Cumulative Changes in Rigid Pavements With Age in Service

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This paper presents the analysis of some 6,000 mi of pavement profile obtained by the Michigan Pavement Performance Study in the 3-year period of 1958-59-60. This mileage on the Michigan State trunklines consists largely of reinforced concrete pavement with service periods of up to 35 years, under a considerable range of traffic intensity, soil conditions, and climatic environment. Emphasis is given to pavement changes over long periods of time, but data are also available on a number of special features bracketing Michigan design conditions.

Procedures developed for evaluating pavement performance are based on two basic criteria for measuring pavement change. The first, or "roughness index," is riding quality based on pavement profiles and recorded in inches of vertical displacement per mile. The second is structural continuity, based on the cracking pattern, expressed as a continuity ratio, and defined as the ratio of uncracked slab length to an assumed slab length of 15 ft. Both of these measures are recorded on pavement condition surveys.

The data afford significant comparisons between current design for year-round service without seasonal load limitations, and older roads considered inadequate for present day traffic; the pavement study includes plain concrete, reinforced concrete of conventional design and joint spacing, and an experimental project with continuous reinforcement. The dominant effects of soil conditions, frost action, drainage, and other environmental conditions are revealed on certain projects where wider variation in these conditions has occurred. Construction control is revealed as an important factor in riding quality, with "built-in roughness" varying through wide limits. Subgrade preparation is also found to be an important influence on initial riding quality and subsequent performance. Differentials in performance between the traffic lane and the passing lane occur on certain projects, whereas on others there is no apparent effect of load application.

• FROM THE VERY BEGINNING pavements have been built simply to provide durable surfaces with improved riding qualities for the safety, comfort, and convenience of the highway user. With the advent of automotive vehicles with constantly increasing speed of travel, smoothness of the pavement surface or riding quality has become increasingly important in pavement design and construction.

Also from the very beginning, pavement builders must have gaged the success of their endeavors by experience and direct observation of their pavements under the service conditions to which they were subjected. Thus, pavement condition surveys, though they may not have been formalized as they are today by systematic procedures, are as old as the oldest pavements. In the development of modern highway systems, the importance of permanence of riding quality or durability has focused increased attention on the strength of the pavement structure and its ability to maintain structural continuity under the increased loads and mounting volume of modern traffic, in combination with the stresses and strains associated with environmental conditions.

The increased use of rigid concrete pavements to provide high quality surfaces has paralleled the rapid development of automotive transportation. The physical characteristics of such rigid pavements have led highway engineers naturally and logically to judge their performance by the rate at which they become rough and lose their riding quality and the rate at which they crack and lose their structural continuity. The point of these introductory remarks is simply to emphasize that the changing condition of rigid pavements, as reflected in cracking and roughness, has always been a natural and realistic measure of pavement performance. The major contribution of recent years has been the introduction of refinements in procedures for making pavement condition surveys and development of more precise criteria for evaluating pavement performance.

This approach must have been apparent to the Highway Research Board Committee on Rigid Pavement Design when it formulated, in January 1959, a research project entitled "Investigation of Existing Pavements." At that time it listed a number of significant changes in rigid pavement design in recent years and made the following statement:

> It is believed to be highly important to determine the effects of these changes in order to avoid the possibility of constructing miles of pavement which might otherwise fail prematurely. It is also believed that, in many respects, the pavements which are presently in existence constitute the only dependable sources of information on which to base future designs.

Well-organized pavement condition surveys in Michigan date back to the middle 1920's, when the late V.R. Burton organized a group of research workers who started a series of statewide pavement condition surveys including comprehensive data on soil conditions and climatic environment (1, 2, 3). This work has been carried on over the years by a number of individuals well-known among highway engineers and soil scientists, including Kellogg, Benkelman, Stokstad, and Olmstead.

These investigators early found significant correlation between pavement performance and environment, including soil type, drainage, and climatic factors, a viewpoint that has continued to exert a dominant influence on pavement design in Michigan. Improvements in this approach to pavement design have led to more accurate evaluation of soil conditions, drainage, and climatic environment; the utilization of local soil materials of favorable characteristics; and the selection of pavement structures that more fully utilize available subgrade support. Though many of these factors are uncontrolled variables, difficult to measure and perhaps impossible to express in a mathematical formula, current pavement performance studies in Michigan have been predicated on the belief that the integrated results of these uncontrolled variables could be measured quantitatively by more accurate field surveys and objective analysis of the results. Furthermore, it was felt that pavement performance, in terms of changes in the pavement profile and cracking pattern, could be expressed numerically by a roughness index and a continuity ratio.

The first attempt in Michigan to measure pavement performance quantitatively in terms of pavement roughness and structural continuity was a cooperative investigation, initiated in 1952, involving the Michigan State Highway Department, the University of Michigan, and the Wire Reinforcement Institute. The data obtained from that investigation, carried on over a period of five years, indicated that pavements with steel reinforcement were measurably smoother and that cracking was measurably less than in the unreinforced concrete pavements involved in that investigation. Of perhaps more importance to the present discussion was the fact that pavement performance was evaluated in terms of a continuity ratio related to the cracking pattern and a roughness index based on measured vertical displacement in the pavement profile.

MICHIGAN PAVEMENT PERFORMANCE STUDY

In further pursuit of these objectives, a cooperative investigation was next undertaken in 1957 by the University of Michigan, the Michigan State Highway Department, and sponsors representing the trucking industry (the Michigan Trucking Association, the American Trucking Associations, Inc., and the Automobile Manufacturers Association). Pavement performance studies under this sponsorship continued for approximately two years, and in July 1959, were taken over by the Michigan State Highway Department as part of the Michigan Highway Planning Survey—Work Program financed by HPS funds, under the supervision of the Bureau of Public Roads. This program has continued to date under a contract with the University of Michigan. In the first two years, equipment for recording pavement profiles was developed and tentative procedures were established for evaluating the data obtained.

A truck-mounted profilometer for accurately recording pavement profiles was built, closely following similar equipment used for some time by the California State Highway Department. Electronic recording equipment and integrators were added to provide a chart-recorded profile of the pavement in both wheelpaths and to compile the cumulative vertical displacement in inches per mile. Means were also provided to record pavement cracks and joints. Early results from these studies (4) were presented to the Highway Research Board in January 1959. There is nothing new about profilometers and measuring roughness as the sum of vertical displacements per mile as a roughness index. In his paper to the Highway Research Board in January 1960, Hveem (5) presented an interesting review of this subject and described a number of such devices, the earliest one in available records dating back to before 1900.

Pavement Profiles for 1958-1960

During the three years 1958, 1959, and 1960, close to 6,000 lane-mi of pavement profile were accumulated. The analysis of these data has proceeded concurrently, insofar as personnel and facilities would permit; it is the purpose of this paper to present some of the significant results presently available, particularly to cumulative change in rigid pavement profiles with age in service. It is felt that the data reveal significant trends in pavement performance and direct relationship to controlling design conditions. There is a tremendous volume of information involved in some 6,000 mi of pavement profile; therefore, the present discussion is limited to several classifications of rigid pavement that have been sampled in sufficient quantity to provide a reasonable basis for analysis. All pavements included in the profile survey are part of the Michigan State trunkline system of some 9,435 mi, including 8,050 mi of two-lane pavement, 135 mi of three-lane pavement, and 1,250 mi of divided four-lane pavement. The trunkline system thus amounts to 21,500 lane-mi of pavement; thus, the three years of profile surveys discussed in this report provide a sample of approximately 27.5 percent of the total trunkline mileage.

Most of the data obtained are for pavements rated as Class 1 and Class 2, although some data are presented from surveys of Class 3 and Class 4 pavements. In this connection, it is necessary to define these four pavement classes as they have been incorporated in the Michigan trunkline surveys. The first pavement evaluation of the Michigan trunkline system was presented as of January 1, 1958, and was compiled from the Michigan State Highway Department's records, including design data, pavement condition surveys, maintenance records, and soil surveys. At that time, 55 percent of the State trunkline system was rated as Class 1 and Class 2 roads, adequate for legal axle loads at all seasons of the year; 45 percent was rated as Class 3 and Class 4, inadequate and requiring Spring load restrictions. In this road classification for legal axle loads, the four levels of adequacy selected are defined as follows:

Class 1.—No seasonal restrictions. Pavement and subgrade adequate for year-round service, as represented by natural sand and gravel subgrades with superior natural drainage.

Class 2.—No seasonal restrictions. Pavement designs that compensate for seasonal loss of strength, as represented by the subgrades of fine-grained soils and generally inferior drainage corrected by the use of free-draining sand and gravel subbases, raising grade line to improve drainage, removal of frost-heave soils.

Class 3.—Spring load restrictions required. Pavement designs that do not compensate for seasonal loss of strength, as represented by fine-grained soils, susceptible to frost-heaving and pumping, and with inadequate drainage provisions.

Class 4.—Spring load restrictions required. Pavement designs inadequate for legal axle loads at all times, as represented by older roads completely deficient and requiring continuous maintenance to provide year-round service for legal axle loads.

The data selected from 6,000 mi of pavement profile, for the present discussion, are shown on a series of charts developed as a standard format after considerable "cut-and-try" experimentation. In these charts, as shown in Figure 1, the roughness index in inches of vertical displacement per mile is plotted as the horizontal abscissa and the years in service as the vertical ordinate. The data in Figure 1 are for the traffic lane of Class 1 rigid pavements and represent pavement profiles of some 556 mi of pavement. At the top of the chart is a tentative roughness rating that has been in use for several years (4). Each plotted point represents an individual pavement profile in the outer or inner wheelpath of a specific construction contract. There are 123 such contracts and 556 mi of pavement included in the figure—when only one lane of a contract has been surveyed, there will be two plotted points for that contract; when both traffic lanes have been surveyed, there will be four such points for that contract. In general, it has been found that the outer wheelpath is rougher than the inner wheelpath; and though special studies have been made of this variation, these studies are discussed in detail in this paper.

Significant Variations in Pavement Profiles

In spite of the wide scattering of roughness index values in Figure 1, there are a number of characteristics of these data, the analysis of which indicates significant trends in pavement performance:

1. There is a general increase in roughness with age which will be discussed as evidence of cumulative changes in rigid pavements with age in service.
2. There are a number of specific projects that exhibit roughness indices much less than the general trend and others with values much greater, both of which may be related to controlling design or construction conditions responsible for this abnormal behavior.
3. There is a discontinuity in average roughness indices at a service period of approximately 25 years which may be related to construction changes in the trunkline system and indirectly influenced by Michigan design procedure.

Cumulative Changes in Pavement Profiles

Evaluation of cumulative changes in rigid pavements with age in service is the major objective of this paper. The method of evaluation proposed after considerable study is to establish a band of normal behavior, as shown in Figure 1. The first step is to compute the average roughness index for each 5-year period as the center of gravity of all observations in that period. These averages are shown as a triangle on the chart, through which the central line of the normal behavior band is drawn. For the first 25 years, the average results fall consistently along a line with an intercept of 65 in. per mi on the horizontal axis and a slope of 4.5 in. per yr as the average increase in the roughness index. After 25 years there is a discontinuity or displacement in this average line, which is discussed later.

The width of this band of normal behavior has also been established by trial and error as parallel lines that bracket 85 percent or more of the observations and balance the excluded observations, indicating abnormal performance, on either side of the band. For example, in Figure 1, for observations in a period of less than 25 years, approximately 7.5 percent of the pavement profiles have roughness indices less than normal and the same approximate percentage, greater than normal. Projects falling outside this band represent abnormal behavior, which may provide the most informative data available

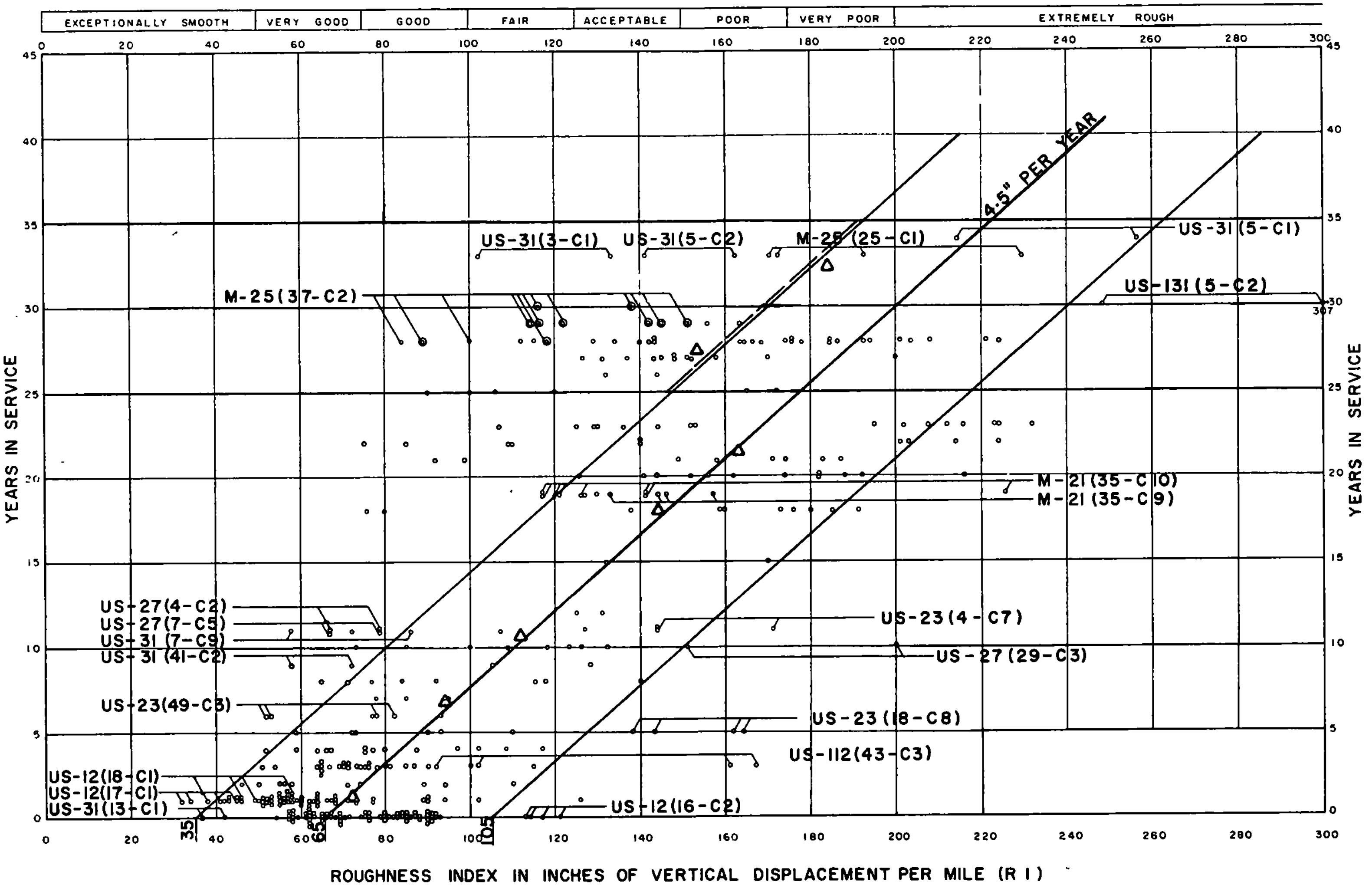

Figure 1. Roughness vs years in service, Class 1, traffic lane, based on 1958-59-60 surveys.

to relate pavement performance to design and construction conditions. Examples are cited later in a discussion of abnormal behavior.

The important deduction from these data at this point is that rigid pavements represented by this sample suffer a continuing or cumulative increase in roughness at an average rate of about 4 to 5 in. per mi per yr. The fact that these pavements have been rated as Class 1 pavements implies that they are adequate or more than adequate for legal axle loads at all seasons of the year; thus, load-carrying capacity is not a controlling factor in this progressive loss of riding quality. From this it follows that environmental factors, mainly associated with seasonal cycles, dominate this type of pavement deterioration, and there is other evidence to support this conclusion.

Older Pavements Showing Abnormal Behavior

There are a number of projects in Figure 1 with roughness indices substantially less or greater than those within the band selected to represent normal behavior. In the first place, there is the definite discontinuity in the 5-year averages, influenced by a grouping of a number of projects with roughness indices much less than those within the band of normal behavior deduced from pavements less than 25 years old.

The first and perhaps major factor in this shift arises from the fact that many of the older pavements built before 1936 have been retired from service by reconstruction, recapping, or a change in classification. With a few exceptions, only those projects exhibiting superior performance are still in service and have been picked up in the profile surveys. A review is in progress to trace the history of all concrete pavements built before 1936, but complete results are not available for this report. Consequently, only a few examples can be cited at this time to illustrate this point and to indicate the close correlation between design and construction conditions and unusual pavement performance.

One such project, US-31 (3-C1), after 33 years of service, shows exceptionally good performance, with a roughness index falling well below the band of normal behavior and a riding quality still rated fair to acceptable. Another project, US-31 (5-C1), after 34 years of service, is rated extremely rough, with a roughness index falling near the upper limit of the band of normal behavior. Both were rated as Class 1 pavements on the basis of an area soil survey identifying the soil type as Plainfield sand, a superior subgrade with high internal stability and excellent drainage. These two projects, within several miles of each other, were built by the same contractor and have closely comparable traffic. The soil classification of Plainfield sand is correct for the project showing superior performance, but incorrect for the second project, which has become extremely rough. In the latter case, the project is located at a transition in soil types, the major portion being on a silty clay loam with inferior drainage conditions; this part of the pavement should have been rated as Class 3 or Class 4. The transition in soil types and marked changes in pavement performance are accurately identified on the pavement profile.

Another revealing example that may be cited is a 33-year-old project, US-31 (5-C2), which appears to have shown much better than average performance. A review of the pavement profile shows that this contract covers an area of well-drained sands of the Plainfield or closely related series, but with several smaller areas of low-lying poorly drained soils. These areas became extremely rough after some 30 years of service, but were recapped with a bituminous surface in 1956. The balance of the pavement had become quite rough, with considerable cracking shown by a reduction in the continuity ratio from 6.66 to 1.35. The roughness indices for this pavement, which is still in service, were reported in Figure 1 as the average for the entire project. Segregation and reclassification of the sections that became very rough and have been resurfaced and correction of the roughness index for the balance of the pavement would bring it more nearly within the band of normal behavior, with slightly better than average performance.

Another group of points showing better than normal performance are identified as Contract M-25 (37-C2). This pavement is on a shoreline road along Lake Huron built along a beach ridge on soil identified as the Eastport series, another high-quality subgrade. This is the clue to its superior performance, but it has nevertheless increased

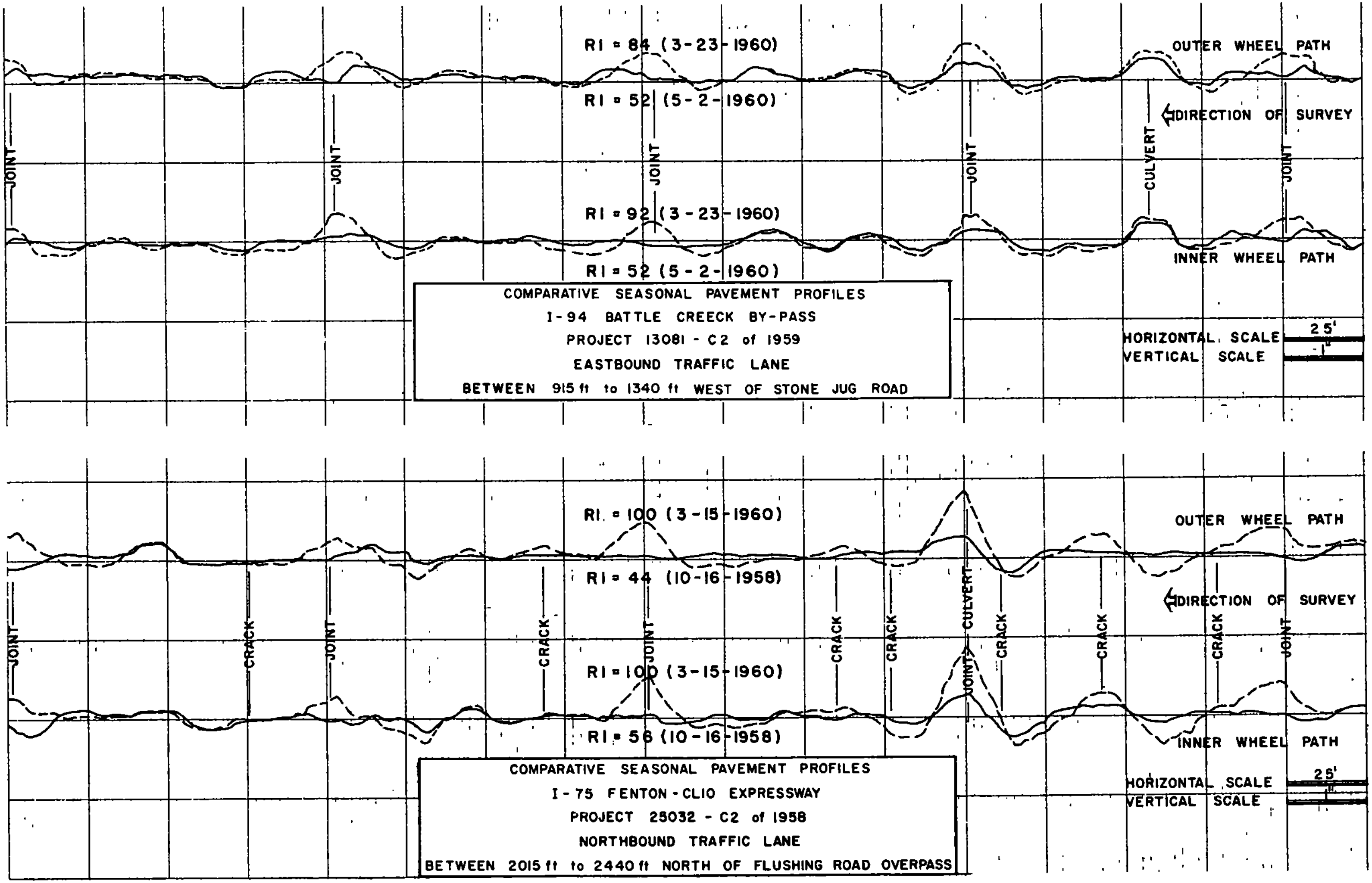

Figure 2. Comparative seasonal pavement profiles.

in roughness, although at a reduced rate, as residual displacement results from seasonal frost action, details of which will be discussed later.

Another example, shown in Figure 1, is Contract US-131 (5-C2), the only project in the survey more than 25 years old that is still in service, even though its roughness index is much greater than those within the band of normal behavior. Roughness indices of 248 in the inner wheelpath and 307 in the outer wheelpath show that it has become extremely rough and is actually beyond the limits of the tentative rating scale. This project is a plain concrete pavement built in 1929 just south of the city limits of Cadillac. In addition to being rough, it is badly cracked with its continuity ratio having been reduced from 6.67 to 0.85. In terms of average slab length, this is a change from 100 ft between joints to an average of about 12 ft between cracks.

As a whole, this old project is the product of outmoded design standards that no longer represent Michigan practice. The rougher sections are over inferior-type soils that would now be compensated for by raises in grade and a free-draining granular subbase. A substantial part of this project was in a relocation over generally good subgrade soils, but was built without adequate control of subgrade compaction and without the advantage of stage construction to condition the subgrade before paving. This project is on a major route and would doubtless have been rebuilt some time ago except that its relocation, long-planned, was postponed until the advent of the major improvement program of the past several years. This relocation is now in progress and only this unusual set of circumstances found it still in service when the profile survey of this route was made in 1959.

Younger Pavements Showing Abnormal Behavior

Pavements less than 25 years old shown in Figure 1 also include about an equal number of projects with roughness indices substantially above and below the limits of normal behavior. In the earlier years, the conclusion is quite inescapable that the wide range in riding quality must have been produced during construction and is thus initial or built-in roughness.

Looking first at the group of eight projects less than 15 years old with superior riding quality, there are three projects, US-31 (13-C1), US-12 (17-C1), and US-12 (18-C1), surveyed the year they were built or one year later, with roughness indices of 50 or less, which would be rated as exceptionally smooth. There are five additional projects, US-23 (49-C3), US-27 (4-C2), US-27 (7-C5), US-31 (41-C2), and US-31 (7-C9), which, allowing for normal increase in roughness, must have been built with an initial roughness in the same range and rated as exceptionally smooth. Five of these eight projects were built by two contractors who have gained special recognition for high quality workmanship. The same may be said for the other projects giving evidence of good workmanship, even though the illustration lacks the emphasis of repetitive coincidence of contractor and excellent performance.

Attention is next directed to a group of five projects less than 15 years old with roughness index values greater than those within the band of normal behavior. Again it may be assumed that normal increase in roughness would leave built-in roughness as the major source of decreased riding quality. Project US-12 (16-C2) was built in 1960 and surveyed in December of the same year. The low temperature may have produced some curling; but, other than this, there are no known job conditions contributing to the increased roughness other than contractor performance.

Project US-112 (43-C3) presents a particularly interesting comparison in that its westbound lane has a roughness index of 167 in the outer wheelpath and 161 in the inner wheelpath, rated as "poor." The eastbound lane, on the other hand, had a roughness index of 102 in the outer wheelpath and 92 in the inner wheelpath, which, while not outstanding, would at least be rated as "good." A report from the project engineer on this contract reveals that there were special job conditions which account for the abnormal result. The westbound lane was paved late in the year to provide for traffic during the winter, until the project was completed, and a considerable portion of it was hand finished. The eastbound lane was completed the next spring and was machine finished. Incidentally, the paving was done by the contractor who paved three of the eight projects previously cited as evidence of high quality workmanship. The pavement was a short

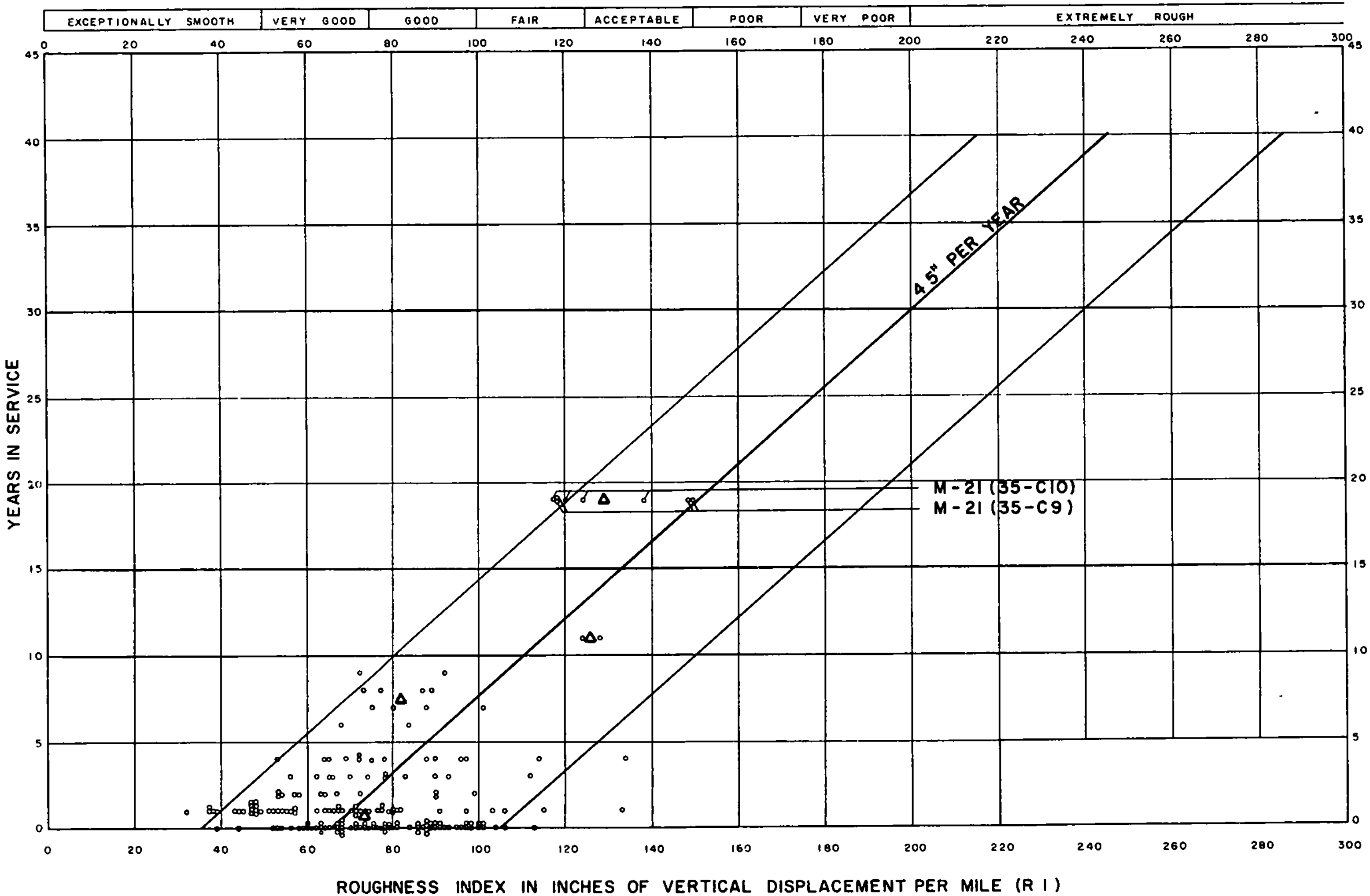

Figure 3. Roughness vs years in service, Class 1, passing lane, based on 1958-59-60 surveys.

stretch of the intersection of two major trunklines where a future grade separation was planned. Actually, it could be considered in the category of a temporary roadway for a limited service of a few years; this may have been a contributing factor in its construction.

The other three projects rougher than normal, US-23 (18-C8), US-27 (29-C3), and US-23 (4-C7), are all by different contractors. There are no special job conditions presently known to affect these results other than contractor performance as the common denominator.

Comparison of 1959 and 1960 Roughness Indices

Although it is not considered a significant variation in pavement performance, there is a rather definite shift in Figure 1 in two groups of observations, for projects built in 1959 and 1960, which does require some explanation. It was first thought that this might be evidence of a change in built-in roughness, reflecting an accelerated construction program and possibly less effective construction control due to overload of inspection facilities and personnel. However, a more searching analysis of these observations points to the conclusion that this shift in roughness observations has been produced by a combination of factors, none of which can be demonstrated to be primarily responsible.

The 1959 projects have an average roughness index of approximately 60, somewhat less than normal, and the 1960 projects have an average roughness index of 75, somewhat above normal. Practically all of these two groups of projects were surveyed in 1960, with the 1959 projects being surveyed in the spring and early summer and the 1960 projects in the fall (after September 1) and some as late as December 15.

One factor that may have affected some of these observations is the temperature differential from June to December, with a similar but reduced differential between the top and bottom of the slab producing curling at the joints. In May and June 1960, when a number of the 1959 projects were surveyed, air temperatures ranged between 60 and 80 F. A number of the 1960 projects were surveyed in December 1960, when the air temperature ranged from 20 to 30 F, mostly in the low 20's. Unfortunately, there were no parallel surveys on the same projects in June and December which would have provided a direct comparison between the two groups of observations under discussion.

Examples of curling due to temperature differentials, however, are available from special studies where abnormal increases in roughness were reported on two recently constructed pavements of similar design. These examples are shown in Figure 2. At the bottom of the chart are pavement profiles on a short section of pavement on I-75, near Flint, where curling at the joints is the major source of the increase in roughness. This increase in roughness may include the residual deformations from two winters of cyclic change as well as some frost displacement in the subbase, which reaches a maximum about the time of the second survey in the middle of March.

A similar example is shown on the top of the chart, with the difference that the timing of the two surveys is reversed. The profile in March 1960 shows maximum roughness as the combined effect of curling and frost action. The second profile, in May 1960, shows the recovery of the pavement from the maximum temporary displacements of the seasonal cycle. Temperature differentials between the two surveys are comparable to those under discussion.

Aside from the temperature effects that may be involved, the possibility of experimental error and some effect of the accelerated construction program cannot be completely dismissed. With respect to the latter, there is no further comment except to make the obvious observation that inspection control is an ever-present problem with results in some proportion to the attention that can be devoted to it.

With reference to experimental error in the rather complex instrumentation involved in recording and integrating pavement roughness, there are always problems to be met, particularly under the requirements for mass production of pavement profiles. There were such problems during the summer of 1960, and, as a matter of fact, the profilometer was out of service for several months for a general overhaul and recalibration. Some changes in electrical circuits and mechanical details were made to improve operating characteristics and to facilitate frequent calibration. A review of the frequent calibrations during this period indicates that the data under discussion could have been

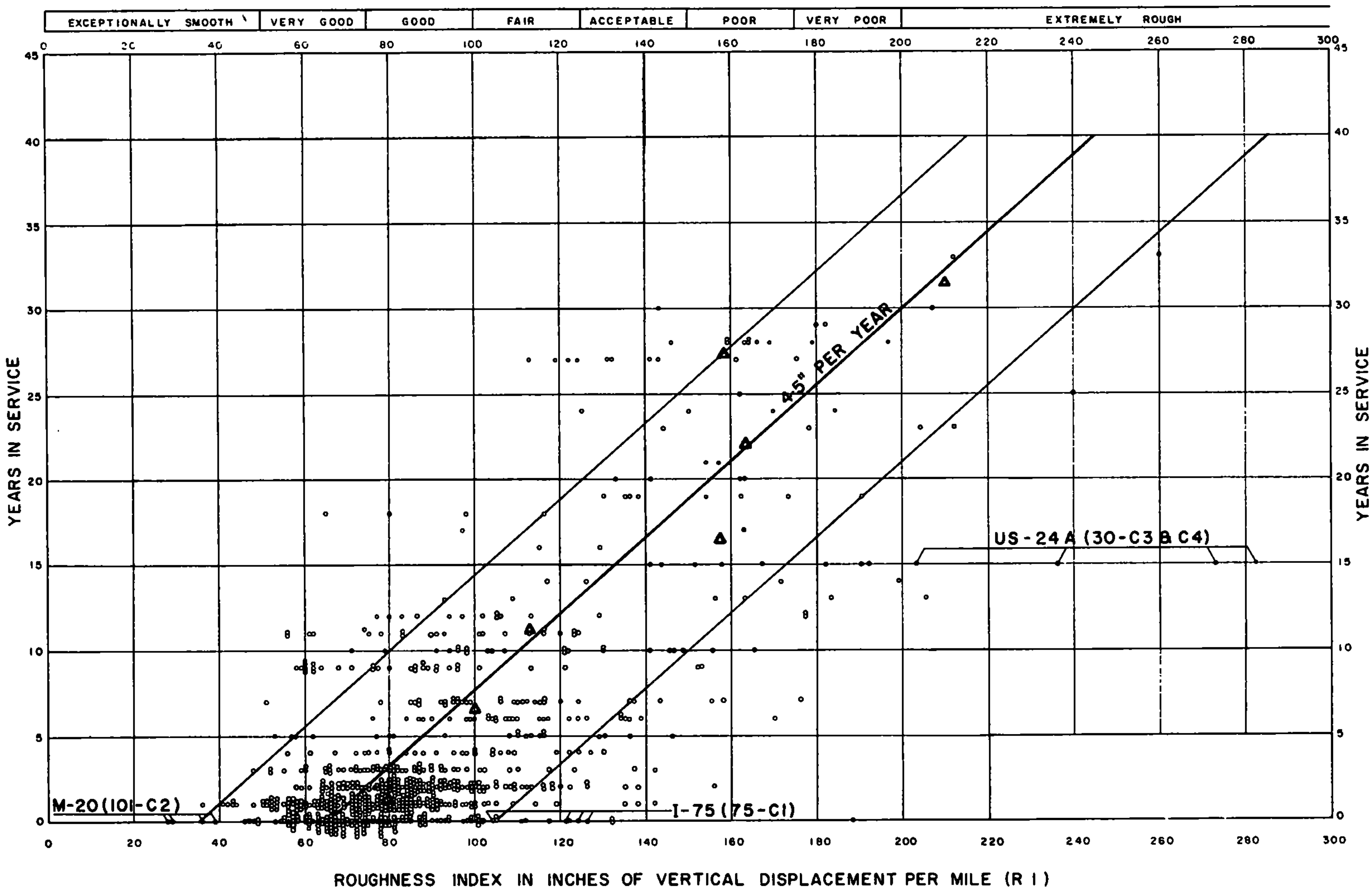

Figure 4. Roughness vs years in service, Class 2, traffic lane, based on 1958-59-60 surveys.

affected in terms of average roughness by as much as 5 percent, or a maximum of 10 percent in individual cases. This is considered to be within the normal operating accuracy of the profilometer; it is the grouping of the two sets of observations at the two time periods involved that makes such equipment error a possible contributing factor.

Passing Lane of Class 1 Rigid Pavements

There are a number of other examples of trends in pavement performance that may be selected from the 6,000 mi of pavement profile covered by the three-year survey. Figure 3 shows the roughness indices from some 290 mi of the passing lane of dual lane divided highways. Practically all of this mileage is less than 5 years old, having been constructed as part of the Interstate system. The same band of normal pavement performance used in Figure 1 has again been used as a basis of comparison. In this case, it is apparent that the volume of data and the short period of service is not sufficient to establish any basis to differentiate between the traffic lane and passing lane. At the same time, Class 1 pavements are not expected to show any significant effect of wheel load applications, being rated as adequate or more than adequate for legal axle loads at all times. Though the available data cannot be considered conclusive, more than 90 percent of the observations in Figure 3 do fall within the band of normal behavior; the cumulative change in roughness of the limited number of older projects also follows the same trend, within the indicated limits.

For a direct comparison, two specific projects have been noted, M-21 (35-C9) and M-21 (35-C10), each with a service period of 19 years. These same projects have also been identified on Figure 1 to show that the roughness indices of the traffic lane and passing lane fall in the same range, within very narrow limits. There is one exception to this statement: a single observation of a roughness index of 225 along the outer edge of a ¼-mi section of pavement widening on this contract. A field investigation of this section is being made, but in the absence of this information it is felt that this abnormality is very probably due to a special field condition.

Again in Figure 3, there is a shift in roughness indices in the passing lane of 1959 and 1960 projects that has already been commented on in connection with Figure 1. The conditions under which these projects were surveyed and the probable contributing factors are identical with those in the traffic lane. The fact that the results are the same needs no further comment. Finally, any conclusion that could be drawn from the comparison between the traffic lane and passing lane of the Class 1 pavements would be that the available data indicate no measurable difference due to wheel load applications.

Class 2 Rigid Pavements

The next two charts (Figs. 4 and 5) show the roughness indices on Class 2 rigid pavements. These pavements were designed to compensate for seasonal loss in strength due to subgrade deficiencies and less favorable environmental conditions. From the standpoint of load-carrying capacity, they are considered adequate for legal axle loads at all seasons of the year. In Figure 4, for the traffic lane, the data cover 244 construction contracts and some 1,275 lane-mi of pavement. The same band representing normal behavior is also shown, inasmuch as there is no evidence to support any change in these limits. Approximately 7 percent of the data show roughness indices less than normal, and 8 percent have roughness indices above normal limits.

As a whole, the data in Figure 4 are quite comparable to those in Figure 1, and show that Class 2 pavements follow the same trends in behavior exhibited by the Class 1 pavements. The cumulative change in pavement roughness with years in service shows observation points fairly well balanced around the average line or norm. The major difference in Class 2 pavements has to do with the change in Michigan design standards over the years and relates to the fact that for the last 15 or 20 years all construction on the State trunkline system has been designed and built to be adequate for legal axle loads at all times of the year. Thus, there is only a scattering of Class 2 pavements that have been in service for periods of more than 15 or 20 years. The bulk of the data in Figure

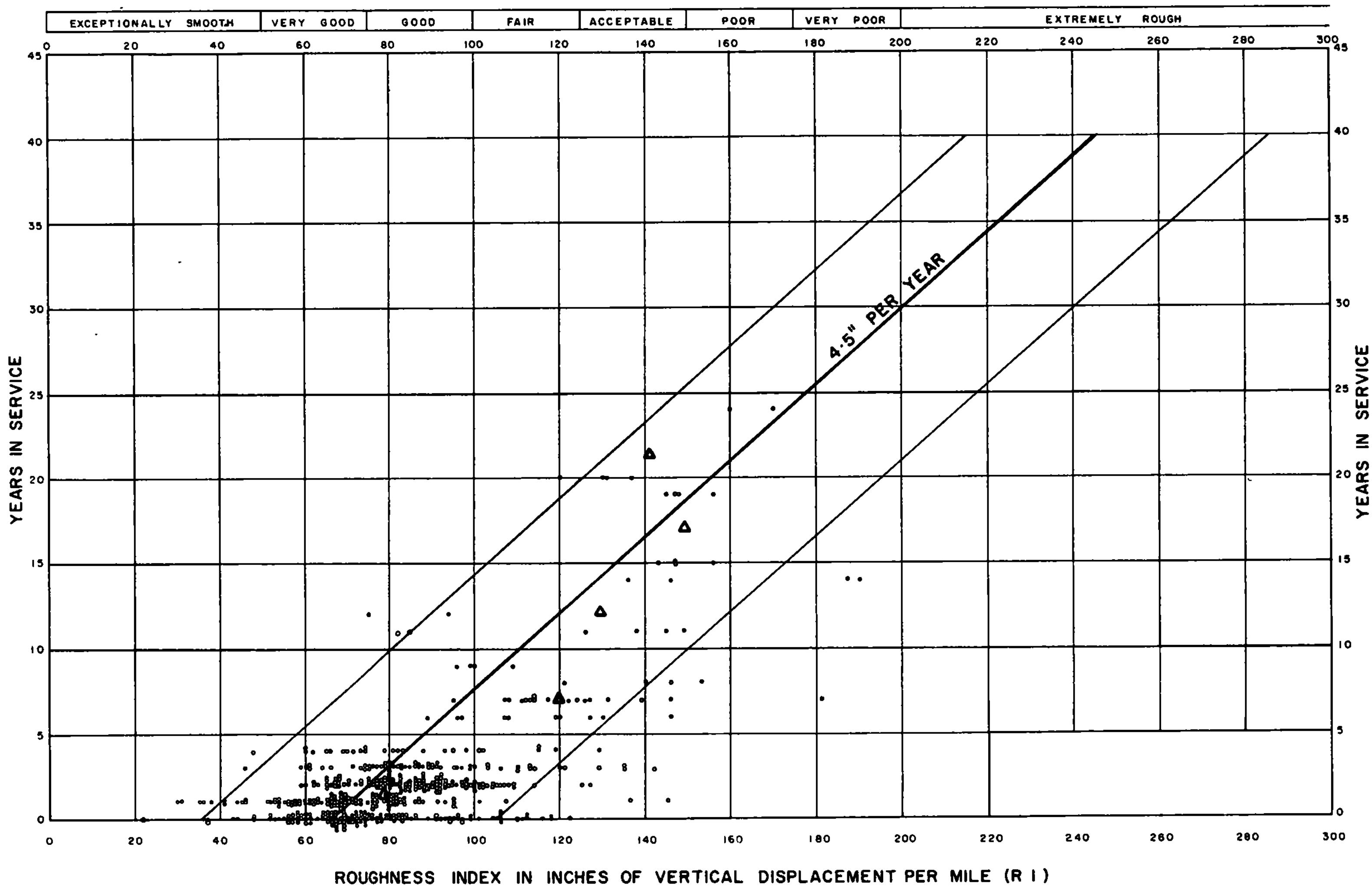

Figure 5. Roughness vs years in service, Class 2, passing lane, based on 1958-59-60 surveys.

4 is consequently concentrated in the first 15 years, with a great preponderance of the mileage having been constructed as part of the major construction programs of the past four or five years. Many of the comments made with respect to performance of the Class 1 pavements also apply to the Class 2 pavements; hence, many of the details previously discussed need not be repeated.

Next are differences in performance of the different classes of pavement as revealed by pavement profile data. The first such difference in Figure 4 is the fact that Class 2 pavements built in the first two or three years show no evidence of any shift in built-in roughness commented on in discussing the Class 1 pavements, including possible changes in construction control or inspection procedure. Inasmuch as the construction of the Class 2 pavements is coincident with the construction of Class 1 pavements, it may then be deduced that construction control was not a factor in the shift of roughness indices for Class 1 pavements. There are some significant data in Figure 4 with respect to built-in roughness, however, these being related to several special projects that have been identified. By 1959, the emphasis on pavement profiles and roughness data had been given sufficient publicity within the State, which, coupled with some competitive endeavor related to different types of pavement, stimulated contractors on certain contracts to make a special effort to build smooth pavements. Project M-20 (101-C2) is a reinforced concrete pavement on the Bay City—Midland expressway where special efforts were made to produce superior riding quality. The fact that the average roughness index on all four lanes of this project was less than 40 is an indication of what can be done with respect to built-in roughness when sufficient effort is applied. Another project shown in Figure 4, I-75 (75-C1), built in 1958 and surveyed the same year, represents the top of the range in initial roughness. Construction reports from the project revealed that poor subbase compaction left the paving contractor with inadequate support for the forms. This difficulty was reported at the time of construction as affecting the quality of the work.

Although all the projects in Figure 4 that showed abnormal performance are being investigated, only one other example has been identified for discussion in this report—Project US-24A (30-C3 and C4). This project stood out because of its poor riding quality in the earliest days of the pavement performance study. Therefore, it received immediate attention and has, as a matter of fact, been commented on in previous reports (4). This contract shows the result of using short, 20-ft slabs of plain concrete without load transfer at the joints in an effort to control pavement cracking. The subgrade was a heavy lake-bed clay with a fill of several feet produced by side-casting from the ditches. This fill was allowed to weather for two years before the pavement was constructed; then, an 18- to 24-in. sand subbase was added to provide more adequate subgrade support and to eliminate pumping action. The crack control was successful in that very few of the 20-ft slabs have cracked, but this design produced one of the roughest riding pavements in southern Michigan due to tilting of the slabs and faulting at the joints.

Passing Lane of Class 2 Rigid Pavements

In Figure 5, roughness indices for the passing lane of Class 2 rigid pavements have been assembled. These data cover 139 construction contracts and 277 lane miles of pavement. There are only a few projects in the survey more than 10 years old, for reasons already cited, and a high proportion of the roughness data are from projects built in the last 5 years. More than 90 percent of the data fall within the same band of normal behavior, with 2 percent of the points indicating roughness indices less than normal, and 6 percent greater than normal. There is no evidence from these limited data of any differential in the cumulative change in roughness between the passing lane and traffic lane of Class 2 pavements.

There are fewer projects showing evidence of abnormal behavior outside the band of normal performance and these are being investigated for special conditions that may have produced these results. With respect to built-in roughness, there are several projects that are exceptionally smooth and several that are rougher than normal. These include the passing lane of projects already cited in connection with Figure 4 for the traffic lane of Class 2 pavements, so no further comment is required.

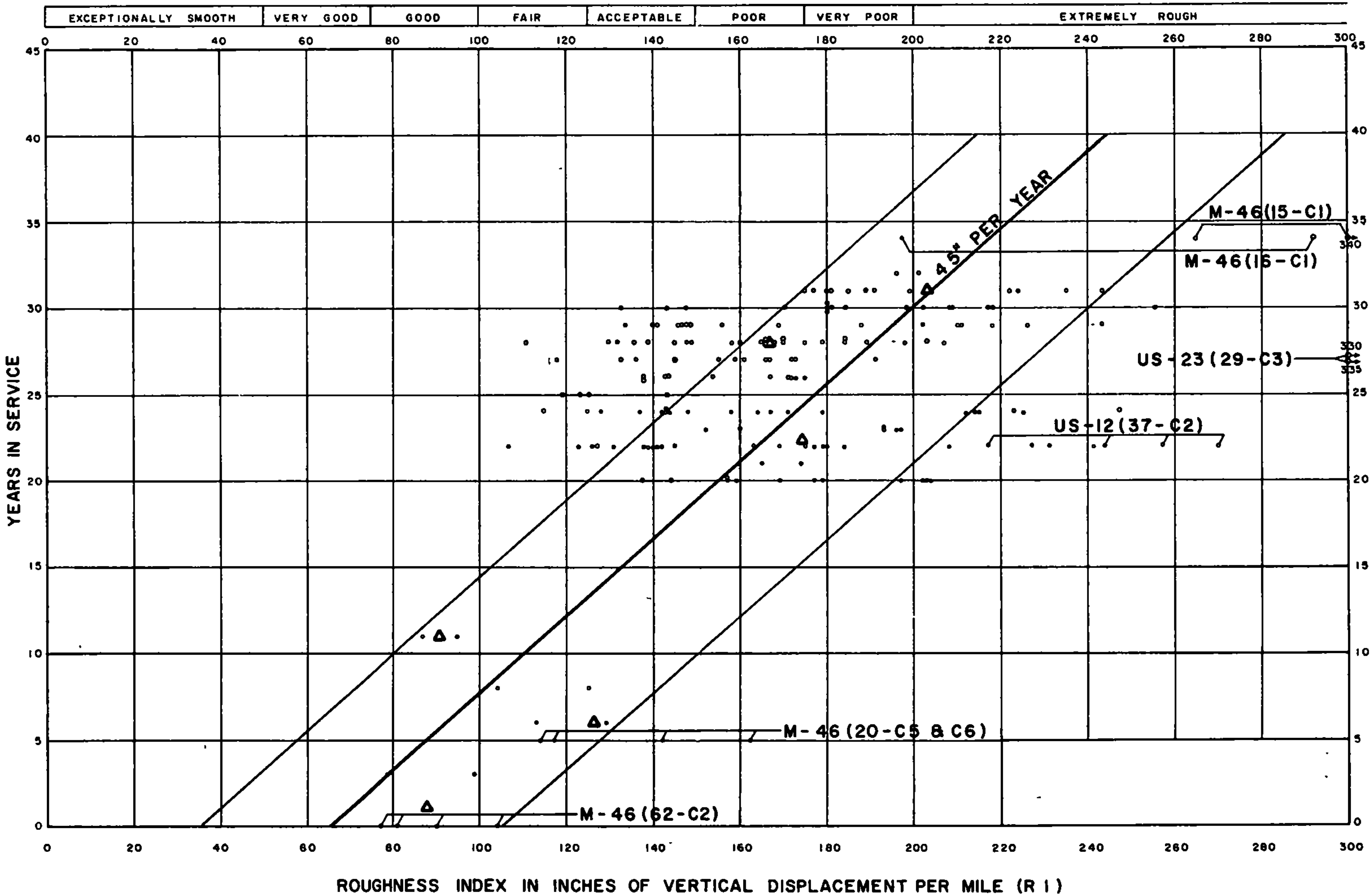

Figure 6. Roughness vs years in service, Class 3, traffic lane, based on 1958-59-60 surveys.

Class 3 Rigid Pavements

The performance of Class 3 rigid pavements, insofar as they are covered in the three-year survey, is shown in Figure 6. The data are from 70 construction projects and 353 lane-mi of pavement. Most of the projects are more than 20 years old and represent outdated design and construction standards which do not compensate for seasonal loss of strength, and may therefore be regarded as deficient for legal axle loads, at least during the spring breakup.

There are a few projects less than 15 years old still rated as Class 3 pavements, a fact that appears to be inconsistent with present Michigan design standards. Further investigation of the two projects identified in Figure 6 determined that they have been rebuilt to present standards and should now be reclassified, but this correction had not been made at the time of the profile survey. M-46 is an east-west trunkline across the State, running west from Saginaw and carrying fairly heavy truck traffic generated by the petroleum industry in this area. The other two projects identified were 34 years old at the time of the survey in 1959 and had become extremely rough, requiring heavy maintenance to keep them in service. These two sections have subsequently been strengthened and resurfaced, but have not yet been resurveyed. These recent construction contracts have been betterment projects consisting of overlays to reinforce the present pavement without complete rebuilding to correct the basic deficiency in subgrade support and inferior drainage, the results of which are still considered debatable. Although the pressure to bring the rest of this road up to present day standards has been heavy, the cost of rebuilding, involving complete relocation, has postponed its programming in competition with other important routes also requiring attention.

Further discussion of the performance of Class 3 pavements would point to the much wider range in performance of those projects more than 20 years old. This wide variation in behavior, as compared to what has been selected as normal performance, suggests less attention in design and construction to those factors most responsible for pavement performance; namely, soil conditions, drainage, and environment. In this connection, it is noted that 25 percent of the roughness indices are less than normal and 14 percent are greater than normal.

It is probable that further investigation of projects showing abnormal performance will lead to reclassification of a number of the projects on both sides of the band of normal performance. It is almost certain that those projects which have become extremely rough would require complete reconstruction or extensive correction of those deficiencies that have lead to poor performance to bring them up to present day standards. One project in this group, US-23 (29-C3), can be used for illustration. This project, which was 27 years old when surveyed in 1959, had roughness indices of 330 and 335 in. per mi and is built over a complex of poorly drained heavy clays and silty sands. It has carried heavy traffic in later years and has required heavy maintenance to keep it in service. It was resurfaced in 1959, shortly after the profile survey, and has now been replaced by a modern expressway, I-75 of the Interstate system. The other project identified, US-12 (37-C2) was built in 1937 and was extremely rough when surveyed in 1959 after 22 years of service under heavy traffic. It, too, was built over poorly drained soils of heavy clay and some areas of muck and swamp-border soils in low-lying areas. The concrete pavement was reinforced and of standard thickness, but lacked the granular subbase now used to compensate for subgrade deficiency and to eliminate pumping. It was resurfaced shortly after the profile survey and has now been replaced in the trunkline system by a modern expressway, I-94 of the Interstate system.

Class 4 Rigid Pavements

A few Class 4 pavements were included in the profile surveys and are shown in Figure 7 more to complete the picture of pavement performance than to provide design data of current interest. There are only 7 contracts and 20 lane-mi of pavement, all of which are more than 30 years old. All of these pavements are rated as extremely rough and fall in the upper range or above the band of normal behavior which has been shown for comparison. This performance is consistent with the Class 4 rating, indicating pavements inadequate for legal axle loads at all times. Special field investigation of these

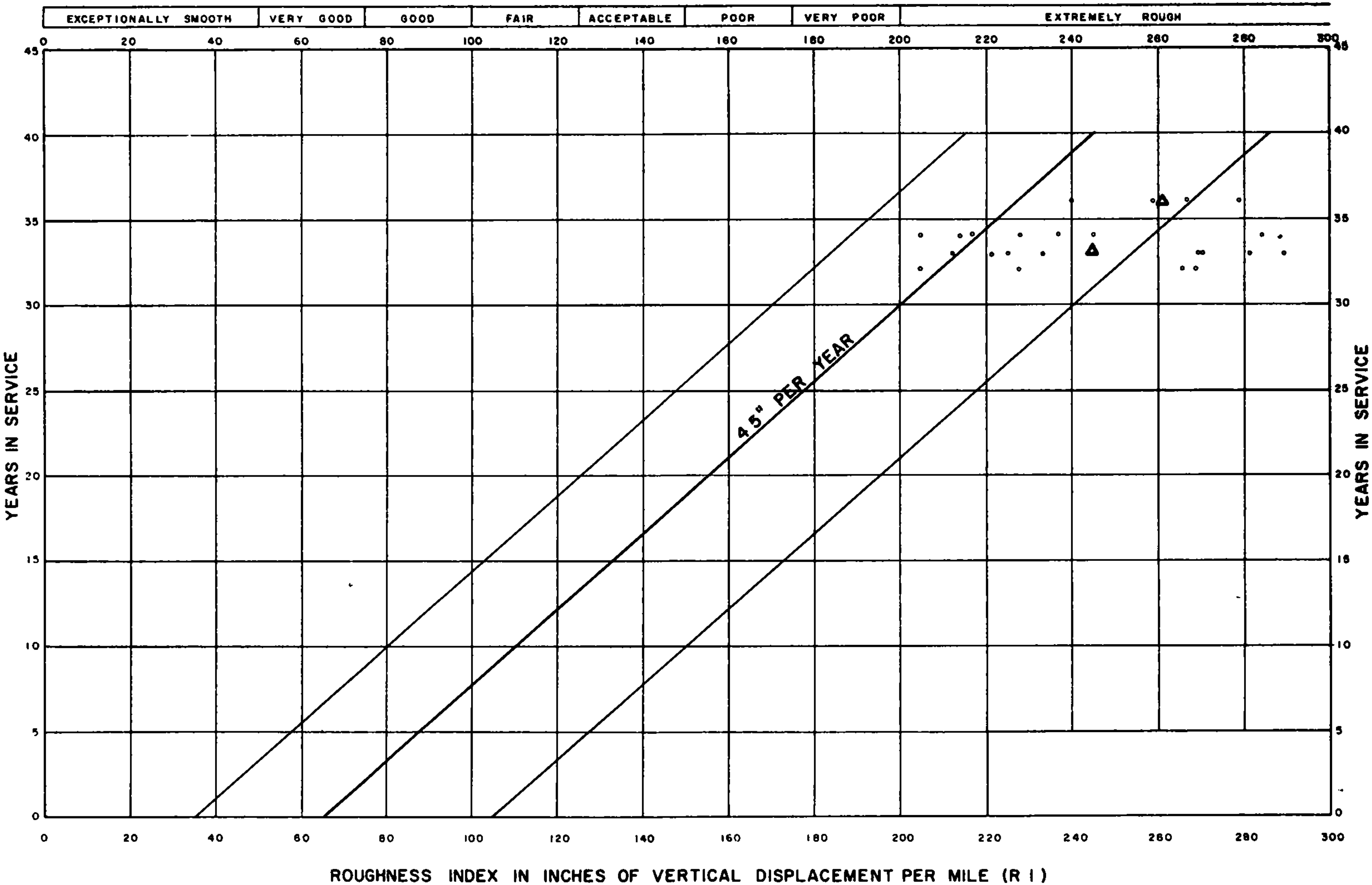

Figure 7. Roughness vs years in service, Class 4, traffic lane, based on 1958-59-60 surveys.

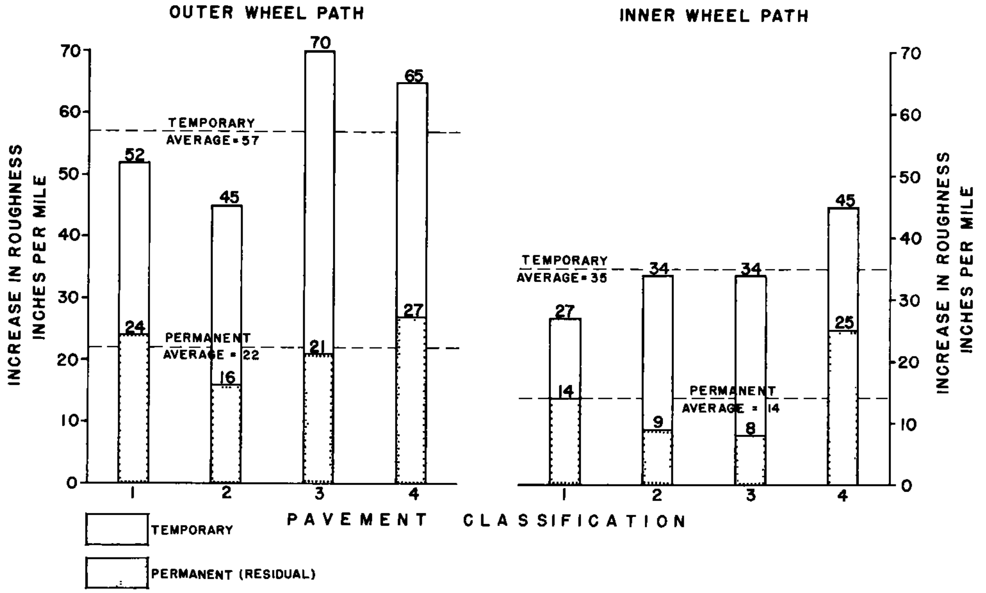

Figure 8. Seasonal fluctuation in pavement profile.

projects has not been made and may not be required as they can be identified with a history of heavy maintenance and substandard conditions.

SOURCES OF PAVEMENT ROUGHNESS

The foregoing review of cumulative changes in rigid pavement with age in service has been based almost entirely on an analysis of 6,000 mi of pavement profiles. It may be desirable to supplement these data by some discussion of special studies which may serve to emphasize several important factors contributing to pavement roughness. These factors may be briefly described as temporary and permanent roughness due to frost displacement, built-in roughness, and deflection due to wheel load applications.

Frost Displacement

In the first two years of the Michigan pavement performance study, a number of special pavement sections were selected throughout the State to measure the seasonal fluctuation in pavement profiles due to frost action. Some of the data have been previously reported and will be only briefly presented here (6). Figure 2 showed several pavement profiles illustrating temporary displacement due to curling at the joints combined with frost displacement in the granular subbase. As shown by a comparison of pavement profiles at different times of the year, much of this displacement at the time of maximum frost action was temporary and disappeared in the summer profile. However, there was some residual or permanent displacement remaining after each cycle to which the pavement was subjected.

Figure 8 shows a seasonal fluctuation in pavement profiles through the rather severe winter of 1959 and the succeeding summer. The frost displacement is shown for four classifications of pavement in terms of the average increase in roughness in inches per mile for all pavement sections in each class. The shaded areas represent the permanent or residual roughness contributing to the cumulative increase in roughness over a period of years. There was no consistent correlation between frost displacement and pavement classification from the standpoint of structural adequacy, although there was some trend in that respect.

This type of frost displacement is to be distinguished from the deep-seated frost-heaving which was a problem in former years, but which has now been largely eliminated

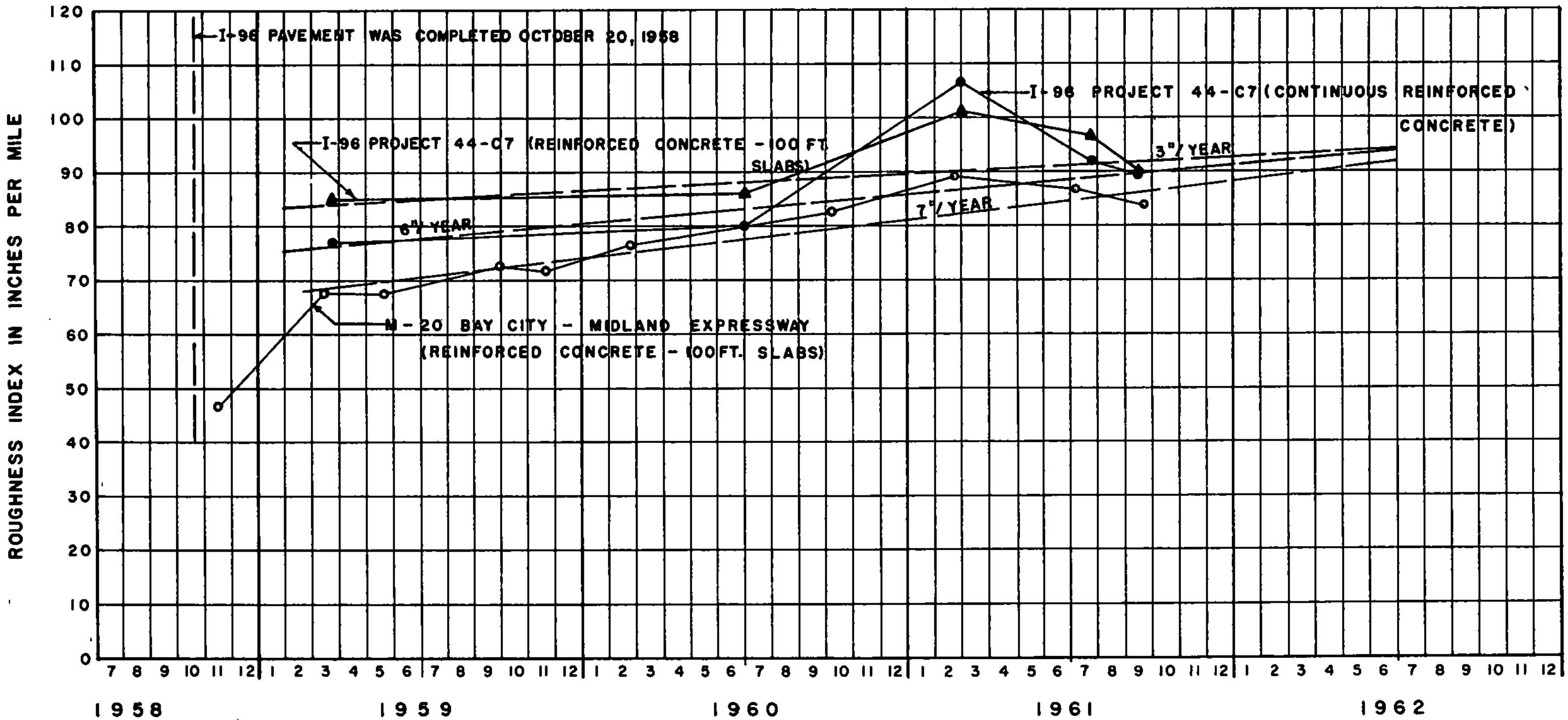

Figure 9. Cumulative change in roughness on specific projects.

from State trunklines. Such frost displacement is associated with freezing of moisture accumulating in the granular bases and subbases through infiltration at the shoulder or through joints and cracks, or condensation under the surface of moisture entering in the vapor phase. Thus, the highest classification of pavements, from the standpoint of load-carrying capacity, were affected, as well as the less adequate roads.

From the standpoint of cumulative change, Figure 9 shows several specific projects for which profile data are available over several successive years, illustrating the rate of increase in roughness the first few years after construction. There are both Class 1 and Class 2 rigid pavements in this example, and data are shown from profiles of an experimental section of continuously reinforced concrete pavement on I-96. The rates of increase in roughness as shown are an approximate average, excluding the first winter, as the residual roughness for the initial cycle of displacement does not appear to be representative. There is also considerable variation depending on the severity of winter from the standpoint of frost action. In general the rate of increase, varying from 3 to 7 in. per mi per year in these several pavements in their early years of service, may be expected to level off over a considerably longer period of service.

Built-in Roughness

Figure 10 shows one source of built-in roughness that relates to pavement finishing in which the cause and effect is so specific that it needs no particular comment. The excessive roughness of bridge decks and short lengths of pavement slab where hand-finishing is employed has been a problem of much concern to the Michigan State Highway Department for some time. Figure 10 shows direct comparison between sections of pavement or bridge deck, as the case may be, where hand-finishing has been employed and adjacent pavement which has been machine finished. Transverse finishing of bridge decks is one of the possibilities under investigation and it has shown some promise.

Roughness Due to Wheel Load Applications

Pavement deflection under wheel load applications and the permanent displacements caused by excessive load are a source of loss in riding quality that has always been of major concern to highway engineers. In the roughness data from some 6,000 mi of pavement profile reviewed in this report, two important facts stand out, qualified necessarily by the limitations in the volume of supporting data available. First, there were measurable increases in the cumulative roughness over a period of years in the Class 3 and Class 4 rigid pavements that were known to be deficient in load-carrying capacity. This deficiency was emphasized in specific projects that were cited where their poor performance had been more definitely related to known deficiency in subgrade support.

Second, there was no measurable difference in the cumulative roughness of the traffic lane and passing lane of Class 1 and Class 2 pavements in the periods of service covered by the profile data presented. The necessary qualification in this statement is in recognition of the short period of service which is related to two developments in highway construction in Michigan. First, the construction of dual-lane divided highways, where such a comparison could be made, has largely taken place in the last 10 years. Second, it is only in the last 15 or 20 years that Michigan design standards have required that all trunkline construction be made adequate to carry legal axle loads at all times of the year.

These qualifications notwithstanding, the evidence accumulated is entirely consistent with the statement made by Commissioner Curtiss of the Bureau of Public Roads in discussing damage caused by highway loads when he said, in effect, that properly built roads would not be damaged by the loads for which they were designed. Evidence bearing on the same point is provided by pavement profile data from Class 1 and Class 2 pavements showing that the cumulative increase in roughness with years in service is closely related to soil conditions, drainage, and climatic environment. This in turn illustrates the point made by the late Commissioner MacDonald of the Bureau of Public Roads when he said: "The roads are more destroyed really by climatic and soil conditions than they are by any use that is made of them."

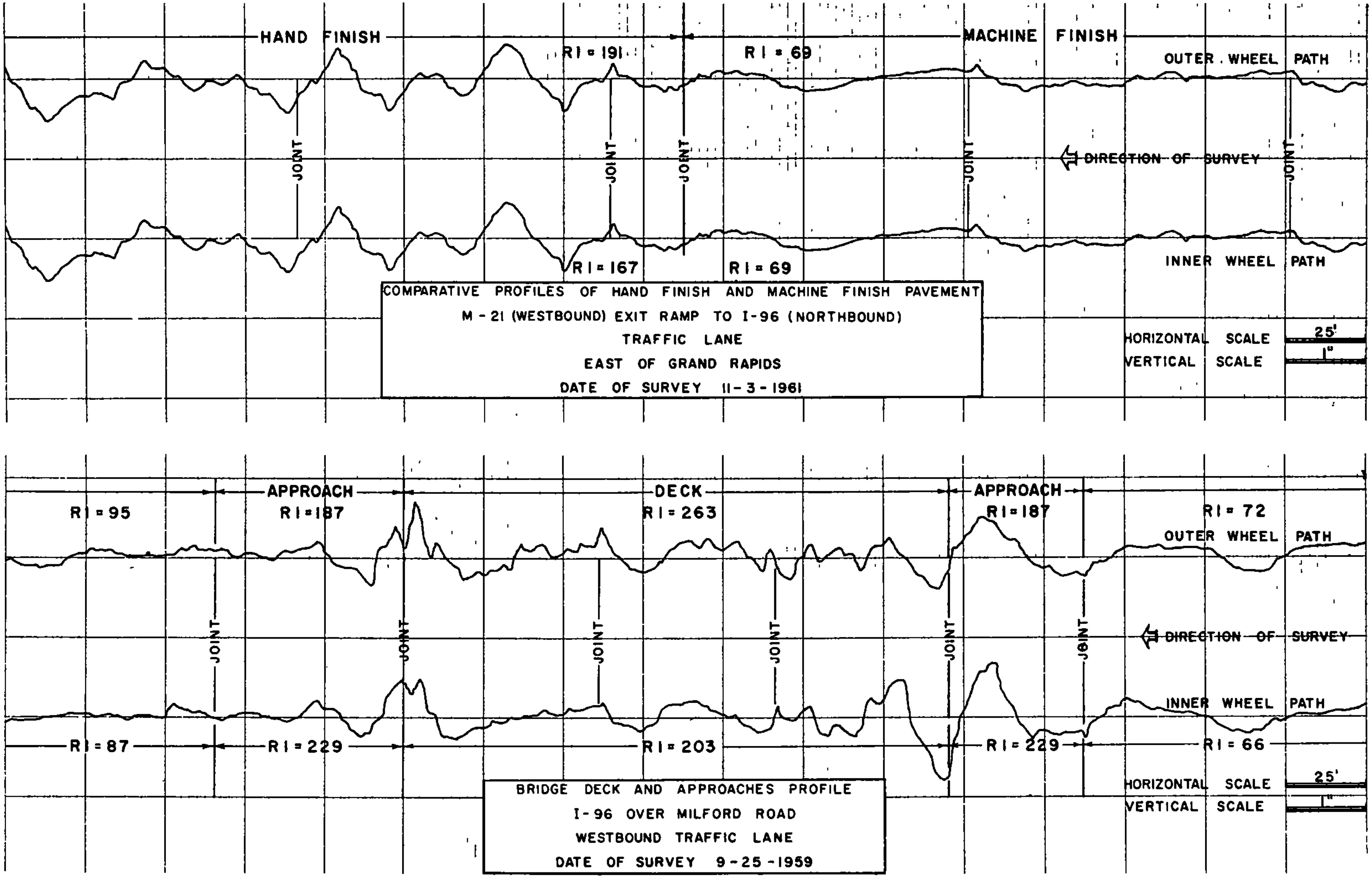

Figure 10. Comparative profiles.

CONCLUSIONS

The Michigan pavement performance study has now been in progress for four years and has accumulated some 8,100 mi of pavement profiles, including those from the 1961 surveys. This paper presents a substantial part of the data on rigid pavements for the first three years, covering 966 construction contracts and some 6,000 lane-mi of pavement in all parts of the State. The analysis of these data is still in progress; it is felt that additional information of value in pavement design and construction is yet to be obtained from the data, particularly in the study of all those projects whose performance varies considerably from normal behavior.

This study has been predicated on the belief that accurate recording of the condition of existing pavements after years of service under actual field conditions and an objective analysis of the resulting data was a most promising approach for evaluating pavement performance and relating it to pavement design and construction. In more specific terms, the procedure involved (a) accurate recording of the profile of the pavement surface which has been evaluated quantitatively in terms of a roughness index in inches of vertical displacement per mile, supplemented by a study of the magnitude and character of these displacements as revealed by the recorded pavement profile; and (b) the cracking of the pavement recorded and evaluated quantitatively as a continuity ratio directly related to the average interval between cracks and joints.

From these data the following tentative conclusions, subject to further study and possible revision, summarize the results:

1. Pavement performance and cumulative change in rigid pavements, under Michigan environment and service conditions, can be expressed in terms of a band of normal performance which brackets approximately 85 percent of the data, excluding those projects showing abnormal performance.
2. The width of this band of normal performance has been taken as 70 in. of vertical displacement per mile as representative of the limits within which variations in riding quality have been and perhaps can be controlled by design and construction practices.
3. Initial or built-in roughness, in terms of inches of vertical displacement per mile, ranges from 35, which is considered exceptionally smooth, to 105, rated as only fair. From a general consideration of this range and from results on specific projects cited, this is one factor in riding quality that appears to offer an obvious opportunity for substantial improvement in the upper limit and any variation above this limit.
4. The progressive increase in pavement roughness, or cumulative change with age in service, which has been characterized as normal, averages 4.5 in. per yr and has been based largely on the performance of Class 1 and Class 2 pavements designed and built to carry legal axle loads at all times of the year under Michigan climatic environment.
5. Both comparison of the traffic lane and passing lane of Class 1 and Class 2 pavements, within the limits of available data, and analysis of specific projects showing abnormal behavior indicate that an average cumulative increase in roughness of a magnitude of 4 to 5 in. per mi per yr results from the characteristics of rigid pavements subjected to Michigan climatic conditions. This finding is confirmed by special studies of frost displacement and effect of temperature differentials and appears to identify this range as one that may not be effectively controlled under present design and construction practices.
6. The data from Class 3 and Class 4 pavements, recognized as deficient in load-carrying capacity, do show evidence of an added increase in roughness due to wheel load applications. These data come from older roads not representative of present design standards in Michigan and consequently provide a limited basis for drawing specific conclusions. However, when supplemented with more definitive results from specific projects showing abnormal behavior and viewed in the light of favorable results from Class 1 and Class 2 pavements, there is clear indication that deficiency in subgrade support is the primary factor in their inferior performance.
7. Finally, with respect to procedure for measuring pavement performance and relating it to design and construction conditions, it is found that the projects showing abnormal behavior provide the most significant information. Analysis of all of these proj-

ects has not been completed, but examples that have been presented in this report provide evidence that the investigation of existing pavements under actual service conditions and environment fulfills the promise it was felt to hold for a realistic appraisal of pavement design and performance.

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