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16. Abstract

This report briefly describes Illinois' study of riding quality of newly constructed pavement, modifications made to the sensing devices of the BPR-Type Roughometer to improve its capabilities in measuring short pavement sections and to increase the operating speed, and calibration techniques. Included is a list of published reports, with abstracts, emanating from the project.

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AN INVESTIGATION OF THE SMOOTHNESS CHARACTERISTICS OF HIGHWAY PAVEMENT SURFACES

By

John E. LaCroix

Final Summary Report
IHR-74
Road Smoothness

Conducted By
Illinois Department of Transportation
in cooperation with
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AN INVESTIGATION OF THE SMOOTHNESS CHARACTERISTICS OF HIGHWAY PAVEMENT SURFACES

PROBLEM STATEMENT

Highway pavements are built to provide for the safety, comfort, and convenience of the highway user. A pavement deficient in any of these categories will draw criticism. Of all the attributes of a pavement, riding comfort has the greatest influence on the highway user in his judgment of service rendered by a pavement. Because of the constantly increasing numbers of vehicles operating at faster speeds, the highway industry has strived to improve pavement smoothness, and as a result riding quality has become increasingly more important in pavement design and construction.

The need for smooth pavement surfaces has resulted in extensive studies for developing equipment and procedures for making objective measurements and evaluations of riding quality.

OBJECTIVE

The Illinois study of pavement riding quality was initiated in 1957 to obtain quantitative knowledge of the riding characteristics of old and new pavement surfaces, and to establish procedures for use of this knowledge in rating the structural adequacy of existing pavements.

A revised work program was prepared in 1970 that modified and clarified the study objectives. As revised, the Road Smoothness study was conducted in three separate phases. The first phase was concerned with assessment of factors of design and construction which influence the as-constructed riding quality of new pavements. The second phase was concerned with modification to the roadometer to extend its usefulness. The third phase was concerned with the development of equipment and procedures for in-place dynamic calibration of roadometers.

SUMMARY OF FINDINGS

General

Objective measurements of pavement riding quality were made with BPR-type road roughness indicators ("Roadometer" in Illinois). The original Illinois roadometer (Roadometer 1) was constructed in-house, and was patterned after the device introduced by the Bureau of Public Roads in 1941. Numerous modifications were made in adapting the device for use in Illinois, and after extensive calibration tests, the device was placed into regular service in 1959. A second BPR-type roadometer (Roadometer 2) was purchased from the Illinois Toll Highway Commission, and after extensive modifications and calibrations it was placed into regular service in 1961.

The major initial problem of the study was the establishment of a working relationship between highway user opinion and the roadometer output - "Roughness Index" - inches of roughness per mile. A working relationship was developed between the roadometer's objective measurements and the highway user's subjective opinions of the pavement's ability to serve the traveling public. The AASHO Road Test's system of rating pavements was adopted, in which AASHO Longitudinal Profilometer output was used to determine the pavement's ability to serve the traveling public. Roadometer 1 output was correlated with profilometer output, and new Present Serviceability Index (PSI) equations were developed for use with the results of the Illinois Roadometer.

For PCC Surfaces

$$p = 12.0 - 4.27 \text{ Log } \overline{RI} - 0.09 \sqrt{C+P}$$

For Bituminous Concrete Surfaces

$$p = 10.91 - 3.90 \text{ Log RI} - 0.01 \sqrt{C+P} - 1.38 \ \overline{RD}^2$$

where

p = Present Serviceability Index
RI = Roughness Index, inch per mile, by Illinois Roadometer
C+P = A measure of cracking and patching in the pavement surface
$\overline{RD}$ = A measure of rutting in the wheelpaths

In addition, the following system was established to allow a determination of the influence of the Roughness Index alone on PSI:

AASHO PRESENT SERVICEABILITY RATING		ILLINOIS ROADOMETER ROUGHNESS INDEX RATING		
Numerical Rating	Adjective Rating	PCC Pavement (in./mi)	Bituminous Pavement (in./mi)	Adjective Rating
5 – 4	Very good	75 or less	60 or less	Very Smooth
4 – 3	Good	76 - 90	61 - 75	Smooth
		91 - 125	76 - 105	Slightly Rough
3 – 2	Fair	126 - 170	106 - 145	Rough
		171 - 220	146 - 190	Very Rough
2 – 1	Poor	221 - 375	191 - 330	Unsatisfactory
1 – 0	Very poor			

Phase I

Under Phase I of the study, road smoothness measurements were made on nearly all of Illinois' newly constructed pavements between 1960 and 1972. A total of 8,778 equivalent two-lane miles of new pavement surfaces were tested for riding quality, of which 2,266 miles were portland cement concrete pavement and 6,512 miles were bituminous concrete surfaces. Roadometer measurements were made at 20 mph in the wheelpaths of each lane of pavement. Results of these measurements were summarized as average Roughness Index (RI) for each mile of each lane or portion thereof in a section as a single weighted average RI for the entire pavement section.

Reports of roadometer measurements that were made on the individual construction sections were sent to the various highway District offices. Yearly summary reports also were provided for use in evaluating the riding quality of new pavements within each district. The summary contained results based on statewide and district weighted average RI and a comparison of the average RI values beginning with 1960 data. Also, over the years, considerable amounts of road smoothness data have been supplied for use in other research studies.

A study was made of the serviceability level at which Illinois pavements are being retired and rehabilitated by resurfacing. The results showed that, on the average, Illinois pavements are being resurfaced when the serviceability level reaches 2.0, and that the terminal serviceability level of major highways and expressways is somewhat higher and averages 2.5.

Analysis of the data to assess the influence of variables of design and construction on as-constructed riding quality were performed. The following conclusions were drawn from the analysis:

The probability of producing a new pavement with excellent riding quality increases as the length of the paving project increases. This is somewhat more pronounced for PCC pavements than for bituminous concrete surfaces. The riding quality, on the average, was best on paving projects over three miles in length, and poorest on those less than one mile in length. "Very smooth" pavements of both types, however, were in all three categories.

The as-constructed riding quality of rural highway pavements is better on the average than that of urban pavements. Because of higher operating speeds, the need for smooth pavements is considered greater for rural highways.

In comparing conventionally reinforced jointed pavements with contraction joints on 100-ft centers to continuously reinforced pavement, no significant difference in as-constructed riding quality was found that could be attributed to pavement design.

PCC pavements constructed by the slipform method of paving were smoother than those constructed with side forms. A 13 in./mi decrease in average RI was obtained for pavements constructed by the slipform method. Both methods, however, have produced "very smooth" pavements.

Slipform pavers that depend upon the prepared track line for grade control have consistently produced better riding pavements than slipform pavers utilizing automatic electronic grade control devices. Data from approximately 400 two-lane miles of pavement constructed with each type showed an average RI of 64 in./mi for pavers without automatic grade control as compared to 81 in./mi for those with automatic grade control. The trend in the construction industry in Illinois has been a rapid change to pavers with automatic grade control.

The use of a machine leveling binder course in conjunction with a bituminous concrete binder course and surface course (three layers) improved the riding quality of bituminous concrete pavement surface over that obtained when only a binder and surface course were used (two layers). The average RI of the three-layer construction was only 6 in./mi less than that of two-layer construction, but the percentage of total mileage tested in the "very smooth" category (RI-60 or less) was five times greater.

No significant differences in as-constructed riding quality of bituminous concrete pavement surface was noted that could be attributed to type of bituminous paver. Both track-type and rubber-tired type pavers can produce satisfactory riding quality.

The use of leveling devices and automatic grade control devices on bituminous pavers improved the as-constructed riding quality of bituminous concrete surfaces.

The RI of 1,317 two-lane pavement miles constructed during the period when the devices were required on leveling binder and binder only averaged 78 in./mi as compared to 66 in./mi on 1,339 miles constructed with devices used on all courses.

Length of grade reference device used in conjunction with automatic grade control on bituminous pavers had a significant effect on the as-constructed riding quality of the completed surface. The 30-ft ski produced a surface 11 in./mi smoother than the reference surface being traced; the 10-ft ski matched the riding quality of the reference surface; and the 6-in. matching shoe produced a surface averaging 12 in./mi rougher than the reference surface.

Several variables of design and construction have been isolated relative to their effects on riding quality which suggest certain actions that should be considered in an effort to produce smoother pavements.

Relative to PCC pavements, the fact that slipform pavers that depend upon the prepared track line for grade control are providing smoother pavements than those equipped with automatic grade control suggests that too much confidence is being placed in the controls without enough attention being given to the condition of track lines. Certainly, more attention needs to be given to this problem. The study has indicated the importance of properly prepared and stable track lines in obtaining quality riding pavements. A possible solution to the problem would be to require the tracks of the pavers to be set back in to ride on the extended edges of the stabilized subbase and obtain grade control from the reference wire used to prepare the subbase. Another solution would be to extend the width of the subbase to accommodate the spread tracks of the pavers, with grade control being obtained by the skis referencing the subbase surface as is customarily being used today. Also, the length of ski should be looked into in light of the information developed in this study relative to ski length for bituminous paving.

With regard to bituminous concrete paving, the study has provided information in two areas where consideration of design and construction revisions appears to be in order to further improve pavement riding quality.

The use of a thin machine-leveling binder course to level the existing pavement prior to placing the binder and surface courses improved pavement riding quality. Probably more important is the fact that its use tended to reduce the overall range in RI and greatly increased the percentage of mileage in the "very smooth" category. Extended use of machine-leveling binder should be considered, especially when resurfacing rough pavements. Its use, of course, adds to the cost of construction, and the data collected in this study have shown that "very smooth" pavements have been obtained in some cases without its use. This strongly suggests detailed studies are needed to establish criteria for use in determining when machine-leveling binder is needed to assure a quality ride.

The study has shown that the length of grade reference device used in conjunction with automatic grade control on bituminous pavers affects riding quality, with quality increasing as the length of reference increased. This suggests the specifications should include minimum length requirements for traveling string lines. In all cases, ski or traveling string lines should be as long as practicable for prevailing conditions. In this connection, it is suggested that it not be less than 30 feet long for the placement of the leveling binder and binder course, and for the first lane of the surface course. The single exception would be on sharp curves on two-lane, two-way pavements where shorter lengths may be necessary to prevent adverse interference with traffic in the work area. In placing surface course mixture adjacent to previously placed surface where joint matching is important, the length of ski should not be less than 10 ft. The past practice of using a 6-in. joint-matching shoe for this purpose should no longer be permitted.

Phase II

Under Phase II of the study, the horizontal distance and vertical displacement sensing devices of a BPR-type road roughness indicator (Roadometer 3 in Illinois) were modified. The modifications were intended to expand the capability of the roadometer for use in measuring relatively short segments of pavement and for testing at higher operating speeds.

A new integrator was constructed with vertical displacement output capabilities of 100 pulses per one in. of vertical displacement. The resolution of the original device was one count per 1-in. displacement. On the new integrator, the double-acting ball-clutch, and the 6-lobe cam were replaced with a commercially available unidirectional photoelectric encoder.

The horizontal distance accumulator was modified to produce one count for approximately one in. of travel. Originally, one count was produced for each wheel revolution (7+ ft). An 82-tooth commercially available gear was attached to the hub of the test tire, and a proximity switch was positioned above the gear. One electrical pulse is generated every time a gear tooth passes under the switch.

A digital printout feature was incorporated in the modified system to accommodate the high-speed operation capabilities and to eliminate the need for the roadometer operator to copy field data during field test operations.

A minor modification included the use of commercially available ball joint rod ends instead of ball and socket joints on the damper units. This modification was made because the old joints were found to be affecting the damping factor.

The field test program carried out on Roadometer 3 was to provide a measure of the capability relative to meeting its intended use, and to compare its operation with that of the original Roadometer No. 1 relative to reliability, repeatability, and accuracy.

The test results show a very high degree of correlation between the roughness obtained at 20 mph with Illinois' original Roadometer No. 1 and the roughness obtained at 20 mph with the roadometer with the new sensing devices (Roadometer No. 3).

Frequency response curves show that there were only slight differences in the damping factors for the two instruments.

The test results show that Roadometer No. 3 is capable of operating in test mode at speeds up to at least 50 mph, and further indicate that the limiting speed is in excess of 60 mph. Roughness measurements recorded at test speeds up to 50 mph correlated well with those obtained at 20 mph. The correlation equations were developed from limited test data, however, and new equations should be developed from an expanded data base using more precise testing procedures before the new roadometer is pressed into service for testing at higher speeds.

The modified roadometer has the capability of measuring both horizontal distance and vertical displacement of pavement as short as 100 ft in length with sufficient accuracy to obtain RI values that are meaningful and useful. The variations that occurred in the limited repeat testing, although greater than for longer segments of pavement, are considered to be within acceptable limits. The field testing indicated the need for an additional modification to the new roadometer to permit automatic activation and deactivation of the recording equipment at the precise beginning and ending of a pavement being tested. This modification will eliminate operator error in manually starting and stopping the recording, and improve the accuracy of results from tests of short segments of pavement. It also should improve the preciseness of equipment calibration and correlation for different testing speeds.

With the modification discussed above, it is believed that the modified roadometer has good potential for use in quality control testing for acceptance of the as-constructed riding quality of new pavement surfaces. Additional work is needed to determine whether the machine actually possesses this capability and to develop the necessary specifications and test procedures.

Phase III

Under Phase III of the study, a new and more reliable calibration method was sought. Several procedures have been used in Illinois to determine the repeatability of roadometer measurements. The integrator-recording system was independently calibrated under static conditions using a reciprocating mechanism. The entire roadometer was calibrated dynamically in the field by operating the roadometer over one-mile calibration courses. Until 1968, correlations between the roadometer and a CHLOE profilometer were made annually to compensate for any difference in roadometer output from time to time.

The various methods used to calibrate the roadometer all provide some indication of the reliability of roadometer data; however, they all have certain limitations.

While static calibration using a reciprocating mechanism has proven to be a satisfactory procedure for checking the operation of the integrator within the available calibration equipment limits, the input frequency and amplitudes are lower than those encountered during the operation of the roadometer. Although the deviations in integrator output have been shown to be $\pm$ 2 percent or less through the recommended test procedures, the accuracy at higher frequencies and amplitudes commonly encountered in the field has not been established.

Field calibrations accomplished by operating the roadometer over a selected section of pavement do not provide conclusive results. Although the calibration indicates that changes have taken place, uncertainties exist as to whether the roadometer or the pavement was the factor that changed.

Periodic correlation of the roadometer with the CHLOE profilometer was not entirely satisfactory because of frequent malfunctions of CHLOE's electronic recording system, and because of the limited range of slope variance which CHLOE was capable of measuring. Consequently, the use of CHLOE as a calibration device was discontinued in 1968.

Because of limitations in the aforementioned calibration procedures, a new and more reliable calibration method was sought. Since the roadometer is basically a viscously damped, spring-mass system, it can be analyzed by frequency response methods. By subjecting the roadometer to sinusoidal forces over a moderate frequency range, frequency response curves can be generated and compared from time to time to indicate whether changes have occurred in roadometer behavior.

To induce the desired input, a simple vertically oscillating platform was constructed. The results of the platform tests indicate that the roadometer output closely follows that of a system having linear damping with one degree of freedom. Although the basic shape of the response curve did not change from one test to another, the position of the curve shifted very slightly.

Because of the shifts of the curve, a standard curve which would serve as a base level for comparison purposes was desirable. The standard curve was developed using an equation that best describes a system having the characteristics of the roadometer, and using test data representing the average roadometer output throughout the test period. Data from periodic tests were compared with the standard curve, and any changes in roadometer output were noted.

On the basis of this study, frequency response analysis appears to be a potentially good method to determine whether the roadometer response to a given input is the same from time to time. The platform method includes the combined effect of the entire roadometer system on the output results under controlled conditions.

Presently, a comparison of the platform calibration results with the standard theoretical curve indicates whether or not the roadometer is operating correctly; however, the cause of any deviation from the standard curve is not pinpointed by the calibration results. This problem possibly could be alleviated in the future by the development of equipment capable of determining the individual effects of the major components of the roadometer system. Also, modification of the oscillating platform to increase its output capability would be helpful by expanding the range of frequency response which the platform is capable of inducing into the roadometer.

IMPLEMENTATION

The study has been successful in isolating several variables of design and construction relative to their effects on riding quality which have provided direction to a course of action that can be taken by the Department in its concern for improving the as-constructed riding quality of new pavements. The implementation of these findings is in various stages of development. Through cooperative meetings, contractor representatives have been informed of the findings of the study as well as the position of the Department in its concern for further improving the as-constructed riding quality of new pavements.

A recommended modification of current specifications regarding bituminous pavers equipped with automatic leveling and traveling grade reference devices has been prepared and submitted to the Specifications Committee for consideration of adoption by the Department. The recommended modification will limit the traveling grade reference device to a length of not less than 30 feet for the placement of leveling binder, binder course, and the initial lane of surface course, and to a length of not less than 10 feet for the placement of subsequent lanes of surface course where it is necessary to match a joint.

Special provisions are being prepared in an attempt to use the new modified roadometer for quality control testing for acceptance of the as-constructed riding quality of completed new pavement surfaces. The special provisions will set up Roughness Index ranges and corresponding adjustments in bid unit prices for pavement that will be paid the contractor for the various ranges. It is the intent that the special provisions will be included in selected jobs for use on a trial basis to evaluate the effect of it on riding quality and on cost of pavement construction. Special provisions governing both portland cement concrete and bituminous concrete paving are being prepared. In this same connection, consideration is being given to the use of the modified roadometer for measuring the quality of the as-constructed ride on new bituminous concrete resurfacing projects where end-result specifications are to be used.

The Illinois Roadometers are being calibrated using the frequency response analysis and the oscillating platform developed under the study in addition to selected calibration courses in the field.

In addition to the above, findings and collected data from this study have been used as necessary inputs to other research studies included in the Illinois program. For example, the results of the study concerning the level at which pavements are being retired in Illinois, combined with field data on road smoothness, were used in the study of the AASHO Road Test performance equations which resulted in the development and adoption of structural design procedures for flexible and rigid pavements and for resurfacing of existing concrete pavements.

PUBLISHED REPORTS WITH ABSTRACTS

(1) "Experience with a BPR-Type Roadometer in Illinois," W. E. Chastain, Sr. and John E. Burke, Highway Research Board Bulletin 328, 1962.

The Illinois Division of Highways in 1957 constructed a road roughness indicator ("Roadometer") patterned after the device introduced by the Bureau of Public Roads in 1941. Numerous modifications were made in adapting the device for use in Illinois. After an extensive series of tests, the Illinois instrument was placed in regular service recording the smoothness of new and old pavements beginning in 1959. The recently developed use of road roughness indicators in furnishing measurements that assist in estimating the present serviceability of pavement under the concept originating at the AASHO Road Test has greatly enhanced the value of these devices. This paper describes the various modifications made by Illinois in constructing its "roadometer," tests to which it has been subjected, and its use in rating Illinois pavements under the present serviceability concept following correlation of the device with the AASHO Road Test profilometer.

(2) "Factors Influencing the Riding Quality of New Pavement Surfaces in Illinois," John E. LaCroix and Donald R. Schwartz, Illinois Department of Transportation, Physical Research Report No. 65, October 1975.

Between 1960 and 1972, road smoothness measurements were made on 8,778 two-lane miles of PCC and bituminous concrete surfaced pavements in Illinois. The results were evaluated to determine the effects of certain design and construction variables on the as-constructed riding quality of new pavement surfaces. Annual weighted average Roughness Index (RI) values were determined for both types of pavement surfaces, and the RI trends are discussed relative to change that occurred in construction specifications and in paving equipment and procedures.

Relative to both types of surface, the results showed that, on the average, longer paving projects were smoother than short projects and that rural projects were smoother than urban jobs. In comparing standard jointed PCC pavement to continuously reinforced, no difference in as-constructed riding quality was found that could be attributed to pavement design. PCC pavements constructed by the slipform process were smoother than those constructed with side forms, and slipform pavers that depend upon the track line for grade control produced smoother pavements than those equipped with automatic grade control. Bituminous concrete pavement surfaces constructed in three separate layers were smoother than those constructed in two layers. Smoothness was not affected by the type of bituminous paver. The use of leveling and grade control devices during the placement of all courses improved riding quality. The length of grade control reference device used with automatic control affected pavement smoothness; longer devices produced smoother pavements.

(3) "Modification of the BPR-Type Roadometer," J. E. LaCroix, and E. J. Kubiak, Illinois Department of Transportation, Physical Research Report No. 63, June 1975.

Modifications were made in the horizontal distance and vertical displacement sensing devices of a BPR-Type Roadometer to improve the capabilities of this device for measuring pavement segments as short as 100 ft in length, and to increase the operating speed. Test results show that the modified system can be operated at test speeds ranging to 50 mph, and strongly suggest that the limiting speed may be in excess of 60 mph. Preliminary tests indicate that the device is capable of measuring pavement segments as short as 100 ft with sufficient accuracy to obtain RI values that are meaningful and usable. Roughness measurements obtained at 30, 40, and 50 mph correlated very well with those obtained at 20 mph.

(4) "Calibration of Illinois Roadometers," J. E. LaCroix, Illinois Department of Transportation, Physical Research Report No. 61, April 1975.

Several calibration procedures have been used in Illinois to determine the repeatability of roadometer measurements. The integrator was independently calibrated under static conditions. The roadometer was periodically calibrated by operating the instrument over a field calibration course. Until 1968, annual correlations were made between the roadometer and the CHLOE profilometer.

Although the use of these fundamental calibration and correlation concepts indicated when changes in roadometer output had occurred, none of them were entirely satisfactory. To overcome limitation in the established calibration procedures, a new roadometer calibration concept was developed based upon frequency response analysis.

The roadometer is a viscously damped spring-mass system; therefore, it has the characteristics which would allow frequency response analysis. In this calibration, response curves were obtained by subjecting the roadometer to sinusoidal forces over a moderate range of frequencies. A standard curve was developed using the average of data from all tests. Data from periodic tests were compared to the standard curve and changes in roadometer output were observed; however, the changes could not be associated with specific components of the roadometer. Therefore, further consideration should be given to the development of equipment capable of analyzing all the major components in the system. On the basis of this study, frequency response analysis appears to be a potentially good method to determine whether the Roadometer response to a given input remains the same from time to time.