ANALYSIS OF ROAD ROUGHNESS OF FLEXIBLE PAVEMENTS USING THE KENTUCKY ACCELEROMETER

JULY 1962
NO. 16

by

L. G. WERMERS

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

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

July 13, 1962

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 3-3-28
Project: C-36-54BB

Several months ago, Miss Velma Nakamura presented a final report to the Advisory Board titled "Serviceability Ratings of Highway Pavements". This report presented the findings of an evaluation of sixty highway pavement sections by panels of persons and by the use of the BPR Road Roughness Indicator. Excellent correlation was found for rigid pavements between the present serviceability rating (PSR) given by the panel and the road roughness index (RRI) measured by the roughness indicator. Correlations for overlay and flexible pavements, however, were not good.

The attached report presents an extension of the research reported in that study by documenting the findings when measurements were taken on a sample of the flexible pavements by the Kentucky Accelerometer. The correlation of PSR with the accelerometer roughness index (ARI) for flexible pavements was found to be considerably better than that obtained for the RRI.

The report is presented for the record. It was authored by L. G. Wermers, graduate assistant on our staff, and prepared under the direction of Professor E. J. Yoder.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:kmc

Attachment

Copy:

F. L. Ashbaucher
J. R. Cooper
W. L. Dolch
W. H. Goetz
F. F. Havey
F. S. Hill
G. A. Leonards
J. F. McLaughlin
R. D. Miles
R. E. Mills
M. B. Scott
J. V. Smythe
J. L. Waling
E. J. Yoder

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Lyle G. Wermers
Graduate Assistant

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Purdue University
Lafayette, Indiana

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INTRODUCTION

In February, 1962, Velma Nakamura submitted a report to the Advisory Board of the Joint Highway Research Project entitled, "Serviceability Ratings of Highway Pavements".[1] This report described in detail a program of pavement evaluation made on sixty highway pavement sections in Indiana.

Nakamura utilized a panel of thirty people to obtain a present serviceability rating, hereinafter referred to as PSR, for each highway section. The PSR was correlated with the pavement surface roughness of each section as measured by the Indiana State Highway roughometer, a modified version of the BPR relative roughness indicator. Roughness of the pavement sections was expressed in terms of a road roughness index, hereinafter referred to as RRI. The RRI was equal to the total inches of accumulated roughness per mile of pavement. The equation of a least squares regression line was then determined which expressed the mathematical relationship between the PSR and RRI. The lines which gave the best correlation for various pavement types were defined by Nakamura as follows:

Rigid Pavement:

$$\log PSR = 3.2457 - 1.3550 \log RRI$$

Overlay Pavement:

$$\log PSR = 1.8874 - 0.7060 \log RRI$$

Flexible Pavement:

$$PSR = 4.90 - 0.0188\ RRI$$

As an evaluation of the validity of these relationships, Nakamura presented the correlation coefficients and squared correlation coefficients as shown in Table 1.

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[1] Numbers refer to list of references at end of report.

TABLE 1

CORRELATION COEFFICIENTS AND SQUARED CORRELATION COEFFICIENTS OF PRESENT SERVICEABILITY RATINGS WITH ROUGHOMETER ROUGHNESS INDEX

Pavement Type	r	r^2
Rigid	-0.98	0.96
Overlay	-0.72	0.52
Flexible	-0.81	0.66

The squared correlation coefficient expresses the fraction of the variability of the PSR which can be explained by the regression line. It is seen that the roughometer roughness explained 96 percent of the variability of the PSR for rigid pavements, but only 52 percent and 66 percent for overlay and flexible pavements respectively.

What measurable quality of the pavement surface accounts for the remaining 48 percent and 34 percent of the variability for overlay and flexible pavements? A value or values highly correlated with the subjective human judgment used in the determination of the PSR is needed to answer this question. Accelerometers, which detect long dips and swells undectable to a roughometer, might give a roughness evaluation which is quite highly correlated with the PSR for flexible pavements and were used in this study.

PURPOSE AND SCOPE

It was the purpose of this study to evaluate correlations which exist among the Present Serviceability Rating (PSR), Roughometer Roughness Index

(RRI), and an Accelerometer Roughness Index, hereinafter referred to as ARI, for flexible highway pavements.

The flexible pavement sections chosen for the study were several originally studied by Nakamura. The PSR and RRI as obtained by Nakamura were correlated with the ARI determined for each pavement section. A least squares regression analysis was then applied to the known PSR, RRI, and ARI for the pavement sections and PSR prediction equations determined.

PROCEDURE

Test Sections

Nakamura's study considered 19 flexible pavement sections in the Lafayette, Indiana area. After visual inspections of these roads, and examination of the roughometer data for these sections, eight (8) of these sections were chosen for further study. These sections were chosen on the basis of homogeneity and to represent a range of surface conditions. The locations of the eight test sections are shown in Figure 1. Section numbers used correspond to Nakamura's identification.

Accelerometer Road Roughness Index

The Kentucky Department of Highways has adopted a method of highway pavement evaluation which utilizes an electronic recording of the acceleration to which a passenger in an ordinary vehicle is subjected when riding over the pavement[2]. The cooperation of personnel from the Kentucky Highway Department enabled the use of their accelerometer equipment and personnel in obtaining the accelerometer roughness index of the test sections.

Their procedure utilizes triaxial accelerometers resting on the chest of a passenger in the test vehicle. The vehicle is driven over the test

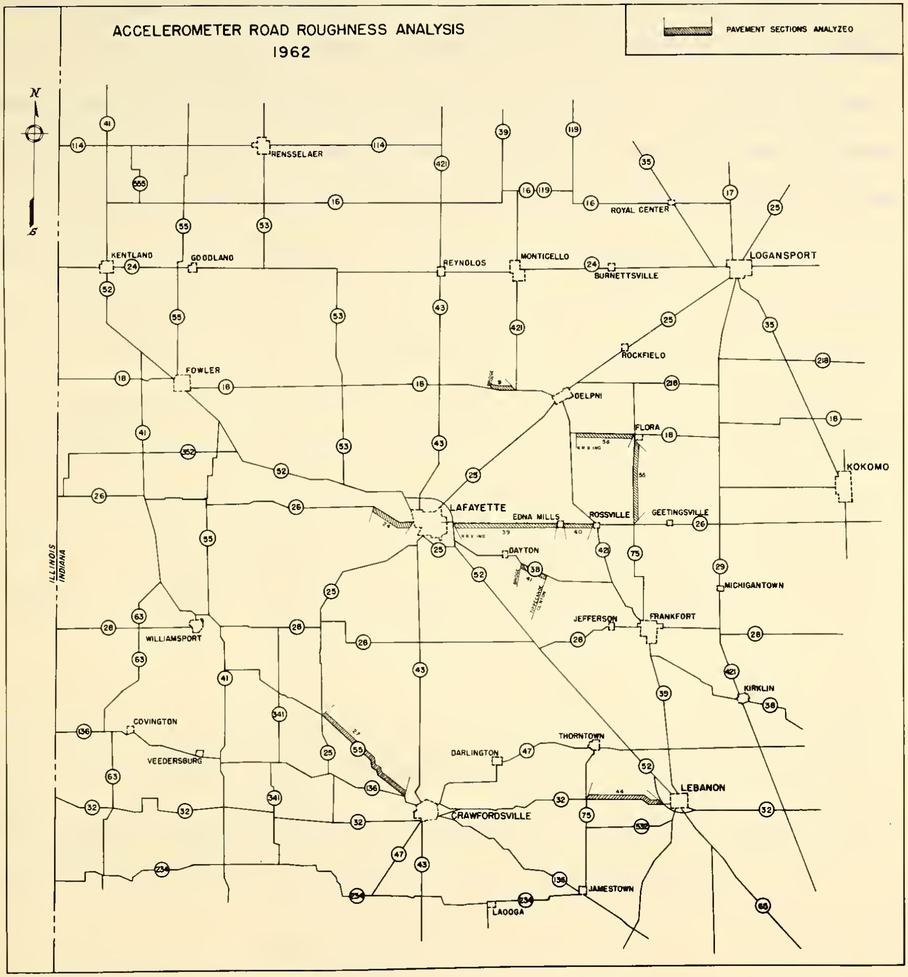

FIGURE 1. LOCATION OF TEST SECTIONS

section at a speed of 51.5 miles per hour; longitudinal, vertical, and transverse accelerations acting on the passenger are recorded electronically. Figures 2 and 3 present resultant acceleration traces from a portion of the pavement sections studied in the research reported here. A visual inspection of the graphs yields a subjective evaluation of the relative roughness of the sections. For purposes of analysis, however, a more precise and objective measure of the roughness is desired. The vertical acceleration trace is utilized to obtain this objective value known as the accelerometer roughness index. The ARI is represented by the average vertical acceleration encountered along the pavement section. Accelerations are recorded such that two inches on the graph equals one g, and the speed of chart travel is such that one-quarter inch on the scale equals one second. Determination of the area enclosed by the vertical acceleration trace and conversion to an average acceleration yields a formula as follows:

$$\text{average acceleration} = \frac{A}{2L}$$

where; A is the area under the graph in square inches, and L is the total length of the recorded chart in inches. To obtain a value which lends itself more readily to mathematical manipulation, the average acceleration value is multiplied by a factor of 10^4. The ARI thus becomes:

$$\text{ARI} = \frac{A}{2L}\,10^4$$

The area enclosed by the acceleration trace was determined with polar planimeters. Since the testing was performed in both traffic lanes, an ARI was computed for each lane and the arithmetic mean of the two lanes was taken as the ARI for the section.

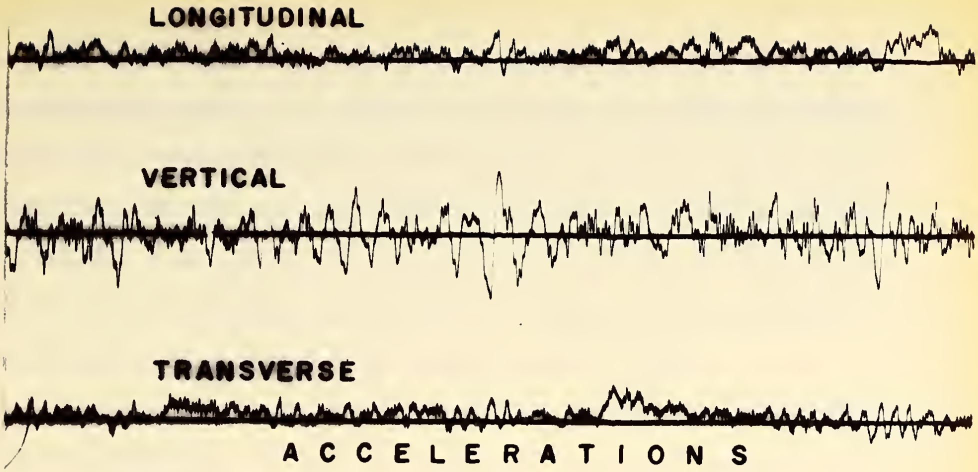

FIGURE 2. 1650 feet of WB lane of section 39, SR 26, East of Lafayette, ARI = 470

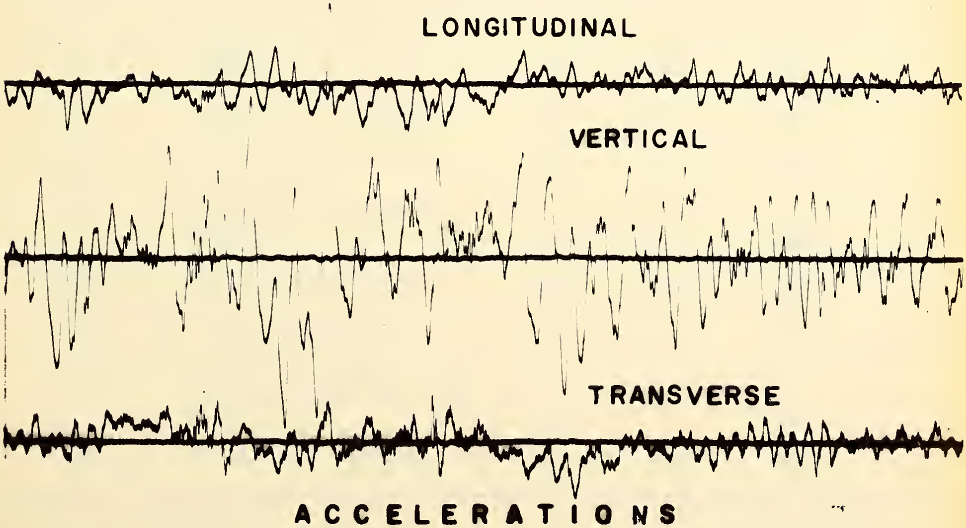

FIGURE 3. 1650 feet of EB Land of Section 40, SR 26, East of Edna Mills, ARI = 1300

Most previous methods of roughness evaluation have consisted of measuring the deviations of the roadway surface from some prescribed datum. The vertical acceleration trace does not reflect the true profile of the roadway surface, nor is it possible to relate mathematically the vertical acceleration trace and the true roadway profile. Also, the ARI does not take into account roughness concentration or nonhomogeneity of section but represents an average roughness throughout the section.

Table 2 presents a tabulation of the PSR, RRI, and ARI for the pavement test sections.

TABLE 2

PRESENT SERVICEABILITY RATING, ROUGHOMETER ROUGHNESS INDEX, AND ACCELEROMETER ROUGHNESS INDEX FOR EIGHT FLEXIBLE PAVEMENT SECTIONS

Section	Location	PSR	RRI	ARI
27	SR 55, NW of Crawfordsville	1.5	144	1222
41	SR 38, SE of Lafayette	2.0	144	1101
55	SR 75, Flora to SR 26	2.3	133	847
40	SR 26, Edna Mills to Rossville	2.6	110	959
24	SR 26, W of Lafayette	2.9	110	870
56	SR 18, W of Flora	2.9	131	899
39	SR 26, Lafayette to Edna Mills	3.2	92	507
44	SR 32, W of Lebanon	3.7	64	572

Correlation of Roughness Indices and PSR

Least squares regression analysis was used to determine regression equations for prediction of PSR as a function of RRI, ARI, and the two in combination. A linear analysis produced the following results:

$$PSR = 5.361 - 0.0224\ RRI \quad \text{- - - - - - - - eq. 1}$$

$$PSR = 4.89 - 0.00258\ ARI \quad \text{- - - - - - - - eq. 2}$$

$$PSR = 5.17 - 0.00771\ RRI - 0.00188\ ARI \quad \text{- - eq. 3}$$

An exponential analysis produced the following:

$$\log PSR = 2.0668 - 0.8095 \log RRI \quad \text{- - - - eq. 4}$$

$$\log PSR = 2.714 - 0.789 \log ARI \quad \text{- - - - eq. 5}$$

$$\log PSR = 2.221 - 0.473 \log RRI - 0.289 \log ARI \quad \text{- - eq. 6}$$

Table 3 presents the correlation coefficients and the squared correlation corresponding to the foregoing equations.

TABLE 3

CORRELATION COEFFICIENTS AND SQUARED CORRELATION COEFFICIENTS OF PRESENT SERVICEABILITY RATING, ROUGHOMETER ROUGHNESS INDEX, AND ACCELEROMETER INDEX ON CURRENT TEST SECTIONS

Equation Number	Equation Type	r	r^2
1	Roughometer - linear	-0.5705	0.3254
2	Accelerometer - linear	-0.8870	0.7868
3	Combined - linear	-0.8890	0.7920
4	Roughometer - Exp.	-0.7522	0.5658
5	Accelerometer - Exp.	-0.8100	0.6561
6	Combined - Exp.	-0.6672	0.4452
7	Combined - Exp. and linear	-0.8932	0.7977

The accelerometer roughness index alone, equation 2, "explains" considerably more of the variability in the PSR than does the roughometer roughness index alone, equations 1 or 4. The two values in a combined function, however, such as equation 3, yield a still higher correlation. The correlations are improved by an exponential analysis in the case of the roughometer value but not for the accelerometer value. A combination of exponential and linear terms as shown in equation 7 was determined to give the best correlation. The corresponding correlation coefficient and squared correlation coefficient are shown in Table 3.

$$PSR = 8.954 - 0.00161\ ARI - 2.395 \log RRI \quad ---- \text{eq. } 7$$

Table 4 presents the actual and theoretical PSR using the functions of RRI, ARI, and combination thereof which yielded the highest degree of correlation as shown in Table 3.

TABLE 4

ACTUAL AND PREDICTED PSR FROM RRI ALONE, ARI ALONE, AND COMBINATION OF RRI AND ARI

		ARI & RRI	ARI	RRI
Section	Actual PSR	PSR From Eq. 7	PSR From Eq. 2	PSR From Eq. 4
27	1.5	1.8	1.7	2.1
41	2.0	2.0	2.0	2.1
55	2.3	2.5	2.7	2.2
40	2.6	2.5	2.4	2.6
24	2.9	2.7	2.6	2.6
56	2.9	2.4	2.6	2.3
39	3.2	3.4	3.6	3.0
44	3.7	3.7	3.4	4.0

DISCUSSION OF RESULTS

It is seen that the function which utilizes both the accelerometer roughness index and the roughometer roughness index gives the most accurate predicting equation. The obtaining of a roughometer value is considerably more time consuming, thus less economical, to obtain than the accelerometer value. Table 3 shows that the accelerometer roughness alone explains very nearly the same fraction of the variability in the PSR that a combination of Roughometer and Accelerometer does. It is therefore feasible on the basis of economic considerations if a physical measurement of pavement serviceability is desired to recommend the use of the accelerometer alone. If, however, more critical evaluation and physical measurements are essential, a combined program of accelerometer and roughometer evaluation will yield a serviceability rating which is very nearly identical to that obtained by the subjective rating of a large panel of individuals.

In summary, if an accelerometer value only is to be used, the equation used to predict the PSR should be:

$$PSR = 4.89 - 0.00258\ ARI$$

This function of the ARI has been shown to explain approximately 79 percent of the variability in the PSR. On the other hand, if both roughometer values and accelerometer values are to be used, the PSR could be predicted using the following formula:

$$PSR = 8.954 - 0.00161\ ARI - 2.395\ \log\ RRI$$

This function, which combines the ARI and the RRI explained approximately 80 percent of the variability of the PSR in the pavement sections studied in this research, as contrasted to just 56 percent for the roughometer alone.

LIST OF REFERENCES

1. Nakamura, V. F., "Serviceability Ratings of Highway Pavements," Joint Highway Research Project, Purdue University, Lafayette, Indiana, February 1962.

2. Rizenbergs, R. L. and Havens, J. H., "Pavement Roughness Studies," Highway Research Laboratory, Kentucky Department of Highways, Lexington, Kentucky, April 1962.

3. Duncan, A. J., Quality Control and Industrial Statistics, Richard D. Irwin, Inc., 1959.