometer signals, combine them, and produce a profile for each wheel path. Rotary switches are provided for each track to select the desired amplitude and wavelength. Filters are incorporated to attenuate the long waves (hills and valleys) using one of four filter selections shown in Table A1. The wavelength capability refers to the maximum wave component of the road profile that is measured without attenuation and less than 10 percent phase shift at a measured speed of 40 mph (17.9 m/s). A "GAIN" switch multiplies the profile amplitude scale of 1.0 volt per inch (25.4 mm) by a factor of 0.2, 0.5, 1.0, or 2.0 as desired.

The "CALIBRATION" switch produces a voltage equivalent to a 1.0-inch (25.4-mm) upward displacement of the road surface. The switch in the "STEP" position maintains the voltage as a road profile signal and, when recorded, allows proper scaling for playback. The switch in the "TRANSIENT" position produces the response of the filter to the unit displacement. The response time is a function of the natural frequency of the filter and, when recorded, can be used to determine which filter was selected. Improper response time indicates improper performance of the filter.

The voltage range of the analog computation electronics is ± 10 volts d-c. If this voltage level is exceeded, the computer will overload. When an overload occurs in the computation of either track, the analog computer is automatically reset and the road profile output voltage of both tracks returns to zero. An overload is indicated by a small, red light located between the filter selector switches and by an audio alarm in the profile computer. Below the overload light is a pushbutton reset switch that allows the operator to manually reset the analog computer.

Two spring-loaded switches provide operational checks on the accelerometers and potentiometers. The switch labeled "ACCELEROMETER CHECK" applies a test current to either the left or right accelerometer. If the test current is applied, as indicated by the test meter, but the reading on the null meter is not zero, the accelerometer is not functioning properly. The switch labeled "POTENTIOMETER CHECK" causes the output of the selected potentiometer to be displayed on the null meter. It is desirable to have the output of each potentiometer near zero prior to recording so that the signal fluctuates around zero during tests. This can be done by means of a bias adjustment with the wheels in the down position. If there is not enough bias adjustment to null one of the potentiometers, the potentiometer is not operating properly.

A switch labeled "CHART DRIVE" is provided for the purpose of recording the profile on a strip-chart recorder. The recorder, a Brush Mark 280, with two analog and event channels, was modified for pulse drive. During tests, the chart drive switch is set at "DIST"; and pulses proportional to vehicle travel drive the chart. However, when the vehicle is not moving, the switch is set to "TIME"; and a constant signal (500 Hz) provides the input. The selected pulses are also recorded on tape and inputed to the QC Simulator.

A switch labeled "VEHICLE SPEED" enables selection of a test speed of 10, 20, 34, 40, 50, or 60 mph (4.5, 8.9, 15.2, 17.9, 22.4, or 26.8 m/s). The selected position provides a zero reading on the speed error meter (Figure A3) at the selected test speed. The meter assists the driver in holding a constant speed. Also, a high frequency audio signal is generated if the speed is greater than the selected speed and a lower frequency signal is emitted if the speed is less than the selected speed. Volume of the signal increases with greater deviation from the selected speed.

MAGNETIC TAPE RECORDER

Signals from the profile computer are recorded on a seven-track, magnetic tape recorder (Sangamo, Model 3561). One of the tracks receives a high frequency signal (400 kHz) for the tape synchronous-speed control to insure that "reproduce" speed is precisely the same as "record" speed. An edge track is provided for voice recordings. Two tracks are used for high-frequency signals and employ direct record-reproduce electronics. The other tracks use FM record-reproduce electronics. The recorder tracks and signals assigned to each are as follows:

Track	Signal
1	Left Road Profile
2	Phototube
3	System Ground
4	400 kHz
5	Right Road Profile
6	Event and 0.1 Mile (161 m)
7	Distance Pulses
Edge	Voice

The tape recorder has record-reproduce speeds of 15/16, 1 7/8, 3 3/4, 7 1/2, 15, and 30 inches per second (ips) (24, 48, 95, 190, 381, and 762 mm/s). A similar recorder is used in the laboratory. It lacks the record-reproduce speeds of 30 ips (762 mm/s) but includes two additional reproduce speeds of 10 times 15/16 ips (24 mm/s) and 10 times 1 7/8 ips (48 mm/s).

OSCILLOSCOPE

A two-channel oscilloscope (Telequipment, Type D54) is usually used in place of the strip-chart recorder to monitor selected signals. The left-wheel profile signal from the profile computer and the right-wheel profile from the reproduce electronics of the tape recorder are displayed during tests.

ELECTRICAL POWER

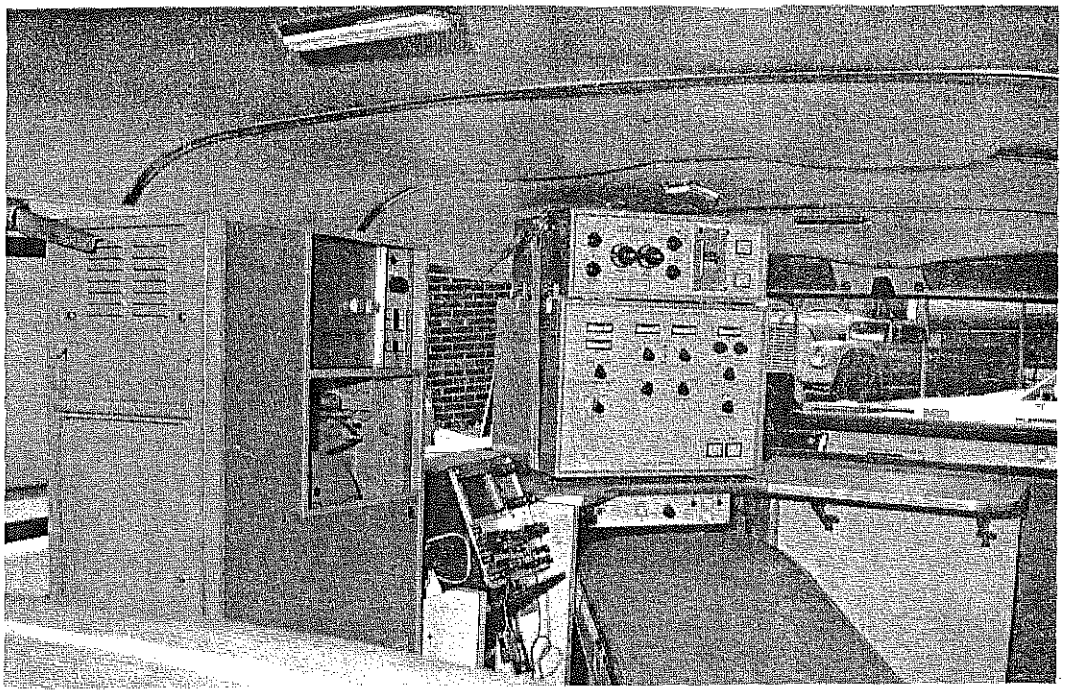
The SD Profilometer has two independent power supplies other than the standard vehicle system. A 24-volt system powers the tape recorder, and a 12-volt system powers all other equipment. The 24-volt system consists of a 70-ampere alternator and two 12-volt batteries connected in series. The 12-volt system has a 55-ampere alternator and a single 12-volt battery. The alternators are driven by the engine and are regulated. A voltmeter on the dashboard is used for monitoring the alternators. The 12-volt system powers a hydraulic pump and drives two inverters supplying 110 volts a-c (Figure A4). A 250-va inverter powers the oscilloscope and, when needed, the strip-chart recorder. A 500-va inverter powers the profile computer, QC Simulator, operator's control panel, and other equipment as needed. A power switch on the operator's control panel is provided to remove the load from the 12-volt system when not in use.

Figure A1. **Surface Dynamics Profilometer.**

TABLE A1. PROFILE-COMPUTER FILTERS

FILTER SELECTION	NATURAL FREQUENCY (RADIANS/SECOND)	WAVELENGTH CAPABILITY AT 40 MPH (17.9 M/S)	
		FEET	METERS
1	0.3	400	122
2	0.6	200	61
3	1.0	133	41
4	3.0	40	12

Figure A2. Interior of Vehicle – Operators Controls (Magnetic Tape Recorder on the Left).



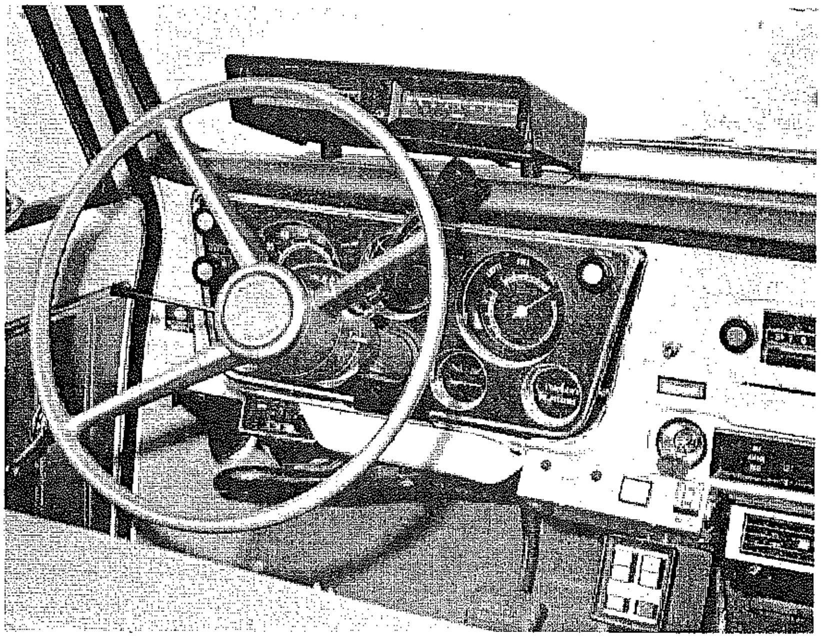
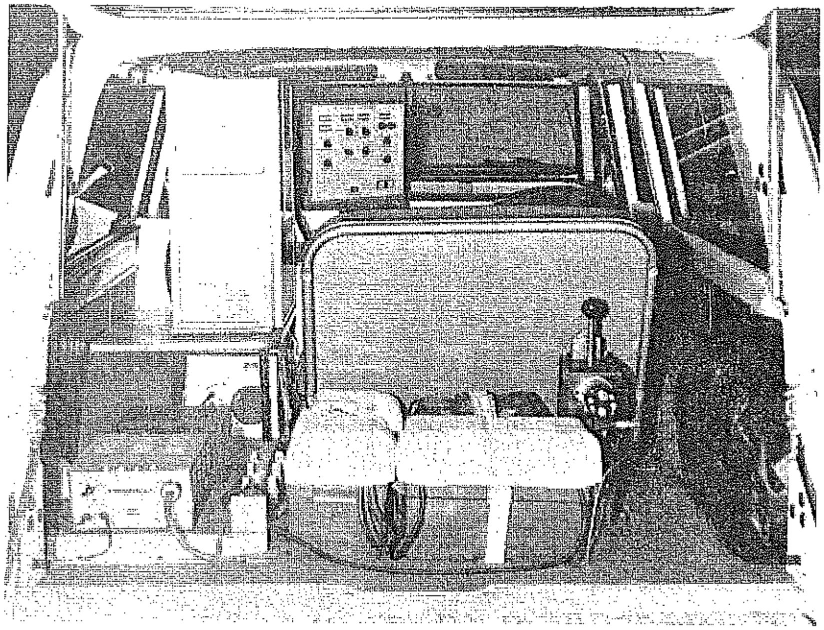


Figure A3. Driver's Controls (Lower Right) and Speed Error Meter (on Top of Dashboard).

Figure A4. Rear of the Vehicle - 110-volt Power Supplies, Batteries, and Hydraulic Pump (at Right).



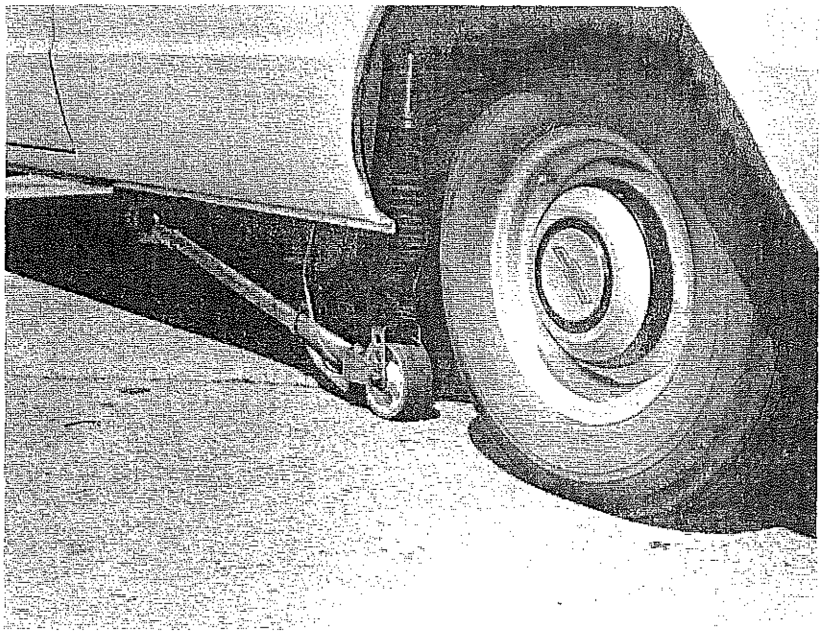


Figure A5. Road-Following Wheels.

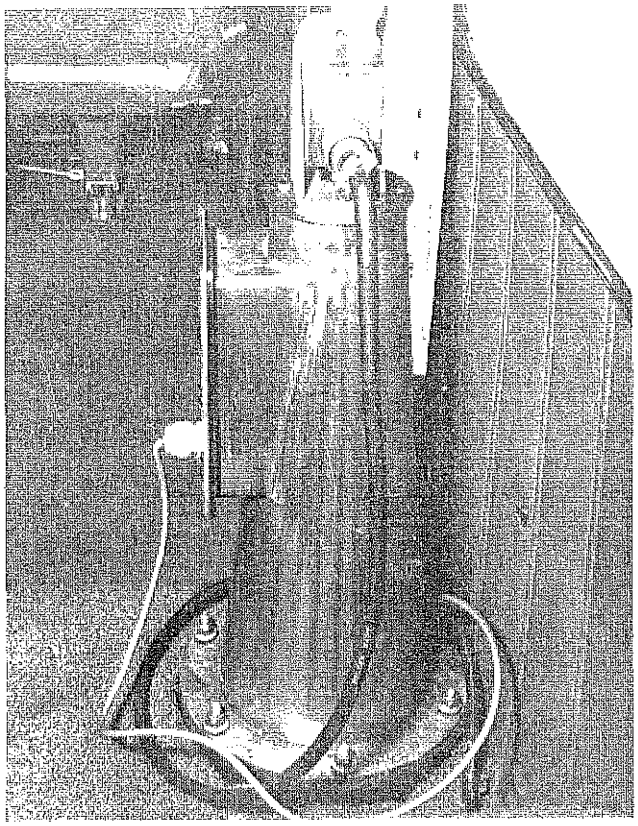
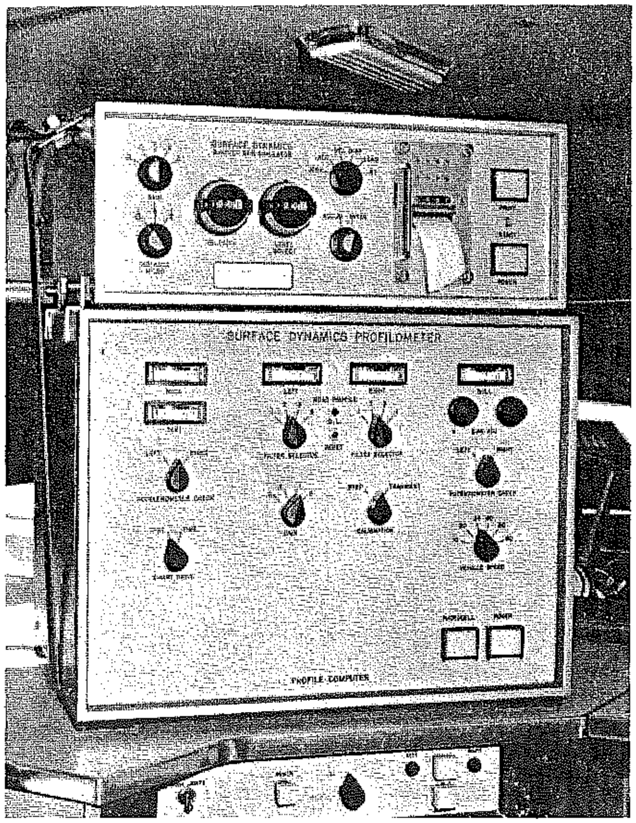


Figure A6. Potentiometer Housing and Accelerometer (on Top).

Figure A7. Profile Computer and Quarter-Car Simulator (on Top).



APPENDIX B

DESCRIPTION OF MODEL 1088 QUARTER-CAR SIMULATOR

DESCRIPTION OF QUARTER-CAR SIMULATOR

DESIGN

In an automobile, the main vehicle mass (sprung mass) is isolated from the wheel and the tire (unsprung mass) by a spring and a shock absorber. The tire also may be represented as a high-rate spring since high frequencies of the measured road profile, inputed to the tire, are attenuated by the tire while low frequencies pass through with no amplitude changes. Thus, components of the system that require simulation are the sprung and unsprung masses, suspension spring rate, tire spring rate, and suspension damping.

The equations of motion which are solved by the analog computer are

$$M_1\ddot{X}_1 + D(\dot{X}_1 - \dot{X}_2) - K_1(X_1 - X_2) = 0$$

and

$$M_2\ddot{X}_2 + D(\dot{X}_2 - \dot{X}_1) - K_1(X_2 - X_1) + K_2(X_2 - P) = 0$$

where M_1 = sprung mass,
M_2 = unsprung mass,
K_1 = suspension spring rate,
K_2 = tire spring rate,
D = suspension damping coefficient,
X_1 = displacement of sprung mass,
X_2 = displacement of unsprung mass,
P = road profile input,
$\dot{X}_1$ = velocity of sprung mass,
$\dot{X}_2$ = velocity of unsprung mass,
$\ddot{X}_1$ = acceleration of sprung mass, and
$\ddot{X}_2$ = acceleration of unsprung mass.

The equations describe only the acceleration, velocity, and displacement of both the sprung and unsprung mass. Three additional variables to be determined are jerk of the sprung mass ($\dddot{X}_1$), tire force (F) on the pavement, and relative displacement ($X_1 - X_2$) of the sprung and unsprung masses. Jerk is the first derivative of acceleration and is obtained by differentiating acceleration ($\ddot{X}_1$). The force from the vehicle tire on the pavement is a function of the displacement of the road profile, the displacement of the sprung mass, and the tire spring rate. The equation for force is

$$F = K_2(X_2 - P).$$

The relative displacement ($X_1 - X_2$) is used to calculate a roughness index (RI) by the equation

$$RI = (1/2) \int_0^s (X_1 - X_2)\, ds$$

where "s" is the distance along the road over which the integration is performed.

SYSTEM PARAMETERS

Performance of the QC Simulation is a function of the physical constants which define the system. The physical constants are referred to as system parameters and include values for the sprung mass, unsprung mass, suspension rate, tire spring rate, and suspension damping coefficient.

Parameter values are presently available for two different vehicle simulations (Table B1). One set of vehicle parameters pertains to the Bureau of Public Roads Roughometer and the other set pertains to the four-door, hard-top Chevrolet Impala equipped with a V-8 engine.

The QC Simulator is designed so that system components which determine the system performance are assembled on one plugable, printed circuit card. Using this approach, the parameters used in the QC Simulation can be changed to a new set by simply exchanging the printed circuit cards.

INPUTS

Inputs to the QC Simulator are provided by the SD Profilometer. Simulation can be performed as the pavement is being profiled or the road profile signals can be recorded on magnetic tape for later processing (playback). Three signals -- road profile, distance pulses, and system ground -- are inputed to the QC Simulator. The distance pulses, in combination with "VELOCITY" selection (see Figure A7), control the percentage of time the input signals are integrated by the simulation electronics. The road profile signal is inputed to the integrator through a switching circuit controlled by distance pulses. Each pulse allows the signal to be integrated. The width of the pulse determines the interval of integration. The sampling rate (one sample per pulse) is about 60,000 samples per mile (37,300 samples per kilometer). The sampling rate remains constant in terms of distance; but, in terms of time, the rate is directly proportional to test speed. The sampling technique, therefore, compensates for different test speeds and for speed variations during testing. The simulated speed -- adjusted with the "VELOCITY" selection (see Figure A7) -- alters the width of the distance pulses and thereby the interval over which the road profile signal is to be integrated. The pulse shaping circuit is preset so that 20 percent of the signal is sampled when the test speed and simulated speed are the same. An increase in simulation speed reduces the width of the distance pulses.

The amplitude scaling of the road profile input signal is a function of the "GAIN" setting on the front panel of the QC Simulator. Simulation is correctly scaled if the numerical setting on the Simulator corresponds to the gain setting on the profile computer.

OUTPUTS

Output of the QC Simulator is the response of the simulated vehicle to the measured road profile. Outputs are available as analog signals or as printed, summary statistics. The various output variables and their scaling (simulator gain settings equal profile computer gain settings) are included in Table B2.

Analog output signals, with one exception, vary about a zero-volt reference and represent the change in amplitude resulting from the road profile input. The exception is for Roughness Index. Its value increases from zero volts to 12 volts, at which time the roughness index count is increased by one and the signal returns to zero. All signals are available for recording on a strip-chart recorder for visual inspection or may be recorded on magnetic tape for later processing.

Summary statistics can be obtained by two methods: (1) summation of the absolute value of amplitude and (2) counting or accumulation of the number of times an output variable exceeds a preselected level. In the integration mode (switch set on "INTG"), the signal is subjected to an analog operation that sums the nondirectional signal displacement. In the accumulation mode (switch set on "ACCUM"), a counting circuit counts the number of times the signal exceeds a preselected, positive amplitude level. The signal level (in units of the selected output variable), above which an occurrence is counted, is selected by using the "LEVEL SELECT" potentiometer located on the front panel. Beginning of the summing or counting is controlled by a reset button (labeled "RESET"). As long as the button remains depressed, the summary statistics remain at zero. Summing or counting begin when the reset button is released.

All summary statistics are normalized for 1 mile (1.6 km) and can be obtained for 1/16-, 1/8-, or 1/4-mile (101-, 201-, or 402-meter) intervals. The desired interval is selected with a switch labeled "DISTANCE-MILES". Only one summary statistic may be printed and displayed during the test run. The desired output is selected using a switch labeled with the six outputs (located to the left of the printer) (see Figure A7). The values are printed and displayed at the end of each distance interval.

TABLE B1. SIMULATED VEHICLE PHYSICAL CONSTANTS

	SIMULATED VEHICLE	
VEHICLE PARAMETER	BPR ROUGHOMETER	CHEVROLET IMPALA
Tire Spring Rate	12,000 lbf/ft (175 kN/m)	13,200 lbf/ft (193 kN/m)
Wheel Mass	97 lb (44.0 kg)	103 lb (46.7 kg)
Suspension Spring Rate	2,400 lbf/ft (35.0 kN/m)	1,128 lbf/ft (16.5 kN/m)
Shock Absorber Damping	72 lbf/ft (1.05 kN/m)	60 lbf/ft (0.88 kN/m)
Vehicle Mass	600 lb (272 kg)	1,200 lb (544 kg)

TABLE B2. QUARTER CAR SIMULATOR OUTPUT VARIABLES AND SCALING

	SIGNAL SCALING	
OUTPUT VARIABLE	ANALOG (PER VOLT)	SUMMARY COUNT (PER MILE (1.61 km))
BPR Roughness Index $(x_1 - x_2)$		1 in. (25.4 mm)
Vehicle Tire Force on the Road (F)	1000 lbf (453.6 kg)	833.3 lbf (378.0 kg)
Displacement of Vehicle Body (x_1)	0.1 ft (0.030 m)	1 in. (0.025 m)
Velocity of Vehicle Body $(\dot{x}_1)$	1 ft/sec (0.30 m/s)	10 in./sec (0.25 m/s)
Acceleration of Vehicle Body $(\ddot{x}_1)$	10 ft/sec^2 (3.0 m/s^2)	100 in./sec^2 (2.5 m/s^2)
Jerk of Vehicle Body $(\dddot{x}_1)$	100 ft/sec^3 (30 m/s^3)	1000 in./sec^3 (25 m/s^3)

APPENDIX C

CALIBRATION PROCEDURES FOR MODEL 690 SURFACE DYNAMICS PROFILOMETER AND MODEL 1088 QUARTER-CAR SIMULATOR

CALIBRATION PROCEDURES FOR MODEL 690 SURFACE DYNAMICS PROFILOMETER

The first step in calibration is to adjust the regulated power supply. The linear potentiometers are then extended 1.0 inch (25.4 mm) using a precision spacer block. The output signals are scaled to 1.0 volt with a gain setting of 1.0. Signals from the accelerometers are scaled by removing the 1 g bias and adjusting the output to 3.864 volts.

Speed, 0.1-mile (160.9-m), and 50-foot (15.24-m) indications are a function of the pulse rate from the distance pulse generator. The pulse rate is determined by counting pulses while traversing a known distance of several miles (kilometers) and dividing the count by number of miles (kilometers) traveled. Counting circuits for the 0.1-mile (160.9-m) and 50-foot (15.24-m) indications are adjusted accordingly. (This pulse rate is also used to adjust the counting circuits of the QC Simulator.) The speed-null circuit (consequently the speed-error meter) is adjusted to an output of zero while inputing a signal whose frequency equals the pulse rate at 60 mph (26.8 m/s). The speed selector switch remains on 60-mph (26.8-m/s) during this calibration.

Recording electronics for all tracks of the magnetic tape recorders are calibrated and scaled for an input signal of 1.0 volt, rms. A signal of known voltage and frequency is inputed to the tape recorder and the reproduce electronics are scaled to output exactly the same voltage as the input. Built-in, synchronous-speed control assures accurate frequency reproduction.

CALIBRATION PROCEDURES FOR MODEL 1[illegible]88 QUARTER-CAR SIMULATOR

The first step in calibration of the QC Simulator consists of comparing circuit performance with the performance of the circuit at the time of acceptance of the device at the manufacturer's plant. Extensive tests were made on the QC Simulator during system check-out to establish the necessary, performance data base. The tests consisted of both transient and frequency response measurements. The transient response was determined by measuring the response of the simulated vehicle to a step input signal of road profile. A typical transient response (displacement -- X_1) of the sprung mass is shown in Figure C1 for the BPR Roughometer simulation. The sprung mass displacement does not immediately equal the step input but rises slowly as would an actual car body responding to an abrupt, roadway excitation. In time, however, the sprung mass displacement (A) will equal the displacement of the step input (P). Other important parameters are the distance (B) the simulated vehicle travels before the sprung mass displacement first equals the displacement of the step input and the maximum displacement amplitude (C) of the sprung mass. Expected values for the distance (B) are 0.206 foot per mph (0.1404 meter per m/s) for the BPR Roughometer simulation and 0.390 foot per mph (0.2646 meter per m/s) for the car simulation. The maximum displacement equals 1.69 times the input in both cases. These values are checked at several, simulated, measuring speeds.

The system frequency response was determined by measuring the response of the simulated vehicle to sinusoidal inputs at various frequencies. The response, expressed as a ratio of output to input (amplitude ratio), was plotted against frequency. A plot for the BPR Roughometer simulation is presented in Figure C2. Subsequent, frequency response measurements were compared with the original curve.

After the vehicle simulation circuitry has been checked, the summary statistics circuitry is calibrated. This is done by inputing into the QC Simulator a sinusoidal wave representing the road profile and by comparing the output to a calculated value. The frequency and amplitude (between 0.1 to 0.3 volts peak-to-peak) of the sinusoidal wave is selected from the frequency response curve for a particular simulation where the curve is the flatest. The amplitude ratio of the selected frequency is noted. The simulated velocity is set at the desired speed and a corresponding distance-pulse signal inputed to the QC Simulator. The calculated value is determined from the following formula:

$$V_c = t \times A \times f \times R,$$

where V_c = calculated output value of selected simulation,
t = time, in seconds, to drive 1 mile (1.6 km) at the selected simulated speed,
A = amplitude, peak-to-peak, of sinusoidal wave in terms of scaling of selected output (see Table 3),
f = frequency of sinusoidal wave, and
R = amplitude ratio from applicable frequency response curve.

The value displayed by the printer should be the same as the calculated value. If it is not, the summing circuits are adjusted until the output value corresponds to the calculated value.

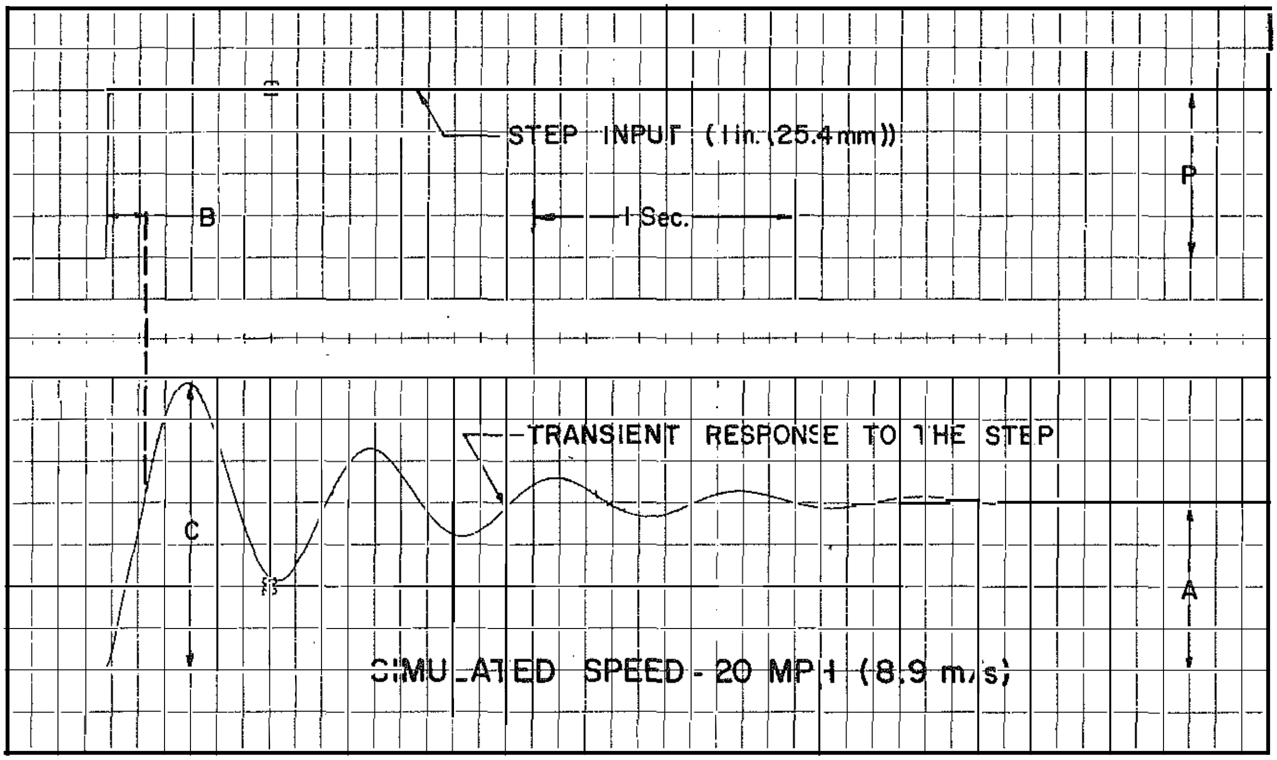


Figure C1. Transient Response of Displacement (X_1) of Sprung Mass (Simulated BPR Roughometer) to Step Input of Road Profile.

Figure C2. Frequency Response Curve of Relative Displacement of Two Masses for the Simulated BPR Roughometer.