# Evaluation of Pavement Performance Related to Design, Construction, Maintenance and Operation

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This paper presents a summary of the findings of the Michigan Pavement Performance Study, a five-year program (1958-1963) to evaluate pavement performance from field surveys of existing pavements. In the five-year period, equipment and procedures for recording and analyzing pavement profiles have been developed and profiles of 10,000 miles of pavement have been accumulated. Although there have been several published reports of this work as it progressed, the final results have now been compiled and analyzed.

The quantitative evaluation of pavement condition and performance and the physical inventory of existing roads provide factual information of direct value in design, construction, and maintenance of both rigid and flexible pavement and in the operation of the state trunkline system as a transportation facility. The findings of the five-year study are reviewed, the adequacy of Michigan design standards is evaluated, and the effect on performance of certain construction practices is pointed out. The use of pavement profile data in more effective and timely maintenance and their value in the operation of the state highway system are discussed.

•STARTING in 1952, the University of Michigan and the Michigan State Highway Department have undertaken several projects in their cooperative highway research program in which special attention has been given to field surveys of existing pavements as a basis for evaluating pavement performance related to the design, construction, maintenance, and operation of highway pavements. At that time, in cooperation with the Wire Reinforcement Institute, a five-year survey was initiated to study the effect of steel reinforcement on the performance of concrete pavements.

Condition surveys of existing pavements as a check on design and a basis for more effective utilization of natural conditions and materials in highway construction are not new. As pointed out in several of the current references, this approach had been used for many years and was the fundamental basis for Michigan design of the roadway structure. As part of the study, definite criteria for measuring pavement performance in a quantitative manner had been set up and put into practice under field conditions (1, 2). The primary function of a pavement is to provide a smooth riding surface, supplying safety, comfort, and economy to the highway user. Recognizing this, riding quality has been defined in terms of a roughness index, RI, expressing the cumulative or total inches of vertical displacement per mile measured from the recorded pavement profile.

It was also recognized that the structural properties of the pavement would control its ability to endure under the combined stresses of continuous load repetition and the rigors of its environment. It seemed logical that failure to survive or inadequacy as a structure would be reflected in cracking or loss of structural continuity even before

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Paper sponsored by Committee on Pavement Condition Evaluation.

riding quality was affected. Timely maintenance or corrective steps would depend on early identification of weakness, so a continuity ratio was adopted as an independent quantitative measure of structural adequacy. The continuity ratio was defined as the ratio of the uncracked slab length of a pavement divided by 15. The control length of 15 ft was selected as a measure of the normal subdivision of a rigid concrete slab due to shrinkage, warping, and curling under temperature, moisture, and other environmental influences. It was considered that such environmental effects did not reflect structural inadequacy; thus, slab lengths of 15 ft or more would not be considered evidence of structural weakness.

The adoption of these criteria and their application to condition surveys of existing pavements in the early 1950's was not a generally recognized approach, and represented simply an attempt to quantify in some integrated form the many factors which affect pavement performance. Others were concentrating their efforts on the road test approach and the AASHO Road Test was then in the planning stage. As late as 1958, field surveys were not being considered as an alternate to the satellite tests in the recommended procedures then being circulated to follow up the AASHO Road Test.

The second phase of the Michigan investigation began in 1957 as a cooperative program with three agencies of the trucking industry, The Michigan Trucking Association, The American Trucking Associations, Inc., and the Automobile Manufacturers Association. After the first two years, the Michigan Pavement Performance Study, as it was known, was taken over more directly by the Michigan State Highway Department, as part of the Michigan Highway Planning Survey Work Program HPS-1, in cooperation with the U.S. Bureau of Public Roads. Acknowledgment of the contributions to the study of a number of organizations and many individuals was made in the "Five-Year Summary of the Michigan Pavement Performance Study," prepared after termination of the study in December 1962. The current paper is a resume of that "Summary," intended to provide reference to the complete series of reports which accompanied it and to abstract from it the more important findings.

Evaluation of pavement performance on a large scale by the procedures used in this investigation was undertaken in the belief that carefully controlled observations of existing pavement under actual service conditions and environment would provide the answers to some of the most perplexing problems facing the highway engineer. The first year, from September 1957 through the first half of 1958, was devoted largely to selecting procedures and designing, planning, and assembling equipment. In spite of a disappointingly long shake-down period for the truck-mounted profilometer, considerable mileage of pavement profile was recorded in the first year and a half.

In the five years that the Michigan Pavement Performance Study was in progress, profiles of almost 10,000 lane miles of pavement were recorded. The annual totals are given in Table 1. On some routes only one lane has been surveyed, normally one of the traffic lanes. On a large part of the mileage, particularly on new construction and certain roads of special interest, all lanes, including both traffic and passing lanes, have been surveyed.

This large mileage of recorded pavement profile and supplemental data represent a volume of basic information on pavement condition and performance, the value of which has been only partially utilized to date. This review illustrates the use of this information in design, construction, maintenance, and operation of the Michigan trunkline system. However, its value as a pavement inventory and a foundation on which to build future applications of practical value can be realized only by its continued use and by keeping it up-to-date and growing as the highway system grows.

Having established criteria and general procedures for the pavement performance surveys, the truck-mounted profilometer with its electronic recording instrumentation was developed as the major piece of equipment. It was modeled after that designed by F.N. Hveem and used by the California Department of Highways. It was selected as the most practical under field conditions and state highway department operation to collect and record a large volume of pavement profile data. Many types of road roughometers have been described and used with varying success, but the choice had to be made from those which were readily available. There was little time to devote to devising and developing instrumentation; the California machine was operating efficiently and, with some modifications, met the needs of the Michigan study.

Modifying the California equipment for recording a continuous pavement profile in only one wheel track, a double recording system was adopted which provided profiles in both the outer and inner wheel paths in one operation. Electronic integrating instrumentation was added to record the cumulative roughness in inches of vertical displacement for each quarter mile. More details on the profilometer and its operation are given in previously published reports included as part of the five-year summary.

TABLE 1

TOTAL MILEAGE OF RECORDED PAVEMENT PROFILE

| Year | Mileage |
|---|---|
| 1958 | 1,969.2 |
| 1959 | 2,128.2 |
| 1960 | 1,769.4 |
| 1961 | 2,366.8 |
| 1962 | 1,535.6 |
| Total | 9,769.2 |

## UTILIZATION OF PAVEMENT PROFILE DATA

The title of this paper indicates that pavement performance data find application in design, construction, maintenance, and operation of highways. It is not always recognized that a highway department actually has four major functions which may be so delineated in describing different phases of its operations. However, in planning this review of the pavement performance study, it appeared not only appropriate but also necessary to so classify highway activities in order to accurately illustrate the usefulness of pavement profile data.

### Design Correlation

The primary objective of the Michigan Pavement Performance Study was to provide more accurate and discerning techniques for checking pavement design and detecting weakness in service performance. It seemed entirely logical that changes in the pavement surface or profile would reflect the integrated result of the various stresses and strains to which a pavement is subjected, originating from variations in the supporting subgrade below or from repeated load application and weather cycles above. Although the uncontrolled variables of environment seem much more difficult to gage than the more precise relationships of applied load and reaction in the pavement structure, they are nevertheless the influences under which pavements must endure. Every one of these variables, controlled or uncontrolled, has its effect on the pavement surface; whether or not they can be identified is a test of the observer and the methods of analysis brought to bear on the problem.

At first it was thought that an initial reference profile would have to be recorded and then, after a sufficient period of time had elapsed to produce a measurable change, a subsequent profile would measure the change. This meant that a period of years, perhaps many, would be required before definitive changes would become apparent. It came then as an unexpected bonus when, after a considerable volume of profile data had been accumulated, it turned out that roads, which had been in service for varying periods of time under varying conditions of service and environment, fell into definite patterns of behavior that could be defined in terms of pavement roughness, structural continuity, and related characteristics of the pavement. This discovery opened the door to a great storehouse of valuable data when it became apparent that the entire highway system was the final testing ground and that the many years these roads had already been subjected to traffic was the ultimate road test and was merely awaiting analysis.

From the standpoint of pavement design, the reports referred to herein contain many examples in which the responsible factors in pavement performance have been clearly identified in terms which demonstrate them to be subject to design control. The overriding importance of soil conditions and drainage stands out in many of these examples and demonstrates the soundness of Michigan design, which follows the unspectacular but time-tried principle that it is the subgrade that "does, in fact, carry the road and the carriage also."

TABLE 2

| Route No. | Service Period (yr) | Roughness Index (in. per mi) |  | Drainage | Riding Quality |
|---|---|---|---|---|---|
|  |  | OWP | IWP |  |  |
| US-112 | 32 | 72 | 75 | Fair | Very Good |
|  | 32 | 291 | 395 | Poor | Prohibitive[1] |
| M-25 | 28 | 91 | 66 | Excellent | Good to very good |
|  | 36 | 218 | 175 | Poor | Very poor |
| M-41 | 22 | 383 | 365 | Poor | Prohibitive[1] |
|  | 22 | 73 | 75 | Good | Very good |
| M-36 | 19 | 84 | 77 | Excellent | Good |
|  | 19 | 363 | 282 | Poor | Prohibitive[1] |

[1] Outside tentative rating scale.

A few illustrations drawn from the supplementary reports to the five-year summary may be cited for illustration. Several of these reports are included in the list of references for this paper and in the "Five-Year Summary of the Michigan Pavement Performance Study" as Publications and Papers, identified as Report Series P (P-1 through P-6). Table 2 lists the correlation between riding quality and drainage previously reported (3). It should be noted that drainage as listed includes internal drainage as controlled by soil texture and ground water level.

Other design correlations reported (3) include the poor performance of short concrete slabs without load transfer at the joints (Fig. 1, top), as compared to the performance of another road also having comparatively short slabs, but with load transfer provided (Fig. 1, bottom). Although there were other factors involved to some degree, the contrast between these two roads was so sharp that the comparison is still valid, with the first pavement becoming extremely rough in its period of service and the second maintaining very good riding quality over a considerably longer period of time.

The most interesting feature of the rough pavement in the preceding example is the characteristic saw-toothed pattern produced by tilting and faulting of the short slabs. This illustrates the unique value of an actual pavement profile that goes beyond the RI derived from it. Such a profile is a realistic picture of the pavement itself and the physical condition produced by some specific factors among a variety of influences that may have been present. Such a profile is as individualistic as a signature, reflecting characteristics that can be fully appreciated only by examining the profile itself and the physical conditions associated with it in whatever detail is necessary to read the pavement's past history.

This leads to perhaps the most important consideration in evaluating pavement performance from condition surveys. The RI or some other quantity derived from the pavement survey may adequately reflect the present riding quality or serviceability of the pavement. This in itself is an important consideration and may be useful in several respects. However, from the standpoint of pavement design, one must know not only the extent to which a pavement has deteriorated or lost riding quality but why it has reached that particular level of serviceability. This is the crux of the situation and the point at which the actual pavement profile shows its real value, as it may provide an insight into events in the past history of the pavement which have left no other clues (4).

An interesting comparison is provided in Figure 2 which demonstrates not only the necessity for detailed study of the profile, but also its intimate relation to the pavement itself, which must also be taken into consideration. In this section, the profile in the outer wheel path again shows a saw-toothed pattern, almost identical to that caused by the tilting of short slabs; one might be tempted to conclude that this pattern of displacement would certainly be due to the tilting of short slabs, except that the inner wheel path does not follow the pattern. Furthermore, the pavement is a 9-in. reinforced concrete pavement, 99 ft between contraction joints, and there are no cracks coinciding with peaks of displacement in the profile. Further investigation indicated that this was "built-in" roughness resulting from careless form setting, with displacement at the junction between 10-ft forms and sagging of the forms between points of support. This type of built-in roughness was most apparent in the outer wheel path, but also showed in the inner wheel path.

There are a number of other examples of the surprising consistency with which accurate pavement profiles and the quantitative criteria derived from them single out abnormalities in pavement behavior or unusual conditions which have affected pavement performance. For more complete study of all such information, reference should be made to the reports submitted as part of the five-year summary.

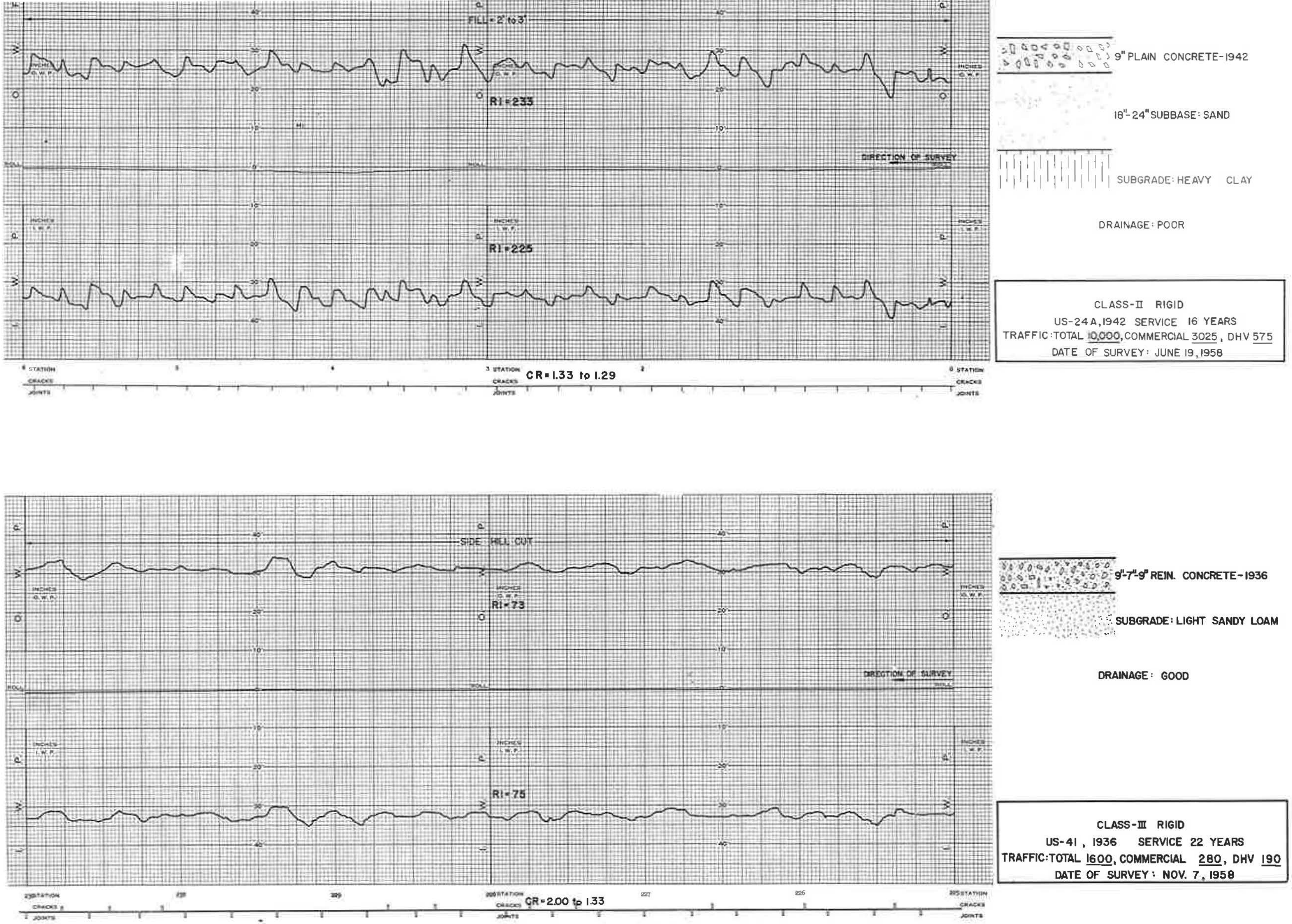
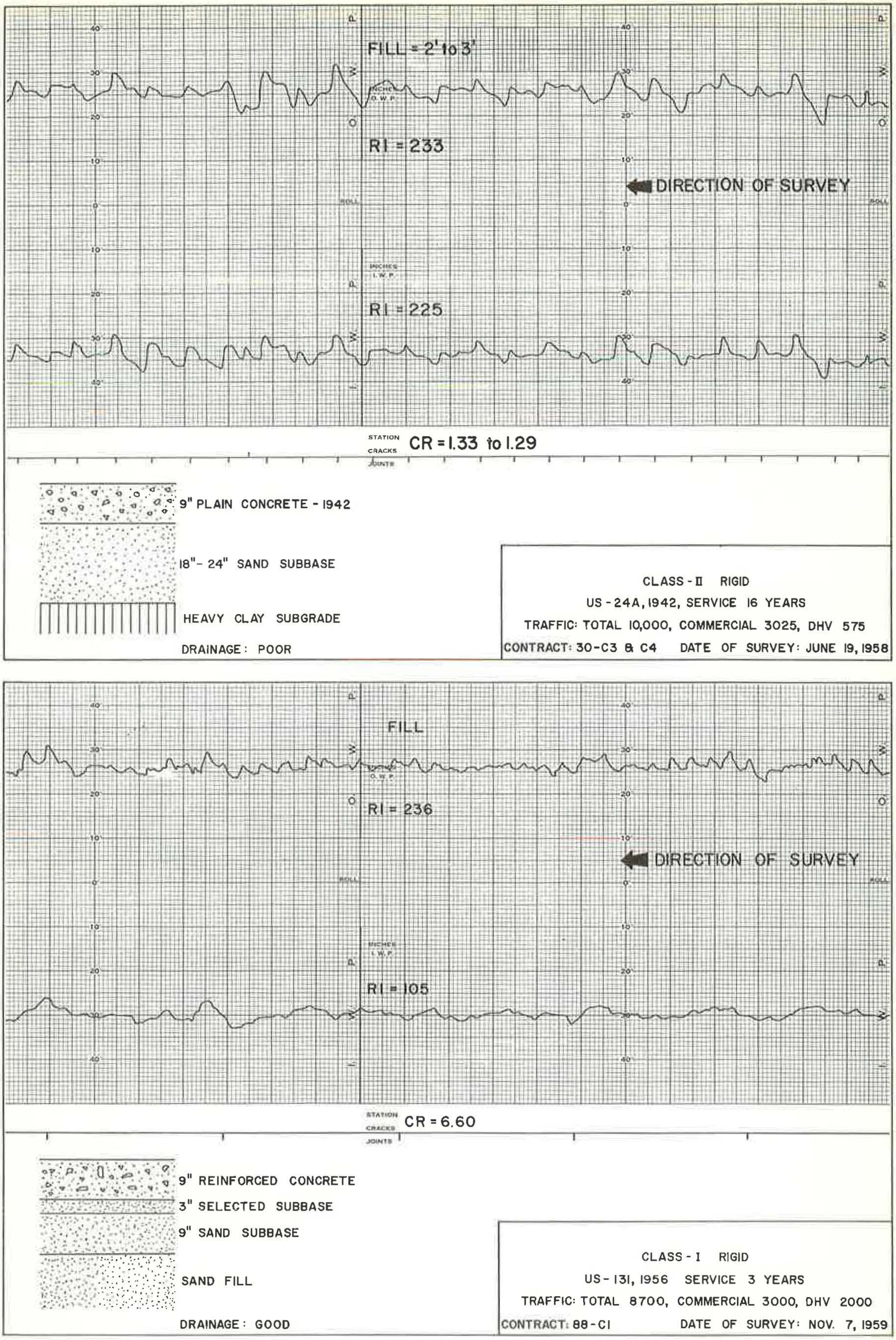

FILL - 2' to 3'
RI = 233
RI = 225
DIRECTION OF SURVEY
CR = 1.33 to 1.29
STATION
CRACKS
JOINTS
9" PLAIN CONCRETE-1942
18"-24" SUBBASE: SAND
SUBGRADE: HEAVY CLAY
DRAINAGE: POOR
CLASS-II RIGID
US-24 A, 1942 SERVICE 16 YEARS
TRAFFIC: TOTAL 10,000, COMMERCIAL 3025, DHV 575
DATE OF SURVEY: JUNE 19, 1958
SIDE HILL CUT
RI = 73
RI = 75
CR = 2.00 to 1.33
9"-7"-9" REIN. CONCRETE-1936
SUBGRADE: LIGHT SANDY LOAM
DRAINAGE: GOOD
CLASS-III RIGID
US-41, 1936 SERVICE 22 YEARS
TRAFFIC: TOTAL 1600, COMMERCIAL 280, DHV 190
DATE OF SURVEY: NOV. 7, 1958

Figure 1.



CLASS - II RIGID
US - 24A, 1942, SERVICE 16 YEARS
TRAFFIC: TOTAL 10,000, COMMERCIAL 3025, DHV 575
CONTRACT: 30-C3 & C4 DATE OF SURVEY: JUNE 19, 1958

CLASS - I RIGID
US - 131, 1956 SERVICE 3 YEARS
TRAFFIC: TOTAL 8700, COMMERCIAL 3000, DHV 2000
CONTRACT: 88-C1 DATE OF SURVEY: NOV. 7, 1959

Figure 2.

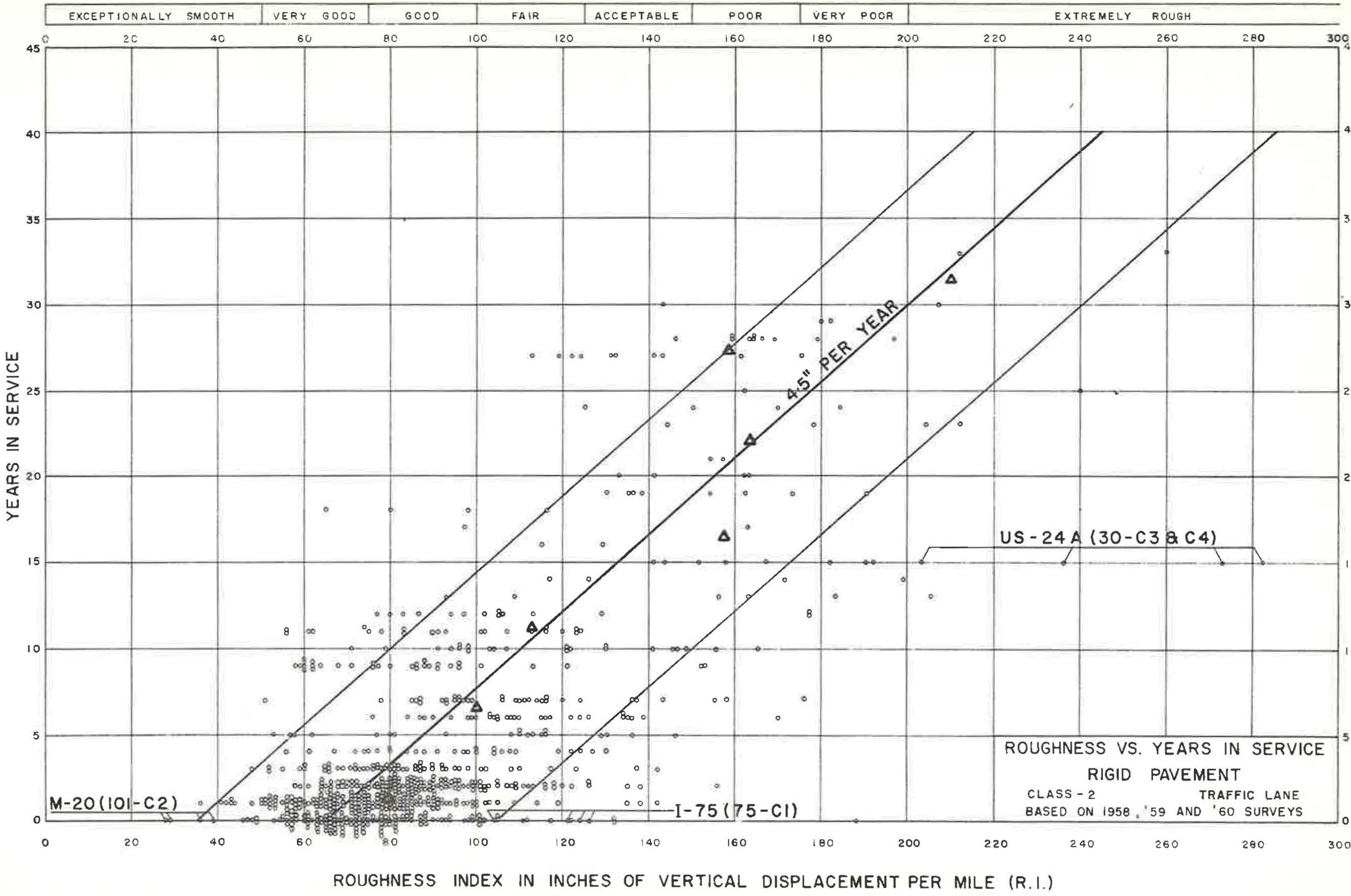

EXCEPTIONALLY SMOOTH
VERY GOOD
GOOD
FAIR
ACCEPTABLE
POOR
VERY POOR
EXTREMELY ROUGH
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
45
40
35
30
25
20
15
10
5
0
YEARS IN SERVICE
4.5" PER YEAR
US-24 A (30-C3 & C4)
M-20(101-C2)
I-75(75-C1)
ROUGHNESS VS. YEARS IN SERVICE
RIGID PAVEMENT
CLASS-2
TRAFFIC LANE
BASED ON 1958, '59 AND '60 SURVEYS
ROUGHNESS INDEX IN INCHES OF VERTICAL DISPLACEMENT PER MILE (R.I.)

Figure 3.

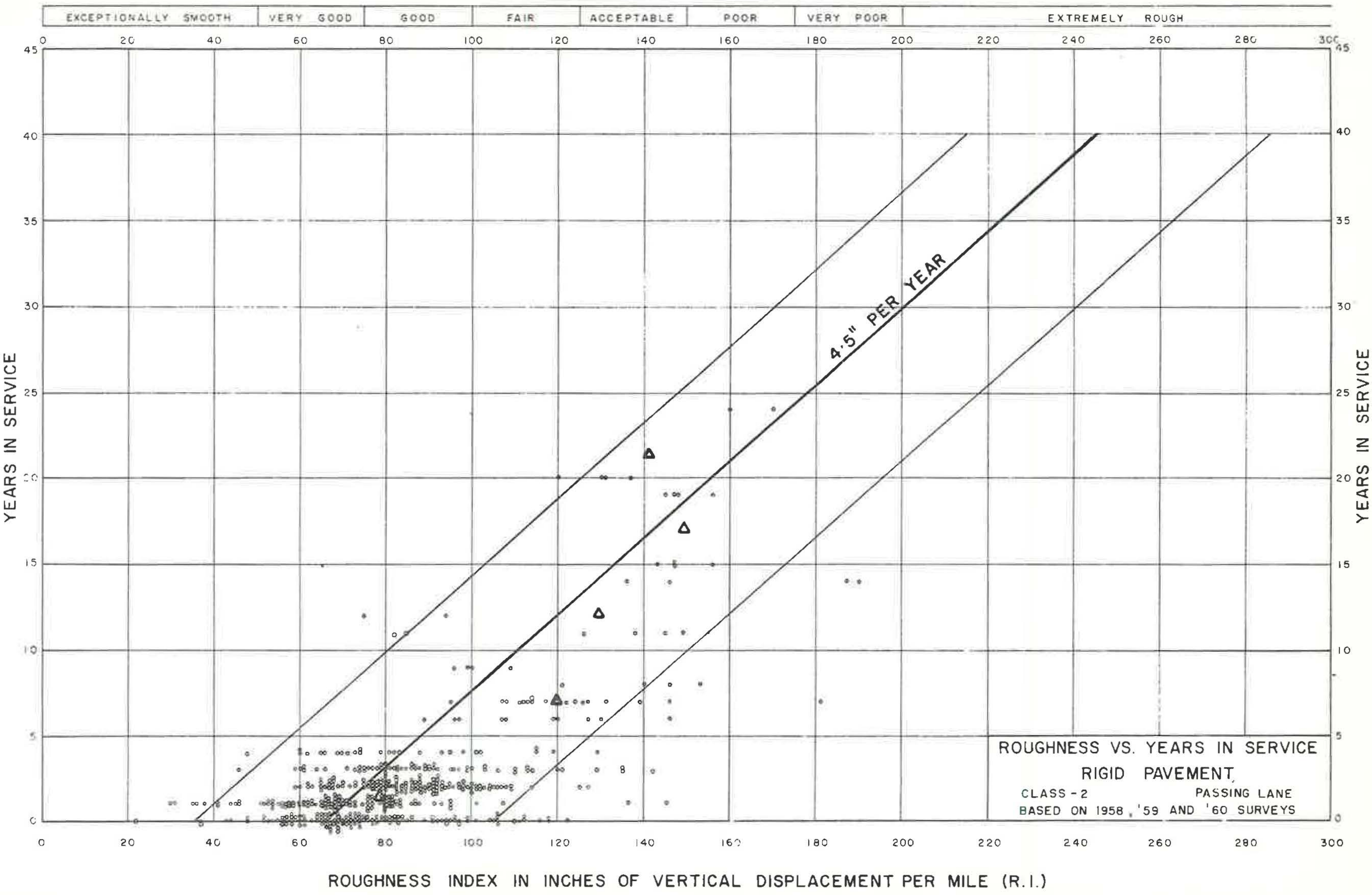

EXCEPTIONALLY SMOOTH
VERY GOOD
GOOD
FAIR
ACCEPTABLE
POOR
VERY POOR
EXTREMELY ROUGH
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
45
40
35
30
25
20
15
10
5
0
YEARS IN SERVICE
4.5" PER YEAR
ROUGHNESS VS. YEARS IN SERVICE
RIGID PAVEMENT,
CLASS - 2
PASSING LANE
BASED ON 1958, '59 AND '60 SURVEYS
ROUGHNESS INDEX IN INCHES OF VERTICAL DISPLACEMENT PER MILE (R.I.)

Figure 4.

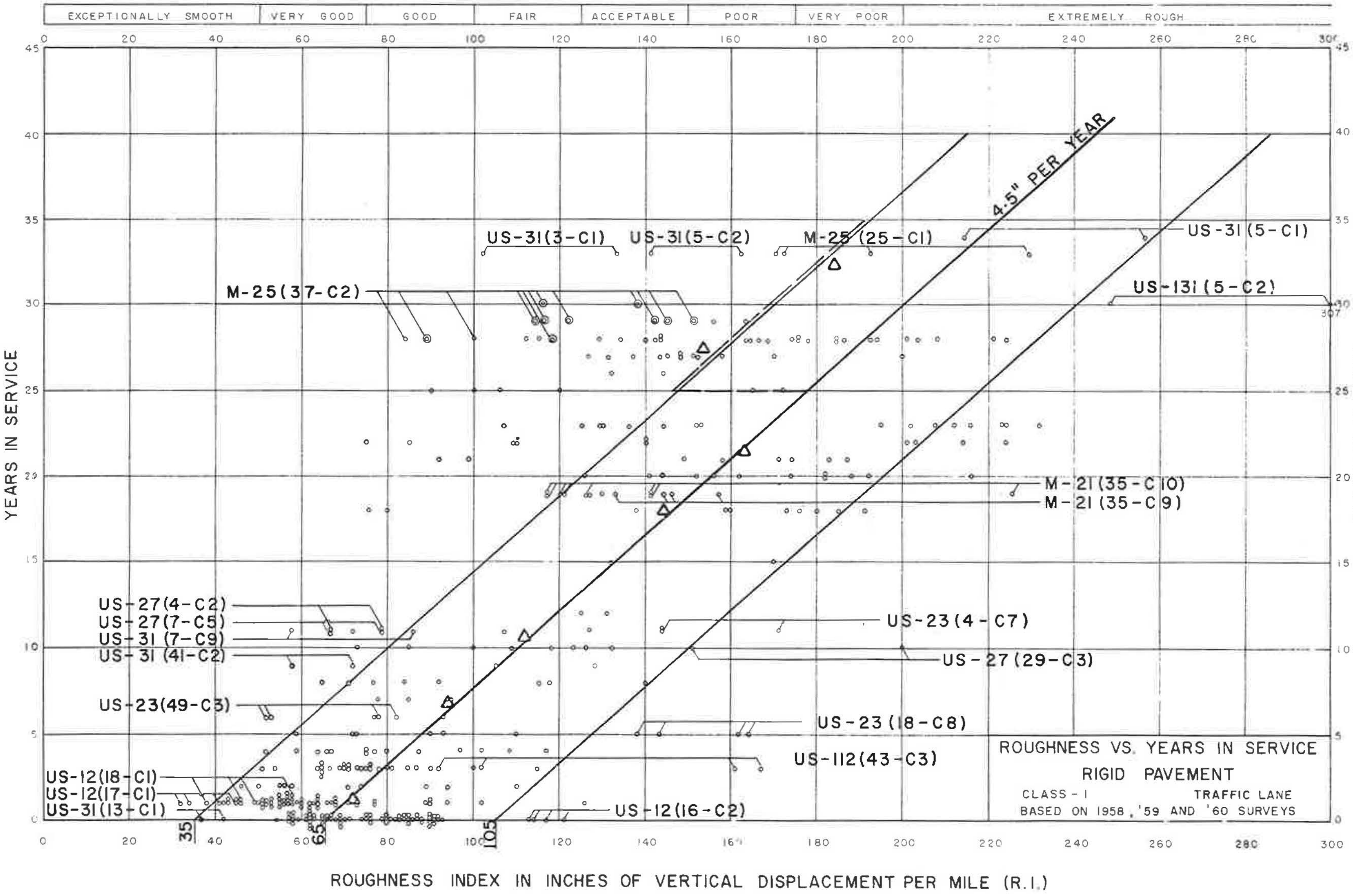
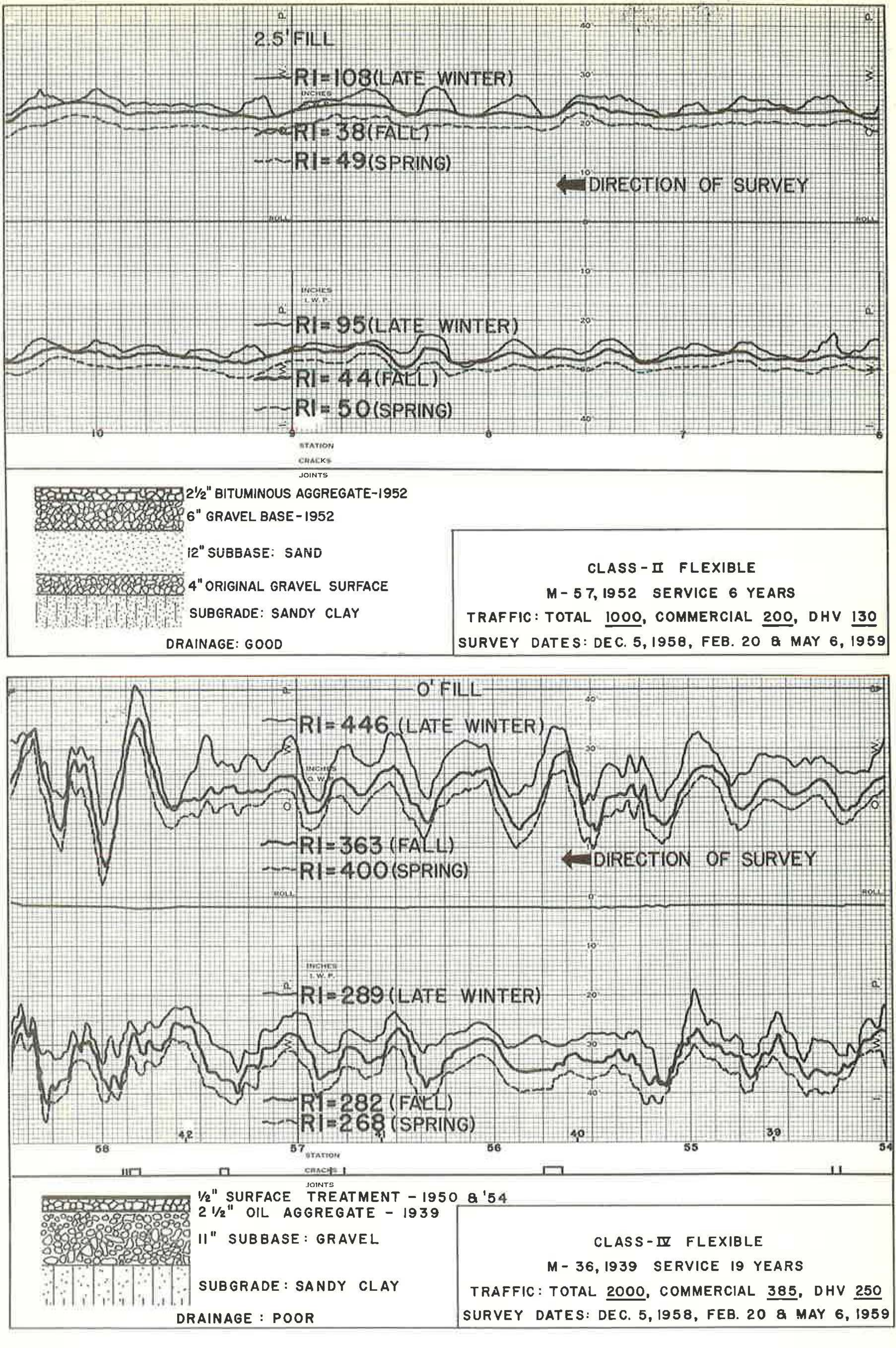

EXCEPTIONALLY SMOOTH
VERY GOOD
GOOD
FAIR
ACCEPTABLE
POOR
VERY POOR
EXTREMELY ROUGH
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
YEARS IN SERVICE
0
5
10
15
20
25
30
35
40
45
4.5" PER YEAR
US-31(3-C1)
US-31(5-C2)
M-25(25-C1)
US-31(5-C1)
M-25(37-C2)
US-131(5-C2)
307
M-21(35-C10)
M-21(35-C9)
US-27(4-C2)
US-27(7-C5)
US-31 (7-C9)
US-31 (41-C2)
US-23(4-C7)
US-27(29-C3)
US-23(49-C3)
US-23(18-C8)
US-112(43-C3)
US-12(18-C1)
US-12(17-C1)
US-31(13-C1)
US-12(16-C2)
35
65
105
ROUGHNESS VS. YEARS IN SERVICE
RIGID PAVEMENT
CLASS-1
TRAFFIC LANE
BASED ON 1958, '59 AND '60 SURVEYS
ROUGHNESS INDEX IN INCHES OF VERTICAL DISPLACEMENT PER MILE (R.I.)

Figure 5.



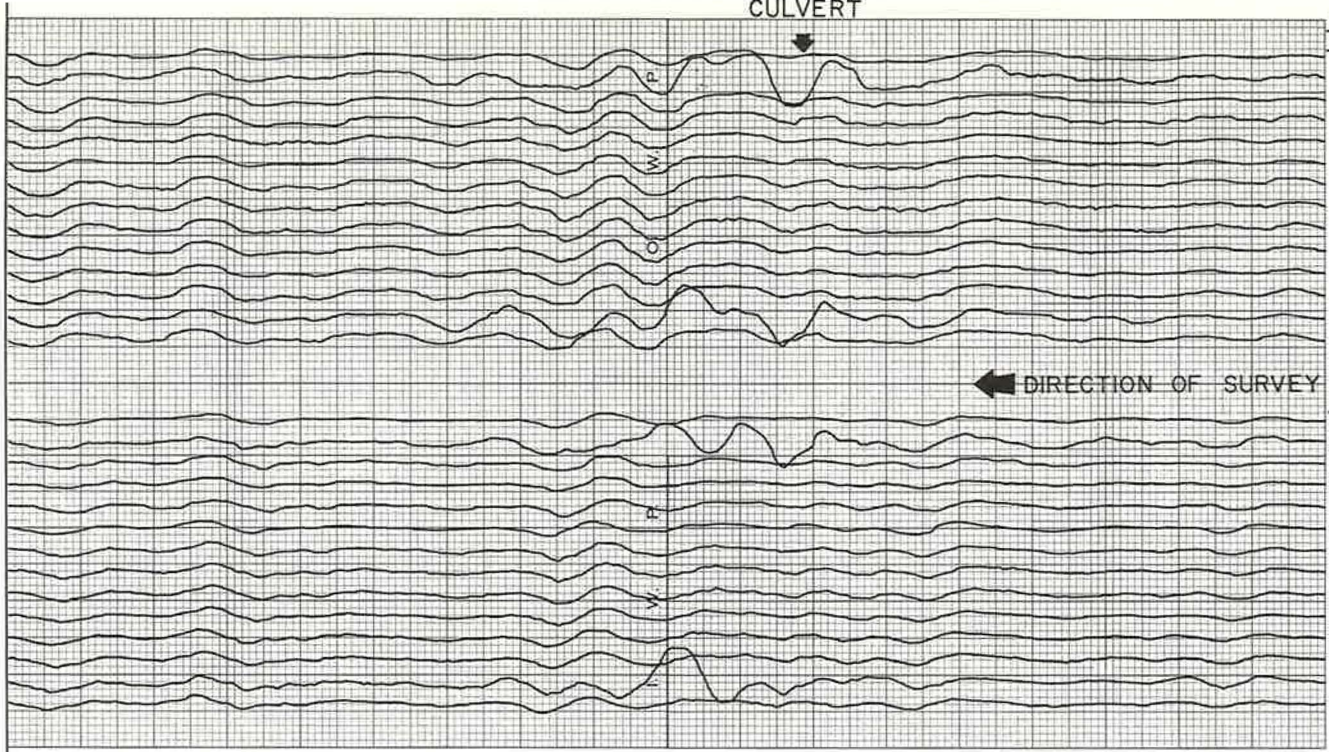
2½" BITUMINOUS AGGREGATE-1952
6" GRAVEL BASE-1952
12" SUBBASE: SAND
4" ORIGINAL GRAVEL SURFACE
SUBGRADE: SANDY CLAY
DRAINAGE: GOOD

CLASS-II FLEXIBLE
M-57, 1952 SERVICE 6 YEARS
TRAFFIC: TOTAL 1000, COMMERCIAL 200, DHV 130
SURVEY DATES: DEC. 5, 1958, FEB. 20 & MAY 6, 1959

½" SURFACE TREATMENT - 1950 & '54
2½" OIL AGGREGATE - 1939
11" SUBBASE: GRAVEL
SUBGRADE: SANDY CLAY
DRAINAGE: POOR

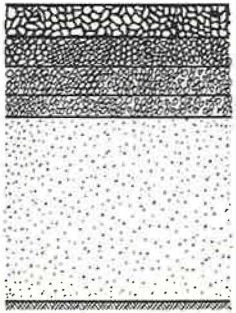
CLASS-IV FLEXIBLE
M-36, 1939 SERVICE 19 YEARS
TRAFFIC: TOTAL 2000, COMMERCIAL 385, DHV 250
SURVEY DATES: DEC. 5, 1958, FEB. 20 & MAY 6, 1959

Figure 6.



| OF SURVEY | INDEX (R.I.) IN./MILE |
|---|---|
| OUTER WHEEL PATH | |
| 9-25-58 | 33 |
| 3-7-59 | 68 |
| 5-21-59 | 36 |
| 10-2-59 | 43 |
| 11-24-59 | 34 |
| 3-8-60 | 36 |
| 9-2-60 | 41 |
| 3-21-61 | 47 |
| 6-21-61 | 45 |
| 9-15-61 | 36 |
| 10-5-61 | 37 |
| 12-27-61 | 41 |
| 3-13-62 | 68 |
| 4-17-62 | 42 |
| INNER WHEEL PATH | |
| 9-25-58 | 23 |
| 3-7-59 | 57 |
| 5-21-59 | 26 |
| 10-2-59 | 23 |
| 11-24-59 | 28 |
| 3-8-60 | 27 |
| 9-2-60 | 30 |
| 3-21-61 | 33 |
| 6-21-61 | 37 |
| 9-15-61 | 29 |
| 10-5-61 | 33 |
| 12-27-61 | 34 |
| 3-13-62 | 61 |
| 4-17-62 | 33 |

THE ABOVE ROUGHNESS INDICES ARE FOR THE PRESENTED SECTION, LOCATED BETWEEN 915' TO 465' SOUTH OF BERG ROAD.



4 1/2" BITUMINOUS CONCRETE
4" AGGREGATE BASE (58% CRUSHED)
4" AGGREGATE BASE (58% CRUSHED) } SPREAD IN ONE
3" SELECTED AGGREGATE SUBBASE } OPERATION

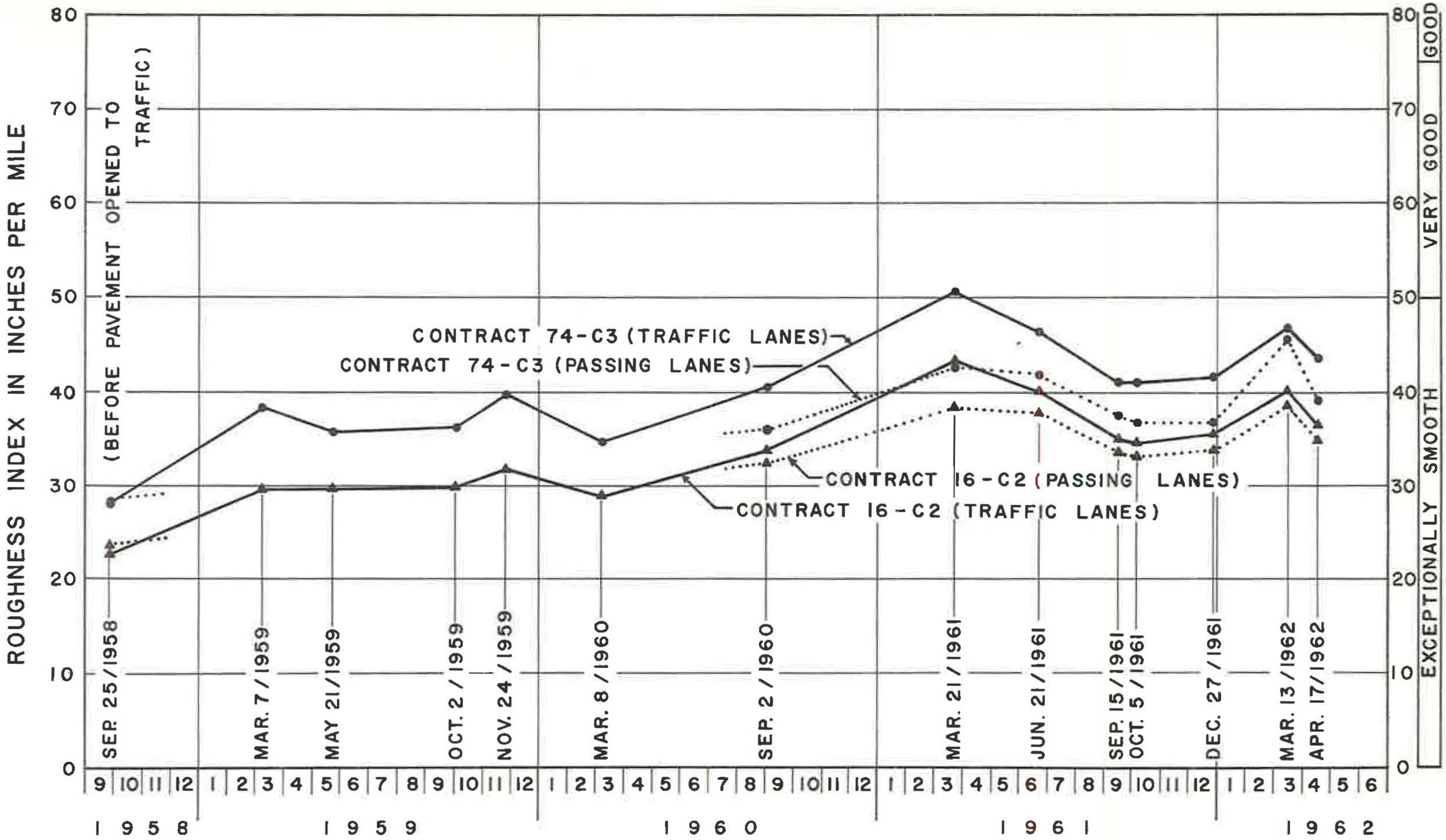
25" (MINIMUM) SAND SUBGRADE

ORIGINAL SOIL - SAUGATUCK SAND

DRAINAGE: EXCELLENT

US-31 MUSKEGON - GRAND HAVEN EXPRESSWAY
CLASS-I FLEXIBLE PAVEMENT
TRAFFIC: TOTAL 8000, COMMERCIAL 1250, DHV 920
PROJECT BM 61074-C3RN, 1958
NORTHBOUND TRAFFIC LANE

Figure 7.



CUMULATIVE CHANGES IN ROUGHNESS

US-31 MUSKEGON - GRAND HAVEN EXPRESSWAY

CLASS-I FLEXIBLE PAVEMENT

Figure 8.

The discussion of the evaluation of pavement performance as related to design may be concluded by summarizing some of the major findings on design correlation during the five-year study.

1. Michigan's current design standards for rigid pavements carrying present legal axle loads are adequate for all-season service without load restriction. In thousands of miles of pavement profile surveys of concrete pavements which by design or natural conditions meet these standards, there has been no significant evidence of loss in serviceability over periods up to 30 yr due to unlimited repetition of legal axle loads. See Figures 3 and 4 with data from the traffic and passing lanes of 244 contracts over 1,275 miles of Class 2 concrete pavement.
2. On the other hand, as shown in Figure 5, concrete pavements that have been designed and built to these standards suffer a cumulative increase in roughness of 4 to 5 in. per mile per year due to climatic and other environmental factors. Chief among these deteriorating influences are the temporary pavement displacements caused by frost action and temperature differentials. Frost displacement appears to originate in the freezing of moisture which accumulates in the subgrade and granular bases and subbases immediately beneath the pavement surface. Temporary displacements, which reach a maximum in late winter, largely disappear in the summer but leave a residual roughness which is the primary source of the cumulative loss in riding quality (5). (See Fig. 6).
3. Flexible pavements with bituminous surfaces built to equivalent all-season standards for present legal axle loads show comparable performance characteristics and evidence of cumulative changes of about the same order of magnitude. The mechanics of flexible pavement are such that cumulative loss of riding quality is not produced by the same type of residual roughness as in rigid pavement; but, on the other hand, there is some evidence of measurable differentials in roughness due to traffic. These considerations and results from short-time studies are inconclusive, although they give some promise that the loss in riding quality may proceed at a lesser rate than in rigid pavements. However, sufficient data over longer periods of service and comparable conditions are still to be accumulated to supplement the present study before these important questions can be answered (4). (See Figs. 7 and 8).

## Construction Practice and Pavement Performance

It has been stated that pavement performance surveys have shown that current design standards provide adequate load-supporting capacity. However, these same surveys show that in terms of potential riding quality, the benefits of adequate design are not being fully realized. Involved in this problem are plans and specifications and construction control that fail to achieve the maximum potential performance from well-designed pavements. This appears to fall largely in the field of construction practices and, therefore, is being discussed under that heading. The accumulation of a large volume of pavement profile data has brought to light, or perhaps emphasized by supplying the figures, several deficiencies in construction practice.

Granting that the end product in building a pavement is riding quality, then current specifications and inspection procedures fail to conserve or protect a considerable percentage of a pavement's potential life. Built-in roughness has become a common term only since pavement condition surveys have included accurately recorded profiles and the RI associatied with them. One of the first observations that was somewhat surprising to those unaware of the problem was the sharp contrast between the RI of bridge decks and bridge approaches and that of the adjacent roadway pavements finished with conventional paving equipment. Representative data from departmental and supplementary reports submitted on bridge decks and approaches show RI ranging from about 100 to 300, averaging around 200 in. per mile. In terms of the tentative rating of riding quality, the average performance of bridge decks would be described as very poor to extremely rough. Bridge approaches fall in about the same classification.

Another observation on built-in roughness is the almost universal characteristic of greater roughness in the outside wheel path or the edge of the pavement. This has been taken to indicate that irregularities in form setting were more completely reproduced close to the forms and damped out, to some degree, in the center of the concrete slab.

Turning next to hand-finishing of paving, which occurs in special cases where machine finishing is impossible or has been eliminated by special permission, the results are comparable to those obtained on bridge decks. Supplementary reports were submitted that dealt with the roughness of hand-finished pavement on the ramps of the grade separation at the intersection of M-21 and I-96 near Grand Rapids. The roughness on the first ramp varied from 167 to 191 in. per mile, which would be rated from poor to very poor. The second ramp showed RI varying from 145 to 154, falling on the borderline between acceptable and poor, but certainly not to be considered as high-quality work.

Occasionally some unusual conditions come to light as pavement profiles are being analyzed that may be related to construction methods, as illustrated by the peculiar built-in roughness shown in Figure 2 and discussed previously.

In presenting examples where construction practice has resulted in abnormally high built-in roughness, it would distort the picture to ignore the equally numerous examples where high-grade workmanship has produced superior riding quality. The fact that there are such examples is particularly significant because it demonstrates that it is within the range of common practice in pavement construction to produce such superior results. There is, then, all the more reason why poor workmanship and inferior riding quality need not be accepted.

Several examples of superior riding quality in both concrete and asphalt pavements may be cited. In Figure 5, a group of three concrete pavements built with RI of 50 in. or less per mile are shown; also shown are five other projects which, allowing for normal increase in roughness, would have had built-in roughness of less than 50 in. per mile. It is significant that five of these eight projects were built by two contractors who had established reputations for doing high-quality work (5). Other illuminating examples were also cited in the same report in the discussion of quality of workmanship.

## Application of Pavement Profile Data to Maintenance

Data from condition surveys of existing roads are of direct value in several phases of maintenance, with particular reference to the pavement structure. The rate of change in both roughness and structural continuity, when compared with normal cumulative changes, may reflect unfavorable physical conditions or weakness in design and construction that may be possible to correct. Cracking in concrete pavements due to environmental factors or load repetition, or to the combination of both, is a natural development; hence, joint and crack maintenance is accepted as normal and considered a routine operation in the early stages of pavement life. In older pavements, or in those for one reason or another subject to excessive cracking, filling of joints and cracks may become ineffective or prohibitive. Such conditions may be the signal for resurfacing or early reconstruction, beyond the scope of maintenance.

In bituminous pavements, both roughness and loss of structural continuity have significance comparable to those in rigid concrete pavements, but the evidence of structural deterioration is not as easy to evaluate in quantitative terms. Identification and classification of cracking, patching, and other types of surface deterioration in bituminous pavements have been worked out by technical committees of the Highway Research Board and also in connection with the AASHO Road Test. The final reports from that test are perhaps the most readily available and the most authoritative for present use. Consequently, they will be considered in some detail.

In the AASHO Road Test, the RI and continuity ratio used in the Michigan pavement performance surveys are combined in a single numerical index, defined as the present serviceability index, PSI. The Michigan RI and the cracking and patching as a measure of structural continuity in a flexible pavement have been translated into terms of the PSI.

The first step in this procedure is illustrated in a previous report in which the

Michigan RI was converted into a function of the AASHO slope variance, $\sqrt{SV}$, by a theoretical equation developed by Irick (4, Fig. 20). Conversion of comparable data from a number of different projects is shown in Figure 20 as a representative of the general correlation. Figure 21 of the same paper shows, on a semilogarithmic plot, the relationship between the PSI and the Michigan RI derived from the rating of 49 rigid pavements by a panel of observers selected to extend AASHO Road Test results to existing pavements. To test the validity of this relationship, comparative values of both measures of serviceability or performance have been plotted from six flexible and six rigid pavements in Michigan.

The preceding discussion of quantitative measures of pavement performance has two objectives. The first was to show that data from the Michigan Pavement Performance Study can be readily translated into terms of the PSI and, conversely, that useful results from that test could be put into practice in Michigan. The second objective was to apply the pavement performance criteria to maintenance and point out relationships of important practical significance.

Directing attention now to the second objective, it seems particularly important to take note of the fact that deterioration of the pavement surface, reflecting loss in structural integrity, is of primary importance as an independent guide to timely maintenance and should not be buried by the statistical combination involved in reducing pavement performance to a single numerical coefficient such as the PSI. Recognition of this fact has entered into some of the most recent discussion of this subject and it seems reasonable to suppose that pavement performance criteria may be adjusted accordingly.

As a first example of the use of pavement condition data from field surveys as a guide to maintenance, reference is made to a previous paper which is devoted largely to describing maintenance of the airfield pavement at Willow Run (6). Maintenance of the airfield paving was a basic responsibility assumed by the University of Michigan when the University took title to the field in 1946. Although the deed stated "... that the entire landing area ... shall be maintained at all times in good and serviceable condition ...," no standards or procedures were prescribed for judging what would be considered "good and serviceable condition."

This paper outlines the periodic surveys and procedures developed for maintaining a continuous record of pavement condition. Prior to resurfacing, structural continuity, as measured by pavement cracking in terms of the continuity ratio, was the basic measure of pavement condition. Pavement roughness was not a serious problem in the airfield pavement and was not recorded during this period. Joint and crack filling and occasional slab replacement constituted the major part of the maintenance program, and the pavement was never allowed to reach a state of disrepair. As the cracking pattern became more advanced, this type of maintenance became prohibitive and bituminous resurfacing was adopted on an annual incremental program.

After resurfacing, and with the availability of equipment to record pavement profiles and RI, the measure of pavement condition was shifted to cumulative change in roughness, supplemented by visual surveys of reflected cracking. Resealing of the bituminous surfaces before reflected cracking reached an advanced stage was the adopted practice, making timely maintenance the keynote of the program.

From the standpoint of the Michigan study and accumulating experience, it appears desirable to retain both RI and the continuity ratio or its equivalent in evaluating pavement performance, with particular reference to pavement maintenance. Several other examples may be cited which indicate that needed maintenance may frequently be reflected in structural deterioration of the surface well in advance of loss in riding quality. In this connection, it may be noted that fairly substantial amounts of cracking, patching, and rutting have an almost negligible effect in the computation of the PSI (4).

## Value of Pavement Performance Data to Operations

In the introductory discussion of the utilization of pavement profile data, the operation of the state highway system as a public facility was set forth as one of the four major functions of a state highway department. Although this may be recognized by highway engineers and administrators, it does not appear to have been given sufficient emphasis as a separate phase of highway responsibility to gain it the public attention its importance deserves. Pavement performance and pavement profile data have to do specifically with the pavement surface itself, the sole purpose of which is to provide superior riding quality for the comfort, convenience, and economic benefit of the highway user.

The Michigan Pavement Performance Study as organized and operated during the five-year period covered by this review provides an excellent example of the value of accurate pavement evaluation in the operation of the highway network to obtain the maximum economic benefit as a statewide transportation facility. One of the major objectives of the sponsors of this project was to provide all-season operation for full legal axle loads and to demonstrate the practicability of such operation by carefully controlled observations of pavement performance.

The first step in this program was the selection of a network of highways on which the spring load limitations could safely be eliminated, and then to expand that network as rapidly as possible. Since 1940, Michigan's design standards for trunkline construction have been gaged to provide all-year service for legal axle loads, without spring load limitation. Consequently, by 1958, a substantial mileage of such roads had been built. The first pavement evaluation, of January 1, 1958 (3, Fig. 1) was prepared as a statewide evaluation of the trunkline system from the standpoint of adequacy to carry legal axle loads without restriction. It included those roads on natural granular subgrades and with natural conditions making them adequate for year-round service (Class 1), and those roads which had been improved with drainage and granular subbases to compensate for seasonal loss of strength (Class 2).

The first pavement evaluation, in 1958, provided an integrated inventory of adequate roads which classified approximately 55 percent of the state trunkline system as adequate for legal axle loads at all times. Based on this evaluation, the first so-called "frost-free" network was established and public notice given of the raising of spring load restrictions on this network as of January 1, 1958. Including additions made as the result of special studies, the unrestricted network during the 1958 "spring break-up" consisted of some 4,545 miles, or about 50 percent of the state trunkline mileage. Judged in terms of public benefit, it was estimated that the cost of spring load restrictions to the state's industry and agriculture was some $20,000,000 per year, of which a substantial part has been saved during the spring season each year since 1958, without significant damage to the roads.

The second phase of the pavement evaluation was the expansion of the unrestricted network as the result of new construction, betterment, and reclassification. The pavement profile surveys entered directly into the reclassification and provided the supporting data to demonstrate that Michigan design standards did provide roads that would not be damaged by legal axle loads under year-round operation. Under this controlled operation of the state trunkline system, the unrestricted mileage has been progressively increased as indicated in Table 3.

TABLE 3

ALL-SEASON TRUNKLINE HIGHWAYS

| Date | Length | | Reference |
|---|---|---|---|
| | Mi | % | |
| 1 Jan. 58 | 4,545 | 49 | 3 (Fig. 2) |
| 1 Jan. 59 | 5,519 | 59 | Files only |
| 1 Jan. 60 | 5,985 | 64 | 7 (Fig. 3) |
| 1 Jan. 61 | 6,344 | 68 | Files only |
| 1 Jan. 62 | 7,031 | 76 | Files only |
| 1 Jan. 63 | 7,455 | 81 | Files only |

Based on the statewide pavement evaluation, two maps are prepared and issued annually, particularly for the guidance of commercial transportation. These maps are the "All Season Trunkline Highways" and the "Truck Operators' Map." The expansion of the "All Season Trunkline Highways" is graphically illustrated by the annual maps that are issued, which are given in Table 3 with references and the consistently increasing mileage in the unrestricted classification.

The map of "All Season Trunkline Highways" designates the network over which full legal axle loads may be operated at all times. The "Truck Operators' Map" shows a network of highways calculated to provide continuous routes leading to any destination in the state. Not all of these routes are unrestricted in the spring of the year, thus the operators must use the "All Season" map to check loadings.

The "Truck Operators' Map" also shows "Special Tandem Routes" on which a maximum load of 32,000 lb on one set of tandem axles or 16,000 lb per axle is permitted. This loading applies when load restrictions are not in force, including the "All Season" highways at all times. When restrictions are in force, all tandem axles are limited to 26,000 lb or 13,000 lb on each axle.

The publication in January of each year of these two maps represents a permit to truck operators and all other highway users for unrestricted use of the designated routes under the authority of the Michigan State Highway Department. They represent the ultimate result of pavement evaluation of state trunklines in the operation of the state highway system as a transportation facility. What this means in terms of savings to state industry and agriculture has been cited here to illustrate the importance of well-informed operation of a state highway system and the value of pavement performance data in the support of that type of operation.

## CONCLUSION

Termination on December 31, 1962, of the last of a series of annual contracts with the Michigan Highway Planning Survey marked the end of the second five-year program of the Michigan Pavement Performance Study. After completion of field surveys of existing pavement in service, providing profiles of 10,000 lane miles of pavement, the Department's concept of a highway pavement has undergone rather substantial change. Some ten years of concentrated study of how pavements react in the field brings realization that pavement performance cannot be measured in terms of static equilibrium of a beam resting on an elastic foundation subjected to static loads with strength controlled by a direct proportionality between load, deflection, and thickness.

On the contrary, an objective viewpoint sees the pavement slab expanding and contracting with changes in temperature; curling and warping with temperature differentials between the top and bottom; growing and shrinking with moisture changes; and distorted by frost displacement, only partially relieved by thawing of the frozen substructure. All of these effects superimposed on stresses due to load make the life of a pavement an everchanging cycle of dynamic effects, which seems to require a new and more realistic concept of pavement performance and poses another set of questions that was new ten years ago. How does an adequate pavement react to these changing conditions? How long does it retain an acceptable riding quality? What is normal behavior, in terms of which abnormal behavior can be identified and defined?

It is hoped that the Michigan Pavement Performance Study has provided some answers to these questions, in terms of which the responsible factors that control pavement performance can be isolated and logical relations between cause and effect may be determined.

In conclusion, it is even more difficult but necessary to restate in concise form the principal conclusions drawn from the study, as follows:

1. Pavement performance has been evaluated in terms of two basic measures of the physical condition of the pavement defined as RI and the continuity ratio. Both of these quantities are required to evaluate the pavement condition at any given time. The RI, in conjunction with the recorded pavement profile, measures the riding quality or serviceability of the pavement; the pavement profile supplies an insight into the source of the progressive changes which have taken place during the life of the pavement. The continuity ratio expresses in quantitative terms the structural continuity of the slab and enables one to anticipate its ability to continue in service without excessive deterioration due to load application. It indicates the need for maintenance or improvements to forestall excessive loss of riding quality.
2. The extensive mileage of recorded pavement profile and supplementary data constitute an accurate and realistic pavement inventory, the value of which has been only partially utilized to date. Its full value to design and construction practice and in the

operation of the state highway system as a transportation facility can be realized only by its continued use and by keeping it up-to-date and growing as the highway system grows.

3. Michigan's current design standards for rigid, portland cement concrete pavements are adequate for legal axle loads, providing all-season service without load restriction. This conclusion is supported by the fact that pavement profile surveys of thousands of miles of such pavement on natural or modified subgrades meeting those standards showed no significant loss of riding quality due to unlimited load application over service periods up to 30 yr.

4. Somewhat in contrast, these surveys provided evidence that concrete pavements deteriorate due to climatic and other environmental influence, losing riding quality in terms of roughness at an average rate of 4 to 5 in. per mile per year. Assuming RI of 200 to 250 in. per mile as the limit of acceptable riding quality, an initial RI of 50 would set the useful pavement life at 30 to 40 yr until resurfacing or reconstruction would be required.

5. Flexible pavements with bituminous surfaces built to equivalent all-season standards show comparable performance. Such flexible pavements also suffer a cumulative loss of riding quality of comparable magnitude even though the mechanics of flexible pavement produce a quite different relation between cause and effect. Conclusions concerning the performance of flexible pavements must be qualified in the Michigan study by the fact that present profile data are limited both in mileage and periods of service.

6. With full realization that pavement life and serviceability are controlled more by environmental effects than by load application, pavement design practice may be pointed in the future more directly toward compensating for these natural destructive influences. The range of pavement performance covered by the present profile surveys is sufficiently large and the contrast between the best and poorest performance such as to indicate that emphasis in design on these environmental factors may produce substantial improvements.

7. Pavement profile data have produced much evidence that pavement construction practice can be improved by more attention to riding quality produced and to those questionable practices which are the primary source of poor riding quality. Initial roughness built into the pavement presently takes up too much of the range available to absorb the cumulative roughness over the years. This may be reflected directly in a reduced useful life of a pavement.

8. Pavement profile surveys and the two factors for evaluating pavement condition, the RI and the continuity ratio, provide reliable and accurate criteria for gaging serviceability and determining when and what maintenance should be provided. To perform this function effectively, profile data as a pavement inventory should be kept up-to-date and these records made readily available to those responsible for maintenance. The development of cracking, as a measure of structural continuity, and other direct evidence of structural deterioration are necessary and timely indications of needed maintenance which anticipates loss of riding quality.

9. A complete and accurate inventory of the state highway system has direct value in several ways in the operation of the highway system as a transportation facility. It provides a factual basis for eliminating unnecessary restrictions on the use of the highways, with economic benefits exceeding many times the cost of providing and maintaining that inventory. It provides the basis for extending the unrestricted network of state highways and the evidence that determines whether or not the continuation of unrestricted use is justified. In this time when pavement design is on trial all over the country, it provides realistic and incontrovertible evidence of the soundness of Michigan design standards and points the way to further improvement in carrying out these standards under varying field conditions.

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