**ROAD ROUGHNESS MEASUREMENTS
ON
INDIANA PAVEMENTS**

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**Joint
Highway
Research
Project**

**PURDUE UNIVERSITY
LAFAYETTE INDIANA**

by
F.M. Holloway

ROAD ROUGHNESS MEASUREMENTS ON INDIANA PAVEMENTS

TO: K. B. Woods, Director
Joint Highway Research Project

June 11, 1956

FROM: Harold L. Michael, Assistant Director

File: 9-3-3-1
C-36-531

Attached is a report entitled "Road Roughness Measurements on Indiana Pavements." This report has been prepared by Mr. Frank M. Holloway, Research Engineer on our staff, under the general supervision of Professor H. L. Michael. Mr. Holloway used this report as his thesis in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering. Mr. Holloway has left the staff and is now associated with the Florida State Highway Department.

This paper presents the development and calibration procedures for the Purdue Roughometer and reports on roughness measurements on certain pavements in Indiana. It includes a study of factors that affect road roughness and suggests standards of roughness for new construction and for the evaluation of surface riding qualities.

This study was an initial one using the Purdue Roughometer and suggests additional research that is needed in this area.

A summary of the paper was presented at the 42nd Annual Purdue Road School.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
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TABLE OF CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES	vi
ABSTRACT	viii
INTRODUCTION	1
History of Early Roughometers.	3
Development of Roughness Measuring Equipment at Purdue	6
GENERAL DESCRIPTION OF THE PURDUE ROUGHOMETER	9
PURPOSE AND SCOPE	18
PROCEDURE	19
Construction of the Equipment	19
Calibration of the Integrator	21
Initial Road Tests of Equipment	27
Calibration of Roughometer	37
Selection of Test Sections	48
Road Testing Procedures	49
RESULTS OF FIELD STUDY	52
New Portland Cement Concrete Pavements	52
Older Concrete Pavements Built on Granular Base Courses	55
Bituminous Surfaces on Flexible Bases.	65
Surface Riding Quality Evaluations	68
PROPOSED ADDITIONAL ROAD ROUGHNESS RECORDING EQUIPMENT	71
SUMMARY OF RESULTS AND CONCLUSIONS	74

TABLE OF CONTENTS (Continued)

	Page
BIBLIOGRAPHY	79
APPENDIX	81

LIST OF TABLES

Table	Page
1. Results of Load Deflection Tests on Special Leaf Springs	20
2. Results of First Integrator Calibration Tests .	22
3. Results of Load Testing of Integrator Cable . .	23
4. Results of Second Integrator Calibration Tests .	24
5. Results of Final Integrator Calibration Tests. .	25
6. Summary of Results - Road Roughness Tests . .	56
7. Road Roughness Data - New Concrete Pavements .	82
8. Road Roughness Data - Older Concrete Pavements Built on Granular Base Courses	83
9. Road Roughness Data - Bituminous Surface Types .	87

LIST OF FIGURES

Figure	Page
1. Elements of Road Roughness Indicator	10
2. Schematic Section of Integrator	12
3. Close-up View of Instrument Panel with Data Sheet. .	14
4. Close-up View of Purdue Roughometer	15
5. Conducting a Road Roughness Test	16
6. Calibration Device for the Roughness Integrator Unit	21-A
7. Inches of Roughness per Mile at Various Speeds for the same Road Section	28
8. Effect of Tire Inflation on Roughness Indices - Nominal Speed of 20 Miles Per Hour.	30
9. Effect of Tire Inflation on Actual Number of Wheel Revolutions for a Measured Mile.	31
10. Variation of Roughness Along Various Longitudinal Paths of Three Portland Cement Concrete Roads . .	33
11. Roughness by 0.1 Mile Increments Along the Center of the Traffic Lane for a New Concrete Pavement. .	34
12. Roughness by $\frac{1}{4}$ Mile Increments Along the Center of the Traffic Lane for a 7 Year Old Concrete Pavement	35
13. A Comparison of the Road Roughness Measurements Made by the Bureau of Public Roads with Those Made by Purdue University on the U.S. 31 Test Sections Built in 1953.	40
14. A Comparison of the Road Roughness Measurements Made by the Bureau of Public Roads With Those Made by Purdue University on the U.S. 41 Test Sections Built in 1949	41

LIST OF FIGURES (Continued)

Figure	Page
15. A Comparison of the Road Roughness Measurements Made by the Bureau of Public Roads with Those Made by Purdue University on the U.S. 40 Experimental Sections Near Stilesville, Built in 1938	42
16. Variation in Indices for Repeated Tests on Three Different Roads	44
17. Results of Purdue Integrator Unit Calibration Tests Made by the Bureau of Public Roads.	47
18. 1955 Road Roughness Test Sites.	50
19. Road Roughness Measurements for Portland Cement Concrete Pavements Built on Granular Base Courses	57
20. The Present Average Roughness Values by Years for Portland Cement Concrete Pavements Built on Granular Base Courses (Subgrade Treatments)	59
21. Effect of Repetition of Loads on Roughness.	62
22. Relationship Between Transverse Cracking and Road Roughness for Concrete Pavements	64
23. Road Roughness Measurements for Flexible Pavements by Surface Type	67
24. Comparison Between Roughness Indices and Surface Qualities as Given by Indiana State Highway Inventory	69
25. Schematic Diagram Showing Method for Recording Oscillograms of Spring Action of Road Roughness Indicator	71-A

ABSTRACT

Holloway, Frank Malvin. M.S.C.E., Purdue University, June 1956. Road Roughness Measurements on Indiana Pavements. Major Professor: Harold L. Michael.

The purpose of this project was first, to develop and calibrate a Purdue relative road roughness indicator; second, to test and compare the riding qualities of certain pavement types currently in place on Indiana highways; third, to investigate certain factors that affect road roughness; and fourth, to suggest standards of roughness that are acceptable for new construction and standards for evaluating surface riding qualities of existing pavements.

A "Relative Road Roughness Indicator" of the Bureau of Public Roads type, constructed by the Purdue University Central Machine Shop in cooperation with the Joint Highway Research Project, was used in making these tests. All road roughness measurements were made in accordance with Bureau of Public Roads' recommended procedures.

Road roughness measurements were made on 115 different pavement sections located throughout Indiana. These pavement sections were divided into three main categories: (1) new portland cement concrete pavements, (2) older portland cement concrete pavements constructed on granular base courses, and (3) bituminous surface types on flexible bases.

It was found that for new pavements apparently workmanship during

construction can account for a large amount of road roughness. It is suggested that roughness standards for new construction could almost eliminate that portion of road roughness that is due to careless workmanship during construction.

Although in general the older road sections showed a tendency to be rougher, it is felt that perhaps part of this difference in roughness between old pavements and new ones may be due to improved finishing methods during recent years and not due entirely to age.

The bituminous surface types that were tested for roughness were ones which had been surfaced or resurfaced recently and no apparent surface or base failures entered into the roughness indices. There appears to be considerable opportunity for further research as to causes of road roughness of bituminous surfaces.

In conclusion, the following possible uses for the Purdue Roughometer are suggested: (1) for research studies of pavement design and performance; (2) for fostering a competitive spirit between contractors; (3) for acceptance for new construction; and (4) for evaluating the surface riding qualities of older pavements in connection with the determination of resurfacing and reconstruction needs.

INTRODUCTION

The riding public is probably as much aware of road smoothness as any other single quality of a modern pavement. The driver often thinks of a smooth riding pavement as a good pavement and a rough riding pavement as a poor pavement. From the time when man first began to travel from one place to another "road roughness" has been a factor in the safety and comfort of the traveler.

Since safety and comfort depend to a great extent upon a smooth riding surface, highway engineers have for many years made a concerted effort to construct and to maintain pavements that are as smooth riding as possible. Considerable progress has been made in this direction with the development of the automobile from the early rugged models to the present day high speed, low clearance models. Road equipment manufacturers have also spent large amounts of time and money in the development of road building equipment to eliminate some of the irregularities inherent with hand construction methods.

A "rough" pavement not only gives rise to effects unpleasant to the passengers but also is detrimental to the vehicle. Smooth riding pavements mean greater mileage with less fatigue, less damage to cargoes, and lower operating costs for the vehicle. The research of the last few years has also pointed out that "road roughness" produced impact and impact contributes to the early deterioration of any type of pavement. Thus, the subject of road roughness is a major economic factor to every citizen.

The roughness of a pavement was estimated by eye or with a straight-edge in the early years of highway building. These visual measurements could not be recorded and were always subject to the variation of opinions of observers. Straight-edge measurements were satisfactory for short sections of road, but were slow and not adapted to use in measuring considerable mileage of pavement. With the rapidly increasing mileage in the highway system, it soon became apparent to highway engineers that there was a need for a more accurate and rapid method for measuring and recording road roughness.

Because of this need, engineers concerned with highway construction and maintenance sought to develop equipment with which to measure and compare pavement smoothness or "roughness". As a result many methods and devices were developed and used. One of the early pioneers in the development of these machines was the U. S. Bureau of Public Roads.

History of Early Roughmeters

One of the earliest machines developed for the purpose of measuring road roughness was the "Profilometer" (1)*. This machine was developed jointly in 1923 by the U. S. Bureau of Public Roads and the Bureau of Tests of the Illinois Division of Highways for an investigation of the roughness of pavement surfaces on the Bates Test Road. This apparatus consisted of a straight-edge on a track 24 feet long, and a recording device which, when drawn over the track, recorded automatically the profile of the pavement beneath. The summation of vertical ordinates divided by the length of the surface passed over gave an average ordinate, which was considered a roughness factor of the particular surface. Several modifications of this machine have been constructed and used. One modification was used in connection with an investigation of the shoving and waving of bituminous surfaces at the U. S. Bureau of Public Roads' Arlington Experimental Farm, Arlington, Virginia. While this machine was satisfactory for short sections of pavement, it could not be operated rapidly over a large mileage of road. Also, the results which were recorded on a graph were rather bulky and their interpretation was slow and complicated.

In 1925, a second machine called the "Relative Roughness Determinator" (2) was developed by the U. S. Bureau of Public Roads. This machine was a radical change from the Profilometer. The fundamental principle upon which the Relative Roughness Determinator depended

* Numbers in parenthesis refer to the references in the Bibliography.

was that the vertical motion imparted to a vehicle by the irregularities in a road surface bears a direct relation to the degree of roughness. In order that the effect of this motion upon the chassis of an automobile may be minimized, body springs and rubber tires are provided. The magnitude of the spring and tire deflections depends not only on the magnitude of the road roughness but also upon the speed of the vehicle, amount and distribution of the load, and the type and condition of the spring and tire equipment. By maintaining constant all of these conditions, the deflection of the vehicle body springs would be a measure of the "relative" roughness of the riding surface upon which the vehicle was driven.

The Relative Roughness Determinator or "Roughometer", as it was sometimes called, consisted of a rack which was attached in a vertical position to the front axle of an automobile. Meshed with this rack was a spur gear which was supported by the frame of the car. Movement of the front axle with respect to the chassis, caused by deflection of the body springs, thus produced translation of the rack and rotation of the gear. This gear was connected through a flexible shaft to a mechanical counter on the instrument board of the automobile. Deflection of the front springs of the vehicle thus caused the rotation of the spindle of the counter. In order that this spindle would not rotate in the reverse direction when the body springs returned from their deflected positions, a ball clutch was interposed between the gear and the flexible shaft which operated the counter. This ball clutch allowed the flexible shaft to turn in only one direction so that the counter operated only during the deflection of the body springs and thus recorded the summation

of these deflections in inches. The Relative Roughness Determinator could be attached to any automobile without impairing the appearance or the normal operation of the vehicle. It also had the advantage that it could be used to measure rapidly the relative roughness of road surfaces in inches per mile. While this machine gave fairly good results, the variation in automobiles on which the machine was used made it difficult to compare pavements tested with different vehicles.

Another apparatus, called the "Dana Automatic Recording Roughometer for Measuring Highway Roughness" (3) was developed in 1932 by the Engineering Experiment Station of the State College of Washington. Its essential features consisted of a record paper running five inches per mile with a faster speed of three inches per one hundred feet available for special roughness studies and a pencil operating through a pantograph system attached to the front wheel of an automobile. This system gave a continuous visible picture of the roughness of the road surface. An automatic stamping device printed the mileage and the integrated roughness on the record every half mile or oftener as required.

The Dana Roughometer had the advantage over previous machines of a permanent record, easily and quickly obtained, and which could be filed for future reference for comparison with subsequent records to show the effect of age, frost, traffic, and other factors on a given pavement. This machine was also subject, however, to the criticism that results obtained with different automobiles were difficult to compare.

Even though these early "roughometers" were not entirely satisfactory, they were used by several states with varying degrees of success. Their greatest value was in bringing to the attention of engineers and con-

tractors the need for a machine to compare riding qualities of roads.

In an attempt to overcome the bad features of existing machines, the U. S. Bureau of Public Roads in the 1930's developed the "Relative Road Roughness Indicator" which was first described in a paper presented to the Highway Research Board (4) in 1940 and later published in Public Roads (5). This machine removed the uncertainties of vehicle operation that were present in earlier equipment when an automobile was a component part of the measuring apparatus. Also of importance was the fact that this machine was so designed that it could be duplicated and thereby duplicate results could be expected from any machine which was constructed according to the same plans and specifications as the original.

Like the earlier Relative Roughness Determinator, the Relative Road Roughness Indicator design is based upon the fundamental principle that the vertical motion imparted to vehicle springs by the irregularities in a road surface bears a direct relation to the degree of roughness. By maintaining constant the speed, the amount and distribution of the loading, and the type and condition of the springs and tire equipment, the deflections of the springs of the Relative Road Roughness Indicator is taken as a measure of the "relative" roughness of the road surfaces being tested.

Development of Roughness Measuring Equipment at Purdue

The Joint Highway Research Project became interested in road roughness measurements when, through the courtesy of Mr. E. F. Kelley, Chief of the Division of Tests, Mr. A. L. Catudal brought the U. S. Bureau of

Public Roads' Road Roughness Indicator to Indiana in September, 1941, and made roughness measurements of some 300 miles of Indiana pavements.

In his report to the Joint Highway Research Project Advisory Board on January 2, 1942, Mr. Tilton F. Shelburne listed the following as the "tentative" results of this study:

- (1) The device developed by the Bureau of Public Roads appears to be very satisfactory for measuring road surface roughness.
- (2) It is believed that such a device could be adopted for acceptance testing as well as for performance and research studies.
- (3) A wide range in values were found for the various types of surfaces tested.
- (4) The newer concrete pavements were found generally to be quite smooth. According to B.P.R. these measurements compare quite favorably with those from other states.
- (5) In general, low-type surfaces showed rougher riding qualities than high-type surfaces.
- (6) Concrete pavements increase in roughness with age. This increase may be rather gradual for the first five or six years, as compared to older pavements.
- (7) Concrete pavements with joints were found to be rougher than those without joints and of comparable age.
- (8) It was indicated that some types of subgrade treatment improved the riding qualities of concrete pavements.
- (9) Subgrade types affect riding qualities and undoubtedly account in part for the wide range in roughness values obtained on some of the older concrete pavements. Weather conditions including temperature perhaps affect pavement roughness; however, these variables were not investigated.
- (10) Bridges and structures were found to be rougher than adjacent standard concrete pavements.
- (11) The measurements indicated that surface consolidation or stabilization was desirable for improving riding qualities of loose gravel surfaces.
- (12) The use of the smaller size covering aggregates (sizes no. 9 and 11) in bituminous surface treatments produced slightly smoother riding surfaces than did the coarse size covering aggregate (size no. 8F).
- (13) These tentative results indicated the desirability of measuring road surface roughness of Indiana pavements on a large scale.

As a result of this first study, Mr. Shelburne presented to the Advisory Board on February 19, 1942, a working plan covering an exhaustive study of road surface roughness in Indiana, but because of the

war the Joint Highway Research Project could neither get materials to build a Road Roughness Indicator nor get the U. S. Bureau of Public Roads to bring their machine to Indiana on a co-operative project.

After the war, the Joint Highway Research Project again was interested in road roughness measurements. Development of a three-wheel type of Roughometer was initiated and a pilot machine constructed. The machine, however, did not prove stable and the idea was eventually abandoned.

On December 8, 1953, the Advisory Board recommended the construction of a Relative Road Roughness Indicator of the Bureau of Public Roads type. Finally, on October 7, 1954, a requisition for the construction of a Road Roughness Indicator was placed with the Purdue University Central Machine Shop through the University Service Enterprises.

Except for minor changes, which are described in a later section, the machine which was built and used for this study is essentially the same as the machines built and used by the U. S. Bureau of Public Roads for measuring relative road roughness. Although the official name given to this equipment by the U. S. Bureau of Public Roads is "Relative Road Roughness Indicator", for simplicity it will be referred to as the "Purdue Roughometer" throughout the remainder of this report.

GENERAL DESCRIPTION OF THE PURDUE ROUGHOMETER

The design of the Purdue Roughometer is quite simple. Its essential elements are shown in Figure 1. It consists of a rectangular frame constructed of standard steel channels within which is a single wheel equipped with a 6.00x16 inch four-ply balloon tire. The axle of this wheel is attached to the center of two single leaf springs, one on each side of the wheel. Single leaf springs are used in the design to eliminate inter-leaf friction which would be present if multi-leaf springs were used.

The ends of the springs are attached to the front and rear cross members of the rectangular frame through standard grease seal ball bearing fixtures. At the front of the frame is a pair of channel sections forged to form a Y-shaped tongue for connection with the towing vehicle. The towing connection is provided at the end of this tongue. Over the wheel there is a cross frame or bridge on which the integrator unit is mounted and to which the pistons of two dash-pot spring damping devices are attached.

A molded lead counterweight is secured to the forward end of the frame, its mass and location being such that the center of percussion of the entire trailer, when suspended from the towing hitch as a horizontal compound pendulum, is in the plane of the axle. It should be noted that the center of percussion of any rigid body free to rotate about a horizontal axis not passing through the center of gravity is that point at which the body may be struck without producing a tangential reaction at the support. Therefore, whenever the wheel of the trailer

FIGURE 1. ELEMENTS OF ROAD ROUGHNESS INDICATOR

COURTESY OF B.P.R.

strikes a bump on the pavement surface all of the reaction is transmitted to the wheel with none being absorbed by the trailer hitch. The hitch to the towing vehicle maintains the trailer in an upright position but provides freedom of motion by means of a universal or gimbal joint device.

The essential elements of the integrator are shown schematically in Figure 2. It consists of a drum and cable connection to the axle, a pair of opposed ball clutches, and a microswitch and six-lobe cam for activating a magnetic counter which is carried in the towing vehicle. The cable used is of stainless steel, light and strong yet very flexible. Its lower end is fastened to the axle with an adjustable connection. The upper end of the cable is wrapped around a special groove on the integrator cable drum; a special tension spring maintains a continuous and practically constant tension in the cable. When the cable is drawn down as a result of the deflection of the leaf springs, the entire internal mechanism of the integrator rotates. On the up-stroke, the tension spring rotates the cable drum and front ball clutch only, the rear shaft and six-lobe cam being held fast by the rear ball clutch. In order to record the progress of rotation of the driven element of the clutch and thus integrate the leaf spring deflections that have occurred at any desired time, the six-lobe cam causes closures of the microswitch that actuates the magnetic counter. Since the pitch circle of the cable drum which drives the six-lobe cam is six inches, each closure of the microswitch actuates the magnetic counter which marks the accumulation of one inch in the vertical movement of the axle with respect to the trailer frame.

FIGURE 2. SCHEMATIC SECTION OF INTEGRATOR

In order that any desired length of pavement may be tested without roadside markers, another microswitch, operated by a cam on the hub of the trailer wheel closes the circuit of a second magnetic counter once for each revolution of the wheel.

On the instrument board (shown in Figure 3) that is carried in the towing vehicle are mounted the magnetic counter that records the road roughness units, the second magnetic counter that records wheel revolutions of the trailer as a measure of distance traveled, a switch controlling both counters, and a stop watch. When used with the wheel revolution counter, the stop watch provides a check on the speed of the towing vehicle. The instrument board also provides a place for data sheets. The magnetic counters operate on the storage battery of the towing vehicle.

The gross weight of the entire apparatus is approximately 640 pounds. A close-up photograph of the Purdue Roughometer is shown in Figure 4.

A 1955 Chevrolet Carry-all was purchased by the Joint Highway Research Project to be used as the towing vehicle for the Roughometer (see Figure 5). Although the principal function of this vehicle is to provide the means for towing the Roughometer along the road at a constant testing speed, it is also used for hauling the Roughometer when traveling from one location to another. In order to load the Roughometer into the Carry-all, a set of wheels is fastened at the front of the frame to permit the machine to stand alone like a tricycle. The Roughometer can then be pushed into the body of the towing vehicle by means of three ramps made from six-inch

Figure 4. Close-up View of Purdue Roughometer

Figure 5. Conducting a Road Roughness Test.

steel channels. After the Roughomster is loaded it is fastened so that it will not roll about when being transported.

PURPOSE AND SCOPE

The purpose of this project was four-fold: first, to develop , to calibrate, and to conduct initial road tests of a new Purdue Roughometer of the U. S. Bureau of Public Roads type; second, to test and compare the riding qualities of certain pavement types currently in place on Indiana highways; third, to investigate certain factors that affect road roughness; and fourth, to suggest standards of roughness that are acceptable for new construction and standards for evaluating surface riding qualities of existing pavements.

The roads tested during the field survey were divided into three main categories: new portland cement concrete pavements, older portland cement concrete pavements constructed on granular base courses, and bituminous surfaces on flexible bases. A total of 115 different road sections in all parts of the state were tested. Each road was tested on the center of the traffic lanes, and two roughness measurements were taken for each traffic lane. All roughness measurements were conducted in accordance with U. S. Bureau of Public Roads recommended procedures (6).

PROCEDURE

Construction of the Equipment

As previously stated, the first part of this project involved the actual construction, calibration, and initial road testing of the Purdue Roughometer.

The Purdue Roughometer was constructed by the Purdue University Central Machine Shop from plans and specifications furnished by the U.S. Bureau of Public Roads. To assure that the Purdue machine was an exact duplicate of the machines used by the U. S. Bureau of Public Roads, each component part was carefully checked by a staff member of the Joint Highway Research Project before assembly.

Loading deflection tests were made on each of the special leaf springs before assembly to determine if they had matching load characteristics. The specifications require that when supported at their eyes, they deflect approximately three inches and be approximately flat under a load of 300 pounds. Load deflection tests showed that the special leaf springs were satisfactorily matched (see Table 1).

After the trailer was completely assembled, including dynamically balancing the wheel, the next important test was that of determining if the center of percussion was properly located in the plane of the axle of the wheel. This was determined by swinging the Roughometer as a compound pendulum suspended at the towing hitch and timing its period of oscillation. The theoretical period was calculated using the compound pendulum formula:

$$T = 2\pi \sqrt{\frac{k_o^2}{g\bar{r}}}$$

where: T is the period of the pendulum in seconds

$k_0^2/\bar{r}$ is the length of the compound pendulum in feet

g is the acceleration due to gravity.

TABLE 1

Results of Load Deflection Tests on Special Leaf Springs

Concentrated Loading at Center (Pounds)	Spring Deflections at Center (Inches)			
	Right Spring	Left Spring	Spare Spring	
0	0	0	0	
100	1.001	0.980	1.020	
200	1.974	1.898	1.923	
300	2.951	2.939	2.907	

For the Roughometer, $k_0^2/\bar{r}$ is known to be the distance from the towing hitch to the axle and is equal to exactly five feet. With " g " taken as 32.2 feet per second per second, the theoretical period, T , is calculated to be 2.40 seconds.

While suspended at its towing hitch, the Roughometer was swung like a pendulum and its period of oscillation was timed through several periods by means of a stop watch. Several checks showed that the time was in error less than 0.1 second for 10 complete periods. It was, therefore, felt that for all practical purposes the center of percussion of the Roughometer was properly located in the plane of the axle of the wheel and that no further adjustment in the lead counterweight was necessary.

Calibration of the Integrator

As a final step before the Purdue Roughometer was road tested, its integrator was calibrated. Since the accuracy of the measurements with the Roughometer depends largely on the accuracy of the integrator, a calibrating device for the integrator which met the general recommendations of the U. S. Bureau of Public Roads was constructed by the Central Machine Shop.

The device developed for calibrating the integrator is shown in Figure 6. It consists of a 1/12 horsepower motor running at 1750 revolutions per minute acting through a gear reduction box and two three-step V-belt pulleys which permit oscillation frequencies of 30, 60, and 120 strokes per minute. On the drive shaft of the oscillating mechanism, a cam having a T-slot and set screw arrangement is fitted so that one end of the connecting rod can be set at any radius from 0.001 to 1.000 inches. Also connected to the drive shaft is a Veeder-Root revolution counter which records the number of revolutions or repetitions of "roughness" of known displacement for which the cam is set. The upper end of the connecting rod is attached to a slider which moves with a reciprocating action and is fastened to the integrator cable. The integrator measures the "roughness" in inches for the applied number of displacements of the slider at a set amplitude of stroke. The calibration unit proved to be a fast and convenient method of calibrating the integrator. It was placed directly below the integrator drum and all calibration was made without dismantling any part of the Roughometer.

The results of the first integrator calibration tests showed that there was an appreciable difference between the applied and the integrated

Figure 6. Calibration Device for the Roughness Integrator.

displacements (See Table 2).

TABLE 2

Results of First Integrator Calibration Tests
(Using regular integrator drum and regular cable)

Amplitude of Applied Stroke (Inches)	Total Cycles	Applied Displacement (Inches)	Integrated Displacement (Inches)	Percent Error
0.100	1000	100	92	-8.0
0.200	1000	200	192	-4.0
0.300	1000	300	292	-2.7
0.400	1000	400	392	-2.0
0.500	1000	500	492	-1.6

An investigation was undertaken to determine the reason for the difference between the applied and integrated "roughness". The integrator was first torn down and a check of each component part showed that it had been constructed exactly according to the plans. A check of the integrator cable also showed that it was the exact cable specified by the U. S.

Bureau of Public Roads, namely, Roebling stainless steel wire cable with a diameter of $3/64$ inch consisting of $3 \times 12 \times 0.005$ inch diameter wires.

As another check, Starrett "Last Word Indicators" were used to check the applied stroke amplitude at both the lower end of the stainless steel cable where it is connected to the calibration device and also at its upper end next to the integrator drum. These measurements showed that there was a loss of approximately 0.003 inch per stroke between the upper and lower ends of the cable due to "stretch".

As a further check of this "stretch" in the cable, a length of cable was tested by static loading. The initial length of test cable was 1.000 feet with a one pound initial load. The cable was allowed to hang freely while one pound increments of weight were added to its load. After the addition of each one pound weight, the length of the test cable was measured with precise instruments and its length recorded. When the applied load reached a total of five pounds, the test cable was unloaded by one pound increments and its length measured at each increment. The stretch in the one foot length of cable amounted to approximately 0.005 inch for each pound of load. The results of this loading test of the integrator cable are given in Table 3.

TABLE 3

Results of Load Testing of Integrator Cable

Applied Loading (Pounds)	:	Total Length of Cable (Inches)	
	:	During Loading	During Unloading
1	:	12.000	12.003
2	:	12.005	12.008
3	:	12.010	12.013
4	:	12.015	12.018
5	:	12.019	12.021
6	:	12.024	12.024

There were at least two methods which could be employed to minimize this loss in roughness due to "stretch" in the integrator cable. Either

the amount of cable used could be reduced to as short a length as possible, or the pitch circumference of the integrator drum could be reduced to less than six inches. The first method employed the use of a 1/8 inch drill rod, 22 inches in length. The end of the drill rod was drilled to take the integrator cable and the connection silver soldered. Twenty-two inches of rod was the maximum length which could be used without interfering with the operation of the integrator. Although this method used less than one-half as much cable, there still was more loss in "roughness" than was felt to be tolerable. The results of the calibration tests made with the use of the 1/8 inch drill rod and the regular six inch pitch circumference integrator drum, are given in Table 4 below:

TABLE 4
Results of Second Integrator Calibration Tests
(using regular integrator drum
and cable modified with 1/8 inch solid rod)

Amplitude of Applied Stroke (Inches)	Total Cycles	Applied Displacement (Inches)	Integrated Displacement (Inches)	Percent Error
0.100	1000	100	96	-4.0
0.200	1000	200	196	-2.0
0.300	1000	300	296	-1.3
0.400	1000	400	396	-1.0
0.500	1000	500	496	-0.8

Even though the loss here was less than that encountered when using

the full-length cable, it still remained considerable.

The second method used to minimize the loss in "roughness" due to cable stretch employed the use of a new integrator drum having a pitch circumference of 5.80 inches instead of the regular six inch pitch circumference. Thus, for every 5.80 inches of travel by the pitch circumference of the integrator drum, six inches of "roughness" are recorded.

With this smaller integrator drum instead of a loss between the applied and the integrated "roughness" for all amplitudes of displacement, there was a loss for the shorter displacements and a gain for the longer displacements. The results of the calibration tests when using the smaller integrator drum and the full-length cable, are given in Table 5.

TABLE 5

Results of Final Integrator Calibration Tests
(Using the smaller integrator drum and the regular cable)

Amplitude of Applied Stroke (Inches)	Total Cycles	Applied Displacement (Inches)	Integrated Displacement (Inches)	Percent Error
0.100	1006	100.6	98	-2.8
0.200	1000	200	201	0.5
0.300	1000	300	305	1.7
0.400	1000	400	409	2.2
0.500	1000	500	514	2.8

It is obvious from the above results that this modified integrator will tend to give more correct roughness readings than the other two

tried, for two reasons. First, the percentage error is less, and second, the plus and minus errors tend to compensate for each other. Therefore, for all roughness measurements made during the remainder of this study, the modified integrator drum and the standard steel cable were used.

There appears to be two other means of getting a more accurate integrator which are worthy of mention at this time. These methods were not tried, mainly because the budget would not allow the extra expense at the time, and also because of the time involved. The first method that is suggested for further study is that of doing away with the cable and integrator drum arrangement and replacing it with a rack and pinion mechanism similar to that used in Ames dial gages used for measuring deflections. The remainder of the integrator would remain the same. The rack and pinion mechanism would translate the vertical reciprocating motion of the Roughometer springs into the oscillating rotary motion that activates the double acting ball clutch and transmits electrically to the magnetic counter the spring deflections. It seems reasonable to assume that this mechanism could be built to the accuracy of an Ames dial deflection gage or to 0.001 inch, at least.

A second method of making the integrator more accurate would be by using a solid rod and cable as described before but using an integrator drum whose diameter is somewhere between the regular diameter drum and the modified drum also previously described. This method would require some experimenting.

Initial Road Tests of Equipment

After the calibration of the integrator, the next step in this project was to road test the Roughometer for the purpose of investigating the operating characteristics as affected by certain conditions. These included the effect of speed and tire inflation pressure upon roughness measurements.

In Figure 7 is shown the relationship between speed of the trailer and the magnitude of the roughness index for a typical portland cement concrete pavement section. The particular section tested is located on S. R. 25 just east of West Point. Other roads would show similar relationship but vary according to type of surface and degree of roughness. The results of this test indicate that a constant speed of operation is essential and a standardized value of this constant speed is desirable in order that data obtained from various road sections may be directly inter-compared.

It appears that a variation in vehicle speed of plus or minus one-half mile per hour at the 20 m.p.h. speed recommended by the U. S. Bureau of Public Roads will not cause material variation in the roughness index. This is the speed recommended for two main reasons. First, it results in the least interference with and by other vehicles on the road because traffic will usually travel faster than the testing vehicle and thus does not impede it; and second, this speed makes it easier for the driver of the towing vehicle to follow a definite path and for the observer to take adequate notes and record the counter readings.

It was noted during these tests that the Roughometer was remarkably stable at all speeds, even at speeds up to 60 m.p.h. All speeds were

FIGURE 7. INCHES OF ROUGHNESS PER MILE, AT VARIOUS SPEEDS FOR THE SAME ROAD SECTION

checked and controlled by means of the stop-watch and wheel revolution counter on the instrument board.

Another operating characteristic test that was made was that of the effect of tire inflation pressure on both the roughness index and the number of wheel revolutions for a measured mile. These tests were run on a measured mile on U. S. 52 near Montmorenci. As shown by the data in Figures 8 and 9 the inflation is important not only because of its effect upon the roughness index but also because of its effect upon the number of wheel revolutions per mile.

A study of Figure 8 also shows that perhaps the $30 \pm \frac{1}{2}$ pounds per square inch may not be the best standard for the tire inflation pressure. It was noted that during these particular tests that as the tire pressure was increased from 20 p.s.i. to 35 p.s.i. that the roughness values increased considerably, but for tire pressures from 35 p.s.i. to 45 p.s.i. that the roughness values changed only slightly. An almost identical relationship was found for the northbound pavement as for the southbound pavement. This seems to indicate that perhaps $40 \pm \frac{1}{2}$ p.s.i. would be a better standard value for the tire inflation pressure.

Since these tests showed the importance of keeping the tire inflation pressure constant, examinations of the pressure were made frequently with a Bourdon tube type pressure gage, to assure that it remained within the U. S. Bureau of Public Roads' recommended value of $30 \pm \frac{1}{2}$ p.s.i. It was also noted that after approximately 10 miles of testing, subsequent operation generally required little readjustment of the inflation pressure. However, considerable changes in the air and pavement temperatures would cause appreciable variations in the inflation pressure.

FIGURE 8. EFFECT OF TIRE INFLATION ON ROUGHNESS INDICES — NOMINAL SPEED OF 20 MILES PER HOUR.

FIGURE 9. EFFECT OF TIRE INFLATION ON ACTUAL
NUMBER OF WHEEL REVOLUTIONS FOR A MEASURED
MILE

Another test that was conducted showed that different longitudinal paths along a road may be different in roughness. Figure 10 shows the variation of roughness along three longitudinal paths of three different road sections. The three paths tested were the right wheel path, the left wheel path and the center of the traffic lane. Since different longitudinal elements of a road surface may be slightly different in roughness, all roughness data during the field study were taken at the center of the traffic lane for two main reasons. First, this is the location normally used by the U. S. Bureau of Public Roads with whose data it was planned to make comparisons; and second, this is the location for the greatest safety and ease of operation of the equipment.

Since different longitudinal elements of a road surface may be different in roughness, it seems that it may be desirable to make tests along a number of such elements for special studies such as the deterioration along the edge of a pavement. Therefore, provision has been made on the Purdue Roughometer for shifting the towing hitch transversely from one side of the towing vehicle to the other in increments of four inches.

During these initial performance tests of the equipment, it was noted that the roughness of a road section varied not only from one longitudinal path to another but also within any particular longitudinal path. Figures 11 and 12 are typical examples of how road sections may vary from one location to another along the same longitudinal path. Figure 11 shows the test results for a new concrete pavement constructed in 1955. It showed an average roughness of slightly over 80 inches per mile. This is higher than the average for all other new concrete pavements tested. The averages for all new concrete pavements are discussed in a later section of this

FIGURE 10. VARIATION OF ROUGHNESS ALONG VARIOUS LONGITUDINAL PATHS OF THREE PORTLAND CEMENT CONCRETE ROADS

FIGURE 11. ROUGHNESS BY 0.1 MILE INCREMENTS ALONG THE CENTER OF THE TRAFFIC LANE FOR A NEW CONCRETE PAVEMENT

FIGURE 12. ROUGHNESS BY 1/4 MILE INCREMENTS ALONG THE CENTER OF THE TRAFFIC LANE FOR A 7 YEAR OLD CONCRETE PAVEMENT.

report. Figure 12 indicates how the roughness value for an older section of concrete pavement varied along the same longitudinal path. This section was constructed in 1948 and had an overall average roughness of 85 inches per mile. These results would seem to indicate the need for some type of profilometer attachment to the equipment so that the reasons for this variation within the same longitudinal path of a road may be studied. This subject is more thoroughly discussed in a later section of this report.

Calibration of Roughometer

After the initial performance tests were completed and it was felt that the equipment functioned properly, the next step in this project was the calibration of the Roughometer by means of comparison tests between the new Purdue Roughometer and the U. S. Bureau of Public Roads' equipment. It had been originally planned that roughness measurements would be made simultaneously with both machines but the Bureau of Public Roads was unable to bring its machine to Indiana at this time. Therefore, it was felt that the next best method of comparing the two machines would be by comparing the results of road roughness tests made by the Purdue machine with the results obtained recently by the Bureau of Public Roads for the same road sections. These comparative measurements were made on the experimental sections of U.S. 31, U.S. 41, and U.S. 40.

The U.S. 31 test road is a dual pavement and is located from 1.8 miles northwest of Columbus to 2.8 miles north of the Bartholomew-Johnson County line. Separate roughness measurements were made on each of the flexible and rigid experimental sections. These sections were opened to traffic in December, 1953.

The U.S. 41 test road is located in the northwest corner of Indiana, in Lake County, beginning approximately 4.5 miles south of Cook and terminating at the south edge of Cook. The experimental sections are on the west pavement carrying only southbound traffic. The east pavement carrying northbound traffic is an Indiana standard pavement section. Both are portland cement concrete pavements. The completed pavement was

opened to traffic in November, 1949.

The other experimental section which was used in the comparison study is located near Stilesville, Indiana, and is a part of the east-bound lane of the divided highway U.S. 40. It is made up of a considerable number of continuously reinforced concrete sections of various lengths.

Figures 13, 14, and 15 show graphically the comparisons of the Bureau of Public Roads and Purdue roughness measurements for each of the three test roads. The values shown are the overall average roughness value for each road. For the U.S. 31 test road, the rigid and flexible types are separated.

These graphs show that in most instances the results of the 1955 Purdue roughness measurements compare very closely to the results of the Bureau of Public Roads measurements made previously. This is especially true for the U.S. 31 test road where the rigid sections in 1953 and 1954 had overall indices of 87 and 88 inches per mile respectively as measured by the Bureau of Public Roads, compared with the 1955 Purdue value of 88 inches per mile. The flexible pavement on this same test road had overall indices of 69 and 65 inches per mile in 1953 and 1954 respectively, compared with 66 inches per mile for 1955.

It seems reasonable to assume that of the three test roads, U.S. 31 would be the best suited for making comparative measurements because it is almost a new pavement, and therefore is less likely to have developed either surface or subgrade failures which would affect roughness measurements.

FIGURE 13. A COMPARISON OF THE ROAD ROUGHNESS MEASUREMENTS MADE BY THE BUREAU OF PUBLIC ROADS WITH THOSE MADE BY PURDUE UNIVERSITY ON THE U.S. 31 TEST SECTIONS BUILT IN 1953

FIGURE 14. A COMPARISON OF THE ROAD ROUGHNESS MEASUREMENTS MADE BY THE BUREAU OF PUBLIC ROADS WITH THOSE MADE BY PURDUE UNIVERSITY ON THE U.S. 41 EXPERIMENTAL SECTIONS BUILT IN 1949.

FIGURE 15. A COMPARISON OF THE ROAD ROUGHNESS MEASUREMENTS MADE BY THE BUREAU OF PUBLIC ROADS WITH THOSE MADE BY PURDUE UNIVERSITY ON THE U.S. 40 EXPERIMENTAL SECTIONS NEAR STILESVILLE, BUILT IN 1938.

In Figure 16 are data obtained on three different roads with four different roughness measurements made on each road. It is of interest to note that along a given path that a dispersion of less than one percent from the mean of the index values was obtained in repeated tests. In considering the matter of consistency, two facts should be kept in mind. First, no two runs would follow exactly the same path although the attempt was made to do so; and second, a dispersion of one unit may be caused by the fact that the microswitch of the integrator might happen to be either in or out of the circuit at the instants of closing and of opening the main control switch at the beginning and end of the test. When a dispersion greater than one percent was noted, a thorough examination of the testing equipment was made, after which the road surface was retested. For this reason, it is felt that the average value of two runs over a given longitudinal path is sufficient to give an accurate roughness index. All roughness values given throughout this report are the average of two tests.

During the first week of April, 1956, the Purdue Roughometer was taken to the Langeley Research Station of the Bureau of Public Roads near Washington, D. C., where their research engineers thoroughly checked and tested the equipment.

The Bureau of Public Roads' engineers noted two conditions which needed correcting. First, they noted a slight end play in the ball thrust joints at each end of the dashpot damping units. Although the amount of play was only about 1/100 of an inch it allowed a slight deflection of the trailer springs before the damping units became effective. This play was probably the result of the fibrous grease having worked out

FIGURE 16. VARIATION IN INDICES FOR REPEATED TESTS ON THREE DIFFERENT ROADS

of the joints leaving this slight play even though the retainer caps were screwed down sufficiently tight at the time the ball joints were greased. This condition was corrected by screwing down the retainer caps sufficiently to eliminate the end play but not so tight as to cause binding. The result of this slight play was to increase the road roughness readings.

The second condition noted was that there existed a slight binding in the leaf spring mountings. Apparently the axes of the bronze bushings were not exactly parallel. When the equipment was constructed standard bushings were fitted into the eyes of the leaf springs with failure to note that the axes of the eyes were not mutually parallel. This resulted in a dampening effect which tended to reduce road roughness readings.

These two effects were opposite and apparently almost equaled each other as shown by the correlation tests made on the U.S. 31 test road previous to taking the Roughometer to Washington, D. C.

As it was not practical to correct the binding condition of the leaf spring mountings at the Bureau of Public Roads Research Laboratory, only the ball thrust joint condition was corrected before direct correlations were made between the Purdue Roughometer and those of the Bureau of Public Roads. This direct correlation was made on their "standard" test section which is a mile length of the Mt. Vernon Memorial Highway located just south of Alexandria, Virginia.

The comparisons were made as follows. The Bureau of Public Roads Roughometer No. 101 was followed by the Purdue Roughometer which in turn

was followed by the Bureau of Public Roads Roughometer No. 192. A series of tests showed that the Purdue Roughometer was measuring only 91% of the standard roughness as measured by both of the Bureau of Public Roads machines. It must be remembered that these series of tests were made after the slight play in the dashpot damping units had been removed.

It was recommended by the engineers of the Bureau of Public Roads that after the Purdue machine was returned to Indiana and before any attempt was made to rebuild the leaf spring mountings that a series of tests be run on a pavement section. These results can then be used as a basis on which to determine after rebuilding the spring mountings if the 9% dampening effect has been eliminated. After this 9% loss in roughness readings is eliminated it is felt that the Purdue equipment will give comparable road roughness measurements with those of the Bureau of Public Roads.

As a check to see that the Purdue integrator unit was operating properly, a series of calibration tests were made using the Bureau of Public Roads' special integrator calibration device. The Bureau of Public Roads' engineers reported that the Purdue integrator unit operated very satisfactorily and the results were well within the three percent tolerance allowed in the specifications (see Figure No. 17). Both the regular and modified integrators were checked.

All of the roughness values given elsewhere in this report were made during the summer of 1955 before the Purdue Roughometer was checked and tested by the Bureau of Public Roads. It is felt that the data reported is sufficiently accurate for making the comparisons which are made.

FIGURE 17. RESULTS OF PURDUE INTEGRATOR CALIBRATION TESTS MADE BY THE BUREAU OF PUBLIC ROADS

Selection of Test Sections

After the calibration and initial tests were completed with the Roughometer, it was necessary to select the roads which were to be tested during the field portion of this study. The term "road section" in this paper will be used to define a section of pavement that is as far as known identical in age, traffic volume, and construction over its entire length. These road sections were generally between one and ten miles in length.

During the field portion of this project a total of 115 road sections were tested. Of these, 17 sections were new portland cement concrete pavements (completed during 1954), 65 sections were older portland cement concrete pavements constructed on granular base course (referred to as "subgrade treatments" in the Indiana Standard Specifications for Road and Bridge Construction and Maintenance, 1952), and 33 sections were various bituminous surfaced pavements.

Roughness measurements for all new projects were made for the purpose of establishing a basis for suggesting specification limits. It was also felt that these measurements would stimulate interest among contractors and might create rivalry for the smoothest riding pavements on future paving contracts. These original roughness readings on all new concrete pavements should be valuable for determining pavement performance at later dates. Thus, the change in riding qualities can be studied for these pavements with age and other factors such as traffic. This information might also be used advantageously for improvement of present design and construction practices.

The older concrete pavement sections which were tested for road roughness are the same sections which are included in a performance study by the Joint Highway Research Project of rigid pavements constructed on granular base courses. It was felt that an evaluation of the roughness data for these sections might give a better understanding of the factors affecting pavement performance.

The third group of road sections tested included various types of flexible pavements. These were selected largely on the basis of surface type. Roads of each type were selected from the available records of the Joint Highway Research Project. These flexible type pavements were included in this study because it was of interest to learn how in general their riding qualities varied from the low types to the high types. The locations of all of the various road sections are shown on Figure 16.

Road Testing Procedures

All roughness tests were made at $20 \frac{1}{2}$ m.p.h. in the direction of traffic movement with the trailer wheel in the center of the traffic lane. This is the normal procedure employed by the Bureau of Public Roads. The tire inflation pressure was checked both before and after each run to make certain that it remained at $30 \frac{1}{2}$ p.s.i. On two-lane single pavement highways, both lanes were tested. On dual pavements the outside or traffic lane of each pavement was tested. Because of the traffic hazards involved, the passing lanes of dual pavements were not tested except where extra help was available to offer protection from rear end collisions by vehicles attempting to use the passing lane at high speeds.

The unit of measurement used in this portion of the study is the same as that used during the preliminary tests, namely, "inches of roughness per mile" and is actually an accumulation of the vertical movements of the trailer wheel within the frame for a mile stretch of road. The roughness values given for each road section represent the average of two test runs in each lane. In the case of dual pavements, each pavement was considered separately. Roughness values were recorded at the end of each mile or fraction of a mile for each test run. The "average roughness" (or roughness index) for any particular road section is the total inches of accumulated roughness divided by the number of miles of road in that section.

The only equipment that was necessary in making these tests was the Purdue Roughometer, the towing vehicle, the instrument panel containing the two magnetic counters and stop-watch, and necessary data sheets and pencils. The usual crew consisted of the towing vehicle driver and the test observer. The successful use of the equipment depends very largely on these two men. Although no highly specialized training is required of either man, it is desirable that both have some knowledge of mechanical equipment and a real interest in the work.

Complete instructions for operating the Roughometer are given in the Manual of Information regarding the Operation and Maintenance of the Public Roads Relative Road Roughness Indicator, prepared by the Physical Research Branch, Bureau of Public Roads, U.S. Department of Commerce, June, 1951 (6). It is recommended that any person who has no previous experience with this equipment, study this manual carefully before attempting to make road roughness measurements.

RESULTS OF FIELD STUDY

The results of the roughness tests for each pavement type are discussed in the following sections.

New Portland Cement Concrete Pavements

Of the 17 new concrete pavement sections that were tested for roughness, 3 were urban sections of less than one mile in length and therefore will be discussed separately from the 14 rural sections of greater length. The rural sections ranged in length from 1.008 to 7.482 miles with the average length being 4.706 miles.

In general, the new rural concrete pavements were relatively smooth. They ranged from a low of 67 inches of roughness per mile for the smoothest section to a high of 85 inches of roughness per mile for the roughest section. The over-all weighted average for all sections was 75 inches per mile. The over-all average roughness, smoothest mile, and roughest mile are given in the appendix for each pavement section tested.

It is interesting to note the general agreement in the results of these tests with the results of other states for new concrete pavements. Prof. Ralph A. Moyer and Mr. John W. Shupe, Institute of Transportation and Traffic Engineering, University of California report (7) that Mr. Swanberg, Engineer of Materials and Research, Minnesota Department of Highways, stated in a letter dated December 4, 1950, that

The B. P. R. machine has been used very successfully during and after construction of pavements to assist in obtaining

smoother riding pavements. Our measurements indicate that concrete pavements can be built with a roughness index as low as 52 inches per mile. Most of our pavements, both bituminous and concrete, recently built are in the range of 65 to 80 inches per mile. If the roughness index exceeds 90 inches per mile, roughness in riding is quite apparent and if it exceeds 100 it is rough. One project built in 1946 gave a roughness of 116 inches per mile and was so rough in riding that it resulted in newspaper criticism.

After having tested many miles of roads, the writer agrees with Mr. Swanberg that roughness in riding is quite apparent when the roughness index exceeds 90 inches per mile and is rough if it exceeds 100 inches per mile. The public has a right to expect a new pavement to be smooth riding.

Prof. Moyer also reports that for 93 miles of new rural concrete pavements in California, the average roughness value was 52 inches per mile with a maximum of 75 inches per mile and a minimum of 38 inches per mile. He gives credit for the smooth concrete pavements in California primarily to the "skillful use of the Johnson Finisher developed in California in 1936".

On the basis of their experiences in checking the roughness of new pavements since 1940 with a Bureau of Public Roads Roughometer, the Minnesota Department of Highways has tentatively adopted the following standards:

<u>Roughness Index</u> <u>(Inches per Mile)</u>	<u>Riding Qualities</u>
Below 75	Good
75 to 100	Fair
Above 100	Poor

The tests of new pavements in this study have shown, as have Minnesota and California tests, that pavements can be built to meet the

Minnesota roughness standards and it seems entirely proper and reasonable to expect that new pavements in Indiana should be built to meet these standards. In fact, it appears that a roughness index between 90 and 100 should be considered for inclusion in the poor riding classification.

Workmanship during construction appears to be one of the greatest factors for the difference in roughness between any two new pavement sections. As an example, S. R. 39 between Frankfort and Lebanon was built as two construction sections by two different contractors. Each section is approximately 7 miles long, each completed in 1954 and each of the same design. One of the sections had an over-all average roughness value of 72 inches per mile while the other had 84 inches per mile.

If adopted by all states, roughness standards for new construction should result in improvement in the design and operation of mechanical finishing equipment and finishing methods for the construction of both portland cement concrete and bituminous pavements. Its use would also give a common denominator for comparing the workmanship of various contractors and should tend to create a competitive spirit among contractors which would result in smoother riding pavements.

As mentioned previously, three new urban portland cement concrete pavement sections were also included in the survey. These are not included in the average values for new rural concrete pavements because of their shortness in length and because in the case of two of the three sections considerable hand finishing was required during construction. The section which appeared to have required no special hand finishing was approximately 0.5 mile in length and had an average roughness of 77

inches per mile. This section rode quite smoothly. The other two urban sections were 0.78 and 0.71 miles in length and had average roughness values of 102 and 112 inches per mile, respectively. For these two latter urban concrete pavement sections the roughness in riding is quite apparent. These results for new pavements would tend to verify the fact that good mechanical finishing machines, when operated properly, will give smoother riding pavements than that normally possible by hand finishing.

It is suggested that one way to obtain smoother riding new pavements would be the adoption by the State Highway Department of sawed contraction joints as standard to replace the present hand finished joints. It is of interest to note that sawed joints were specified as standard in 14 states during 1954 (8).

Older Concrete Pavements Built on Granular Base Courses

During the field portion of this study, roughness measurements were made on 65 sections which were older portland cement concrete pavements constructed on granular base course materials (sometimes referred to as subgrade treatments). The purpose of these measurements was to determine if possible if there exists any direct relationship between roughness and the performance of rigid pavements built on granular base courses. This study received supporting data from a pavement performance study that was in progress.

The factors that were considered in this study included the following:

- (a) Type of granular base course material.
- (b) Age of pavement.

(c) Traffic age of pavement.

(d) Amount of transverse cracking.

During the past several years the State Highway Department of Indiana has constructed several hundred miles of rigid pavements on granular base course materials. The main purpose of the granular bases has been to minimize pumping of the subgrade. Besides tending to prevent pumping, the granular base material gives added structural strength to the pavement. Three types of granular base course material have been used, gravel, stone, and sand.

This study included roughness measurements of every known concrete pavement in Indiana that has been constructed on a granular base course except those which have been resurfaced and short sections located within urban areas.

A summary of test data is shown in Table 6 and presented graphically in Figure 19.

TABLE 6

Summary of Results - Road Roughness Tests
(Concrete Pavements Built on Granular Base Courses)

Type of Granular Base Course	Length Tested (miles)	Roughness Measurements (in. per mile)			No. of Sections Tested
		Avg.	Max.	Min.	
Gravel	224	88	118	68	48
Sand	53	86	108	71	11
Stone	33	84	96	70	6
All Types	310				65

FIGURE 19. ROAD ROUGHNESS MEASUREMENTS FOR PORTLAND CEMENT CONCRETE PAVEMENTS BUILT ON GRANULAR BASE COURSE

It is noted that of the three types tested, pavements built on stone base courses had the smoothest surfaces with an average of 84 inches per mile. The roughness averages for pavements with sand and gravel bases were rather close behind with 86 and 88, respectively. It is interesting to note the range between maximum and minimum values for each of the three types. The pavements built on stone base courses had the lowest range in roughness values (26 inches per mile) while pavements built on gravel base courses had the highest (50 inches per mile). There appears to be very little relationship between road roughness and type of granular base course used when that is the only factor considered.

The summary of the results of comparing the present average roughness in inches per mile with the year of construction is presented graphically in Figure 20. The number of miles that were tested for each construction year is also shown.

Although in general the road sections which are older tend to be rougher than those built in recent years, it is not necessarily true that just because a road is old it is rougher than a newer road. A good example of this is shown by the average roughness for the six miles of pavement constructed in 1938. The average roughness for 1938 construction is lower than any of the others except the 1953 and 1954 construction years, and here the 1938 construction is only slightly higher. This does not necessarily mean that as a particular road grows older it does not get rougher, but rather that it is difficult to predict how much road roughness is due to age alone. It must be remembered that of the older pavements only the smoothest ones remain because the roughest ones have

FIGURE 20. THE PRESENT AVERAGE ROUGHNESS VALUES BY YEARS FOR PORTLAND CEMENT CONCRETE PAVEMENTS BUILT ON GRANULAR BASE COURSES (SUBGRADE TREATMENTS)

more likely been resurfaced and are therefore not included in this study. Also, new pavements are not normally resurfaced very soon even though they may be quite rough at the time of construction.

There are other factors which must be taken into consideration, probably the most important of which is "How rough was the road when it was new?" From the discussion of new rural concrete pavements it is noted that there is a spread in roughness of almost 20 inches per mile between the smoothest and the roughest sections. From this it would seem that it is not possible to state how much of the present roughness of a pavement is caused by age and other factors unless the original roughness index for the particular pavement in question is known. This would be similar to trying to estimate the gain in weight of a child for a period of time from knowing only his present weight without knowing his original weight.

Even though most of the older pavement sections were rougher than the newer ones, this does not necessarily mean that they have grown rougher with age. It may be that a large part of this difference in roughness may be due to improved finishing methods during the more recent years, rather than to differences in ages. It may even be that a new pavement during its lifetime may become smoother with age for a short period of time before becoming rough with its breaking up.

In order that the relationship between age and roughness might be determined, it is suggested that annual roughness measurements be made on specific pavement sections. These pavement sections could be picked from among the new sections which were tested during this study. As a part of such a study, measurements should be taken along a number of

longitudinal paths of the pavement such as (1) next to the edge of the pavement, (2) next to the center line of the pavement or inner edge of the traffic lane, and (3) the center of the traffic lane. A study of this type over a period of time should give valuable information not only as to how a pavement changes in roughness with time but also how the various longitudinal paths change in relation to each other. To minimize the effect of temperature warping of the pavement, these periodic roughness measurements should be made as near as practical when the pavement temperatures are approximately the same.

Another factor that was considered as perhaps affecting road roughness was traffic age of the pavements. Thus, not only the actual age of the pavement is considered, but also the amount of traffic that has used the facility. For example, if two pavement sections were constructed the same year but the first has had twice as much traffic as the second, the traffic age of the first would be considered as twice that of the second.

Figure 21 presents graphically the relationship between road roughness and traffic age for 20 road sections. The traffic age which is considered here is the estimated number of repetitions of 18,000 pound axle loads that have been applied to the pavement during its lifetime. The type of base course for each section is shown, also.

From this data, the type of base course when considered alone appears to be of little importance in relation to roughness and traffic age. Taking all the pavements as a whole there appears to be a trend of increasing roughness with increase in traffic age, although its magnitude is not definite because of other variables. The same problem arises here

FIGURE 21. EFFECT OF REPETITION OF LOADS ON ROUGHNESS

as arose when roughness was being correlated with age of pavement. The increase in roughness of the pavement from what it was originally must be known before one can definitely correlate the effect of traffic age with road roughness. As pointed out previously, there is such a wide spread among roughness values for new pavements that it is impractical to determine how much of the present roughness was built into the pavement and how much has developed through other causes. This further emphasizes the need for a continuous study over a period of time.

An attempt was made to correlate road roughness with transverse cracking for a large group of the roads for which the number of transverse cracks was counted, but no such relationship appeared to exist (See Figure 22). This can probably be explained by the fact that as long as the crack is held together by the pavement reinforcement and there is no displacement of the slab across the crack, the tire of the vehicle will pass across it without registering any roughness.

FIGURE 22. RELATIONSHIP BETWEEN TRANSVERSE CRACKING AND ROAD ROUGHNESS FOR CONCRETE PAVEMENTS

Bituminous Surfaces on Flexible Bases

As previously stated, the bituminous pavement sections were included in the field study mainly because it was of general interest to learn just how their riding qualities varied from the lowest to the highest type. It was not intended to be a performance study of either their surfaces or their bases. For this reason only sections that had been surfaced or resurfaced since 1950 were included and therefore base and surface failures were in general not a factor in their roughness and no attempt was made to evaluate these factors. This would require a more extensive study than time and resources would permit at this time. It might also be noted that because the portland cement concrete pavement sections were so widely spread throughout the state, it required very little additional travel time and effort to include these bituminous pavement sections in the study.

The 33 bituminous road sections that were tested for roughness included 10 natural rock asphalt surfaces, 10 hot asphaltic concrete surfaces, 7 bituminous coated aggregate surfaces (open graded), 5 bituminous surface treatments, and one silica-sand asphaltic surface. Roads of each of these types were selected from the "Inventory of the Indiana State Highway Conditions" which is on file with the Joint Highway Research Project. These sections were chosen mainly on the basis of their locations with respect to the rigid pavement sections that were to be tested and no attempt was made to select a random sample. Even though these sections were not chosen at random, it is felt that these roads are fairly representative of all such roads in the State. None of the bituminous surfaces tested were constructed on rigid bases.

A summary of the test data for bituminous surfaces is presented graphically in Figure 23. With the exception of the single silica sand asphaltic section, with an average roughness value of 66 inches per mile, it is noted that of the other four bituminous surface types, natural rock asphalt was the smoothest with an average of 69 inches per mile with bituminous concrete slightly higher with an average of 74 inches per mile. The average for the bituminous coated aggregate surfaces was 127 inches per mile and the bituminous surface treatments was 141.

It is interesting to note the range between the smoothest and the roughest pavement sections for each of the surface types. As there is only one pavement section of silica-sand asphaltic mixture, there is no maximum or minimum value shown. Natural rock asphalt which has the lowest average roughness (excluding silica-sand) also has the lowest range (30 inches per mile) between maximum and minimum. Bituminous coated aggregate surfaces have the largest range (123 inches per mile) between maximum and minimum. The bituminous surface treatments with the highest average have a smaller range (94 inches per mile) than does the bituminous coated aggregate.

Although there are many factors, such as subgrade or base support, age, amount of traffic, and the amount of patching, which may affect road roughness, it is felt that because of the basis of selection as previously outlined, the greatest factor which accounts for the range of roughness values within any particular type of surface is workmanship during construction. This would be especially true for the natural rock asphalt surfaces. It should also be recognized that for some types of bituminous

FIGURE 23. ROAD ROUGHNESS MEASUREMENTS FOR FLEXIBLE PAVEMENTS BY SURFACE TYPE

surfaces the type and gradation of aggregates used will probably affect the roughness.

From this brief study of bituminous surfaces, it would seem that additional investigation might be warranted to determine the effect such factors as size, type, and gradation of aggregates and methods of construction have on the riding quality of the finished pavement.

Surface Riding Quality Evaluations

To further emphasize and illustrate the need for a common denominator for comparing the riding qualities of pavements, a comparison was made between Roughness Indices and the opinions of various observers for a large number of road sections.

As a part of the "Inventory of Indiana State Highway Conditions", conducted during the winter of 1954 and 1955, the inventory parties recorded the surface riding qualities of the pavements as excellent, good, fair, or poor. This was largely a "seat of the pants" determination and was subject to the variations of opinions of different observers. These observers are engineers of the Indiana State Highway Department and as such it seems reasonable to assume that their opinions would be better than that of the ordinary layman.

The comparison between road roughness indices and the surface riding qualities as expressed by the highway inventory observers is shown graphically in Figure 24. The conclusion indicated by this comparison is that personal opinion is widespread concerning the surface riding quality of a road and is therefore an unsatisfactory evaluation method.

Suggested index values for evaluating road roughness on rural primary highways are as follows:

28

SURFACE RIDING QUALITY FROM HIGHWAY INVENTORY

FIGURE 24. COMPARISON BETWEEN ROUGHNESS INDICES
AND SURFACE QUALITIES AS GIVEN BY INDIANA
STATE HIGHWAY INVENTORY

Roughness Index
(in. per mile)Surface Riding Qualities

Below 60

Excellent

60 - 75

Good

76 - 90

Fair

91 - 150

Poor

Above 150

Very Poor

These standards are suggested for use in evaluating existing portland cement concrete pavements and would be valuable in connection with a highway condition survey.

PROPOSED ADDITIONAL ROAD ROUGHNESS RECORDING EQUIPMENT

In connection with any further road roughness study, it is proposed that Brush direct recording oscillograph equipment be added to the present road roughness measuring equipment. One of the criticisms of the Roughometer has been that it does not give an indication of the type of roughness but only provides the accumulated values of road roughness for a given length of road. A pavement having a few large irregularities in its surface, with the rest of the pavement exceptionally smooth, may have roughness values as low or lower than another pavement which has a large number of small irregularities in its surface.

By means of the Brush direct recording oscillograph equipment it would be possible to obtain a graphical record of the road roughness as measured by the Roughometer. The Brush equipment could be used for many other purposes and could be readily attached to the Roughometer as needed.

There are two methods which could be employed to connect the recording equipment to the Roughometer. The first method to be briefly described is that used by the U. S. Bureau of Public Roads and is shown schematically in Figure 25. It consists essentially of (A) an S.R. 4, Type A, strain gage attached to one of the leaf springs of the Roughometer, (B) a Brush BL 310 Strain Analyzer, (C) a Brush BL 202 direct recording oscillograph, (D) an inverter, and (E) a 12-volt D.C. battery. The 12-volt storage battery of the towing vehicle may be used to provide the current for the vibrator power supply unit which changes the 12-volt D.C. to 110-volt A.C. required for the BL 202 oscillograph and the BL 310

FIGURE 25. SCHEMATIC DIAGRAM SHOWING METHOD FOR RECORDING OSCILLOGRAMS OF SPRING ACTION OF ROAD ROUGHNESS INDICATOR

COURTESY OF B.P.R.

strain analyzer. The unbalance from the strain gage, developed by the vertical movement of the leaf spring, is transmitted to the strain analyzer and then to the oscillograph recorder. The wheel revolution counter is tied in with the oscillograph recorder by a direct connection to the pen motor. To reduce the high induced voltage across the pen motor terminals developed by the revolution counter at the break in contact, a filter is included in the circuit.

The second method which may be used to connect the Brush recording equipment to the Roughometer is that used by the University of California and a number of other organizations. This method is essentially the same as the previously described method except for the way in which the spring deflections are picked up. In this method a potentiometer and two precision resistors form a bridge circuit. The potentiometer may be connected to the trailer spring in two different ways. In the first way the potentiometer is attached to the top of the frame of the Roughometer and a steel tape is attached to the axle of the trailer wheel and to a pulley on the shaft connecting with the potentiometer. The other way is to connect the shaft of the potentiometer directly to the rear shaft of the integrator. In either method, the vertical movements of the springs of the Roughometer are transmitted to the two-channel direct recording oscillograph. The 12-volt storage battery of the towing vehicle should be sufficient to provide the current for the vibrator power supply unit and for the D.C. amplifier unit. The unbalance from the bridge, developed by the vertical movement of the Roughometer springs, is transmitted to the D.C. amplifier and then to the oscillograph recorder. The vibrator power supply changes the 12-volt D.C. to 110-volt A.C. required for the oscillograph

chart motor and the profilograph pen motor. The wheel revolution counter is tied in with the oscillograph recorder by a direct connection to the pen motor, except that a filter circuit is included to reduce the high induced voltage across the pen motor terminals developed by the revolution counter at the break in contact. A more detailed description of the bridge circuit and potentiometer is given in a paper by Prof. Ralph A. Moyer and Mr. John W. Shupe (7).

Another piece of equipment which should be adapted to use with the Purdue Roughometer is the "Pick-up Device for Recording Road Roughness Values" developed by Harry Thanos in partial fulfillment of the degree of Master of Science in Electrical Engineering, under the general direction of Professor John M. Cage of the School of Electrical Engineering, Purdue University (9). This unit is unique in that it not only counts the total number of irregularities, but also sorts these irregularities into five predetermined amplitudes. The counter unit consists of five identical channels of counters each made up of a trigger circuit and an electromagnetic counter.

Before any of the above suggested modifications can be made, it will probably be necessary for a student of electrical engineering to thoroughly study the problem and make recommendations for attaching this recording equipment.

SUMMARY OF RESULTS AND CONCLUSIONS

The following summary of results and conclusions are made from this study:

1. The Purdue Roughometer, built in accordance with the U. S. Bureau of Public Roads' Relative Road Roughness Indicator design, is a convenient, satisfactory, and rapid means of evaluating the riding quality of a pavement. This machine is so designed that it removes the uncertainties of vehicle operation that were always present in the earlier machines where an automobile was a component part of the measuring apparatus. It is also so designed that it can be duplicated and thereby duplicate results can be expected from any machine constructed according to the Bureau of Public Roads plans and specifications.

2. From the magnetic counters that record the road roughness units and the distance tested, the results can be recorded in a form convenient for study and comparison of two or more road sections.

3. Calibration tests of the integrator unit showed that there is some loss in roughness measurements due to stretch in the stainless steel cable. This was partly compensated for by slightly reducing the pitch diameter of the integrator drum until the integrator unit was in error less than three percent for amplitudes between 0.100 and 0.500 inches. It is suggested that the cable and integrator drum arrangement be replaced by a rack and pinion mechanism similar to that used in the dial gages made for measuring deflections. The remainder of the integrator unit would remain the same.

4. Initial road tests of the Roughometer indicated that a constant speed of operation is essential and a standardized value of this constant speed is necessary in order that data obtained from various road sections may be directly inter-compared. The importance of keeping the tire inflation pressure constant during testing was also noted.

5. Along a given longitudinal path a dispersion of less than one percent from the mean of the index values was obtained in repeated tests with the Roughometer.

6. Different longitudinal paths along a road may be different in roughness. It seems that it would be desirable to make tests along a number of longitudinal paths for special studies such as the deterioration along the edge of a pavement.

7. The roughness of a road section may vary not only from one longitudinal path to another but also within any particular longitudinal path. This was not only found to be true for older pavements but also for new pavements.

8. A comparison between measurements made with the Purdue Roughometer and those made previously by the Bureau of Public Roads for the same pavement sections gave results that were almost identical.

9. After checking and testing the Purdue Roughometer, Bureau of Public Roads' engineers recommended some minor adjustments after which they believe the Purdue equipment will make comparable roughness measurements with those made by them.

10. In general, the new rural portland cement concrete pavements were relatively smooth. They ranged from a low of 67 inches of roughness per mile to a high of 85 inches per mile with the over-all weighted average

of 75 inches per mile.

11. Road roughness measurements and therefore riding qualities of new pavements are affected by workmanship during construction.

12. For portland cement concrete pavements there appears to be very little relationship between road roughness and type of granular base course used when that is the only factor considered.

13. Although in general the older portland cement concrete pavements showed a tendency to be rougher, it may not be necessarily true that age alone is the cause of this greater roughness. It is suggested that perhaps a large portion of this difference in roughness between these older pavements and the newer ones may be due to improved finishing methods used during the more recent years.

14. There appears to be a trend of increasing roughness with increase in traffic age of portland cement concrete pavements, although it is not definite because of other variables. As with the correlation of age with roughness, the original roughness values for the pavements must be known before the increase in roughness due to traffic can be evaluated.

15. Transverse cracking of portland cement concrete pavements appears to have little or no effect on road roughness as long as the cracks are held together by the pavement reinforcement and there is no displacement of the slab across the crack.

16. For the particular bituminous surfaces tested, with the exception of the single silica sand asphaltic surface, natural rock asphalt surfaces built on flexible bases were the smoothest with an average of 69 inches per mile. The bituminous concrete surfaces built on flexible bases averaged slightly higher at 74 inches per mile. The average roughness for

all bituminous coated aggregate surfaces built on flexible bases was 127 inches per mile and for the bituminous surface treatments was 141.

17. For the particular bituminous surfaces tested, the natural rock asphalt surfaces built on flexible bases had the smallest range in roughness values while the bituminous coated aggregate surfaces built on flexible bases had the greatest range.

18. More research is needed to determine the effect of age, traffic, and other factors, on road roughness.

19. In order to increase the value of the Roughometer in future road roughness research, it is recommended that Brush direct recording oscillograph equipment be added to the present road roughness measuring equipment. The Brush equipment could be used for many other purposes and could be readily connected to the Roughometer as needed.

20. It is also suggested that an effort be made to adapt the "Pick-up Device for Recording Road Roughness Values" developed by Harry Thanos to use with the Purdue Roughometer.

21. The psychological effect from the publication of the road roughness measurements of all new projects constructed should tend to develop a competitive spirit among contractors which would result in smoother riding pavements.

22. The possibility of using road roughness measurements as part of the basis for acceptance of new high-type pavement construction should be given consideration. It is suggested that the following index values for evaluating road roughness be given consideration:

<u>Roughness Index</u> <u>(inches per mile)</u>	<u>Riding Qualities</u>
Below 75	Good (Acceptable)
75 - 90	Fair (Acceptable)
Above 90	Poor (Not acceptable)

23. For evaluating the surface riding qualities of portland cement concrete pavements as a part of a highway condition survey, in connection with the determination of resurfacing and reconstruction needs, the following roughness indices are suggested:

<u>Roughness Index</u> <u>(inches per mile)</u>	<u>Riding Qualities</u>
Below 60	Excellent
60 - 75	Good
76 - 90	Fair
91 - 150	Poor (possible resurfacing)
Above 150	Very Poor (resurfacing required)

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APPENDIX

TABLE 7
ROAD ROUGHNESS DATA
NEW CONCRETE PAVEMENTS (COMPLETED IN 1954)

Route	Project No.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low mi.	High mi.
S.R. 324	U724(5)	3.0 mi.	Allen	85	73	92
U.S. 41	FL69(28)	5.2 mi. (dual)	Newton	78	68	80
S.R. 39	S417(4)	7.2 mi.	Boone	84	76	99
S.R. 39	S417(5)	7.2 mi.	Clinton	67	61	73
S.R. 135	S124(3)	6.7 mi.	Harrison	69	62	75
S.R. 64	S38(9)	5.0 mi.	Dubois	70	64	76
S.R. 64	S38(8)	7.5 mi.	Dubois	73	62	79
U.S. 41	F35(6)	2.7 mi.	Sullivan	83	67	89
S.R. 19	S422(6)	3.9 mi.	Lake	74	73	76
S.R. 26	S106(2)	4.7 mi.	Jay	72	66	78
S.R. 109	F791(4)	1.0 mi.	Madison	78	-	-
S.R. 109	F791(5)	1.1 mi.	Madison	82	-	-
U.S. 41	F65(8)	4.3 mi.	Gibson	80	73	90
S.R. 62	FL6(23)	1.7 mi.	Spencer	72	-	-
U.S. 50	F325(14)	0.8 mi.	Dearborn	102	-	-
S.R. 101	S812(1)	0.5 mi.	Ripley	77	-	-
S.R. 32	251-E	0.7 mi.	Madison	112	-	-

TABLE 8
ROAD ROUGHNESS DATA

OLDER CONCRETE PAVEMENTS BUILT ON GRANULAR BASE COURSES

Route	Within Sec.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low Mi.	High Mi.
U.S. 41	J	4.0 mi.	Vigo	98	89	108
U.S. 41	J	4.0 mi.	Vigo	91	82	100
U.S. 41	J	2.0 mi.	Vigo	74	74	74
U.S. 41	J	2.0 mi.	Vigo	84	84	84
S.R. 39	K	1.0 mi.	Morgan	79	-	-
U.S. 31	H, I	5.0 mi.	Johnson	76	71	80
U.S. 31	H, I	12.0 mi.	Johnson	85	76	92
S.R. 46	K	1.8 mi.	Bartholomew	78	72	84
S.R. 107	A	2.6 mi.	Jefferson	78	74	81
S.R. 37	J, K	7.0 mi.	Morgan and Monroe	87	74	98
S.R. 37	J	6.0 mi.	Monroe	93	88	98
S.R. 135	B	3.4 mi.	Harrison	88	78	97
S.R. 135	B	3.0 mi.	Harrison	85	76	96
S.R. 135	B	6.7 mi.	Harrison	69	62	75
U.S. 52	P-2	6.0 mi.	Tippecanoe	85	75	97
U.S. 52	P-2	6.0 mi.	Tippecanoe	81	73	94
U.S. 52	N	1.0 mi.	Clinton	76	-	-
U.S. 52	N, O	11.0 mi.	Tippecanoe & Clinton	84	79	90

(Continued Next Page)

TABLE 8 (Continued)

Route	Within Sec.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low Mi.	High Mi.
U.S. 52	L, M	2.0 mi.	Boone	95	78	120
U.S. 40	A	4.0 mi.	Vigo	88	84	92
U.S. 40	A	4.0 mi.	Vigo	91	82	97
U.S. 52	P-2, Q	8.0 mi.	Tippecanoe & Benton	68	64	74
U.S. 52	P-3, Q	4.5 mi.	Tippecanoe & Benton	71	68	78
U.S. 41	J	4.0 mi.	Vigo	106	84	123
U.S. 41	J	4.0 mi.	Vigo	103	92	118
S.R. 25		1.0 mi.	Tippecanoe	118	-	-
U.S. 52	M	1.0 mi.	Boone	95	-	-
U.S. 40	P	4.0 mi.	Henry	105	94	113
U.S. 40	P	1.6 mi.	Henry	101	100	102
S.R. 100	H	3.0 mi.	Marion	117	125	112
U.S. 40	Q-2	5.2 mi.	Henry	98	87	103
U.S. 40	Q-1	6.6 mi.	Henry	91	76	107
U.S. 40	T	1.8 mi.	Wayne	100	86	114
U.S. 40	T	1.8 mi.	Wayne	107	104	110
U.S. 31	P	1.0 mi.	Howard	88	81	96
S.R. 100	H	3.0 mi.	Marion	80	78	82
U.S. 31	P	6.9 mi.	Howard	102	92	107
S.R. 32	D	1.6 mi.	Hamilton	98	89	105
S.R. 100	E	4.7 mi.	Marion	85	78	90

(Continued Next Page)

TABLE 6 (Continued)

Route	Within Sec.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low. Mi.	High Mi.
S.R. 100	H	1.4 mi.	Marion	101	98	106
S.R. 3	K	1.7 mi.	Henry	109	94	121
S.R. 157	K	7.0 mi.	Greene	69	64	72
S.R. 64	C,D	5.0 mi.	Pike	75	70	78
S.R. 37	F	3.0 mi.	Lawrence	80	76	83
U.S. 41	B	4.4 mi.	Vanderburg	79	72	83
U.S. 41	B	4.4 mi.	Vanderburg	83	75	88
U.S. 41	C	9.0 mi.	Gibson	74	65	84
U.S. 41	C	9.0 mi.	Gibson	75	74	78
U.S. 41	B	4.7 mi.	Vanderburg	87	82	90
U.S. 41	B	2.0 mi.	Vanderburg	87	84	90
S.R. 37	F	5.0 mi.	Lawrence	71	66	79
S.R. 62	D,E	5.6 mi.	Vanderburg	83	78	99
S.R. 662	A,B	5.5 mi.	Vanderburg & Warrick	78	71	89
S.R. 66	G	3.6 mi.	Perry	76	72	84
U.S. 30	L	1.0 mi.	Whitley	95	-	-
U.S. 24	O	11.0 mi.	Huntington	94	88	98
U.S. 30	L	16.0 mi.	Kosciusko & Whitley	85	70	106
U.S. 30	W	3.8 mi.	Allen	95	86	108
S.R. 15	B	10.0 mi.	Wabash	99	87	118

(Continued Next Page)

TABLE 8 (Continued)

Route	Within Sec.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low Mi.	High Mi.
U.S. 41	S	9.0 mi.	Newton	96	85	115
U.S. 41	S	5.2 mi.	Newton	87	81	90
U.S. 31	X	6.0 mi.	St. Joseph	102	96	110
U.S. 31	X	6.0 mi.	St. Joseph	99	96	102
U.S. 41	V	8.0 mi.	Marshall	106	95	115
U.S. 41	V	3.8 mi.	Marshall	98	93	106

TABLE 9

ROAD ROUGHNESS DATA - BITUMINOUS SURFACE TYPES

Route	Within Sec.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low Mi.	High Mi.
<u>Silica Sand Asphaltic Surface</u>						
S.R. 46	N-1	4.0 mi.	Decatur	65	59	81
<u>Natural Rock Asphalt Surfaces</u>						
S.R. 2	F-1	5.0 mi.	LaPorte	62	57	68
S.R. 29	P	5.0 mi.	Cass & Carroll	69	61	87
S.R. 39	P	5.0 mi.	LaPorte	58	52	68
S.R. 39	Q	5.0 mi.	LaPorte	59	54	66
S.R. 4	B	5.0 mi.	LaPorte	66	51	79
U.S. 421	U	5.0 mi.	Starke	86	73	112
U.S. 421	B	5.0 mi.	Ripley	76	70	91
S.R. 3	A	5.0 mi.	Clark	64	54	74
S.R. 3	F-2	5.0 mi.	Decatur	58	53	72
S.R. 64	F-3	5.0 mi.	Dubois	86	71	123
<u>Bituminous Concrete Surfaces</u>						
S.R. 45	J-2	5.0 mi.	Greene	64	58	71
S.R. 46	G	3.5 mi.	Monroe	59	55	62
S.R. 3	B-1	5.0 mi.	Scott	52	42	61
S.R. 46	D-2	5.0 mi.	Owen	66	59	74
U.S. 224	M	5.0 mi.	Allen	74	62	88
S.R. 1	P-2	2.7 mi.	Allen	90	81	105
S.R. 3	U-1	5.0 mi.	Allen	91	77	107

(Continued Next Page)

TABLE 9 (Continued)

Route	Within Sec.	Length Tested	County	Inches of Roughness/mi.		
				Avg.	Low Mi.	High Mi.
<u>Bituminous Concrete Surfaces (continued)</u>						
S.R. 39	R	5.0 mi.	LaPorte	114	106	129
S.R. 421	T	5.0 mi.	Pulaski	71	63	89
U.S. 231	G-1	4.0 mi.	Martin	74	64	88
<u>Bituminous Coated Aggregate Surfaces (Open Graded)</u>						
S.R. 60	D	5.0 mi.	Washington	104	89	124
S.R. 56	M	5.0 mi.	Scott	71	64	81
S.R. 28	D	5.0 mi.	Tippecanoe	155	134	180
S.R. 18	C	5.0 mi.	White	135	81	175
S.R. 26	C-1	3.0 mi.	Tippecanoe	92	71	107
S.R. 46	D-1	5.0 mi.	Owen	67	54	74
S.R. 532	C	5.0 mi.	Boone	194	140	227
<u>Bituminous Surface Treatments</u>						
S.R. 49	C-2	3.5 mi.	Jasper	161	145	186
S.R. 39	L-1	5.0 mi.	White	127	103	162
S.R. 39	M	5.0 mi.	Pulaski	162	128	224
S.R. 39	O	5.0 mi.	Starke	144	118	165
S.R. 48	D	5.0 mi.	Greene	186	152	207