Road Roughness Measurements on Indiana Pavements

F. M. Holloway
Research Engineer
Joint Highway Research Project
Purdue University

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.

Since safety and comfort depends to a great extent upon a smooth riding surface, highway engineers have for many years made an all-out effort to construct and to maintain pavements that are as smooth riding as possible. Considerable progress has been made in this direction. Road equipment manufacturers have 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.

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 variations 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 pavements. 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.

In the 1930's, the U. S. Bureau of Public Roads, recognizing the need for a machine to compare riding qualities of roads and that would
be capable of standardization in all of its parts, developed the “Relative Road Roughness Indicator.” This machine, which was first described in a paper presented to the Highway Research Board in 1940 later published in *Public Roads*, removed the uncertainties of vehicle operation that were present in earlier equipment when an automobile was a component part of the measuring apparatus.4, 5 *

The Relative Road Roughness Indicator design is based upon the fundamental principle that the vertical motion imparted to a vehicle spring by the irregularities in a road surface bears a direct relation to the degree of roughness. By maintaining constant speed, the amount and distribution of the loading, and the type and condition of the springs and tire equipment, the deflection of the springs of the Relative 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 Bureau of Public Roads’ Road Roughness Indicator to Indiana in September, 1941, and made roughness measurements on some 300 miles of Indiana pavements.

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

“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 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. The 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

* Superior figures refer to references in the Bibliography.
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.

Although the official name given to this equipment by the 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. The machine which was built and used for this study is essentially an exact copy of the machines built and used by the Bureau of Public Roads for measuring relative road roughness.

**Purpose and Scope**

The purpose of this project was four-fold: first, to develop and to calibrate the new Purdue Roughometer of the 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 two main categories: new portland cement concrete pavements and older portland cement concrete pavement constructed on granular base courses. A total of 79 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 Bureau of Public Roads recommended procedures.²

**General Description of Equipment**

The design of the 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 6.00—16 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. 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 the tongue. 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.
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.

The integrator unit consists of a drum and cable connection to the axle, a pair of opposed ball clutches, and a microswitch and six-lobe cams for activating a magnetic counter which is carried in the towing vehicle. The cable used is Roebling stainless steel wire cable with a diameter of \(\frac{3}{16}\) inch consisting of \(3 \times 12 \times 0.005\) inch diameter wires. 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 interval 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 elements 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 a magnetic counter which marks the
accumulation of one inch in the vertical movement of the axle with respect to the trailer frame.

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.

Fig. 2. Close-up view of instrument panel with data sheet.

On the instrument board (shown in Figure 2) 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.

A 1955 Chevrolet Carry-All was purchased by the Joint Highway Research Project to be used as the towing vehicle for the roughometer. Although the principal function of this vehicle is to provide the means for towing the Roughometer along the road at a constant 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 to 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 steel channels. After the Roughometer is loaded it is fastened so that it will not roll about when being transported. A general view of the Roughometer and towing vehicle making a road roughness test is shown in Figure 3.

Fig. 3. Conducting a road roughness test.

Procedure
Calibration Tests

The Purdue Roughometer used in the road roughness tests described herein was constructed by the Purdue University Central Machine Shop from plans and specifications furnished by the Bureau of Public Roads and 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 assure that they had matching load characteristics. After assembly, the trailer was tested to determine the weight necessary to place the axle at the center of percussion.

As a final step before the Purdue Roughometer was road tested, the 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 recommenda-
tions of the Bureau of Public Roads was constructed by the Central Machine Shop.

After initial road tests showed that the equipment apparently functioned properly, the next step in this project was the calibration of the Roughometer by means of correlation tests between the new Purdue Roughometer and the Bureau of Public Roads' machine. Because the Bureau of Public Roads was unable to bring its machine to Indiana at this time, 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 Indiana road sections.

Fig. 4. 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 4 shows graphically a comparison of the Bureau of Public Roads and Purdue roughness measurements for one of the road sections. This section is the U. S. 31 test road located near Columbus 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 Purdue 1955 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.

Selection of Test Sections

During the field portion of this project, a total of 79 road sections were tested. Of these, 14 sections were new portland cement concrete pavements (completed during 1954) and 65 sections were older portland cement concrete pavements constructed on granular base courses (referred to as “subgrade treatments” in the Indiana Standard Specifications For Road and Bridge Construction and Maintenance, 1952). 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 10 miles in length with most being between four and six miles long.

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 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.

Road Testing Procedures

All roughness tests were made at 20 ± ½ 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 $30 \pm \frac{3}{4}$ p.s.i.

The unit of measurement used in this study is “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 represents the average of two test runs in each lane. In the case of dual pavements, each pavement was considered separately. The “average roughness” (or Roughness Index) for any particular road section is the total inches of accumulated roughness divided by the number of miles in that section.


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**

The 14 new concrete pavement sections tested ranged in length from 1.008 to 7.482 miles with the average length being 4.706 miles.

In general, these 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. The over-all weighted average for all sections was 75 inches per mile. (See Figure 5)

It is interesting to note the general agreement in the results of these tests with the results of other states for new concrete pavements. Mr. Swanberg, engineer of materials and research, Minnesota Department of Highways reports that their measurements indicate that concrete pavements can be built with a roughness index as low as 52 inches per mile and most of their pavements, both bituminous and concrete, recently built are in the range of 65 to 80 inches per mile.7

Prof. Ralph Moyer of the Institute of Transportation and Traffic Engineering, University of California, also reports that for 93 miles of new rural concrete pavements in California, the average roughness value was 52 inches per mile with a range of 38 to 75 inches per mile.7 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 experience in checking the roughness of new pavements since 1946 with a Bureau of Public Roads Roughometer, the Minnesota Department of Highways has tentatively adopted the following standards:
Roughness Index
(in. per mile) Riding Qualities
Below 75 Good
75—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 inches per mile should also be considered for inclusion in the "poor" riding classification.

Workmanship during construction appears to be one of the factors for the difference in roughness between any two new road 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 seven miles long, each completed in 1954, and each of the same design. One of the sections had an overall average roughness of 72 inches per mile while the other was 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. Roughness measurements would give a common denominator for comparing the workmanship of various contractors and would tend to create a competitive spirit among contractors which would result in smoother riding pavements.

Older Portland Cement Concrete Pavements Built on Granular Base Courses

Roughness measurements were made on 65 older concrete pavements constructed on granular base course materials (sometimes referred to as subgrade treatments). The purpose of these measurements was to determine if any measurable relationship existed between roughness and the performance of rigid pavements built on granular base courses. This part of the study received supporting data from a pavement performance study that was in progress. It includes 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.
Three types of granular base course material have been used under rigid pavements in Indiana, namely, gravel, crushed stone and sand. Of the three types tested, pavement with crushed stone base courses were the smoothest with an average of 84 inches per mile. The roughness averages for the sand and gravel types were rather close behind with averages of 86 and 88, respectively. It is concluded that there appears to be very little relationship between road roughness and type of granular base course used when that is the only factor considered.

Although in general the road sections which are older tend to be rougher than those built in recent years, it was found that it is not necessarily true that just because a road is older it is rougher than a newer road. A good example of this is shown by the average roughness for six miles of pavement constructed in 1938 which was lower than any of the others except the 1953 and 1954 construction years, and here the 1938 construction is only slightly rougher. Of course it must be kept in mind that the roughest of the older pavements are more likely to have been resurfaced than the newer pavements. Relatively new pavements are not normally resurfaced even though they may be rough riding.

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. 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 may be noted that there was 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 that particular pavement in question is known.

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

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.
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 was 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 twice that of the second. 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.

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 as arose when roughness was being correlated with age of pavement. The increase of 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. 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 Roughometer will pass across it without registering any roughness.

Summary of Findings

The findings of this study are:

1. The Purdue Roughometer, built in accordance with the Bureau of Public Roads' Relative Roughness Indicator design, is a convenient, satisfactory, and rapid means of evaluating the riding quality of a pavement.

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

3. 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.
4. In general, the new rural portland cement concrete pavements are relatively smooth. They range from a low of 67 inches of roughness per mile to a high of 85 inches per mile with the overall weighted average of 75 inches per mile.

5. Riding qualities and therefore road roughness measurements of new portland cement concrete pavements are affected by workmanship during construction.

6. There appears to be very little relationship between road roughness and type of base course under concrete pavements when that is the only factor considered.

7. Although in general the portland cement concrete road sections which are older 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 a large portion of this difference in roughness between old pavements and new ones may be due to improved finishing methods during recent years.

8. There appears to be a trend of increased roughness with increase in traffic-age of concrete pavements. As with the correlation of age with roughness, the original roughness values for the pavements must be known before the increase in roughness can be evaluated.

9. Transverse cracking of concrete pavements appears to have little or no effect on road roughness as long as there is no displacement of the slab across the crack.

10. More research is needed to determine the effect of age, traffic, and other factors, on road roughness. To determine these effects, periodic roughness measurements must be made on selected roads over an extended period of time.

11. 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.

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

<table>
<thead>
<tr>
<th>Roughness Index (in per mile)</th>
<th>Riding Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 75</td>
<td>Good (Acceptable)</td>
</tr>
<tr>
<td>75—90</td>
<td>Fair (Acceptable)</td>
</tr>
<tr>
<td>Above 90</td>
<td>Poor (Not Acceptable)</td>
</tr>
</tbody>
</table>
13. For evaluating the surface riding qualities of portland cement concrete pavements as a part of a highway condition survey or in connection with the determination of resurfacing and reconstruction needs the following roughness criteria are suggested:

<table>
<thead>
<tr>
<th>Roughness Index (in. per mile)</th>
<th>Riding Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 60</td>
<td>Excellent</td>
</tr>
<tr>
<td>60—74</td>
<td>Good</td>
</tr>
<tr>
<td>75—90</td>
<td>Fair</td>
</tr>
<tr>
<td>91—150</td>
<td>Poor (possible resurfacing)</td>
</tr>
<tr>
<td>Above 150</td>
<td>Very Poor (resurfacing required)</td>
</tr>
</tbody>
</table>

BIBLIOGRAPHY


