

UNIVERSITY OF MICHIGAN

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SERVICE BEHAVIOR AS A CRITERION  
FOR PAVEMENT DESIGN

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by

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Most highway users, as laymen not familiar with the problems of highway design and construction, probably assume that highway design is a relatively accurate science regulated by well established physical laws which provide competent engineers with precise methods of pavement design. An uninitiated public would probably find it hard to understand if they were told that pavement design and construction at this late date in the history of highway transportation is still an unsolved problem with sharply contrasting viewpoints which, for some strange reason, are still unresolved after hundreds of years of highway building. Many have asked the question, the answer to which is still a subject of vigorous debate. How do you know when a pavement is structurally adequate?

To answer this question requires first the answers to a number of corollary questions. How thick must a pavement be to carry a specified axle load? Should a pavement be rigid to bridge over a weak subgrade, designed as an elastic beam on an elastic support (Westergaard theory)? Or, should it be flexible in order to develop full subgrade support, relying on the time-honored statement of MacAdam that it is the subgrade which really carries the pavement and the loads also. How is the subgrade support put in a design formula? How about drainage, frost action, and soil type? These are the uncontrolled factors of environment -- how do they affect service behavior and how are they put into a formula for pavement design? What about volume and character of traffic?

Michigan believes that the answers to these questions can be found in the behavior of roads that have been subjected to these conditions over many years. Pavement design in Michigan has been developed over a period of more than 35 years, using pavement performance studies and pavement condition surveys to correlate soil type and climatic environment with service behavior. With the coming of increased traffic and heavier loads, there has been some modification of the pavement structure including nominal increases in thickness; but, Michigan continues to emphasize the dominant role of climatic environment and soil types in pavement design. Briefly stated, actual field experience has indicated to Michigan highway designers that the most effective and the most economical method of providing for increased axle loads and increased load repetition of modern traffic is to supply the required load carrying capacity in the foundation of the pavement. This has been done by more accurate evaluation of soil conditions, drainage, and climatic influence; the utilization of local soil materials of favorable characteristics; and, the selection of pavement structures which more fully utilize available subgrade support.

It is recognized that many of these factors are difficult to measure and are not subject to control. Nevertheless, it is this same group of uncontrolled variables for which successful pavement design must provide. Pavement performance studies in Michigan over the past few years have been formulated

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on the proposition that the integrated result of these uncontrolled variables on pavement performance can be measured by changes in the pavement profile (roughness index) and structural continuity (cracking pattern). These two factors in pavement performance are the quantitative counterparts of riding quality and durability, which are the two most important attributes of a highway pavement.

This may appear to be only stating the obvious, as highway builders from the very first have focused their attention on pavement roughness and cracking as direct evidence of its adequacy or, rather, its inadequacy. What has been lacking, however, is a practical yet sufficiently accurate method of measuring these indicators of pavement capacity and durability in quantitative terms. As once stated by Lord Kelvin, "When you can measure that of which you speak, and express it in numbers, you know something about it." These accurate, quantitative measures of pavement performance are also necessary in order to identify physical changes in the pavement associated with the various physical conditions which cause these changes. Corollary to this is the fairly obvious fact that such measurements can only be made under actual service conditions on pavements subjected to real traffic in the natural environment in which they must serve over a period of years that may mark the useful life of each pavement.

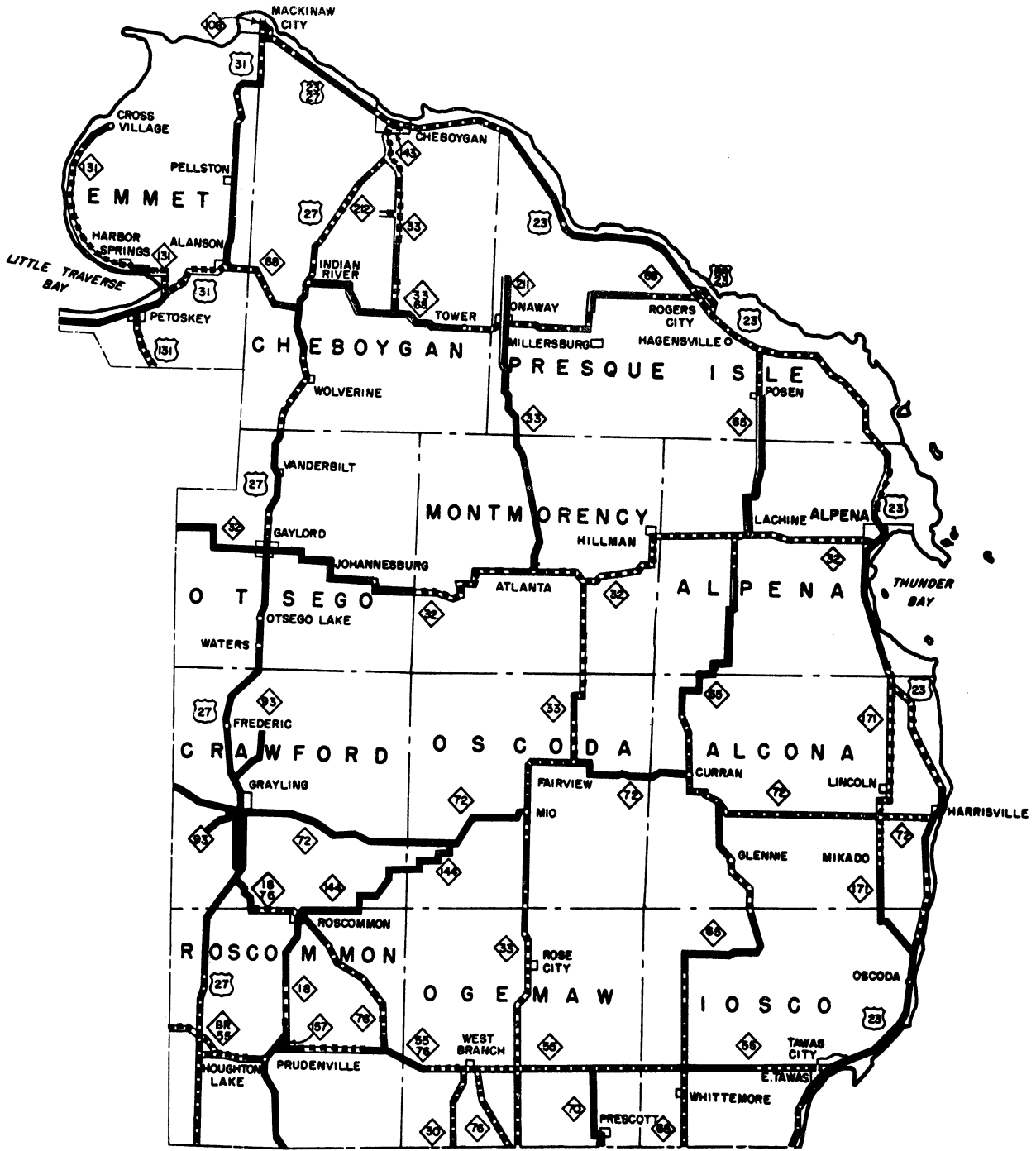
Pavement performance studies which have been in progress in Michigan since 1952 have been predicated on the belief that an accurate field survey of existing pavements followed by intelligent analysis of the results would provide the most effective method of answering some of the unsolved problems of pavement design. This viewpoint has recently received some encouraging recognition. In a statement on urgently needed research in connection with rigid pavements, the Committee on Rigid Pavement Design of the Highway Research Board has proposed a priority project on the "Investigation of Existing Pavements". In outlining the problem, this statement lists a number of significant changes in design of rigid pavements in recent years, and concludes with 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 many 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."

The first attempt to measure pavement performance quantitatively in terms of pavement roughness and structural continuity by the roughness index (RI) and a continuity ratio (CR), as defined in this paper, was in 1952. During the period from 1952 to 1956, the University of Michigan, the Michigan State Highway Department, and the Wire Reinforcement Institute collaborated in a study to measure the effect of steel reinforcement on concrete pavements under actual service conditions. Pavement performance surveys were conducted on selected projects in southern Michigan which had been in service for periods varying from 10 to 25 years. Each project included comparable reinforced and unreinforced sections which were observed for approximately 5 years. The data that were obtained from the pavement condition survey of these selected projects showed that pavements with steel reinforcement were measurably smoother and the cracking was measurably less than in the unreinforced pavements.

These studies gave positive evidence of the value of steel reinforcement in pavement design as a means of maintaining structural continuity and





### DISTRICT NO. 4

#### ROAD CLASSIFICATION FOR LEGAL AXLE LOADS





-  No Seasonal Restriction - Pavement and Subgrade Adequate for Year-around Service.
-  No Seasonal Restriction - Pavement Designs Which Compensate for Seasonal Loss of Strength.
-  Spring Load Restriction Required - Pavement Designs Which Do Not Compensate for Seasonal Loss of Strength.
-  Spring Load Restriction Required - Pavement Design Inadequate for Legal Axle Loads at all Times.

FIGURE-2

preserving riding quality. However, of more importance in the present discussion, was the demonstration that the behavior of existing pavements under actual service conditions could be measured quantitatively in terms of pavement roughness and structural continuity. The results obtained on this first cooperative research program encouraged the later studies in which the problems of pavement design were attacked on a wider front. This program included several phases. In the first place, the Michigan State Highway Department established in 1958, for the first time, an "All Season" network of selected state trunklines on which the Spring load restrictions were to be lifted. In the second place, the Department joined with the University of Michigan in a cooperative research program involving a continuing pavement performance survey in which quantitative measures of pavement roughness and structural continuity on a large scale were to be accumulated.

The results of these surveys were then used to confirm pavement classifications and inclusion of selected projects in the "Frost Free" network, to provide a basis for reclassification of other roads, and for assessing the deficiencies in those roads not capable of carrying legal axle loads at all times. This project was sponsored by three trucking association groups which included the Michigan Trucking Association; the American Trucking Associations, Inc.; and the Motor Truck Division of the Automobile Manufacturers Association. Equipment was designed and built and procedures were developed for pavement performance surveys and this project ran for approximately two years, until July, 1959. Approximately 2000 miles of pavement profile were obtained and the results have been analyzed and reported in part in published form.<sup>1,2</sup> It is from these data that examples have been selected for the present discussion to illustrate the value of a study of existing pavements as a guide to pavement design.

To fully appreciate the examples that will be given, it is necessary to review briefly the development of pavement design in Michigan over the past 35 years to serve as a background for present practice and procedures. During this period, the Department has accumulated a tremendous volume of information on pavement performance, maintenance, and correlation of behavior with soil conditions, drainage, and other environmental factors. The first step in the program of statewide pavement performance studies was to assemble all of the presently available information into a single statewide inventory of pavement adequacy. Four classifications were made with respect to the ability to support legal axle loads. These classifications are subsequently referred to as Class 1, 2, 3, and 4 and are shown on both Figs. 1 and 2 in the terms by which they are defined. Fig. 1 is a state map showing the first statewide pavement classification of January 1, 1958. Fig. 2 is a typical district map, indicating the classification of state trunkline roads within the several counties and made to a little larger scale, making it easier to identify the four road classifications which are defined as follows:

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- 1 "Pavement Profile Surveys to Correlate Michigan Design Practice with Service Behavior", Proceedings, Highway Research Board, Vol. XXXVIII, pp. 149-177, 1959.
  - 2 "Legal Weight Limitations on Motor Vehicles", Presented at the 44th Annual Michigan Highway Conference, Grand Rapids, Michigan, March 17-19, 1959.

#### Class 1 (Solid black)

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 (Dot-dash black)

No seasonal restrictions. Pavement designs which compensate for seasonal loss of strength, as represented by 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 (Dot-dash red)

Spring load restrictions required. Pavement designs which 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 (Solid red)

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.

In this first pavement evaluation, covering some 9300 miles of the state trunkline system, approximately 55% of the pavements were rated as adequate for year-round service, leaving 45% as inadequate. The first practical result of significance from this program was the raising of Spring load restrictions on the selected network of state trunklines that were opened for full legal axle loads in the Spring of 1958. Some 4600 miles of highway, or approximately 50% of the state trunkline system, were included in the first year's "Frost Free" network. Due to new construction, betterments, and reclassification of pavements, the "All Season" network was increased in 1959 to 5784 miles, or a little more than 60% of the state system.

Fig. 3 is the map of the "All Season Trunkline Highways for 1960" showing a network of unrestricted roads amounting to 6240 miles which is two thirds of the total mileage in the state trunkline system. When this policy was inaugurated three years ago, the Michigan State Highway Department made a survey of state industries from which it was estimated that the Spring load restrictions cost industry in the state approximately \$20,000,000 each year; and, as recently pointed out by the State Highway Commissioner, the expanded "All Season" system has saved Michigan's industries, agriculture, and consumers many millions of dollars annually.



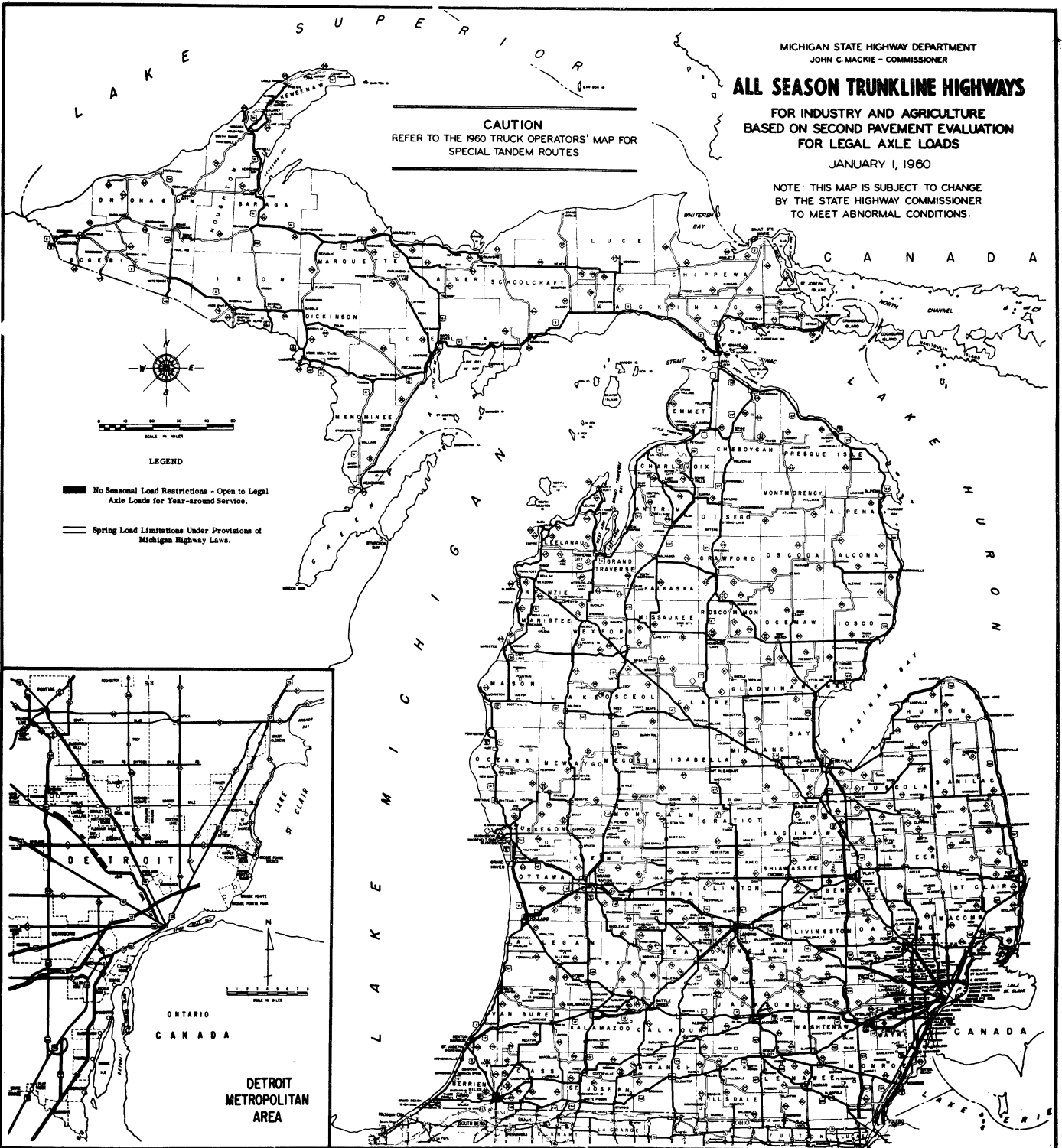


FIGURE - 3



**FIGURE-4 MICHIGAN TRUCK-MOUNTED PROFILOMETER**

## PAVEMENT PROFILE SURVEYS

The essential piece of equipment for measuring and recording pavement profiles is the truck mounted profilometer or profilograph shown in Fig. 4. This truck is equipped to trace and record an accurate profile in each wheel track of the pavement. Two sets of so-called "bogie wheels", located in front and in back of the truck, 30 feet apart, provide reference points on the pavement surface from which vertical displacement is measured by the recording wheel midway between these reference points. Pavement profiles are recorded on a continuous chart and may be retraced after a designated period of service to measure any progressive changes that may have taken place. The tracing and recording mechanism is connected to electronic integrators which measure the cumulative vertical displacement of the pavement in inches per mile for any selected length of pavement. This cumulative vertical displacement in inches per mile is used as a roughness index in subsequent pavement classification. The roughness is stamped on the profile chart for each quarter mile to aid in selecting critical sections which may be isolated for further investigation of possible defects in design or construction.

The University of Michigan equipment is modeled after that designed and used by the California State Highway Department; their design was made available for this program by F. N. Hveem, Materials and Research Engineer for California. In addition to recording the cumulative vertical displacement, equipment is provided for measuring and recording the location of cracks and joints to provide a measure of the structural continuity of the pavement surface. A device has also been provided to measure and record the relative elevation in both wheel tracks by what is called a "roll indicator" with a recording pen in the center of the profile chart. If progressive changes in the pavement profile are to be used to measure pavement performance, it is obvious that the profile trace at any one time and the recorded roughness index must be very accurately measured and recorded. One of the first questions which arises in this connection is, "Just what is it that the profile truck is measuring, and how accurately will it produce an actual pavement profile?" The answer to this question depends primarily on the selection of a datum or reference to which the measured vertical displacements may be referred. For the purpose of explanation, several pavement profiles taken on a test course at the Willow Run Airport have been plotted for comparison in Fig. 5.

The profile shown as a heavy line is the trace recorded by the profilometer truck. The profile shown as a thin line has been plotted from elevations taken from levels at intervals of 2.5 feet along the test course. The latter profile represents the vertical difference in elevation at the recording station at the center of the truck with respect to the average elevation of the bogie wheels at the front and the back of the truck. In other words, the reference plane for vertical displacement is represented by a straight line drawn from the center of gravity of the two sets of bogie wheels. This computed trace is considered to be most representative of the vertical displacements recorded by the profile truck, which is actually measuring deflection at the center of a floating base line 30 feet in length.

By visual inspection, there is reasonably good agreement between the recorded profile and that constructed from the level survey. There are, however, several other problems in measurement and instrumentation which are too involved to take up in the present discussion. Suffice it to say that the problem

is one of reproducing pavement profiles with sufficient accuracy to reflect significant differentials in the pavement surface and still keep the equipment itself within practicable limits. Data from successive pavement profiles which have been analyzed to date indicate that the profilometer equipment as now designed is capable of achieving this objective.

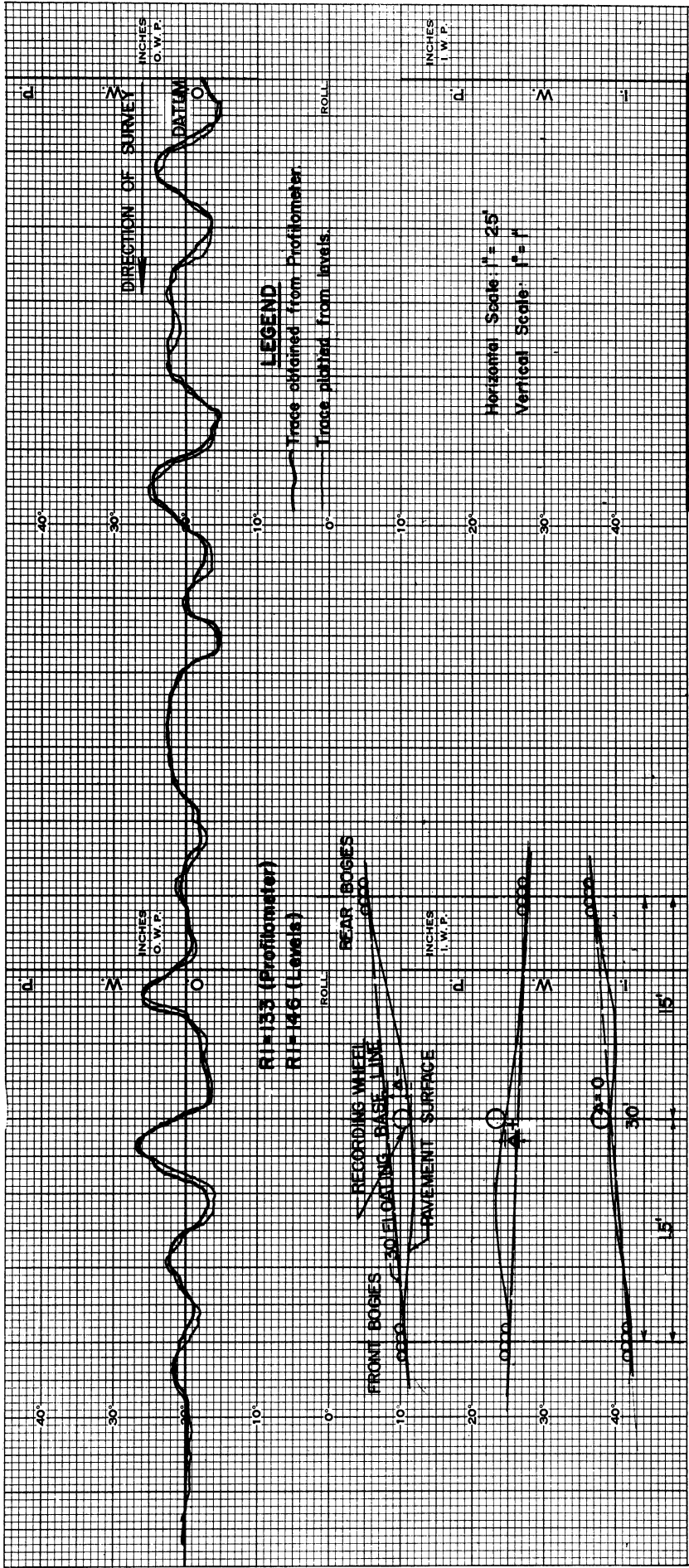
### Typical Pavement Profiles

In order to illustrate the use of pavement profiles as a means of differentiating between adequate and inadequate roads on the basis of service behavior, a number of typical pavement profiles will now be presented. In reviewing these examples, there are several things to be kept in mind as a means of correlating the data on some comparative basis. In Fig. 6 is shown a tentative roughness rating to associate with the measured roughness indexes, as representative of varying degrees of riding quality from exceptionally smooth to extremely rough. Roughness indexes in excess of 200 inches per mile are considered unacceptable, although there are many examples of such roads in service. For those familiar with the more widely used single wheel roughometer, comparative roughness indexes have been established on the basis of a relatively small number of projects where both types of equipment have been used.

Pavement profiles are presented in a series of charts of which Fig. 7 is the first. These charts follow a definite format which will be explained at the outset, with no further reference thereafter. Each chart presents 600 feet of profile in the outer and inner wheel paths of the traffic lane. The outer wheel path is generally at the top of the sheet on the right hand side of the lane, with the direction followed by the profile truck generally being to the left. Cut and fill in feet is indicated at the top of the sheet. The roughness index in inches per mile taken from the recorded profile is shown in the center of the sheet below each of the two profiles. It should be kept in mind that vertical displacements are recorded full scale (1 inch = 1 inch) while the horizontal distances are to a scale of 1 inch = 25 feet. This results in a 1:300 magnification of vertical displacements, thus exaggerating the roughness in terms of pavement grade or slope.

Pavement joints and cracks are shown along a horizontal line at the bottom of the sheet, above which the continuity ratio is given. The first figure is for the pavement as originally constructed, and the second figure, on the right, being computed for the combination of joints and cracks which develop after some period of service. In this connection, it should be noted that the continuity ratio is defined in terms of a standard slab length of 15 feet representing a continuity ratio of 1. Thus, an uncracked slab between hundred foot joints would have a continuity ratio of 6.67. From the results of previous studies it has been assumed that the structural integrity of a concrete pavement has not been impaired until the slab length has been reduced by cracking below the standard length of 15 feet.

To the right of the pavement profiles are given pertinent data on the pavement section including pavement type and thickness of the various components, subgrade classification, drainage, road classification from the standpoint of adequacy, project identification, traffic count based on the 1957 survey, and the date of the profile survey.



**FIGURE-5**  
**COMPARATIVE PAVEMENT PROFILE**  
**ON TEST COURSE - WILLOW RUN AIRPORT**

TENTATIVE  
 PAVEMENT ROUGHNESS RATING  
 VERTICAL DISPLACEMENT - INCHES PER MILE

U.S. BUREAU OF PUBLIC ROADS(1) <u>SINGLE WHEEL ROUGHOMETER</u>	RATING	U. OF M. PROFILE TRUCK(2)
LESS THAN 100	EXCEPTIONALLY SMOOTH	LESS THAN 50
100-125	VERY GOOD	50-75
125 - 150	GOOD	75-100
150 - 175	FAIR	100-125
175 - 200	ACCEPTABLE	125-150
200-225	POOR	150-175
225 - 250	VERY POOR	175-200
MORE THAN 250	EXTREMELY ROUGH	MORE THAN 200

(1) OPERATED AT 20 MILES PER HOUR.

(2) OPERATED AT 4-5 MILES PER HOUR.

FIGURE - 6

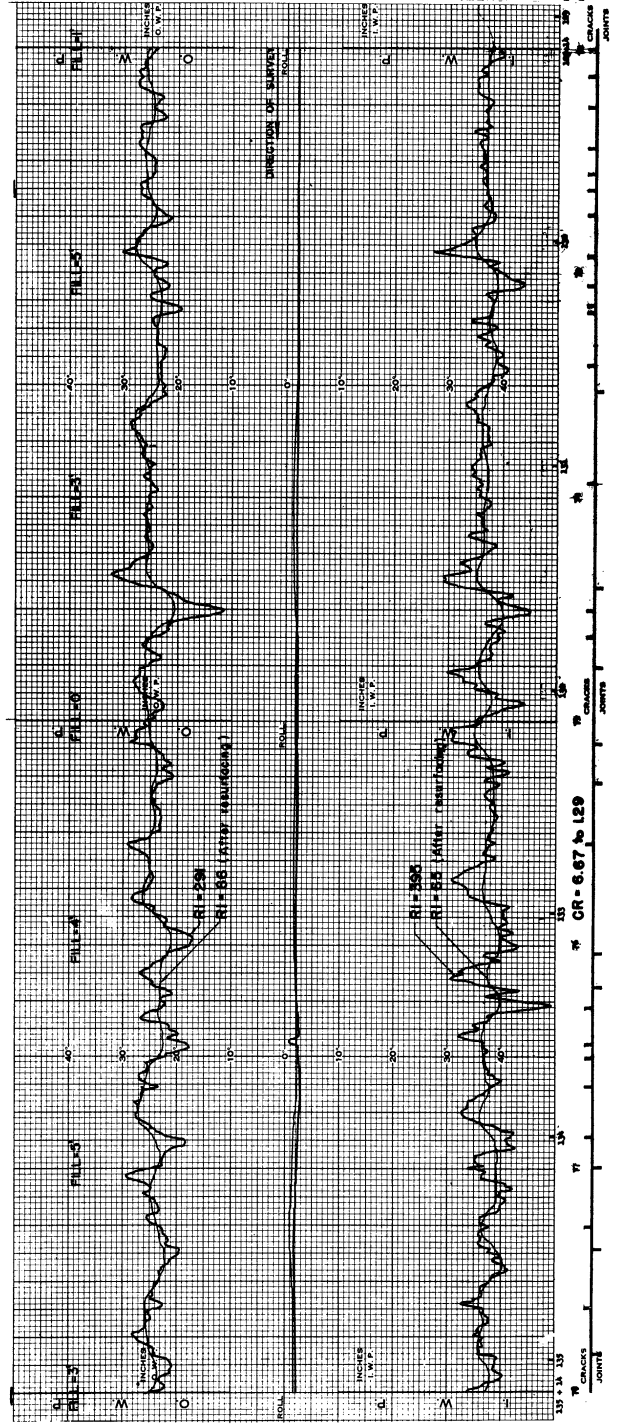
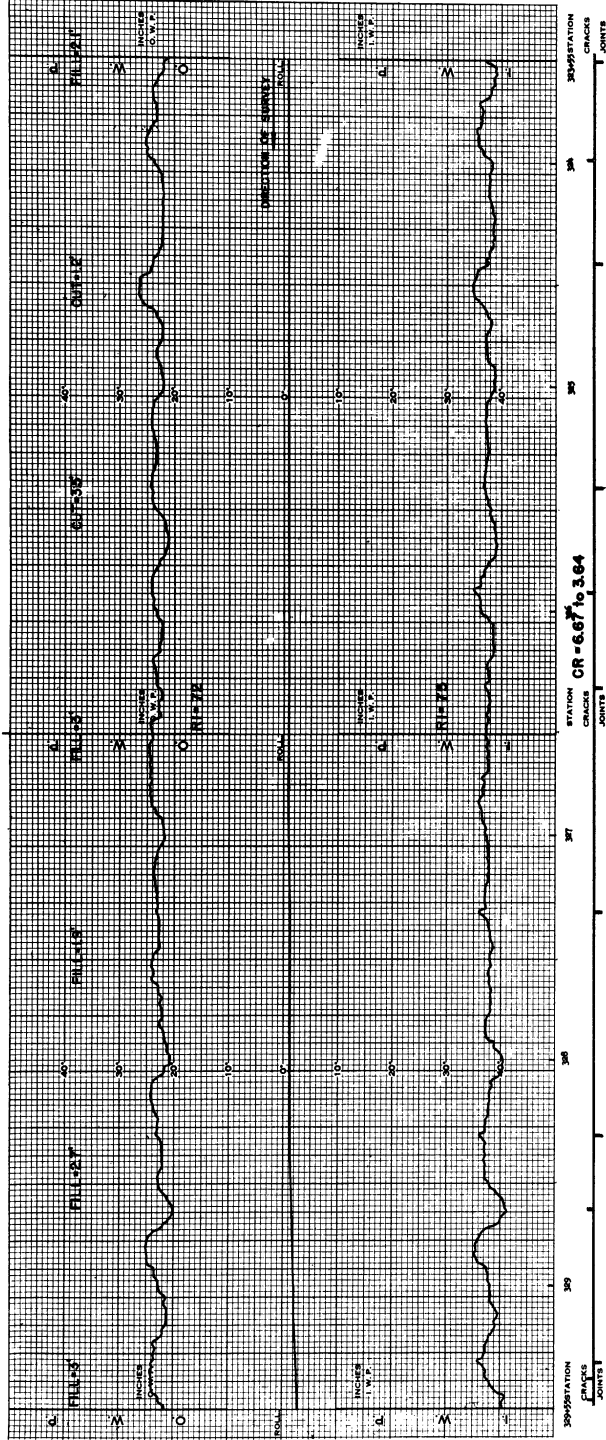
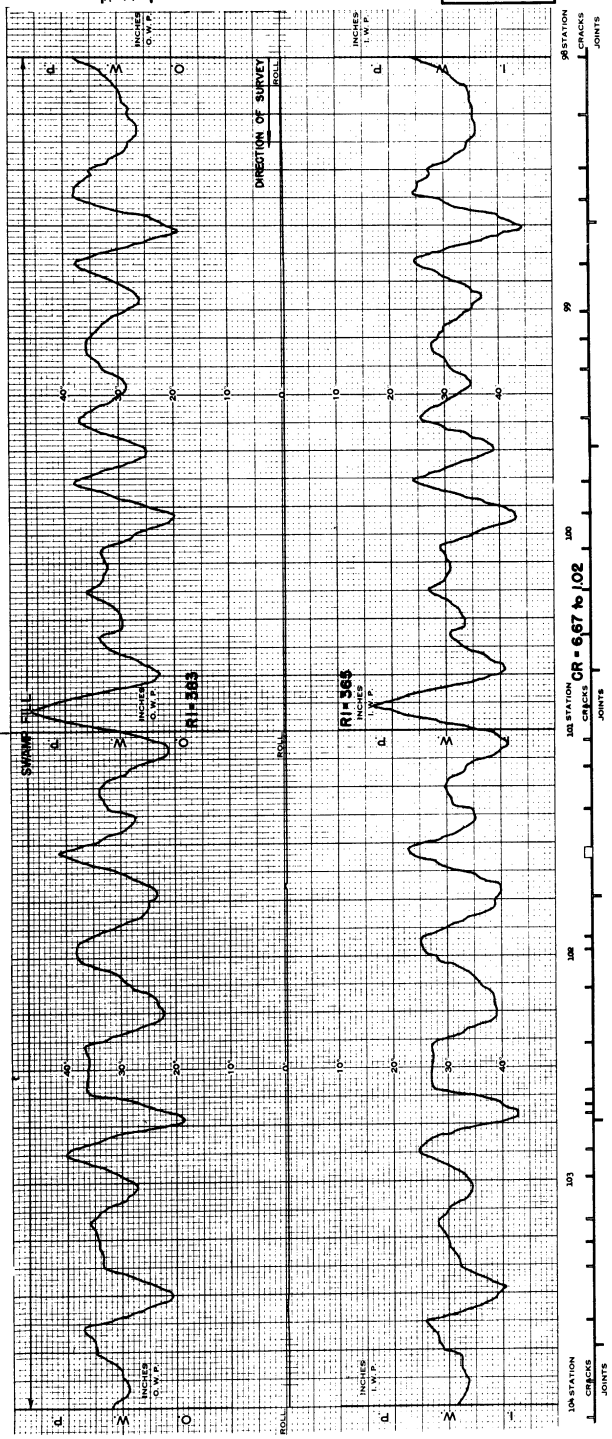


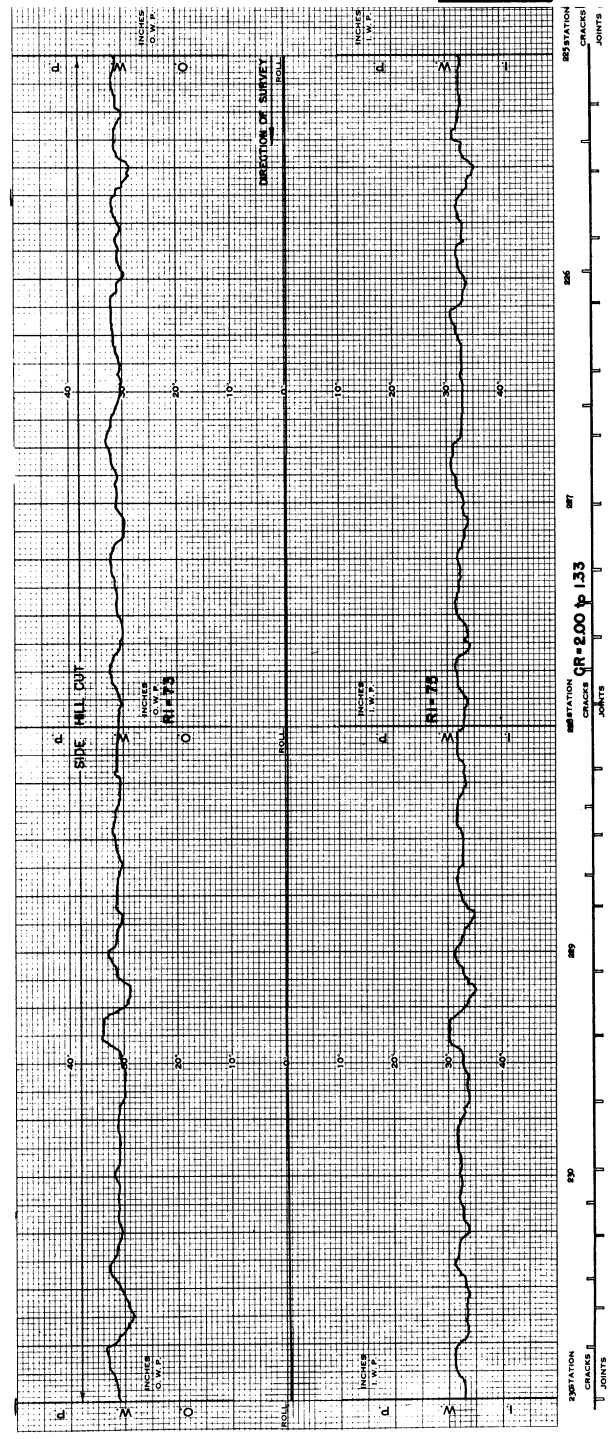
FIGURE - 7



9'-7"-9" REIN. CONCRETE-1936  
 5'-8" SUBGRADE: HEAVY SANDY LOAM

DRAINAGE: POOR

FIGURE-12 A  
 CLASS-III RIGID  
 US-41, 1936 SERVICE 22 YEARS  
 TRAFFIC: TOTAL 2000, COMMERCIAL 280-550, DHV 310  
 DATE OF SURVEY: NOV. 8, 1958



9'-7"-9" REIN. CONCRETE - 1936  
 SUBGRADE: LIGHT SANDY LOAM

DRAINAGE: GOOD

FIGURE-12 B  
 CLASS-III RIGID  
 US-41, 1936 SERVICE 22 YEARS  
 TRAFFIC: TOTAL 1600, COMMERCIAL 280, DHV 190  
 DATE OF SURVEY: NOV. 7, 1958



Class 1 and Class 4 Rigid Pavements. The first two profile charts shown in Fig. 7 are taken from one of the older, heavily traveled roads in Michigan, US-112. The pavement profiles in Fig. 7-A, with roughness indexes of 72 in the outer wheel path and 75 in the inner, would still be rated very good from the standpoint of riding quality after some 32 years of service insofar as the original concrete pavement is concerned or 10 years of service on the bituminous resurfacing laid in 1948. The traffic is 4800 vehicles per day, of which 1525 are commercial. There are relatively few cracks between the 100 foot joints, with a reduction in the continuity ratio of something less than 50% since construction in 1926.

The pavement section in Fig. 7-B, which is only a short distance from the first section with which it is compared, has been in almost continuous trouble since it was built, requiring continuous maintenance with an unusual amount of concrete patching and continual cracking of the old pavement. After having been resurfaced with bituminous concrete in 1943, it developed the rough profile shown by the heavy line, with a roughness index of 291 in the outer wheel path and 395 in the inner wheel path. It was resurfaced in 1958, with the pavement profile indicated by the finer line superimposed on the profile before resurfacing. In connection with this resurfacing, it is interesting to note the degree to which vertical displacements are ironed out and the riding quality recovered. There is a much greater reduction in the continuity ratio in Fig. 7-B, but it should be noted that these data are not completely satisfactory. In a pavement that has been resurfaced as much as this, it is difficult to locate all the cracks in the original slab as many of them do not show through the resurfacing. The extensive amount of concrete patching also has been indicated as joints, producing the irregular spacing of joints that were originally 100 feet apart.

The significant difference in these two sections of pavement lies in the subgrade type and drainage. The pavement giving very good service, in Fig. 7-A, falls within a relatively small area of glacial outwash which is predominantly sandy with fair internal drainage. The example of Class 4 pavement, in Fig. 7-B, is characterized by a subgrade soil of sandy clay loam and poor drainage, a combination which provides inadequate subgrade support for this heavily loaded pavement.

Class 3 Rigid Pavement. The two pavement sections shown in Fig. 8 provide one of the most interesting comparisons found in the pavement profiles obtained during the first year. Both sections are taken from US-41 running north out of Menominee in the Upper Peninsula, and are only a few miles apart. This road, incidentally, is known as one of the roughest riding pavements in the state and the two sections selected represent the roughest and the smoothest sections in this stretch of highway. There is a startling differential in roughness index in these two sections, with the rough section being entirely outside the rating scale while the smooth section would be rated good or very good. This contrast is the direct result of a difference in subgrade soil and drainage. The rough section is over a swamp fill following peat excavation, with backfill material being described as a heavy sandy loam. The water table is close to the surface and in this area of deep frost penetration the combination of conditions promotes severe frost action. The smooth section, on the other hand, is on a side hill cut and fill with the subgrade material being described as a light sandy loam, sufficiently granular to supply adequate internal drainage. This in combination with the side hill surface drainage has produced very good performance over a service period of 22 years. Similar differentials are shown in the changes in structural continuity, although, to some extent, the small amount of cracking in the good section is the result of the 30 foot joint spacing.

## Flexible Pavements

During the first year's survey, the attempt was made to obtain profile data on representative pavements of the various types subjected to the range of variation in soil type and traffic service. The first two examples were of rigid concrete pavements and the next two will be typical flexible or bituminous type pavements.

Class 1 and Class 4 Flexible Pavements. The two pavement sections shown in Fig. 9 are representative of high type bituminous construction which, on the basis of performance, is being given increased consideration in the state. Both are on superior type subgrades of a sand outwash with excellent drainage characteristics. In both cases, gravel bases were constructed first and subjected to traffic for a sufficient period of time to be thoroughly compacted before laying the bituminous wearing course. In terms of riding quality, both would be rated exceptionally smooth -- indicating excellent construction practice as well as completely adequate carrying capacity. It may also be pointed out that subgrade stabilization, in one case with earth fill and in the other case with stabilized gravel, was employed to assist in the thorough compaction of the rather loose incoherent sand before adding the gravel bases. Aside from the superior physical conditions involved in the construction of these two roads, the steps taken to obtain good compaction in all portions of the supporting foundation are important factors in the superior riding quality that has been produced.

One other special circumstance should be noted and that is that the pavement in the lower part of Fig. 9 was resurfaced in 1956 because, after a period of some 20 years, surface abrasion and hardening of bituminous material had produced a fragile surface which either had to be sealed or resurfaced. This, combined with the necessity for widening the road from 20 to 22 feet, led to the use of a bituminous concrete retread; but, insofar as the structural capacity of the pavement is concerned, there was no indication before resurfacing of loss in load carrying capacity resulting in increased pavement roughness.

In Fig. 10 is shown a Class 4 flexible pavement that supplies another study in contrast between two sections taken from the same road just a few miles apart. This is an old road, having been built up over a period of years by county forces and later by the State Highway Department when the road was taken over as a trunkline. The comparison is mainly of interest as a demonstration of the dominant influence of a good sand subgrade over a comparatively limited stretch as compared to a poorly drained, sandy clay subgrade. In the good section, after 19 years of service, the riding quality is still rated as good; whereas, on the weak section, there are no terms included in the rating table which would provide an adequate description. These two examples would also seem to be another illustration of the value of the pavement profilometer in differentiating between those sections which would eventually have to be rebuilt and those which would not require rebuilding, thus adding a quantitative tool to supplement good engineering judgment.

## Special Sections

Several special pavement sections have been selected to illustrate examples of pavement design and construction which are of particular interest. The top profiles in Fig. 11 show the effect of using short, 20 foot slabs of plain



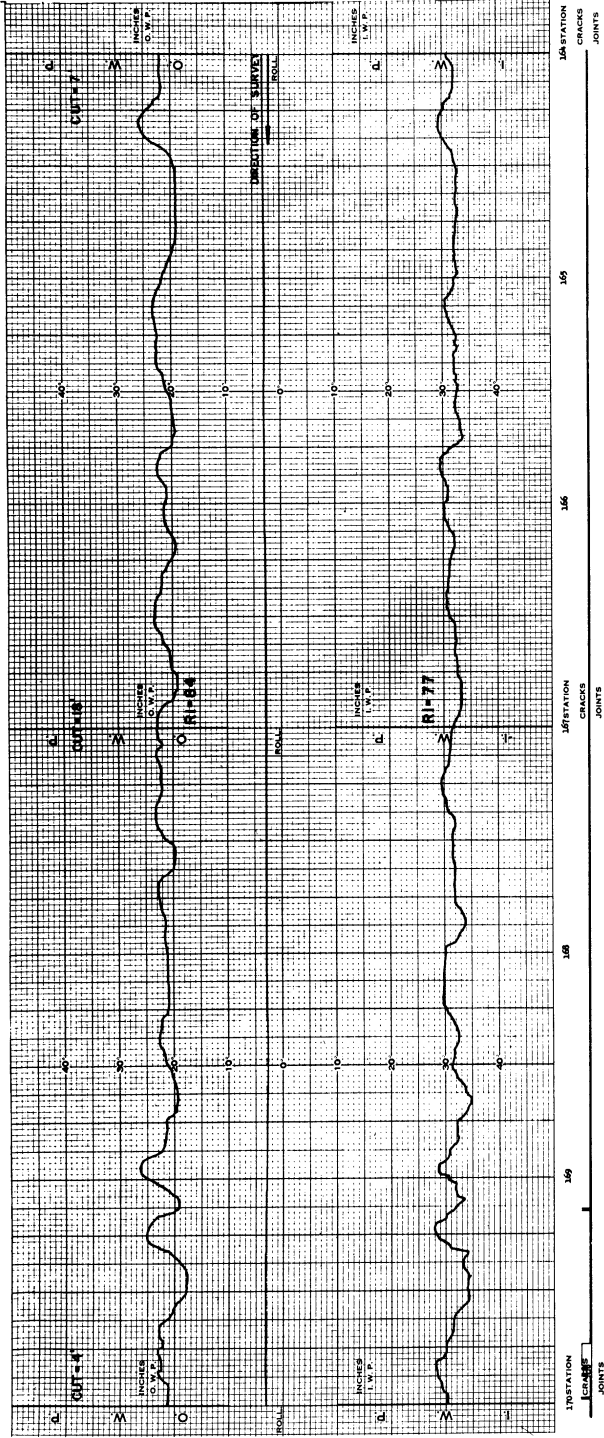


FIGURE-16 A  
 CLASS-IV FLEXIBLE  
 M-36, 1939 SERVICE 19 YEARS  
 TRAFFIC: TOTAL 2000, COMMERCIAL 385, DHV 250  
 DATE OF SURVEY: DEC. 5, 1958

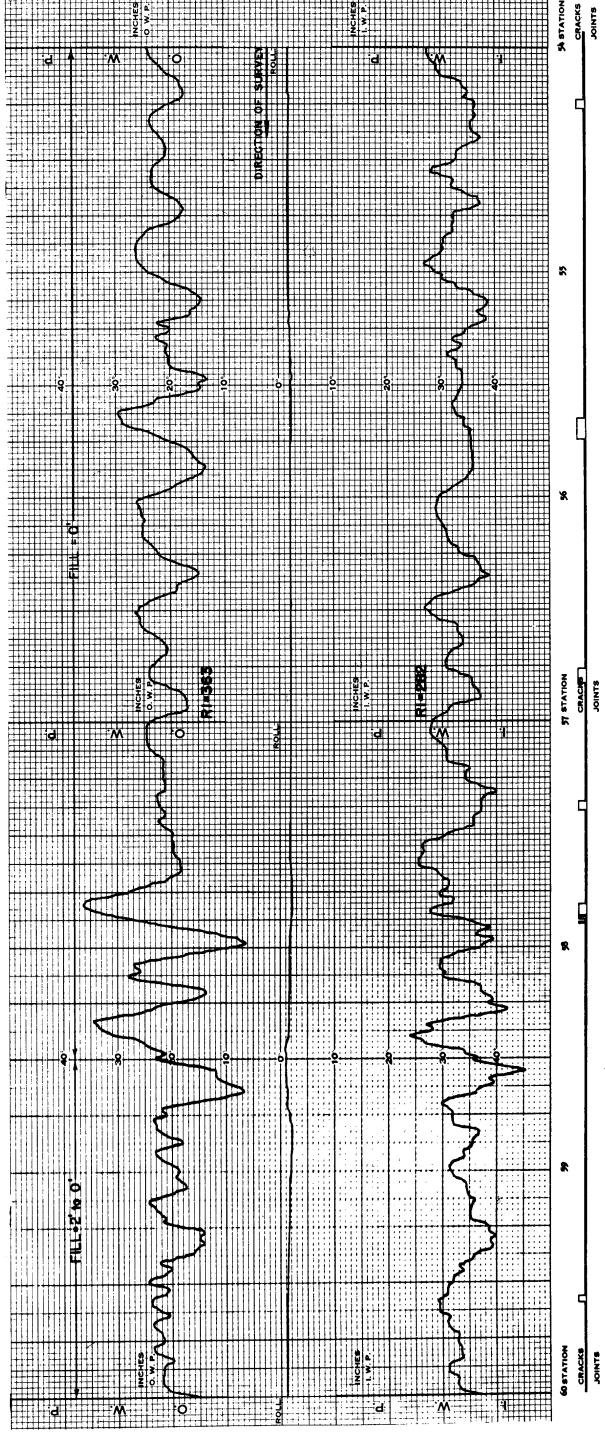


FIGURE-16 B  
 CLASS-IV FLEXIBLE  
 M-36, 1939 SERVICE 19 YEARS  
 TRAFFIC: TOTAL 2000, COMMERCIAL 385, DHV 250  
 DATE OF SURVEY: DEC. 5, 1958

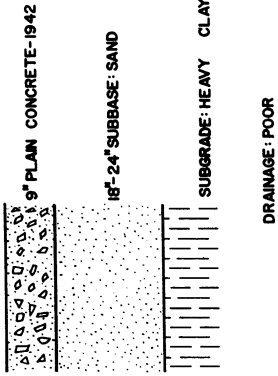
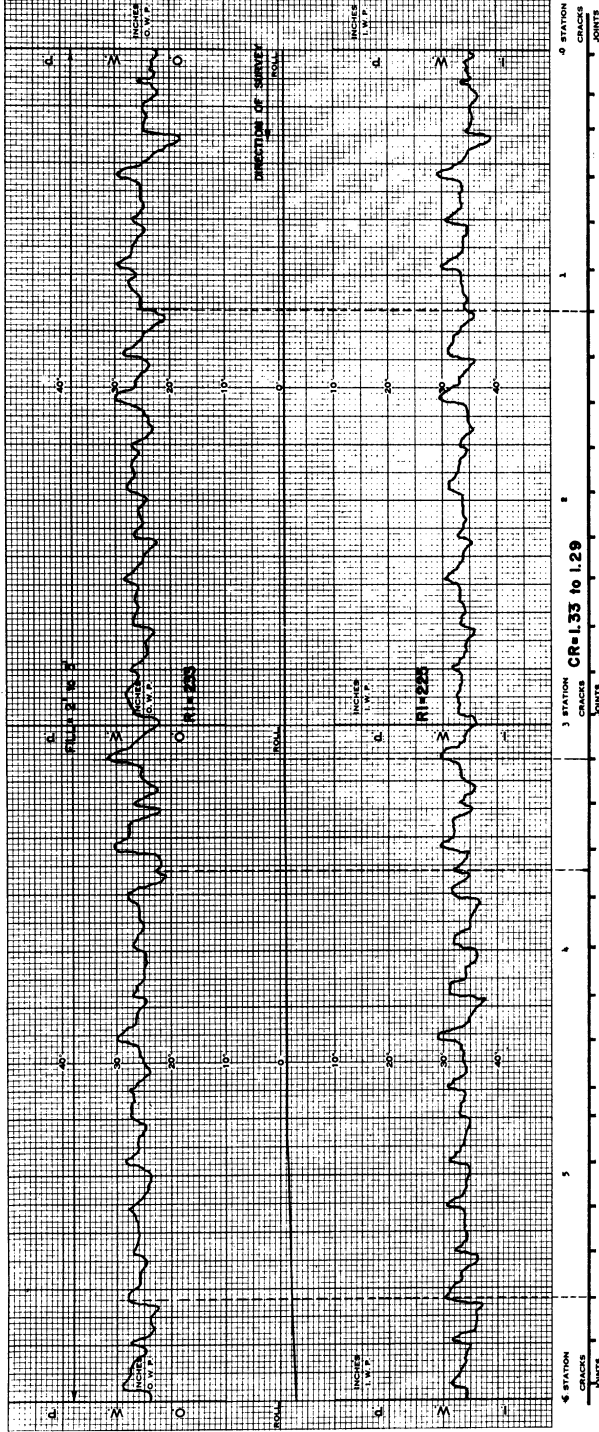


FIGURE-17  
 CLASS-II RIGID  
 US-24A, 1942 SERVICE 16 YEARS  
 TRAFFIC: TOTAL 10,000, COMMERCIAL 3025, DHV 575  
 DATE OF SURVEY: JUNE 19, 1968

DRAINAGE: POOR

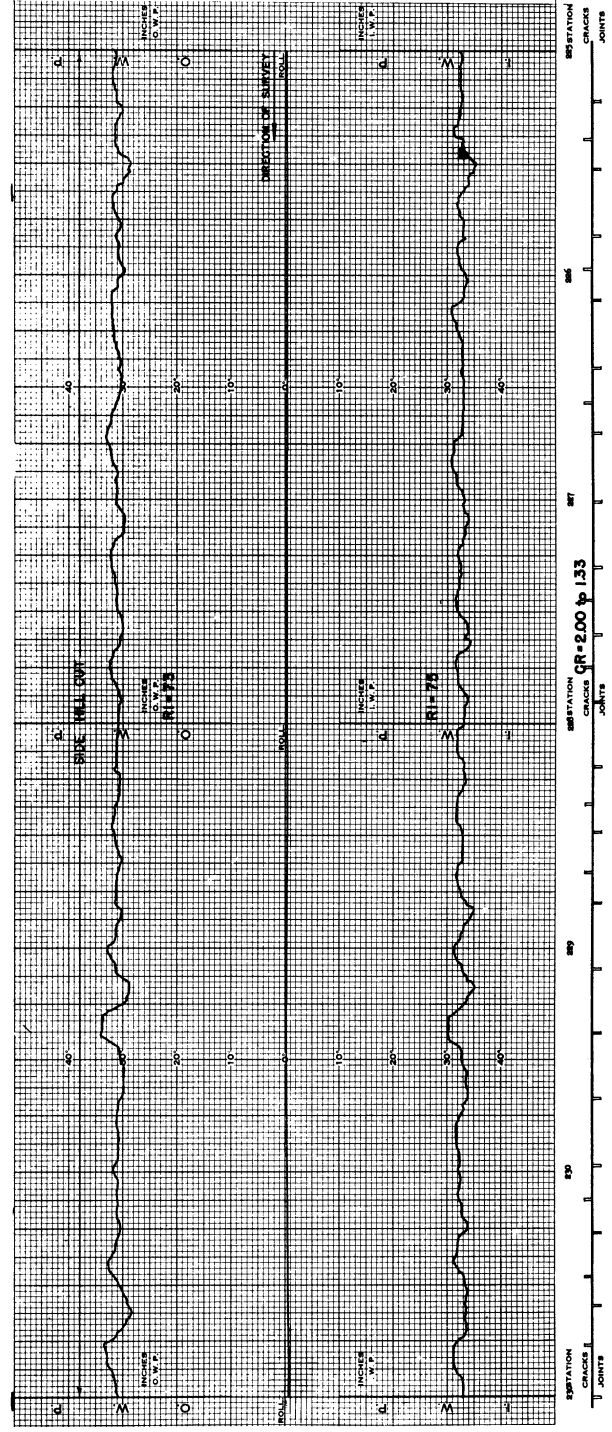


FIGURE-12 B  
 CLASS-III RIGID  
 US-41, 1936 SERVICE 22 YEARS  
 TRAFFIC: TOTAL 1600, COMMERCIAL 280, DHV 190  
 DATE OF SURVEY: NOV. 7, 1968

DRAINAGE: GOOD



concrete without load transfer at the joints in what is presumably 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, at which time an 18 to 24 inch subbase was added on top of the grade to protect the 9 inch plain concrete from quite certain pumping action. The small reduction in the continuity ratio indicates that the crack control was excellent, but this design produced one of the roughest riding pavements in southern Michigan. Perhaps the most interesting feature of this pavement is the characteristic sawtooth pattern that has been produced by the tilting and faulting of the short slabs, illustrating the value of pavement profiles in identifying different types of pavement distress. From the standpoint of design, the absence of load transfer at the joints is probably the critical weakness. For purposes of comparison, the profile shown in the bottom half of Fig. 11 is from the smooth section of US-41 where there are 30 foot joints, but with load transfer provided. Expansion joints at 60 feet are supplied with trans-load expansion joint base and the reinforcing is carried through the 30 foot dummy joints, adding necessary structural continuity to the concrete pavement.

The last two pavement sections, in Fig. 12, are examples of new pavements constructed in 1958 with profiles that give some measure of the high quality of pavement construction that can be produced when the effort is made to do so. The section in the top half of the figure is a reinforced concrete pavement on a divided lane highway, M-20 between Bay City and Midland, with a 12 inch granular subbase consisting of 9 inches of sand and 3 inches of selected gravel used for subgrade stabilization. This pavement would be rated as exceptionally smooth, with roughness indexes of 40 and 27 in the two wheel tracks. In the lower half of the figure is an example of a heavy duty flexible pavement constructed on the Muskegon - Grand Haven Expressway and it is representative of the type of heavy duty flexible pavement construction proposed for use on the Interstate Highway System on certain selected projects. The riding quality of the pavement is exceptional, with roughness indexes of 18 and 15 in the two wheel paths of the pavement.

Having obtained the basic profiles immediately after the pavements were constructed, these projects will be watched with considerable interest over the next few years and will provide the type of data needed to record the complete history of pavements during their useful period of service.

#### FROST ACTION ON PAVEMENTS

During the winter of 1958-59, a special investigation was made of selected sections of pavement in southern Michigan and in the Upper Peninsula to determine the effect of a one year cycle of freezing and thawing. The selected sections included all four classifications of both rigid and flexible pavements, with the primary objective of determining the effectiveness of pavement design in protecting pavements from the detrimental effects of frost action. The results of this investigation were very interesting and somewhat surprising and will be illustrated in the next few figures.

In Fig. 13 are shown some typical sets of profiles of sections of a flexible pavement on Highway M-100 in southern Michigan. In the top part of the figure is a well designed flexible pavement built on an old grade which had previously been inadequate for more than light traffic. There are several

weak sections in this pavement, shown in the bottom part of the figure, which have led to its being identified as a Class 3 pavement even though its design should justify a Class 2 rating. The good sections are actually Class 2 pavement which are completely adequate for year-round service.

The heavy full line on these profiles is for the late Summer or Fall survey, representing the relatively stable condition of the pavement surface. The good section is exceptionally smooth from the standpoint of riding quality, with a roughness index of 34 in the outer wheel path and 40 in the inner wheel path. The second, lighter, full line is the late winter profile taken at a time presumed to be close to the period of maximum frost action. The roughness indexes of 130 in the outer wheel path and 98 in the inner wheel path show a significant amount of frost displacement which is also apparent from the profile itself. The amount of frost displacement in a well designed road with presumably free draining, granular subbase and base courses was somewhat surprising, but these results were confirmed on similar sections throughout the investigation. The differential between the outer and inner wheel paths indicates the source of water as infiltration from the shoulder, although on this and other sections it was also apparent that water was moving through the granular base course in vapor phase and condensing under the surface to produce the moisture that upon freezing resulted in the displacement of the pavement surface.

The next profiles in the series, shown by the dashed line in Fig. 13, were run in the Spring after all frost had left the ground and had as their objective the determination of the permanent or residual displacement resulting from the winter's freezing and distortion of the pavement surface. In the good section, the results are rather satisfying as they indicate that the pavement surface went back to very nearly its stable Summer profile, with roughness indexes of 40 and 44 in the outer and inner wheel paths, respectively, as compared to 34 and 40 in the previous summer. While the residual or permanent displacement due to the single cycle of freezing was measurable, it was very small in this particular case which was exceptional. In most of the pavement sections included in this investigation, the residual displacement was substantially greater than in the examples shown in Fig. 13.

The rough section in the lower part of the figure requires some special comment. The frost displacement is again maximum in the outer wheel path with no significant change in the inner wheel path. One may surmise that after a pavement gets very rough it can get no worse and reaches some limiting value about which it may continue to fluctuate. The Spring profiles indicated that a substantial part of the frost displacement in the outer wheel path becomes permanent or residual displacement. In the inner wheel path, the Spring profile actually had a smaller roughness index than in the initial survey during the previous summer. The negative differential is small and may be experimental error in recording. This could result from a change in periodicity of the wave-like displacements, sluggishness in the recording mechanism, or failure to follow precisely the same wheel path. On the other hand, similar results were obtained on a number of the very rough pavements, so it may actually represent a true change in the pavement profile. It is not unreasonable to suppose that traffic may have a tendency to iron out the larger and more abrupt pavement displacements in very rough sections. In passing, it should be noted from the standpoint of design that the rough section resulted from settlement over peat trapped beneath the roadway and temporary patching to fill in the depressions.



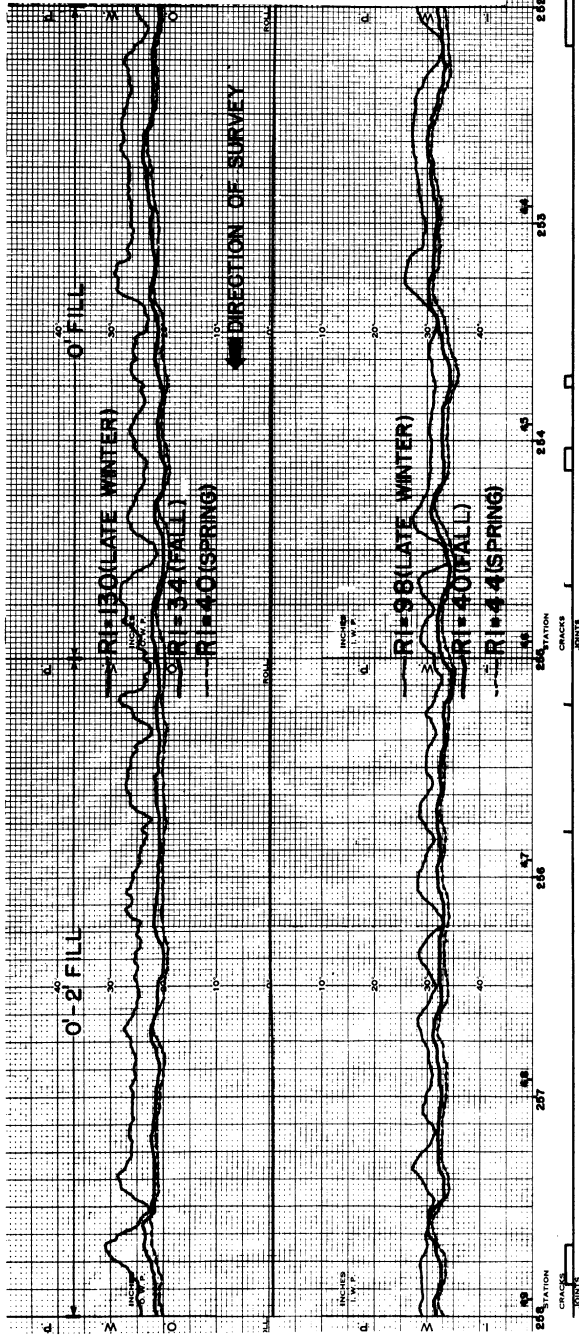


FIGURE - 15 C

CLASS-III FLEXIBLE

M-100,1953 SERVICE 5 YEARS

TRAFFIC: TOTAL 800, COMMERCIAL 160, DHV 200

DATE OF SURVEY: DEC. 4, 1958 & FEB. 20, 1959

2 1/2" BITUMINOUS AGGREGATE - 1953  
5" GRAVEL BASE - 1953

12" SUBBASE: SAND

4" ORIGINAL GRAVEL ROAD (1917-1946)

SUBGRADE: SANDY CLAY

DRAINAGE: POOR

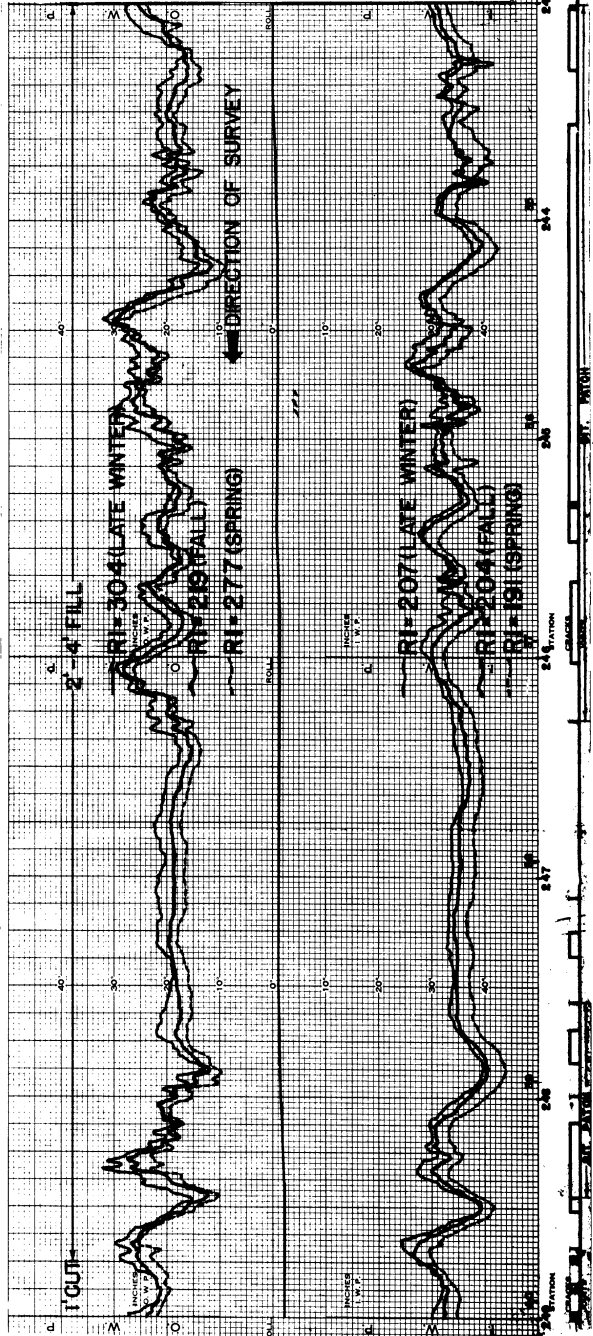


FIGURE - 15 D

CLASS-III FLEXIBLE

M-100,1953 SERVICE 5 YEARS

TRAFFIC: TOTAL 800, COMMERCIAL 160, DHV 200

DATE OF SURVEY: DEC. 4, 1958 & FEB. 20, 1959

2 1/2" BITUMINOUS AGGREGATE - 1953  
5" GRAVEL BASE - 1953

12" SUBBASE: SAND & GRAVEL

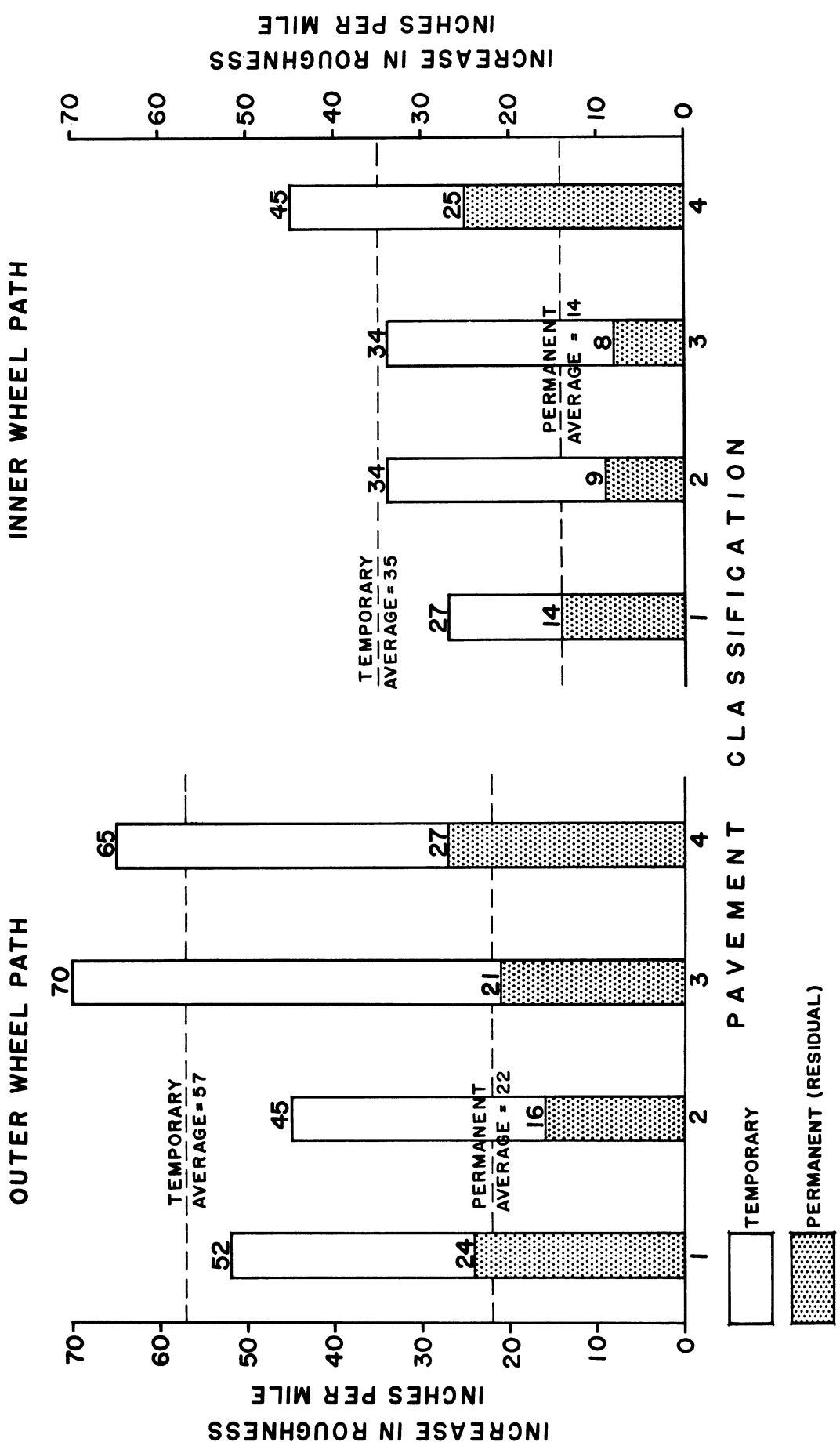
4" ORIGINAL GRAVEL ROAD

2'-4" SANDY CLAY

PEAT

DRAINAGE: FAIR TO POOR

FIGURE - 13



SEASONAL FLUCTUATION IN PAVEMENT PROFILE

FIGURE - 14

Fig. 14 is a graphical presentation of the average frost displacement on sixteen pavement sections of various classifications in southern Michigan. The vertical ordinate is the increased roughness in inches of vertical displacement per mile, greater than the normal, summertime profile. The classification of the pavement is indicated on the horizontal axis and the left hand group of bar graphs is for the outer wheel path and the right hand group for the inner wheel path. The maximum ordinates in both cases are the maximum frost displacement averages in late winter. It may first be noted that adequacy of the design from the standpoint of load carrying capacity makes little difference in the susceptibility to frost displacement. On the lower part of each bar is shown the permanent or residual pavement displacement caused by the distortion during the period of maximum freezing but remaining in the pavement after the frost has left the ground. The permanent or residual displacement is shown by the cross-hatched portions of each bar and indicates the increased roughness remaining in the late spring profile. The subsequent late summer profile indicated some minor changes in these figures, but no significant trends from the data now available. One rather definite difference is shown in Fig. 14 in the differential between the outer wheel path and the inner wheel path, which, as previously mentioned, indicates that the maximum heaving in the outer wheel path suggests that the source of displacement is the freezing of moisture which has infiltrated from the shoulder of the pavement. This observation also identifies the moisture as being in the base and subbase rather than deep-seated heaving in the underlying subsoil.

#### Cumulative Roughness over a Period of Years

In the analysis of the tremendous volume of data included in 2000 miles of pavement profile, there are obviously a great many studies and comparisons that may be made. While these data are still under examination, there are certain significant trends that immediately become apparent and some of these will be presented in the next few figures. In Fig. 15 is shown the roughness index values for all of the Class 1 and Class 2 rigid pavements included in the 1958 survey. The roughness index in inches of vertical displacement per mile is the ordinate and the number of years in service is plotted as the abscissa. In the center of the figure is shown a scale indicating the rating of the pavement in accordance with the roughness scale in Fig. 6. The data on the left hand side of Fig. 15 are for Class 1 pavements which are presumed to be the highest rating from the standpoint of structural adequacy of any of the pavements on the trunkline system. In general, they are pavements built over natural sand and gravel subgrades of high internal stability and excellent drainage conditions. Class 2 pavements, on the right hand side of the figure, are also structurally adequate, being designed for year-round service. However, they required subgrade improvement as represented by the addition of a granular base course over clay soils with drainage improvement through raises in grade, removal of frost susceptible soils, and subdrainage where required.

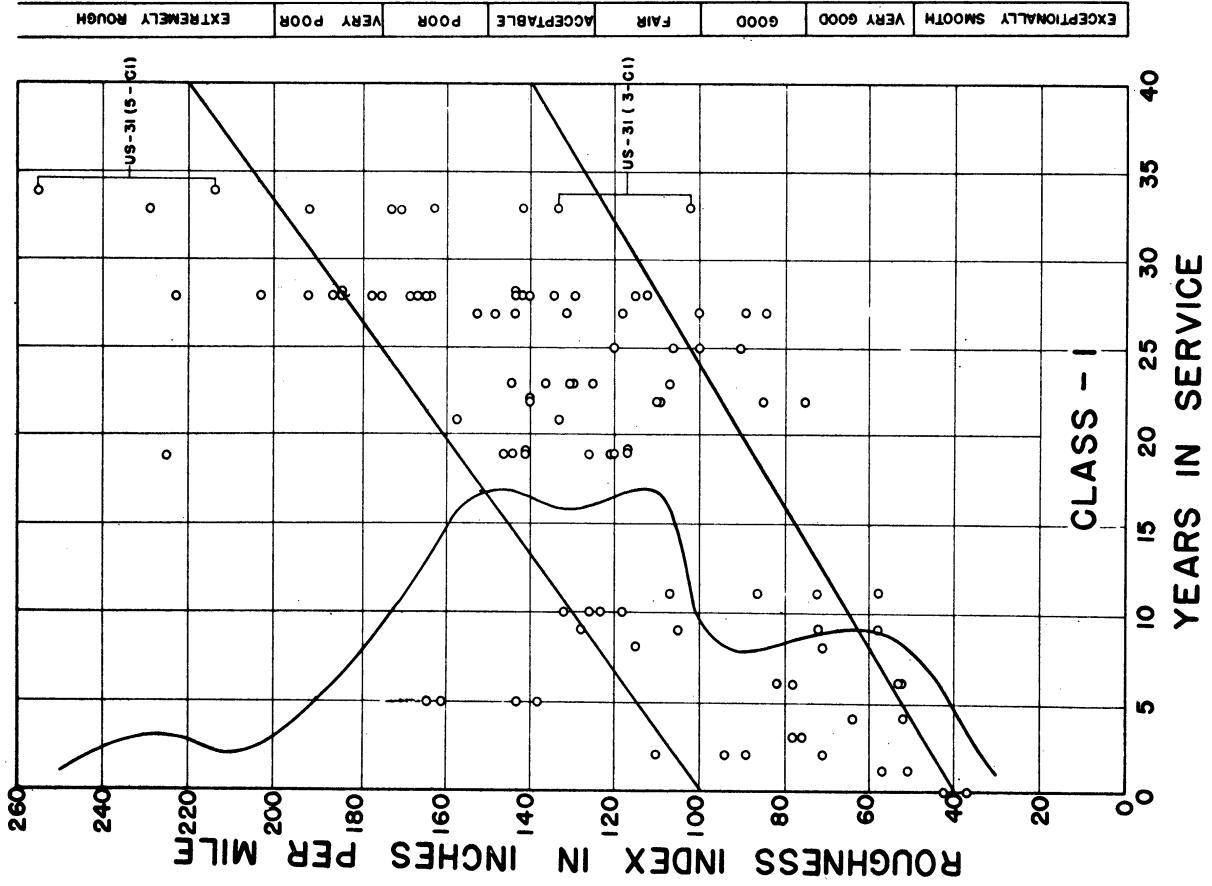
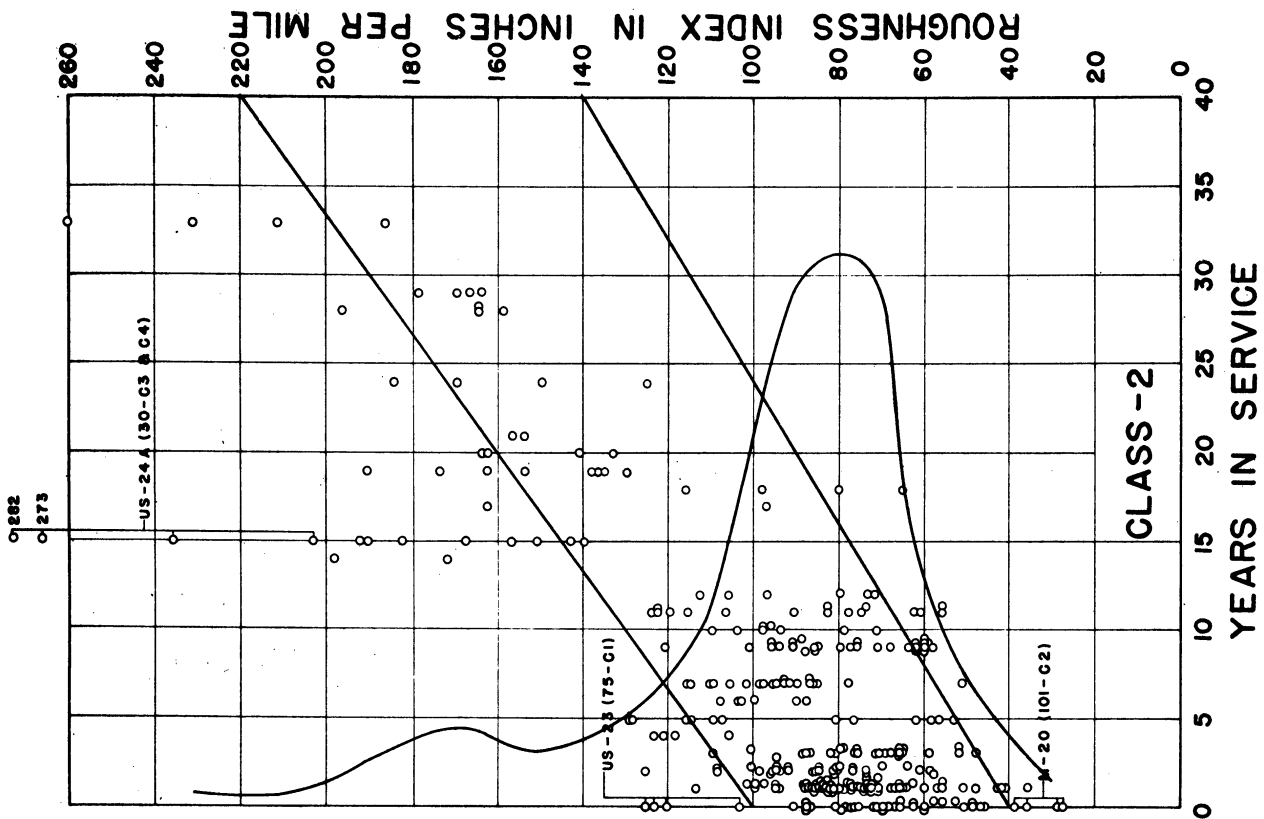
In spite of their structural adequacy, it is perhaps surprising to find that these pavements continue to lose their riding quality at a more or less uniform rate throughout their entire period of service. There are, on the chart, pavement sections from those most recently built to some that have a period of service approaching 35 years. If this is true for those pavements which are rated as structurally adequate for legal axle loads at all times of the year, the question naturally arises, "What is the normal performance of a pavement, and what is to be expected of a pavement that is structurally

adequate in every sense of the word?" While it is too early to draw conclusions from presently available data, further analysis of these observations may suggest some concepts of service behavior of pavements not generally recognized.

Several rather tentative procedures have been attempted in an effort to represent trends in the data in Fig. 15. As a first attempt, a band has been selected on the chart between the two straight lines shown, within which approximately 80% of the roughness index data will fall, with 10% of the more scattered points lying both above and below the band. If normal performance may be said to lie within this band, it would indicate that these well designed pavements lose riding quality or become rougher at a rate of from 2 to 3 inches of vertical displacement per mile for each year of service. This does not seem like a rapid rate of deterioration; but, nevertheless, it means that pavements which may be built within a range of roughness from 40 to 100, rated as good or very good in terms of riding quality, will in 40 years develop a roughness index from 140 to 220 which would rate them as poor to extremely rough in terms of riding quality. This change, which may presumably take place in spite of good design and superior construction, would appear to be consistent with the cumulative residual or permanent displacement of the pavement surface observed in the annual cycle of freezing and thawing already discussed in connection with frost displacement. This first attempt to define what may be normal behavior of a structurally adequate pavement will be left as food for thought while attention is directed to some other interesting features of the data in Fig. 15.

In addition to the suggested band of normal behavior, two distribution curves have been sketched in on the two charts in Fig. 15 and these show quite a contrast in distribution of the pavement sections with respect to their roughness indexes. Class 1 pavements on the natural sand and gravel subgrades are spread out over a much wider range of roughness index than the Class 2 pavements, where there is a distinct grouping of points or peak in the curve at roughness indexes from 40 to 120. This suggests that the natural sand subgrades represent an uncontrolled condition insofar as compactness of the supporting subgrade is concerned, producing a much wider range of riding quality. Class 2 pavements, it may be recalled, are designed and built with sand subbases and granular base courses providing an opportunity for greater uniformity in texture and for improved compaction which has been practiced particularly in more recent years. The result, in terms of riding quality, is naturally enough much better and much more consistent, as should be expected under reasonably good construction control. As a matter of general observation and construction experience, road designers in the Michigan State Highway Department have come to the conclusion that it would be desirable to undercut the pavement structure itself and mix and compact the natural subgrade materials for a depth of some 18 inches in order to eliminate some of the variations due to nonuniformity in soil textures and soil densities. The data in Fig. 15 present positive evidence in support of such a construction procedure and it is being adopted by the Department.

In passing, it should be noted that there is a fairly uniform distribution in terms of years of service for the Class 1 pavements in Fig. 15; while, in the Class 2 pavements, the great majority of projects are concentrated in the first 15 years. This relates to the fact that the Department for the past 15 or 20 years has been correcting deficient subgrades to provide year-round service by the use of sand subbases and improved drainage. Prior to that time, there were very few Class 2 pavements built and they did not come up to present



ROUGHNESS VS. YEARS IN SERVICE  
RIGID PAVEMENT  
BASED ON 1958 SURVEY

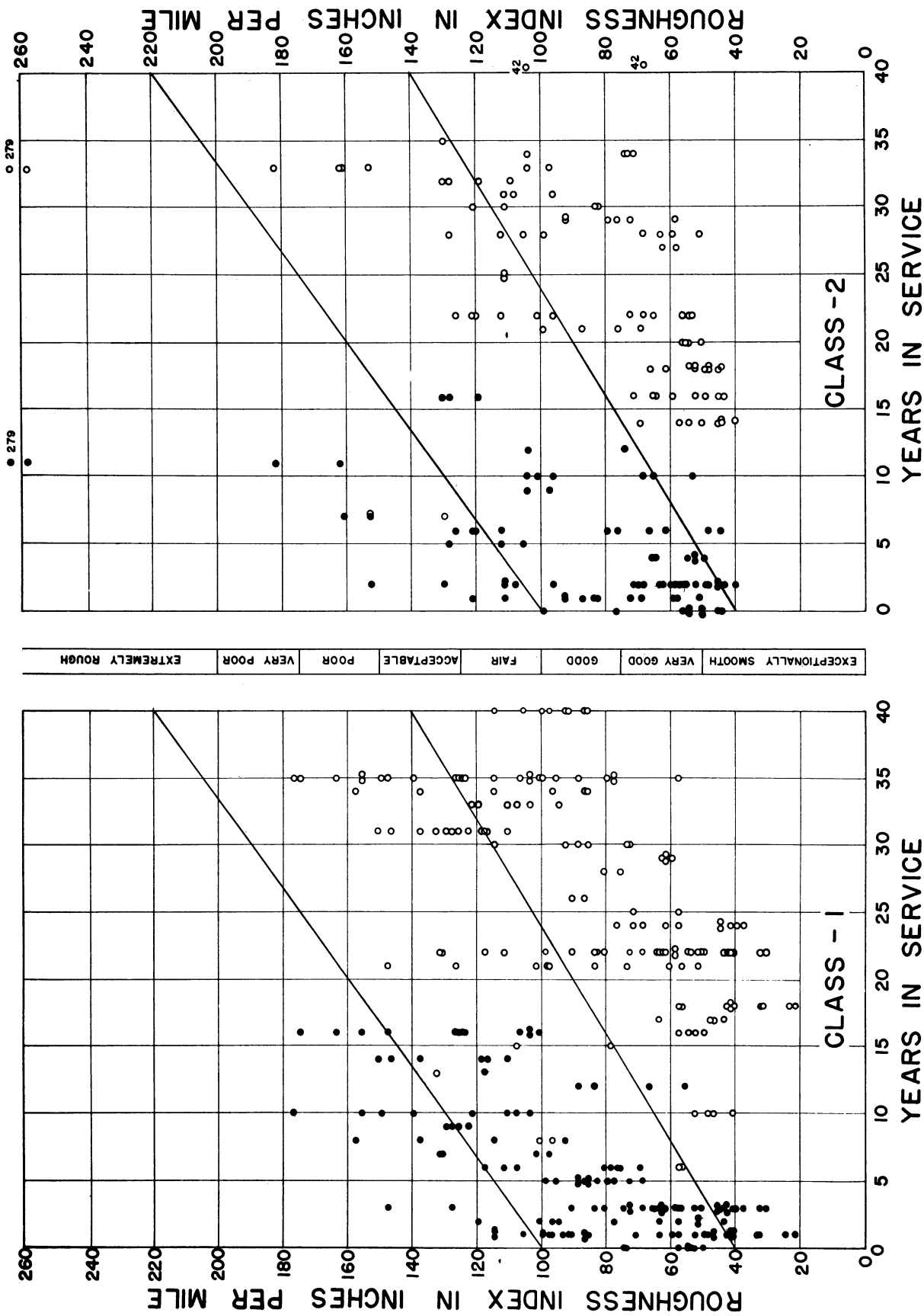
FIGURE - 15

day standards, which accounts for their poor service behavior. The group of projects with service periods from 15 to 20 years represent wartime construction under emergency conditions where steel reinforcement was not being used and there was a general relaxation of the more rigid construction specifications which has clearly left its mark in terms of poor service behavior.

To further emphasize the direct correlation between performance and design and construction conditions, several projects on the charts in Fig. 15 have been identified by contract. In the Class 1 pavements, two such contracts on US-31 provide a significant comparison. One of them, after 33 years of service, shows excellent performance falling at the lower limit of the band of normal service, with riding quality which is still rated as fair to acceptable. The other contract, after 34 years of service, is extremely rough and well above what has been suggested as normal behavior. These two pavement sections are within a few miles of each other and have practically the same traffic count. They were classified as Class 1 as the subgrade was a Plainfield sand which is one of the superior subgrades with high internal stability and excellent drainage conditions. This classification is correct for the project showing the superior performance, but is incorrect for the project showing poor performance. The latter is at a transition in soil types and the major portion of the section is over a silty clay loam with inferior drainage conditions and actually should be rated as Class 3 or Class 4.

Among the Class 2 pavements, three contracts have been selected for special comment. US-24A with roughness indexes which fall off the chart is the pavement of 20 foot, unreinforced concrete slabs without load transfer at the joints that has already been commented on in connection with Fig. 11. The other two projects, built in 1958, are M-20 and US-23. M-20 has an initial roughness index below 40, which would be rated as exceptionally smooth, and is the result of special care in placing and finishing the concrete slab. It too has already been commented on in connection with Fig. 12, and represents riding quality which can be produced under construction conditions when the effort is made to do so. The other section, US-23, represents a poorly built job with roughness index which would be rated only fair, and represents poor performance on the part of the contractor. When it is considered that riding quality is the basic commodity which is being purchased when a pavement is built, it seems fairly obvious that a large proportion of the investment has been lost by poor construction practice. "Built-in roughness" of this character is something that has not been given the attention it deserves, and one immediate benefit of the statewide recording of profiles has been to call attention to this deficiency in pavement construction practice and to provide a quantitative basis for correcting it.

In Fig. 16 are shown two similar charts comparing roughness index with years in service for older concrete pavements that have been recapped with a bituminous surface. The bands that have tentatively been used to represent normal behavior of structurally adequate pavements are shown on these charts largely for a basis of comparison. Roughness indexes for the pavement sections in question have been plotted against the years in service of the original concrete pavement and also in terms of years of service of the resurfacing. In this discussion, comment will be limited to the groups of points falling above and below the normal service band as they may provide the clue to the more important design conditions which are involved in service behavior.



ROUGHNESS VS. YEARS IN SERVICE  
 RECAPPED PAVEMENT  
 BASED ON 1958 SURVEY

FIGURE - 16

In both the Class 1 and Class 2 recapped pavements, those points which fall well above the norm represent recapped pavements which have become just as rough as the original pavements in a relatively short period of service. Several of these projects have been resurfaced more than once and their rapid loss of riding quality demonstrates that they are structurally inadequate for one reason or another, unless they were built just as rough as the original pavement which is not likely judging by experience with construction practice in recapping old pavements. To determine the source of this inadequacy may require a field investigation and a determination of the soil conditions and environment of each of these pavements and this has not been done as yet. However, the accuracy with which the characteristics of the pavement profile, expressed in terms of the roughness index, have identified the source of difficulty in other pavements showing abnormal service behavior indicates that the weakness of the pavements under discussion can be reliably determined.

The other group of points in Fig. 16 which are of particular interest are those that fall well below the band of normal service. When the roughness index on these projects is plotted in terms of the service period of the original pavement, it must be granted that the low roughness index of the resurfaced pavement is not truly representative of the service behavior of the original pavement. On the other hand, in this group of points there are a number of projects in which the resurfaced pavement has retained its superior riding quality over a number of years in service, indicating exceptionally good performance which must be evidence of superior design or unusually favorable soil conditions and environment.

## CONCLUSION

The preceding examples of pavement performance derived from studies of the pavement profile have been presented to demonstrate that service behavior of existing pavements is a most promising source of design information and a reliable basis for isolating the important factors in building adequate pavements. Analysis of the large volume of data gathered in the pavement performance surveys has just begun and there is much yet to be learned. In such a state of affairs it is not appropriate to draw conclusions with any thought that they constitute final answers. However, there is enough evidence available and enough analysis has been made to indicate the value of this approach to pavement design. While there may be much more to do in extracting the full value of these data, pertinent evidence already points to the fact that pavements of all classifications, not excepting those judged most adequate, become progressively rougher with age, confirming the implications of the one year's study of frost displacement. This 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 stress.

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. This may pose another set of questions. 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? Only when these questions have been answered can the responsible factors which control pavement performance be isolated and logical relations between cause and effect be determined.





