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FACTORS INFLUENCING THE RIDING QUALITY OF NEW PAVEMENT SURFACES IN ILLINOIS

By

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Road Smoothness

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16. Abstract
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 changes that occurred in construction specifications and in paving equipment and procedures.

Relative to both types of surfaces, 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 reference device used with automatic control affected pavement smoothness; longer devices produced smoother pavements.

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SUMMARY

The Road Smoothness study was initiated in 1957 to obtain quantitative knowledge regarding the smoothness 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 plan 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 the assessment of factors of design and construction which influence the as-constructed riding quality of new pavements. The second phase was concerned with modifications 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.

This report covers the work completed under Phase 1 of the study. Road smoothness measurements were made during the period 1960 through 1972 on 8,778 equivalent two-lane miles of new pavement surfaces, of which 2,266 miles were portland cement concrete pavements and 6,512 miles were bituminous concrete pavements. The statewide weighted average Roughness Index (RI) was determined at the end of each field testing season for each type of pavement surface. Histories of statewide weighted average RI's were formulated and the resultant trends were analyzed.

Analyses of the data to assess the influence of variables of design and construction on as-constructed riding quality were performed in three separate categories, the first being a general category concerned with both types of pavement surfaces and the next two dealing specifically with portland cement concrete and with bituminous concrete surfaces.

The length of paving project appears to have an effect on pavement smoothness, with the probability of obtaining a smooth pavement increasing as project length is increased. This appears to be more pronounced for PCC than for bituminous pavement 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 constructed in all three project-length categories. For both types of pavement surfaces, the as-constructed riding quality of rural highway pavements was better, on the average, than the riding quality of urban pavements.

Relative to PCC pavements, a comparison was made of the as-constructed riding quality of conventionally reinforced jointed pavement with contraction joints on 100-ft centers to that of continuously reinforced pavement, and no significant difference was found that could be attributed to differences in pavement design. PCC pavements constructed by the slipform method of paving were smoother on the average by 13 inches per mile than those constructed with side forms. Also, slip-form pavers that depend upon the prepared track line for grade control consistently produced smoother pavements than the slipform pavers equipped with automatic electronic grade control. The average RI on 412 miles of slipform pavement paved without automatic grade control was 64 in./mi as compared to 81 in./mi for 386 miles paved with automatic grade control.

Relative to bituminous concrete surfaces, the study indicated that pavement riding quality is improved with the construction of additional layers of mixture. The use of a leveling binder course in conjunction with a binder and surface course improved the riding quality over that of a binder and surface course only by 6 in./mi. Moreover, the percent of total mileage tested that was in the "very smooth" range (RI = 60 or less) was five times greater when a leveling binder course was used.

The results did not indicate any significant difference in pavement smoothness that could be attributed to type and make of bituminous paver. Both the track-type and rubber-tired type can produce very good riding bituminous surfaces.

The use of leveling devices and automatic grade control devices on all courses of the pavement has contributed toward improving the as-constructed riding quality. An overall improvement of 12 in./mi was realized when the devices were used on all courses as compared to being required only on the leveling binder and binder courses.

The length of traveling grade reference devices used with automatic grade controls on bituminous pavers also affects the quality of ride, with quality increasing as the length is increased. A 10-ft-long ski produced the same smoothness in the layer being placed as existed in the reference surface being traced by the ski. A 30-ft-long ski improved the surface smoothness of the layer being placed over that of the reference surface and a 26-inch joint-matching shoe produced a significantly rougher surface.

FACTORS INFLUENCING THE RIDING QUALITY OF NEW PAVEMENT SURFACES IN ILLINOIS

INTRODUCTION

The Road Smoothness Study was established to gain information about paving techniques and equipment that produce the smoothest riding pavements. The study was started in 1956 in cooperation with FHWA as part of a three-phase research study identified as IHR-74, "Road Smoothness."

This report covers work that has been done in Phase I. In this phase, smoothness measurements made on new portland cement concrete and new bituminous concrete pavement surfaces between 1960 and 1972 were analyzed to assess the effects of several factors of design and construction on the riding quality of those surfaces.

Factors evaluated which influenced the riding quality of both new portland cement concrete and bituminous concrete pavements include length of construction contract, and rural versus urban construction.

The factors analyzed for new portland cement concrete pavement were pavement design, paving procedures (slipform versus side forms), and type of slipform paver (with or without automatic electronic grade control). Those factors analyzed for new bituminous concrete pavements were number of layers placed, type and make of paver (track-type versus rubber-tired type), use of leveling and grade control devices, and length of grade reference device.

BACKGROUND

The road smoothness indicator used by Illinois is patterned after the device introduced by the Bureau of Public Roads in 1941. Various names have been used to identify this piece of equipment, including road roughness indicator, roughometer, and roadometer. In Illinois, the device is most commonly referred to as the "Roadometer."

Planning for the original Illinois roadometer commenced in 1955, and construction of the device was completed in 1957. First tests with this device were conducted April 18, 1957 on Route US 66 near Joliet. This roadometer was wrecked in an accident on October 30, 1957, and was rebuilt between October 1957 and February 1959. Numerous modifications (1) were made in adapting the device for use in Illinois and, after extensive calibration tests, the device was placed in regular service in 1959.

A second roadometer was purchased from the Illinois Toll Highway Commission and, after extensive modification and calibration, was put into regular service in May 1961.

The major initial problem of the study was the establishment of a working relationship between the results of roadometer measurements and highway user opinion of pavement riding quality. This was solved with the adoption of the AASHO Road Test system of rating pavements (1).

The original Illinois roadometer was correlated with the AASHO Longitudinal Profilometer in 1960. New Present Serviceability Index (PSI) equations were developed for use with the results of the Illinois Roadometer. In addition, the following system was established to allow a determination of the influence of the Roughness Index alone on the PSI:

AASHO Present Serviceability Rating		Illinois Roadometer Roughness Index		
Numerical	Adjective	Rigid Pavement (in./mi)	Flexible Pavement (in./mi)	Adjective Rating
5				
	Very Good	75 or less	60 or less	Very Smooth
4				
	Good	76 - 90	61 - 75	Smooth
		91 - 125	76 - 105	Slightly Rough
3				
	Fair	126 - 170	106 - 145	Rough
		171 - 220	146 - 190	Very Rough
2				
	Poor	221 - 375	191 - 330	Unsatisfactory
1				
	Very Poor			
0				

The system was developed by removal of the patching, cracking, and rutting terms in the PSI equations. Thus, the system provides a means of using roadometer measurements to estimate highway user opinion of pavement riding quality.

Throughout the study, pavement sections were tested for use in comparing contractor performance, to determine public acceptance based on riding quality, and to gain information on the effects of the various factors of design and construction on the surface smoothness of pavements.

Reports of pavement completion were submitted by the district highway offices of Illinois DOT prior to field testing. These pavement completion reports identified the pavement sections, the contractors, the resident engineers, pavement type and thickness, paving methods, paver and finishing equipment, type of grade control, type of grade reference used, and construction dates. Construction projects were scheduled for testing as reports of pavement completion were received, and were tested as soon thereafter as the weather and work load permitted. All results were reported and evaluated on the basis of the year tested, which does not in all cases correspond with the year in which paving was completed.

When testing a pavement in the field, roadometer measurements were made at 20 mph in each wheelpath of all lanes of pavement being tested. Results of these measurements were summarized as average Roughness Index (RI) for each mile of each lane or portion thereof, and as a single weighted average RI for the entire section.

Reports of roadometer measurements that were made on the individual construction sections were sent to the various district highway offices. Yearly summary reports also were provided for use in evaluating the riding quality of new pavements constructed 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 (2).

Over the years, considerable amounts of road smoothness data have been supplied for use in other research studies. One such study was made of the level of serviceability at which pavements were being retired or resurfaced in Illinois. The study showed that the average terminal serviceability level for Illinois pavements is about 2.0, and that major highways and expressways are being retired at higher serviceability levels, generally around 2.5. The results of the terminal serviceability study have been applied to the flexible and rigid pavement design manuals being used by Illinois DOT (3) (4).

The results of roadometer measurements on new pavement surfaces have also played an important role in the selection of contractors for the Contractor-of-the-Year Awards, a program initiated by Illinois DOT to provide recognition to contractors for outstanding achievements in the field of PCC and bituminous paving.

TRENDS OF STATEWIDE FIELD TEST RESULTS

Road smoothness measurements were made on 8,778 equivalent two-lane miles of new pavement surfaces, including 2,266 miles of portland cement concrete pavements and 6,512 miles of bituminous concrete surfaces. Nearly all of Illinois' pavements constructed between 1960 and 1972 were tested. Trends of smoothness results from portland cement concrete pavements and bituminous concrete pavements are presented separately.

A plot of the annual statewide weighted average RI for new portland cement concrete pavements for the period 1960 to 1972 is shown in Figure 1. Included in the figure are the equivalent two-lane miles tested and the adjective rating limits. As shown in Fig. 1, the annual average RI's between 1960 and 1965 were relatively uniform, averaging about 88 in./mi. From 1965 through 1968 there was a continued improvement in the as-constructed riding quality of PCC pavement, with the average

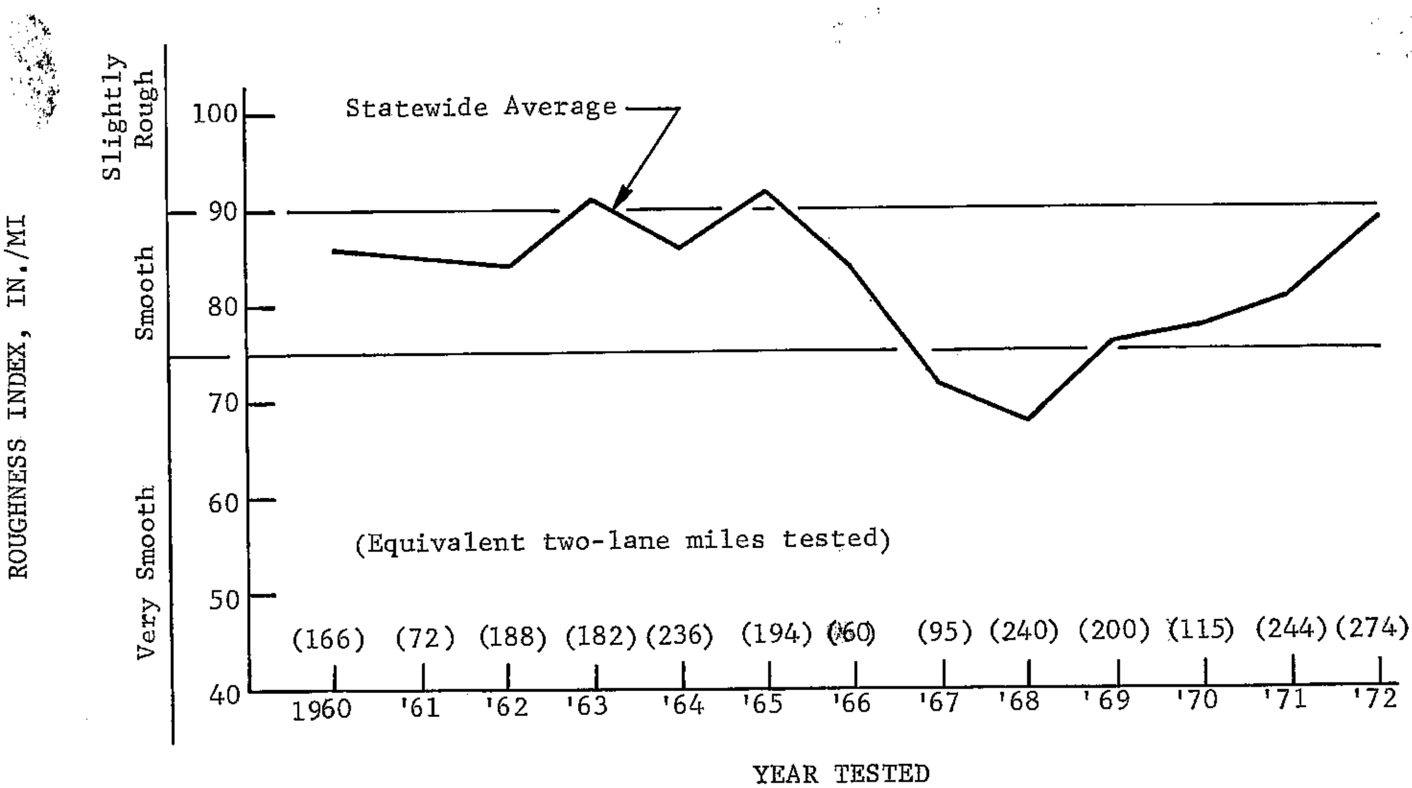

Figure 1. Annual statewide weighted average Roughness Index for new portland cement concrete pavements

RI decreasing from 92 in./mi in 1965 to 68 in./mi in 1968. Since 1968, the annual average RI has been increasing, reaching a value of 89 in./mi in 1972.

A similar plot of annual RI values for bituminous concrete surfaces is included in Fig. 2. As can be seen, the general trend in the annual average RI was an increase in value during the period 1960 through 1966. Considerable improvement in the as-constructed riding quality then occurred from 1966 through 1968, with the average RI decreasing from 85 in./mi in 1966 to 66 in./mi in 1968. The average annual RI then remained fairly stable through 1969 and 1970, and then again started to increase, reaching a value of 80 in./mi in 1972.

In comparing the two figures, it can be seen that the changes in statewide average RI with time are similar for both PCC and bituminous concrete surfaces. The continued improvement in the as-constructed riding quality of the new pavements that occurred during the period 1965-1966 through 1968 coincides with and is explained by changes that were made in construction specification requirements, and that occurred in paving procedures and equipment. The changes included the permissible use and the subsequent rapid adoption by construction industry of the method of slipform paving in portland cement concrete pavement construction, and the required use of leveling devices and electronic controls on pavers for bituminous concrete surface course construction. Analyses of data collected in this study have shown that these changes have resulted in improved as-constructed riding quality and are discussed in more detail in the following section on "Factors Influencing the Riding Quality of New Pavement Surfaces."

The subsequent increase in average RI that has occurred since 1968 in new PCC pavements and since 1970 in bituminous concrete surfaces is less fully explained by the analysis of the data collected in the study. There were, however, certain

Figure 2. Annual statewide weighted average Roughness Index for new bituminous pavements

changes made in construction procedures and equipment that are worthy of mention and that undoubtedly accounted for part of the upward trend in RI that occurred during this period.

Relative to PCC surfaces, a revision in the method of surface texturing accompanied the adoption of the slipform method of paving. Prior to slipform, texturing was accomplished by two passes of a double-thickness burlap drag, usually mounted on a bridge riding on the forms. With the adoption of slipform paving, the burlap drag was mounted on the trailing forms of the paver and the specifications were revised to require only one pass. This revision resulted in a reduced surface texture, and the specifications were again revised in 1968 and reverted to requiring two passes of the burlap drag.

The riding quality of a pavement is influenced by surface texture as well as by longitudinal and transverse undulations in the pavement surface, and it is believed that the roadometer output is sensitive to surface texture. This belief is supported in part by the difference in RI between a new PCC and bituminous pavement having the same adjective rating or Present Serviceability Rating (PSR). A pavement rated as "very smooth" with a PSR of 4.0 has an RI of 75 in./mi for PCC as compared to 60 in./mi for bituminous concrete. Further support is evidenced by the results obtained on several pavements constructed in the early 1960's that included a thin sand-resin binder wearing course (Colorphalt). The resin binder surfaces had a very smooth surface texture; the resultant RI's were consistently in the 30's and low 40's as compared to much higher RI's for the smoothest bituminous concrete pavements.

Thus, while the reduced surface texture that resulted following adoption of slipform paving undoubtedly had an influence on the reduction in RI of PCC pavements that occurred from 1965 to 1968, the increased surface texture following the

1968 specification change offers an explanation for much of the increase in average RI that occurred from 1968 to 1969.

The increase in RI of new PCC pavement occurring since 1968 is further explained by the type of slipform pavers that were used. In the data analysis, which is discussed in detail later in this report, slipform pavers were separated into two categories--those without electronic grade control that depend upon the trueness of the prepared track line for control and those that are equipped with electronic grade controls. The results showed that lower RI's were obtained with the pavers without electronic controls while the trend in industry was toward the other type. Only 17 of 169 two-lane miles of slipform pavement tested in 1968 utilized pavers with electronic controls. By 1972, this ratio had increased to 152 of 190 two-lane miles.

The expedited resurfacing program to upgrade and temporarily improve the level of service of older pavements prior to reconstruction which was initiated in 1969 and continued through 1972 also undoubtedly had a major influence on the increasing trend in RI of both PCC and bituminous concrete pavements since 1969. During this 4-year period, construction was completed on almost 4,600 two-lane miles of pavement in Illinois, of which 833 two-lane miles were PCC and the remainder was bituminous concrete resurfacing. This was almost 400 two-lane miles more than the total mileage completed during the previous nine years (1960 through 1968). The entire expedited program was completed without any major increase in work force, which placed a heavy burden on the technical and engineering staff. With the main thrust being one of completing the program as soon as possible, specification controls were relaxed in several areas and the machine leveling binder course customarily used prior to placing binder and surface courses was not included in many projects.

FACTORS INFLUENCING THE RIDING QUALITY OF NEW PAVEMENT SURFACES

The analyses of data relative to the various factors influencing the as-constructed riding quality of new pavement surfaces were performed in three separate categories, the first being a general category concerned with factors influencing both types of pavement and the next two dealing specifically with portland cement concrete and bituminous concrete pavement surfaces, respectively.

Fairly early in the life of the study it became apparent that there were other factors interacting with those of pavement design and construction affecting the as-constructed riding quality of new pavement surfaces, and that a fairly large data base would be needed to minimize bias and obtain reliable results. For example, evaluations of contractor performance indicate general quality of workmanship to be a variable affecting pavement smoothness. Certain contractors consistently produce smooth pavements regardless of changes in procedures or equipment while others have consistently produced poorer riding pavements. Similar trends exist when comparisons are made among the various districts within the State, indicating construction engineering supervision and control to be a variable affecting the as-constructed riding quality. This is further reinforced when comparing results obtained by individual contractors on projects located in different districts. Fairly consistently, a given contractor will construct better riding projects in those districts producing the smoother pavements and his poorer riding jobs in those districts producing poorer riding pavements.

It is considered that the data base used in the following analyses is sufficiently large that biases are minimized and conclusions are valid. As previously mentioned, a total of 8,778 equivalent two-lane miles of pavement were tested, including 2,266 miles of PCC and 6,512 miles of bituminous concrete surfaces.

GENERAL

The variables of design and construction that were evaluated under this category as influencing the riding quality of both PCC and bituminous concrete pavements include length of construction section and rural versus urban designs.

Length of Construction Section

In evaluating the effect of construction section length of the as-constructed riding quality of new pavements, data from all projects tested during the period 1960 to 1972 were used. The projects were separated into three categories - those under one mile in length, those 1-3 miles in length, and those over 3 miles in length. Altogether there were 523 PCC pavement projects totalling 2,266 two-lane miles and 1,366 bituminous concrete paving projects totalling 6,512 two-lane miles. For each category of section length, the number of paving projects, total equivalent two-lane miles of pavement, the mean Roughness Index (RI) and the standard deviation were determined. The results are given in Table 1.

As shown by the results, the mean RI is inversely related to project length for both PCC and bituminous concrete surfaces. Paving projects over three miles in length have lower mean RI's or better riding surfaces. Comparing the mean RI's with corresponding standard deviations for the three categories of project lengths, however, shows that smooth riding pavements can be built regardless of paving length. Also, in comparing the results for the two types of pavement, it would appear that the effect of project length on the as-constructed riding quality is somewhat more pronounced for portland cement concrete than for bituminous concrete surfaces.

The above results are as might be expected since longer paving projects permit better and smoother production and provide an opportunity to make minor adjustments

TABLE 1. Effect of Paving Project Length on Roughness Index of New Portland Cement Concrete and Bituminous Concrete Pavement Surfaces

Paving Project Length	Number of Projects	Equivalent 2-lane miles	Mean RI in./mi	Standard Deviation
	Portland Cement Concrete Pavement Surfaces			
Under 1 mile	102	61	107	23
1-3 miles	195	349	96	18
Over 3 miles	226	1856	79	15
	Bituminous Concrete Pavement Surfaces			
Under 1 mile	339	186	87	20
1-3 miles	336	628	80	15
Over 3 miles	691	5698	72	15

in mixtures, equipment and procedures that are often required to produce a quality ride. Short projects, on the other hand, are lower production jobs and often require considerably more hand work and modifications in paving trains, especially with PCC paving, because of limited space. The results are interpreted as indicating the probability of obtaining a high-quality riding surface is increased as the length of the paving project is increased.

Rural versus Urban Paving

The comparison of the as-constructed riding quality of rural versus urban paving projects was based on field test data collected during 1961 through 1971 for those construction projects located in northeastern Illinois since this is the area of the State containing most of the urban projects. To further minimize bias in the results, the data for PCC pavements were analyzed separately for jointed and continuously reinforced pavements, and further separated by method of paving--side forms or slipform.

The results are summarized in Table 2. As expected, the average RI was somewhat lower for rural sections for both types of pavement. The average RI for rural projects ranged from 2 to 13 in./mi less for the various categories of PCC surfaces and was 14 in./mi less for bituminous concrete surfaces. Urban sections, in general, are shorter than rural sections and thus less conducive to high-speed production. Also, they usually require more paving gaps to maintain traffic at cross streets and are involved with more hand work than rural sections, all of which tends to adversely affect the as-constructed riding quality. It is considered, however, that urban pavements need not be as smooth as rural pavements because of reduced operating speeds.

TABLE 2. Smoothness of Rural and Urban Paving Sections in Northeastern Illinois 1960-1971

Rural Sections				Urban Sections			
No. of Projects	Equivalent 2-Lane Mi.	RI, in./mi. Mean	RI, in./mi. Std. Dev.	No. of Projects	Equivalent 2-Lane Mi.	RI, in./mi. Mean	RI, in./mi. Std. Dev.
Portland Cement Concrete Pavement Surfaces							
Jointed PCC - Side Forms							
34	95	105	18	7	16	118	12
CRCP - Side Forms							
5	20	100	10	47	76	102	20
CRCP - Slipform							
8	71	55	8	3	12	67	14
Bituminous Concrete Pavement Surfaces							
194	631	70	15	38	181	84	16

PORTLAND CEMENT CONCRETE PAVEMENTS

The PCC pavements were of two general designs - conventionally reinforced jointed, or continuously reinforced (CRC). The conventionally reinforced PCC pavements have sawed contraction joints spaced at 100-ft intervals, contain smooth wire pavement fabric weighing 78 pounds per 100 square feet, have steel dowel-bar load transfer devices at the joints, and thicknesses ranging to 10 inches. A granular subbase of 4-inch or 6-inch thickness completes the total pavement design. The CRC pavements contain longitudinal reinforcement consisting of deformed bars or deformed steel fabric. The longitudinal steel reinforcement equals 0.6 or 0.7 percent of the cross-sectional area of the pavement slab. Pavement thickness ranges from 7 to 10 inches. A stabilized subbase 4 inches thick completes the total pavement design.

Pavement Design

Comparisons were made of the as-constructed riding quality of conventionally reinforced jointed and continuously reinforced PCC pavements placed by the side form method of construction between 1963 and 1970. Six hundred thirty-nine equivalent two-lane miles of conventionally reinforced jointed PCC pavements were tested, resulting in an overall average RI of 88 in./mi with a standard deviation of section averages of 9 in./mi. For the same period, tests were made on 241 equivalent two-lane miles of CRC pavements, giving an average RI of 90 in./mi and a standard deviation of 10 in./mi. A statistical test for significance indicated no difference in the average RI's from the two designs.

Like mileages of both designs placed at similar locations were constructed by a contractor in 1964 and again by another contractor in 1969. Examination of the RI's from these revealed no differences between the two designs by each contractor although differences in RI values did exist between the contractors.

Consequently, the evidence of a difference in the as-constructed riding quality of new PCC pavements that can be attributed to pavement design was found..

Paving Procedures - Slipform versus Side Form

Prior to 1964, all PCC pavements in Illinois were placed using metal side forms. The first use of slipform paving in constructing a PCC pavement on the primary highway system in Illinois was reported in 1964 by Burke and Mascuñana (5). This method was rapidly adopted by the construction industry, and since 1967 the bulk of newly constructed PCC pavements has been placed by the slipform paving process.

Roadometer data obtained during the period 1960 through 1966 from PCC pavements constructed with metal side forms were compared with the data collected during 1966 through 1972 from slipform paving projects. The 1960 and 1966 results include 1,075 equivalent two-lane miles of side form paving with a mean RI of 88 in./mi. The 1966 to 1972 results include 935 equivalent two-lane miles of slipform paving with a mean RI of 75 in./mi. Student's t-test of these results showed a highly significant difference between paving methods, indicating that the slipform method provides a smoother pavement.

Type of Slipform Paver

For the purpose of evaluating the effect of type of slipform paver on the as-constructed riding quality of new PCC pavements, the pavers were divided into two general types - with and without automatic grade control. Those without automatic grade control operate from a prepared track line consisting of an extension of the stabilized subbase beyond the pavement edges and depend upon the track line for grade control. Those with automatic electronic grade control are individually suspended and controlled from each of the four corners of the paver. Grade control is obtained either from a grade reference wire set along the pavement edge or from a short ski at each corner of the paver riding on the outer edges of the prepared subbase surface. There are other differences in operation of the pavers in each of the two general categories but these were not noted in the field reports nor taken into consideration in the analysis.

Roadometer data obtained during the period 1966 through 1972 on CRC pavement projects paved by the slipform method were used in the analysis. The results are summarized in Table 3. The table includes a summary of the data by individual years as well as an overall summary for the total period. The data clearly show that slipform pavers without automatic grade control have consistently provided smooth pavement surfaces. Of the 798 two-lane miles of pavement included in the analysis, 412 miles were paved without automatic grade control, resulting in a weighted average RI of 64 in./mi, which averages 17 in./mi smoother than the 386 miles paved with automatic grade control. On a yearly basis, the average RI of pavements constructed without automatic grade control ranged from 8 to 21 in./mi smoother than those constructed with automatic grade control. Statistical tests show the difference in overall average weighted RI's to be highly significant.

The rapid change in the construction industry to pavers equipped with automatic electronic grade control is very evident from the information given in Table 3. 1968 was the first year of testing new pavements in Illinois constructed with pavers equipped with automatic grade control. Only 17 of 169 two-lane miles tested that year used this type of equipment. By 1972, 152 of 190 miles tested were paved with automatic grade control.

It should be pointed out that, while the slipform paver without automatic grade control overall has consistently produced smoother pavements, both types of pavers are capable of and have produced pavements with excellent riding quality. Also, the data collected in this study do not explain why pavers with automatic grade control on the average are not producing as smooth a surface as those without the controls. There are several factors which could contribute to

TABLE 3. Comparison of Slipform Paver Performance by Paver Type on Continuously Reinforced Concrete Pavement

Year Tested	No. of Projects	Without Automatic Grade Control 2-Lane Mi.	Without Automatic Grade Control Avg. RI	Std. Dev.	No. of Projects	With Automatic Grade Control 2-Lane Mi.	With Automatic Grade Control Avg. RI	Std. Dev.
1966	2	6	79	6	-	-	-	-
1967	10	54	58	12	-	-	-	-
1968	14	152	58	9	3	17	79	17
1969	5	51	62	14	6	44	71	11
1970	9	55	72	16	2	12	80	4
1971	12	56	70	14	9	161	79	20
1972	4	38	76	7	16	152	86	8
TOTALS	56	412	64	12	36	386	81	13

this difference; however, it is suspected that the major factor could be a difference in attention given to the preparation of the track line. It is recognized that pavers without automatic grade controls must have well-prepared track lines to produce smooth surfaces. Also, they are operated on the prepared surface of the stabilized subbase. With the addition of automatic electronic controls, the tendency is to be less careful in the preparation of the track line and to depend too much on the controls for a smooth ride. In addition, the trend has been to widen out the tracks of the paver to straddle the subbase and use the outer edges of subbase as a grade reference by means of short skis riding on the edges. The tracks of the paver then ride directly on a portion of the earth subgrade in the pavement shoulder area, which provides a poorer track line and one that is less stable than the stabilized subbase, especially following inclement weather.

BITUMINOUS CONCRETE PAVEMENT SURFACES

The bituminous concrete pavement surfaces included in the study for the most part were new bituminous concrete surfacings over existing PCC pavements or over previously resurfaced PCC pavements. A small percentage of the pavement tested included new bituminous concrete surfacings over existing brick or resurfaced brick pavements and over granular and stabilized granular bases.

The variables of design and construction relative to bituminous concrete surfacings that were evaluated to determine their effect on as-constructed riding quality included number of bituminous concrete layers constructed, type and make of asphalt paver, use of leveling and grade control devices, and length of grade reference device used with automatic grade control devices.

Number of Layers of Bituminous Concrete Surfacing

In rehabilitating existing PCC pavements in Illinois it has been the practice to widen if necessary, and resurface with a nominal 3-inch thickness of bituminous concrete consisting of a 1 1/2-inch-thick binder course and a 1 1/2-inch-thick surface course. On many of the projects, especially if the existing pavement was rough, a nominal 1/2-inch machine leveling binder course was placed to level the existing pavement prior to placing the 1 1/2-inch-thick binder and surface courses. Thus, normal resurfacing contracts included either two-layer or three-layer construction.

Data collected during 1971 and 1972 were used in evaluating the effect of number of layers constructed on riding quality. Data collected prior to 1971 could not be used as only total thickness of overlay for the sections tested had been requested. In 1971, the form requesting surface smoothness testing was revised to request the thickness of each layer placed, including leveling binder, binder, and surface courses.

A summary of the results is shown in Table 4. The results indicate the as-constructed riding quality of the pavement was improved when a leveling binder course was used. The average RI was 75 in./mi for surfaces constructed in three layers as compared to 81 in./mi for two-layer construction.

Figure 3 depicts the frequency distribution of the test results. In both cases, the distributions tend to approach a normal distribution. Also, "very smooth" pavements (RI=60 or less) were obtained for both two-layer and three-layer construction, but the percentage in this category was more than 5 times greater when a leveling binder was used.

Type and Make of Paver

The bituminous pavers used in the construction were either track-mounted or rubber-tire mounted and manufactured by three different companies. Manufacturer A

TABLE 4. Comparison of Surface Smoothness of Bituminous Concrete Surfaces Constructed in Two and Three Layers

Number of Layers	No. of Projects Tested	Mileage Tested (2-Lane)	Roughness Index (in./mi) Average	Roughness Index (in./mi) Standard Deviation
2 1/	64	346	81	13
3 2/	99	845	75	11

1/ Includes a binder and surface course

2/ Includes a leveling binder, binder, and surface course

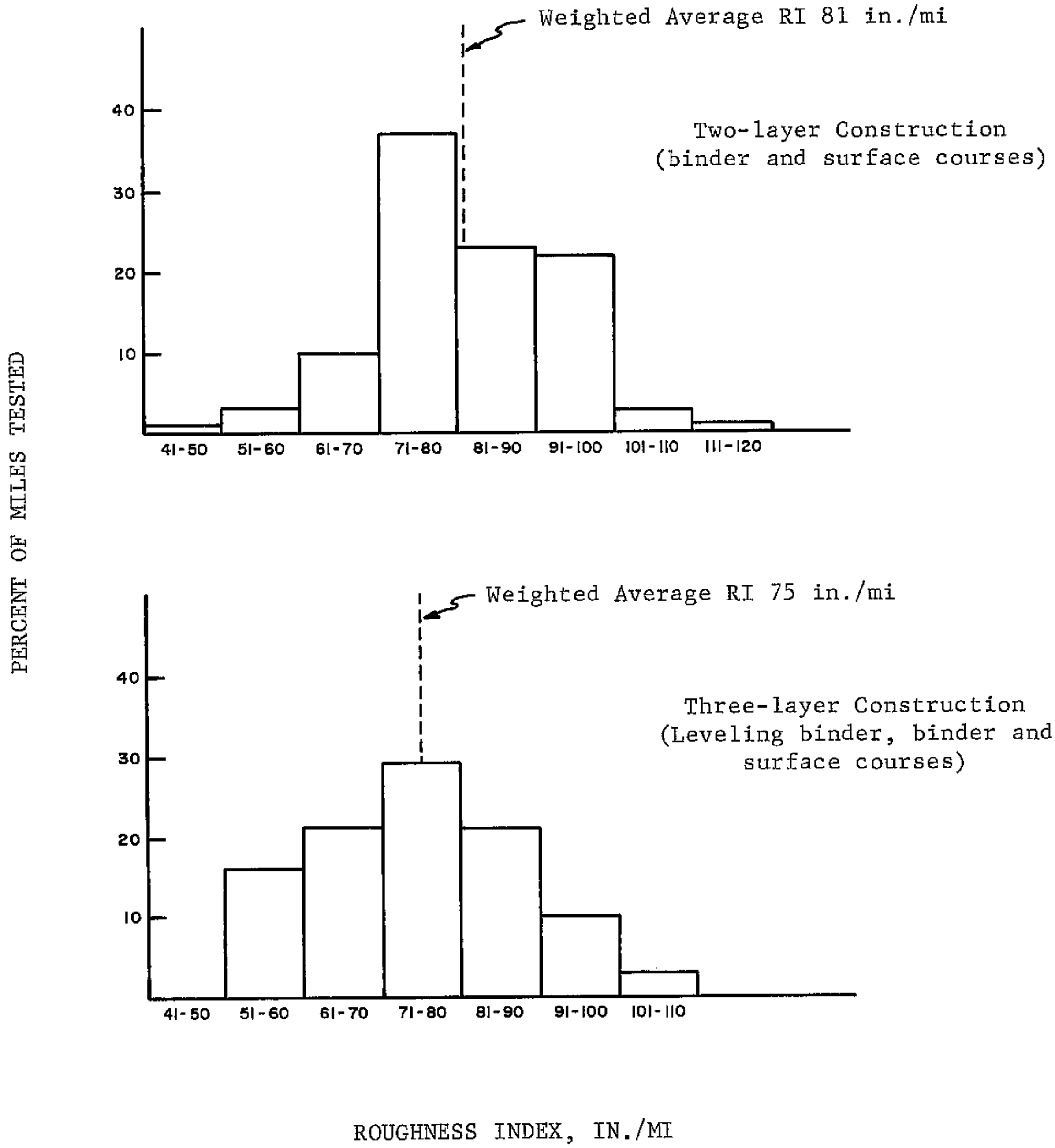

Figure 3. Frequency distribution of Roughness Index on multiple-layered bituminous pavements

produced both types of pavers while Manufacturer B made the track-type and Manufacturer C produced the rubber-tired type.

Test data collected during the period 1960 through 1971 were used in evaluating the effect of paver type and make on surface smoothness. Altogether, there were 959 construction projects totalling 4,388 two-lane miles of pavement included in the analysis. A summary of the results is given in Table 5. Included in the table for each type and make of paver are the number of construction projects, the two-lane mileage tested, the average RI value obtained, and the standard deviation for each test year.

As can be seen from the data, a majority of the total mileage tested was constructed with track-type pavers (3,288 of 4,388 total miles tested), with more extensive use of the rubber-tired paver occurring during the last two years. Of the total of 1,100 miles tested that were paved with a rubber-tired paver, 681 miles were tested in 1971 and 1972.

Annual average test results from pavements constructed with Manufacturer A's track-type paver were, for the most part, somewhat higher than those for all others. On the other hand, however, the average RI for surfacings placed with the track-mounted paver made by Manufacturer B is the same as those for pavement constructed with rubber-tired pavers made by Manufacturers A and C. Further, it can be seen from the yearly averages and standard deviations that pavements rated "very smooth" (RI=60 or less) were obtained with both types of paver and from all manufacturers.

The results are interpreted as indicating that type of paver does not have a significant effect on pavement smoothness of bituminous concrete surfaces.

Use of Leveling and Grade Control Devices

Mechanical leveling devices, or attachments, for bituminous pavers were introduced in Illinois in the early 1950's. The devices support the paver screed midway

TABLE 5. Comparison of Surface Smoothness by Type and Make of Paver

Year Tested	No. of Projects	Mileage Tested (2-Lane)	RI (in./mi) Average	RI (in./mi) Std. Dev.	No. of Projects	Mileage Tested (2-Lane)	RI (in./mi) Average	RI (in./mi) Std. Dev.
			Track-Mounted Paver					
		Manufacturer A				Manufacturer B		
1960	20	122	76	6	9	14	79	9
1961	25	71	69	9	9	46	73	7
1962	58	186	74	10	16	62	68	11
1963	75	316	77	18	18	105	79	22
1964	77	198	77	20	29	89	71	18
1965	38	111	91	15	20	104	81	15
1966	36	144	80	15	5	17	67	16
1967	29	62	68	17	9	34	64	9
1968	19	62	69	7	21	89	60	15
1969	42	179	75	19	27	132	59	15
1970	45	233	77	11	29	177	60	15
1971	64	445	74	19	35	299	70	16
1960-71	528	2129	76	16	227	1159	68	14
			Rubber-Tired Paver					
		Manufacturer A				Manufacturer C		
1960	-	-	-	-	-	-	-	-
1961	-	-	-	-	1	1	49	-
1962	-	-	-	-	11	65	68	13
1963	-	-	-	-	14	94	70	15
1964	1	1	72	-	9	42	71	6
1965	-	-	-	-	19	85	76	12
1966	1	1	76	-	3	12	68	5
1967	8	19	67	6	6	14	56	5
1968	-	-	-	-	14	24	71	11
1969	11	28	77	11	9	33	61	11
1970	-	-	-	-	51	309	61	18
1971	2	28	62	7	44	344	73	15
1960-71	23	77	69	8	181	1023	68	14

between two sets of bearing points, with the back bearing points riding on the surface of the mixture being placed. Adjustment screws provide positive control of the thickness or grade of the lift being placed. The device was adopted in 1952 and its use was required for the placement of the leveling binder course. Subsequently, on many projects the device was left on the machine with the leveling screws locked in-place during placement of the binder course.with good results. As a consequence, the specifications were revised in 1963 to extend the required use of the devices for the placement of the binder course, and again in 1966 for the placement of all courses, including the surface course. During this period, automatic electronic grade control devices were appearing on the market and being tested in the field with satisfactory results. The specifications were again revised in 1968 to permit the use of approved automatic grade control devices in lieu of the leveling device.

In evaluating the effect of leveling and grade control devices on the as-constructed riding quality of new bituminous concrete pavement surfaces, data collected during the period 1963 through 1966 were summarized and compared with that collected during the period 1967 through 1970. Only data from those projects utilizing a nominal 3-inch or 3 1/2-inch-thick surfacing were used. The utilization of data from specific periods was necessary in this analysis since the information collected on the individual sections tested did not sufficiently define the extent of use of leveling devices nor was it sufficient to permit a comparison of results obtained with automatic grade control devices to those obtained with mechanical leveling devices.

The period 1963 to 1966 represents the time during which leveling devices were required on leveling binder and binder courses but not on the surface course. The period 1967 to 1970 represents the time during which leveling devices or automatic grade control devices were required on all courses, including the final surface course, and is prior to the time when specification controls were relaxed in several areas and a reduction in the use of a leveling binder course occurred in connection with the expedited resurfacing program previously discussed.

During the period 1963 to 1966 when leveling devices were not required on the surface course, roadometer measurements on 1,317 two-lane miles of pavement resulted in a weighted average RI of 78 in./mi. During 1967 to 1970 when leveling devices or automatic grade control devices were required for surface course placement, tests on 1,339 two-lane miles resulted in an average RI of 66 in./mi. The results show that the required use of leveling devices on all courses did provide a significant improvement in the as-constructed riding quality of bituminous concrete surfaces. The overall average RI for the 1967 to 1970 period was 12 in./mi less than that for the 1963 to 1966 period when leveling devices were required for leveling binder and binder courses only.

Length of Grade Reference Devices

A special study was conducted to evaluate the effect of length of grade reference device used with automatic electronic grade controls on pavement smoothness. The study was carried out on a large resurfacing project, utilizing the southbound pavement on Route US 66 between Gardner and Chenoa. The same paving machine and crew were used throughout, with three different reference devices - a 10-ft and 30-ft multi-foot ski and a 6-inch joint-matching shoe. The pavement was divided into five separate sections. The 30-ft ski was used for placement of all binder course and the first lane of the surface course in all five sections. The 10-ft multi-foot ski was used for placement of the second lane of surface course in the first two sections and the 6-inch joint-matching shoe was used in the other three sections. The sequence of paving operations was

(1) Place the 1 1/2-inch I-11 binder course in the driving lane using a 30-ft multi-foot ski sensing the existing PCC pavement surface in the passing lane.

(2) Place the 1 1/2-inch I-11 binder course in the passing lane using a 30-ft multi-foot ski sensing the new binder course in the driving lane.

(3) Place the 1 1/2-inch I-11 surface course over the new binder course in the driving lane using a 30-ft. multi-foot ski sensing the new binder course in the passing lane.

(4) Place the 1 1/2-inch I-11 surface course over the new binder course in the passing lane using the 10-ft ski sensing the new surface course in the driving lane of Sections 1 and 2, and the 6-inch joint-matching shoe in Sections 3, 4, and 5.

Roadometer measurements were made on each lane of the binder course and of the surface course for direct comparison. The results are summarized in Table 6. The use of the 30-ft multi-foot ski resulted in an improvement in the as-constructed riding quality. The RI of the binder surface being placed ranged from 9 to 15 in./mi less than that of the binder surface being traced and averaged 11 in./mi less for all five sections. The use of the 10-ft ski resulted in an average RI of the surface course being placed equal to the RI of the reference surface, being 2 in./mi less for Section 1 and 2 in./mi greater for Section 2. The use of the 6-inch joint-matching shoe resulted in a substantially poorer riding quality in the surface course being placed over that of the reference surface. The RI of the surface

TABLE 6. The Effect of Length of Grade Reference Devices on Surface Smoothness

	Roughness Index in./mi		
Section	Reference Surface	Placed Surface	Difference (--decrease)
	(Traffic Lane) (Binder Course)	(Passing Lane) (Binder Course)	
	30-foot multi-foot ski		
1	111	101	-10
2	108	97	-11
3	95	80	-15
4	95	84	-11
5	93	84	- 9
Average	100	89	-11
	10-foot multi-foot ski		
1	77	75	- 2
2	76	78	+ 2
Average	77	77	0
	6-inch joint-matching shoe		
3	60	70	+10
4	62	75	+13
5	62	75	13
Average	61	73	+12

course being placed increased over the reference surface by an average of 12 in./mi and ranged from 10 in./mi to 13 in./mi for the three sections.

CONCLUSIONS

The following conclusions are drawn from the analyses of the data reported herein.

(1) 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 than for bituminous concrete surfaces.

(2) 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.

(3) 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.

(4) 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.

(5) 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.

(6) The use of a machine leveling binder course in conjunction with a binder course and a surface course (three layers) improved the riding quality of bituminous concrete pavement surface over that obtained when just 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.

(7) No significant difference in as-constructed riding quality of bituminous pavement surfaces was noted that could be attributed to type of bituminous paver. Both track type and rubber-tired type pavers can produce satisfactory riding quality.

(8) 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 the devices used on all courses.

(9) 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-inch matching shoe produced a surface averaging 12 in./mi rougher than the reference surface.

RECOMMENDATIONS

The analyses of the data collected in this study have established the Statewide trend in as-constructed riding quality of new PCC and bituminous concrete pavement surfaces during the period 1960 through 1972 and have provided much information to help explain the ups and downs in average annual RI's that have occurred. 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 skis 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 is increased. This suggests the specifications should include minimum length requirements for traveling string lines. In all cases, the ski or traveling string line should be as long as practicable for prevailing conditions. In this connection, it is suggested that it not be less than 30 ft long for the placement of the leveling binder and binder courses, 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-inch joint-matching shoe for this purpose should no longer be permitted.

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