Pavement Profile Surveys to Correlate Michigan Design Practice with Service Behavior

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The paper first presents the correlation of Michigan pavement design with service behavior as developed from pavement performance surveys. Such surveys, initiated in 1925, serve as the primary basis of pavement design and emphasize soil conditions, drainage, moisture susceptibility, frost action, and climatic environment as controlling factors in pavement design. Methods devised in recent years for more precise evaluation of pavement performance are described. The significance of structural continuity and riding quality are discussed as integrated measures of pavement performance. A continuity ratio based on the cracking pattern of concrete pavements and a roughness index taken from accurately recorded pavement profiles are analyzed as quantitative measures of pavement performance. A truck-mounted pavement profilometer used in these surveys is described. Typical examples are presented from some 1,500 mi of pavement profiles obtained in 1958 to show the relation between design practice and pavement performance and to bring out the promising possibilities of measuring pavement behavior under actual service conditions.

• PAVEMENT PERFORMANCE surveys have been used in Michigan for many years to correlate pavement design and performance under actual conditions of service. In 1925 a group of highway engineers and pedologists started making state-wide surveys of pavement condition as related to soil types and climatic environment. The results of some of these early surveys (*1, 2, 3*) indicate that these investigators early found significant correlation between pavement performance and environmental factors, including soil type, drainage, and climatic influences. This general approach has continued to be used in Michigan as the primary basis of pavement design, utilizing subgrades of high bearing capacity, providing good drainage, and eliminating frost-susceptible soils.

Since 1940 the Department's engineers have designed new roads in the state trunkline system to carry legal axle loads at all seasons of the year. Also, every opportunity has been seized to rebuild the old roads and bring them up to the same standards. During development of the Michigan pavement design procedures, it has been recognized that more precise methods of evaluating pavement performance and measuring the effect of various design conditions were desirable and in more recent years several research studies have been directed toward development of such improved procedures.

From 1952 through 1956 the University of Michigan, the Michigan State Highway Department and the Wire Reinforcement Institute collaborated in a study to evaluate the effect of steel reinforcement in 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 un-reinforced sections, which were observed over a period of approximately 5 years. Analysis of these projects indi-

cated that performance of rigid pavements could be measured in terms of two basic factors — structural continuity and riding quality, or their counterparts, cracking and pavement roughness. Loss of structural continuity is reflected in pavement cracking, with relative performance being shown in progressive changes in the cracking pattern. Similarly, progressive changes in the pavement profile or pavement roughness give evidence of continued displacement in the supporting subgrade.

Analysis of pavement condition in these selected projects showed a significant difference, inasmuch as pavements with steel reinforcement were measurably smoother and the cracking was measurably less than in unreinforced pavements. Although these studies gave positive evidence on the effect of steel reinforcement as a factor in pavement design, the importance to the present discussion lies in 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 reported results (*4, 5*) encouraged the continuation of such studies and when the opportunity came, a state-wide survey of the Michigan trunkline system was undertaken.

FIRST PAVEMENT EVALUATION

This work was organized as a cooperative research program in which the Transportation Institute of the University of Michigan collaborated with the Michigan State Highway Department. The first phase of this program was the review and recapitulation of pavement adequacy on the state trunkline system, an objective that was accomplished with publication of the first pavement evaluation survey of January 1, 1958 (Fig. 1). This first state-wide evaluation provides the foundation for future surveys and the basis for reclassification of highways and future improvements that will be made from time to time. In this road classification for legal axle loads, the four levels of adequacy selected are defined as follows:

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

Class 2. — No seasonal restriction; 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. — Spring load restriction required; pavement designs which do not compensate for seasonal loss of strength as represented by fine-grained soils, susceptible to frostheaving and pumping and with inadequate drainage provisions.

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

The results of the first pavement evaluation, covering some 9300 mi of trunkline highway, may be summarized as follows:

Status	Class	%
Adequate	1	30.5
	2	23.8
	Total	54.3
Inadequate	3	31.5
	4	14.2
	Total	45.7

There are several other interesting points in connection with Figure 1. In the ten districts in the state, District 1, the western portion of the Upper Peninsula, has the lowest percentage of adequate roads, amounting to only 35 percent as compared with 65 percent of inadequate roads. This is an area of highly frost-susceptible soils, frequently inadequate

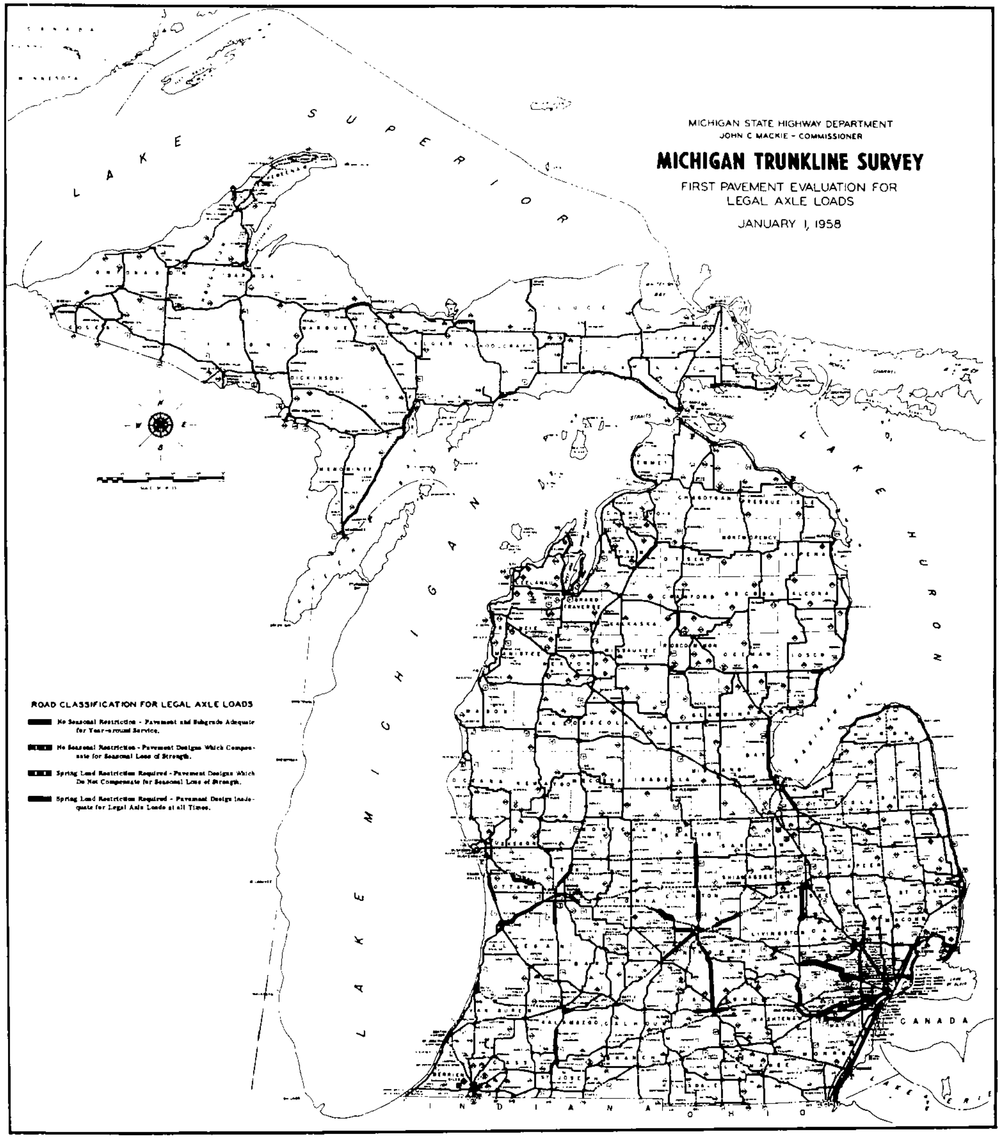


Figure 1. First Michigan pavement evaluation survey for legal axle loads, January 1, 1958.

drainage, and severe frost action. On the other hand, there are several locations in the state where soil conditions are exceptionally good. Thus, in Districts 3 and 7 adequate roads total approximately 73 percent, whereas only 27 percent are inadequate. In the central portion of the state there is a large area including Kalkaska and Crawford Counties where natural sand subgrades have provided Class 1 roads on all state trunklines in the area. Similar areas are found in District 7 in the southwest corner of the state. Another feature shown on this map is the network of divided-lane expressways radiating from the metropolitan centers of Detroit, Lansing, and Grand Rapids, representing the accomplishment

of the early years of modern expressway or turnpike construction characteristic of the interstate highway system.

The first pavement evaluation brought together a great volume of basic design data available in the Department's records, as well as other pertinent information on soil types and drainage, maintenance experience, and pavement performance data going back to the previously mentioned condition surveys of many years ago. Through the collaboration of the District Soil Engineers and other department personnel, much of this classification reflects the unrecorded knowledge of the men who have lived with these roads for many years. The pavement evaluation map brings together this great store of working knowledge and for the first time presents it in a completely integrated form as a matter of definite record.

Pavement performance surveys now in progress have as their objective more precise measurement of pavement adequacy leading to improvement in the accuracy of this first classification. It is expected that weak sections will be found in roads now classified as adequate and strong sections in those classified as inadequate. In the case of weak sections, more extensive field investigations will be made to pinpoint the sources of weakness and determine the most practicable corrective measures. This leads directly to the reconstruction or betterment of such roads, and already preliminary study of the problems involved has led to including several strategic sections in early construction programs. Guided by experience from previous surveys, the methods of measuring pavement condition are predicated on the idea that the ability of a pavement to carry the loads of present-day traffic are shown by the two types of pavement behavior which in inadequate pavements result in progressive changes in pavement cracking and pavement roughness.

ELIMINATION OF SPRING LOAD RESTRICTIONS

The first concrete result of the Michigan Pavement Performance Study was the lifting of Spring load restrictions on a selected network of state trunklines which were opened for full legal axle loads during the Spring of 1958. The so-called 1958 Frost-Free Network (Fig. 2) originally included some 3720 mi opened to full legal axle loads. Before the state-wide Spring load restrictions were invoked, some 825 mi were added to the original network, making a total in the frost-free network of some 4545 mi, or almost 50 percent of the state trunkline mileage. Included in this network was some 27 percent of roads rated inadequate on which restrictions were lifted to provide a reasonable number of through routes, both east and west and north and south, and certain access roads to important industrial areas.

This first year's experience was considered satisfactory, with surprisingly little apparent damage due to lifting of restrictions and only a few isolated cases of roads which had to be taken off the frost-free network because of abnormally weak sections not practical to keep in service by heavy maintenance. Judged in terms of public benefit, there has been little question of the justification of the forward move represented by the raising of load limitations during the Spring period under the controlled conditions represented by this action. In this connection it can be pointed out that the cost of Spring load restrictions to industry and agriculture in the state of Michigan was estimated to be some $20,000,000 a year, a substantial part of which was saved during the 1958 Spring period by providing for the free movement of legal axle loads on the frost-free network.

MICHIGAN STANDARDS OF PAVEMENT DESIGN

As indicated by the road classification used in the first state-wide pavement evaluation survey and in the frost-free network, the Michigan standards of pavement design depend on a correlation of pavement performance in actual service with associated conditions of environment. The important environmental factors are soil conditions as reflected in texture, susceptibility to moisture change

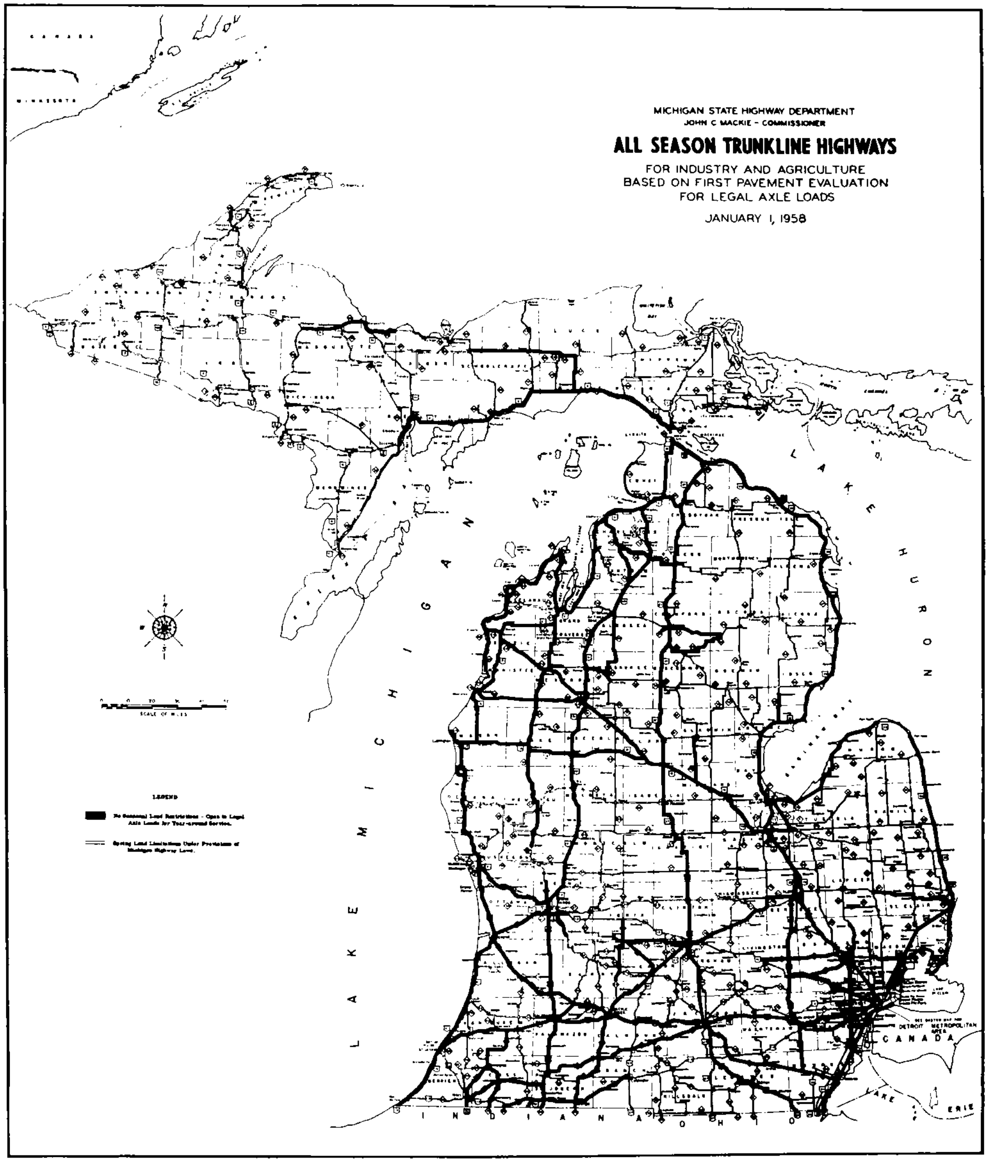


Figure 2. Frost-free trunkline highway network on which Spring load restrictions were removed in 1958.

and frost action, drainage as affected by grade line and drainability of the subgrade soils, and climatic influences of rainfall and temperature. At the risk of some over-simplification, the design procedure can be described as one of providing an adequate foundation to carry the applied loads but primarily capable of resisting the destructive effects of environment. In such a procedure the pavement surface becomes a protective cover of sufficient thickness and structural continuity to distribute concentrated loads to the supporting subgrade, but its major function is to confine that subgrade to preserve its internal stability

and protect it from the wear and surface deterioration caused by rapidly moving loads.

As a matter of design procedure it was indicated in the road classification that miles of highways are built on natural granular materials perfectly capable of carrying legal axle loads throughout the year regardless of the effect of environment. Where soil conditions and environment require measures of improvement, the most effective design compensations consist of employing a high grade line for improved drainage, removal of the frost-susceptible soils (silt and very fine sand) to the depth of frost penetration and, finally, use of free-draining sand subbases over clay soils for pumping control, compensation for volume changes, and load distribution.

In terms of pavement cross-section, the result of the Michigan method of pavement design has been summarized in a table of recommended designs for the several classifications of traffic in terms of volume and vehicle size and weight. In Table 1 are represented Michigan's present design standards, so formulated as to indicate the corrective measures required to compensate for subgrade deficiencies where they occur. Thus, it is assumed that Class 1 roads require no subgrade compensation and the conventional paved surfaces may be laid directly on the natural subgrade. It is also assumed that in all cases inadequate surface drainage will be met by normal grade raises and frost-susceptible soils will be removed to the depth of frost penetration, or in lieu of such provisions equivalent alternates will be provided.

The important provisions in the pavement sections listed in Table 1 come in the cases where normal grade lines and removal of objectionable soils provide only partial protection. Thus, in fine-grained undrainable subgrade soils subject to concentration of soil moisture, the most effective compensation for seasonal loss of strength and certain other deficiencies, such as pumping, is the use of free-draining granular subbases. In this

TABLE 1

INCREMENTAL COST STUDIES; RECOMMENDED DESIGNS[1]

Axle Load (kips)	Range in Two-Lane Traffic Volumes (Veh./day)			
	Low 0-100	Low-Medium 100-400	Medium-High 400-1000	High 1000 & Over
Basic 0-4	6-22-6 6 in. Gravel	8-22-8 ¾ in. Bit. surf. 6 in. Gravel 12 in. Gran. subbase	8-22-8 2 in. Bit. surf. 6 in. Gravel base 12 in. Gran. subbase	10-24-10 2½ in. Bit. surf. 6 in. Gravel base 14 in. Gran. subbase, or 6 in. Reinf. conc. 14 in. Sand subbase
Light 4-10		8-22-8 1½ in. Bit. surf. 6 in. Gravel 12 in. Subbase	8-22-8 2 in. Plant mix 22 in. Gran. base and subbase 2 in. Bit. surf. 6 in. Base 14 in. Subbase	10-24-10 8 in. Reinf. conc. 14 in. Gran. subbase, or 3 in. Bit. surf. 7 in. Base 18 in. Subbase
Medium 10-18			8-22-8 8 in. Reinf. conc. 14 in. Gran. subbase, or 3 in. Bit. surf. 7 in. Base 18 in. Subbase	10-24-10 9 in. Reinf. conc. 14 in. Gran. Subbase, or 3 in. Bit. surf. 8 in. Base 18 in. Subbase
Heavy 18-22				10-24-10 9 in. Reinf. conc. 14 in. Gran. subbase, or 4 in. Bit. surf. 8 in. Base 20 in. Subbase
Heavier than now permitted 22-30				9 in. to 11 in. Reinf. conc. 14 in. Gran. subbase, or 4 in. Bit. Conc. 8 in. Base 28 in. Subbase

[1] Minimum design for P.C. Concrete: 6 in. surface and 14 in. subbase.

connection it is significant that the design standards given in Table 1 require substantially the same foundation treatment throughout the entire range of traffic volume and classifications of vehicle size and weight. In terms of what is commonly called the "basic road" or the first increment of pavement required only for light vehicles, Michigan design standards would provide the same drainage and substantially the same subbase and base construction for all classifications of road use to protect the pavement surface against the destructive effects of environment. From this it follows that the Michigan standards are more closely related to soil conditions, drainage, and climatic environment than they are to vehicle size and weight. Consequently, the variation in thickness as related to vehicle size and weight is limited to rather nominal increases, except in the case of heavy-duty flexible pavements where greater increase in total thickness is required for load distribution.

PAVEMENT PROFILES TO MEASURE SERVICE BEHAVIOR

The second phase of the pavement performance survey reported herein has to do with the more detailed measurement and recording of pavement profiles and structural continuity of the pavement surface. This part of the project has been carried on with the cooperation and support of the Michigan Trucking Association, the American Trucking Associations, Inc., and the Motor Truck Division of the Automobile Manufacturers Association. These three sponsors financed the research now being carried on by the Transportation Institute of the University of Michigan, whose representatives work directly with the Michigan State Highway Department.

Active work on this project began in December 1957 with the building of a truck-mounted profilometer (Fig. 3). This truck is specially equipped to trace and record an accurate profile in each wheel track of a pavement. Two sets of so-called "bogie wheels" located in front and back of the truck 30 ft 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. The tracing and recording mechanism is connected

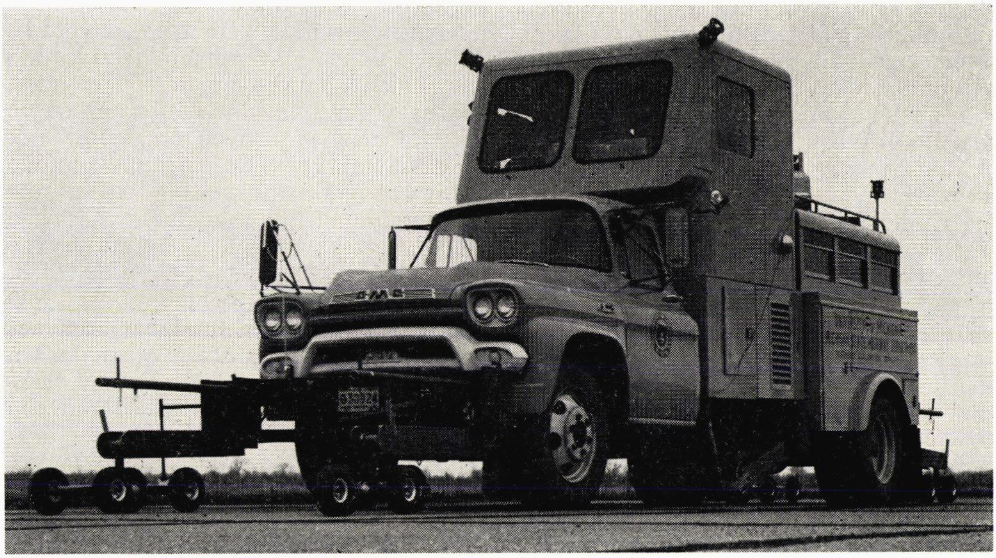


Figure 3. Michigan truck-mounted profilometer.

to electronic integrators, which measure the cumulative vertical deflection of the pavement in inches per mile for any selected length of pavement. This cumulative vertical deflection is used as a roughness index in the subsequent pavement classification reported herein. The roughness is stamped out on the profile chart for each quarter mile to aid in selecting critical sections that may be isolated for further investigation, or possible defects in design or construction.

The Michigan equipment is modeled after that designed and used by the California State Highway Department. 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. Photographic equipment is also being developed to take a continuous film strip of the pavement coordinated with the recorded profile, but this has not been available for the surveys so far completed. Means are also provided to measure and record the relative elevation in both wheel tracks, by a device called a "roll indicator," with a recording pen in the center of the profile chart.

The importance attached to pavement profiles arises from the fact that even an infinitesimal amount of permanent displacement in the pavement structure will under many repetitions of load lead to increasing roughness and eventual destruction. When the pavement is first built, assuming a reasonably good job, the surface irregularities are small and the riding quality is good or excellent. If the subgrade is of potentially high capacity, such as sand or gravel, it should be capable of supporting the pavement surface without continued deformation or displacement. If the subgrades are poorly compacted and non-uniform, they may nevertheless consolidate under traffic and produce a rough-riding pavement. However, after a period of conditioning under service, they become stable and the riding quality of the pavement can be recovered by resurfacing. It would then seem reasonable to expect that this riding quality could be preserved for an indefinite period of service.

On the other hand, if the subgrade is weak and actually deficient in supporting capacity, such as plastic clay, there may be continued permanent deformation under applied loads. Such pavements not only become rough but also continue to get rougher and eventually must be rebuilt or periodically resurfaced without any expectation of ever being adequate for modern traffic. In the same category must be placed those pavements built on soil susceptible to moisture fluctuation or frost action. Such subgrade soils lose their stability periodically and also will be subjected to pumping action in pavements not properly protected against this phenomenon.

Progressive changes of this character would be revealed by subsequent profiles of a selected pavement taken after some significant period of service. Measurement of differences of this kind represent the normal use of the truck-mounted profilometer in the planned research program. This plan requires an initial or basic profile taken, preferably, as soon as the road is built, to which all future profiles could be compared. This means that data of the kind being gathered would not become of value for some period of years, during which successive pavement profiles were being recorded. Although such long-range objectives are very much a part of the present program, the need for immediate information in determination of pavement adequacy and reclassification of Michigan trunkline highways has focused attention on possible value of the roughness measurements that have been made during the first year's operation of the profile truck.

Up to the end of 1958 more than 1,800 mi of pavement profiles have been accumulated, covering some of the main traffic routes within the state and certain projects of special interest from the standpoint of research and design procedure. These data show that there is a wide variation in relative roughness on various roads throughout the state, with differentials which appear to be great enough to serve as a means of identifying

deficiencies in design or in the natural conditions to which the pavement is subjected. However, use of a specific figure in terms of vertical inches of displacement per mile of pavement as a roughness index poses a somewhat different problem than relying on the differential between two successive pavement profiles. In this connection it would be desirable to record actual vertical displacement that could be checked by precise level measurements or some other means so that it represents a definite physical condition rather than simply a relative roughness in empirical terms. Looking at it from this viewpoint, one of the first questions which arises in connection with the recorded pavement profiles is just what it is that the profile truck is measuring. The answer depends primarily on the selection of a datum or zero elevation to which the measured vertical deflections may be referred. For the purpose of explanation, several pavement profiles taken on a test course at Willow Run Airport have been plotted for comparison in Figure 4.

The profile shown as a heavy line is the trace recorded by the profilometer truck. The profile shown as a thin line was computed from elevations taken from levels at intervals of 2½ ft along the test course. The latter profile represents the vertical difference at the recording station at the center of the truck with respect to the average elevation of the bogie wheels in front and 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 ft long. By visual inspection there is reasonably good agreement between the recorded profile and that constructed from the level survey. This does not mean that the cumulative vertical displacement previously defined as the roughness index will necessarily be the same for both of the profiles shown, as there are at least two basic differences in the two methods of measurement which cannot be readily resolved.

In the first place the elevation at reference points at the center of gravity of the bogie wheels is taken with the level rod at a specific point and is subject to pavement irregularities at that point. In the machine-recorded profile the bogie wheels cover an area approximately 1 ft by 3 ft and will reflect the average elevation of four points within that area. Local high and low spots will, in effect, be leveled off. The bogie wheels may be described as selecting a flat surface as a reference plane which would presumably be roughly parallel to the grade line at which the pavement was laid. By introducing more pairs of bogie wheels and extending the area they cover, the more completely would local irregularities be damped out and the more closely would this reference plane approach the pavement grade.

The problem is one of extending the area of reference enough to produce profiles with sufficient accuracy to be reasonably reproducible and reflect significant differentials in position of the pavement surface and still keep the equipment itself within practical limits. Data from pavement profiles analyzed to date indicate that the profilometer equipment as now designed is capable of achieving this objective within practical limits. The second source of difference in recorded vertical displacements and those taken by levels results from the fact that the recorded displacements are those taken with wheels equipped with pneumatic tires. The inflation pressure of these tires is kept constant at 60 psi, but obviously the tires will deflect and further damp out any sharp discontinuities, which may be reflected in the level measurements.

In spite of these differences, it is surprising to find that the cumulative vertical displacement recorded by the profilometer is 12.45 in. in 492.5 ft, or a roughness index of 133 in. per mile, as compared to 13.45 in. in 485 ft, or a roughness index of 146 in. per mile. The

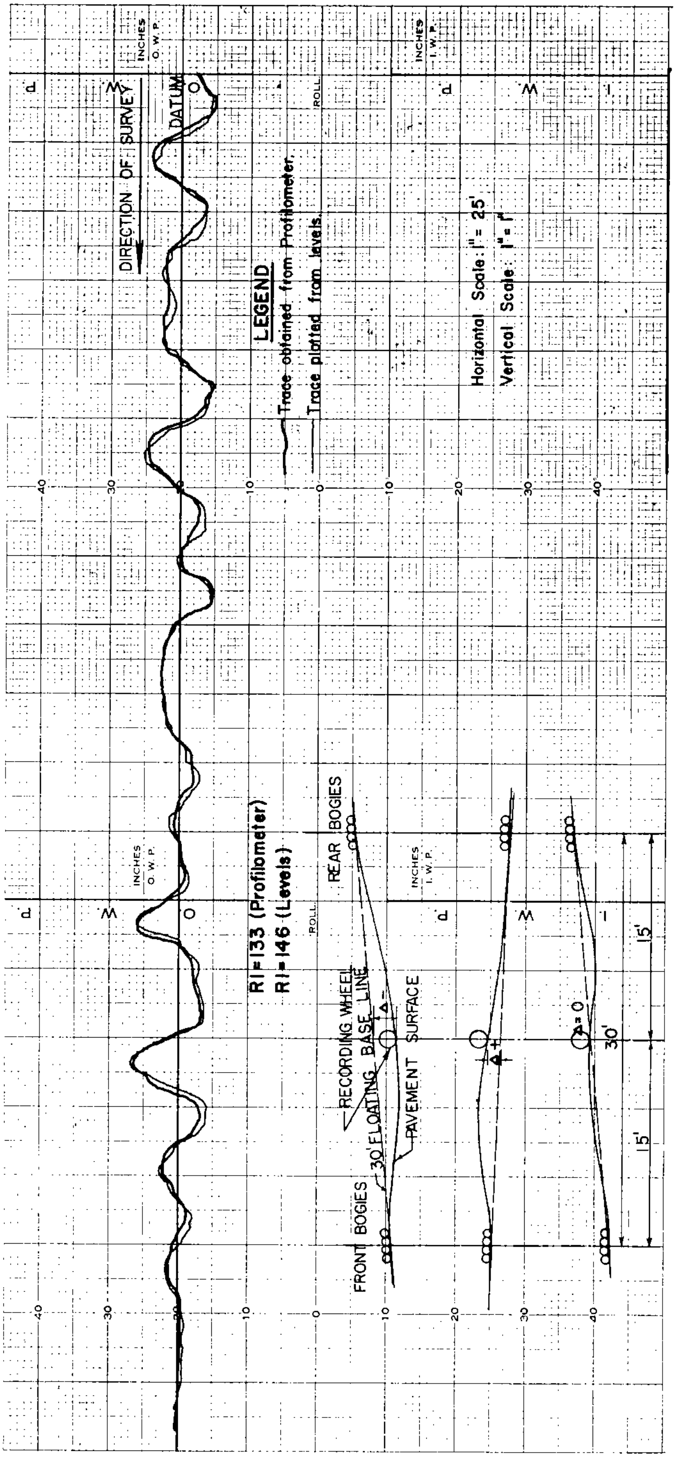


Figure 4. Comparative pavement profile on test course, Willow Run Airport.

question to be answered here with respect to accuracy or validity of results is not which is the more accurate in absolute units of measurement, but which is the more realistic as the measure of pavement roughness. It is considered that either type of measurement is sufficiently accurate to be reproducible within practical limits and that the cumulative vertical displacement recorded by the profilometer is the more representative of pavement roughness experience by pneumatic-tired vehicles using these pavement surfaces.

TABLE 2

TENTATIVE PAVEMENT ROUGHNESS RATING; VERTICAL DISPLACEMENT, INCHES PER MILE

B.P.R. Single-wheel Roughometer [1]	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 mph.
[2] Operated at 4 to 5 mph.

TYPICAL PAVEMENT PROFILES

The primary objective of this report is to present recorded data from projects selected from more than 1,800 mi of available profiles to illustrate the various conditions of service for which the Michigan design standards have been formulated. Examples of pavements have been selected in all four classifications of adequacy and their performance measured in terms of the roughness index and the structural continuity where applicable. In this way it may first be possible to find significant evidence on the relative importance of soil type, drainage, frost action, and other environmental conditions in pavement performance, as compared to the effect of vehicle size and weight and traffic volume.

In the second place, the examples should provide evidence of the reliability and selectivity of pavement profiles as a means of differentiating between adequate and inadequate roads on the basis of service behavior. The data should also provide some idea of the validity of pavement roughness and structural continuity as measures of pavement adequacy and, further, show their value as a means of identifying the factors responsible for variations in behavior.

Attention may now be given to the examples selected for illustration. In reviewing these examples there are several things to be kept in mind as a means of correlating the data on some comparative basis. Table 2 gives tentative roughness ratings 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 in. 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 that follow a definite format. Each chart presents 600 ft of profile in the outer and inner wheel path 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 between the two profiles. It should be kept in mind that vertical displacements are recorded full scale (1 in. = 1 in.), whereas the horizontal distances are to a scale of 1 in. = 25 ft. This results in a 1-to-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 this is given the continuity ratio, the first value being for the pavement as originally constructed, the second being computed for the combination of cracks and joints. In this

connection it should be noted that the continuity ratio is defined in terms of a standard slab length of 15 ft representing a continuity ratio of 1. Thus, an uncracked slab between 100-ft 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 of 15 ft.

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

Rigid Pavements

The first series of charts is for rigid pavements consisting of portland cement concrete, both plain and reinforced, with some of the older pavements covered by a bituminous surface.

Figures 5A and 5B, Class I and Class IV, Rigid. — The two charts shown in Figures 5A and 5B are taken from US 112, one of the older, heavily traveled roads. The pavement profiles in Figure 5A, 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 and 10 years of service on the bituminous resurfacing laid in 1948. The traffic is 4,800 vehicles per day, of which 1,525 are commercial. There are relatively few cracks between the 100-ft joints, with a reduction in continuity ratio of something less than 50 percent since construction in 1926.

The pavement section in Figure 5B, which is only a short distance from the first section, has been in almost continuous trouble since it was built, requiring continuous maintenance with an unusual amount of concrete patching and continued cracking of the old pavement. After being resurfaced with bituminous concrete in 1943, it developed the rough profile shown by a 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, the pavement profile being 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 slab displacements are ironed out and the riding quality recovered. There is a much greater reduction in continuity ratio in 5B, 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 of the cracks in the structural 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 ft apart.

The significant difference in these two sections of pavement lies in the subgrade type and drainage. The pavement giving very good service in Figure 5A falls within a relatively small area of glacial outwash that is predominantly sandy with fair internal drainage. This short stretch of pavement was originally included in a much larger area of Class IV road rated inadequate at all times of the year. Its performance, as indicated by the pavement profile and roughness index, suggested reclassification and this was confirmed by field investigation. The example of Class IV pavement in Figure 5B is also a reclassification on the basis of the pavement profile, this section having been included in an area of Class I pavement due to an error in transposing soil survey data on the pavement evaluation map. Although the classification of subgrade soil accompanied by poor drainage as Class IV is obvious, the error was discovered by a study of the pavement profiles taken over this portion of US 112.

Figures 6A and 6B, Class I and Class IV, Rigid. — The comparisons shown in Figures 6A and 6B again show the dominant influence of subgrade with good performance over the sand subgrade with

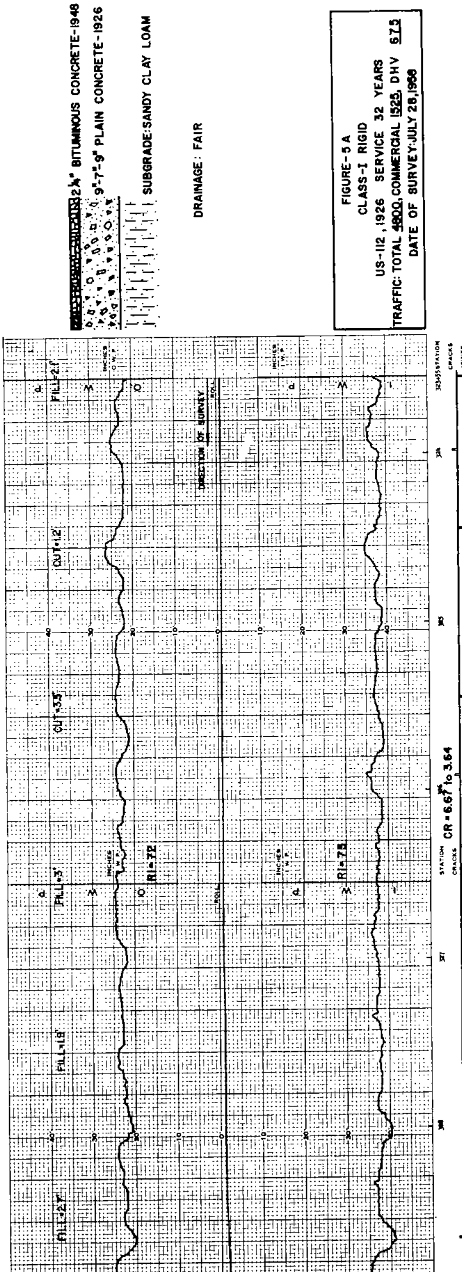


FIGURE-5 A
CLASS-I RIGID
US-112, 1926 SERVICE 32 YEARS
TRAFFIC: TOTAL 4800, COMMERCIAL 1525, DHV 675
DATE OF SURVEY: JULY 28, 1958

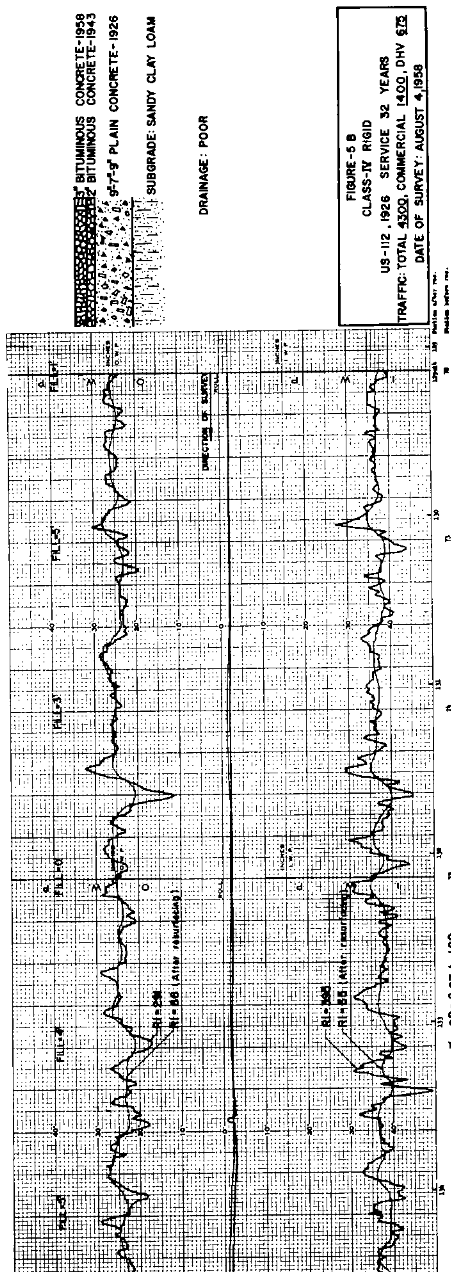
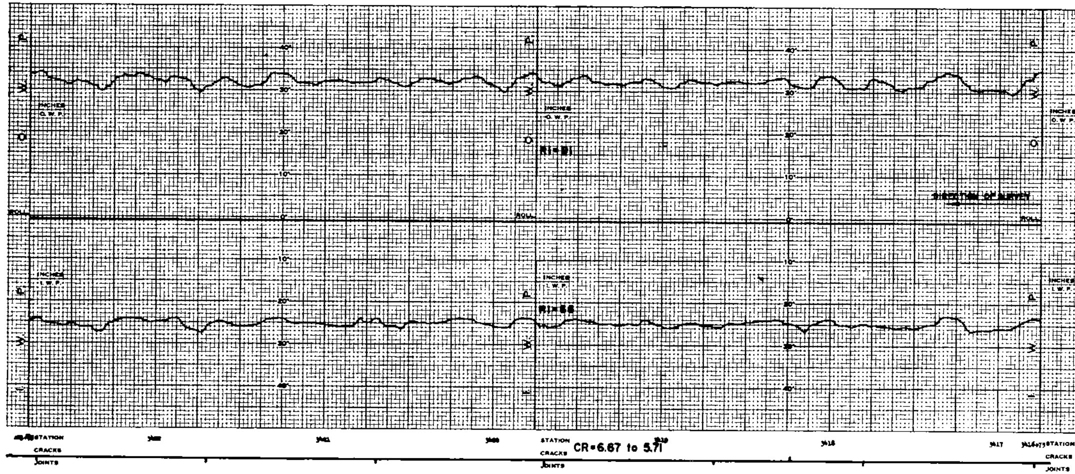


FIGURE-5 B
CLASS-IV RIGID
US-112, 1926 SERVICE 32 YEARS
TRAFFIC: TOTAL 4300, COMMERCIAL 1400, DHV 675
DATE OF SURVEY: AUGUST 4, 1958



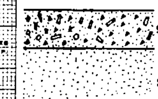
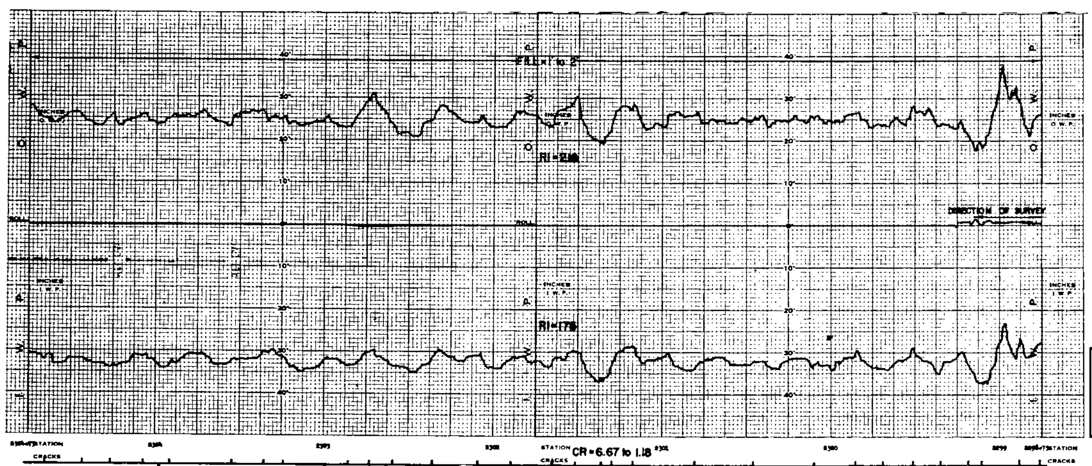


FIGURE-6 A
CLASS-I RIGID
M-25, 1930-31 SERVICE 28 YEARS
TRAFFIC: TOTAL 700, COMMERCIAL 60, DHV 140-150
DATE OF SURVEY: JUNE 5, 1959



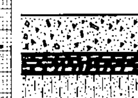


FIGURE-6 B
CLASS-IV RIGID
M-25, 1922-26 SERVICE 36 YEARS
TRAFFIC: TOTAL 1800, COMMERCIAL 310, DHV 350
DATE OF SURVEY: JUNE 6, 1958

excellent drainage and poor performance over the lake bed clay with poor drainage. Other contributing factors may have entered into this difference in behavior in that the good performance is on a reinforced concrete pavement with lighter traffic and a service period of 28 years as compared to the plain concrete pavement over a heavy lake bed clay with poor drainage and 36 years of service under substantially heavier traffic. The poor performance in the latter case is also associated with a marked reduction in continuity ratio, even though the older pavement has the advantage of being laid over an old road of 4 to 5 in. of waterbound macadam. The extra support of this old road probably has enabled this pavement to last over this long period of years under otherwise rather unfavorable conditions. One thing that may be noted in connection with most of the profile charts is the fact that the roughness index of the outer wheel path is generally greater than that of the inner wheel path, a condition which may be either built in at the time of construction or the result of weakness along the free edge of the pavement associated with unpaved shoulders.

Figures 7A and 7B, Class I and Class II, Rigid. — The Class I pavement in Figure 7A is an example of a long period of service on a heavily traveled route where the condition of the pavement is still fair, a condition credited to the superior subgrade of outwash sand with excellent drainage. Although the continuity ratio of this pavement has been substantially reduced by cracking, there is little evidence of faulting at the joints and cracks. The Class II pavement in Figure 7B is an example of the effectiveness of a 12-in. sand subbase in compensating for a natural subgrade that would be rated inferior as a heavy clay with inadequate drainage.

The Class II pavement with a service of only 9 years is included to show the results of two successive profiles taken several months apart with a considerable differential in air temperature. At the time the first profile was run (early October) the weather was mild and the air temperature was 77 F. When the second profile was run (December 4, 1958) there had been a considerable period of freezing weather and the air temperature was 38 F. A comparison of the two profiles given by the heavy line and the light line indicates excellent reproducibility insofar as the profilometer truck is concerned. From the standpoint of pavement performance, it indicates that the temperature differential had produced little difference in the roughness index, although there was a measurable change along the inner wheel path. Although considerably more data would be required to establish the significance of such a small differential in roughness, it may be that the greater roughness at the time of the last survey (and lower temperature) could have been caused by slab curling and greater upward displacement at the joints. Close examination of the two profiles along the inner wheel path indicates that there is some evidence of greater vertical displacement at the joints and cracks at the time of the second survey.

Figures 8A and 8B, Class II Rigid, Plain and Reinforced Concrete. — The two pavement sections shown in Figures 8A and 8B provide a direct comparison between plain and reinforced concrete pavements with other design factors substantially the same. This pavement represents one designed to Michigan's present standards, with 12 in. sand subbase over a clay subgrade, good drainage, and subjected to fairly heavy traffic. Both sections are in excellent condition and would be rated very good or exceptionally smooth, with the slightly better performance in favor of the reinforced concrete. The service life of 11 years is rather short, but is long enough to reveal any serious weakness in the pavement. Structural continuity is still high, with the absence of cracking in the plain concrete a function of the 50-ft slab length as compared to the 100-ft slab length in the reinforced section. In both cases the high-capacity foundation with the 12-in. well-compacted sand subbase is the major factor in the excellent performance of both plain and reinforced sections. The

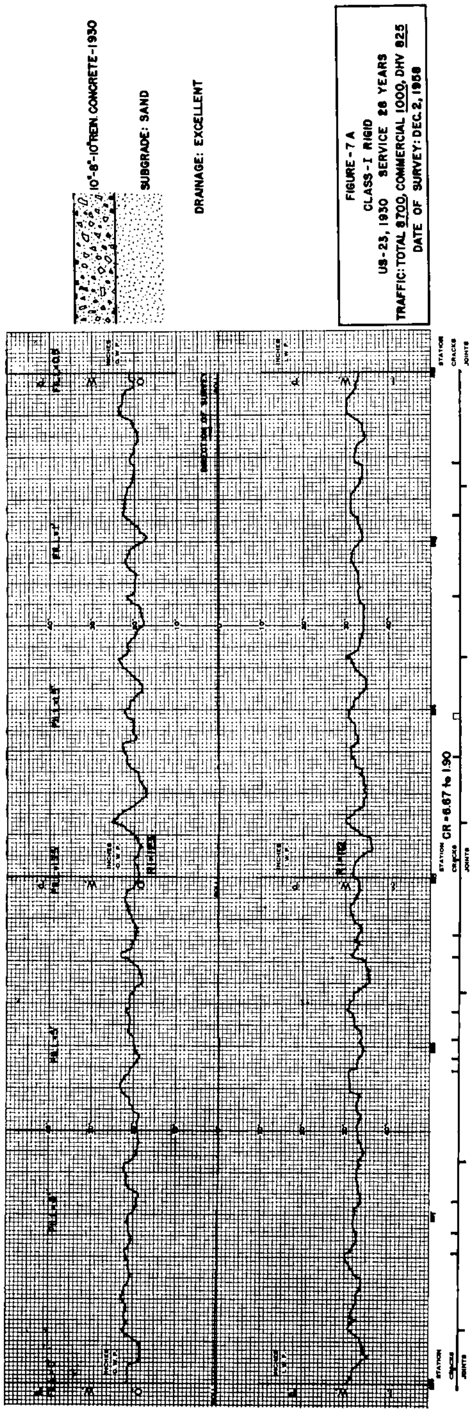


FIGURE-7 A
CLASS-I RIGID
US-23, 1930 SERVICE 28 YEARS
TRAFFIC: TOTAL 8700, COMMERCIAL 1000, DHV 825
DATE OF SURVEY: DEC. 2, 1958

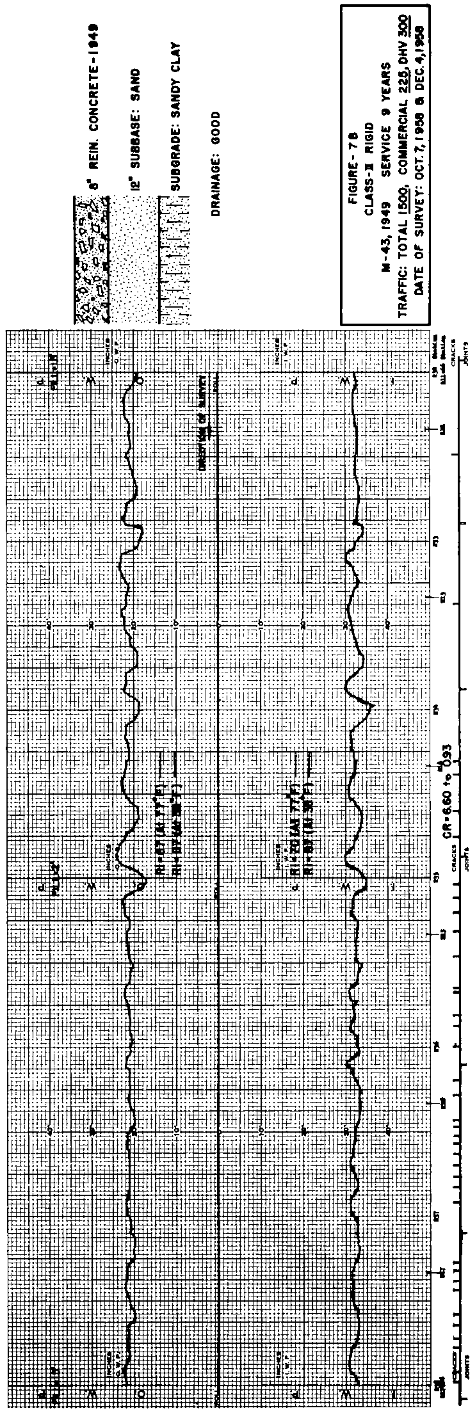


FIGURE-7 B
CLASS-II RIGID
M-43, 1949 SERVICE 9 YEARS
TRAFFIC: TOTAL 1500, COMMERCIAL 225, DHV 300
DATE OF SURVEY: OCT. 7, 1958 & DEC. 4, 1958

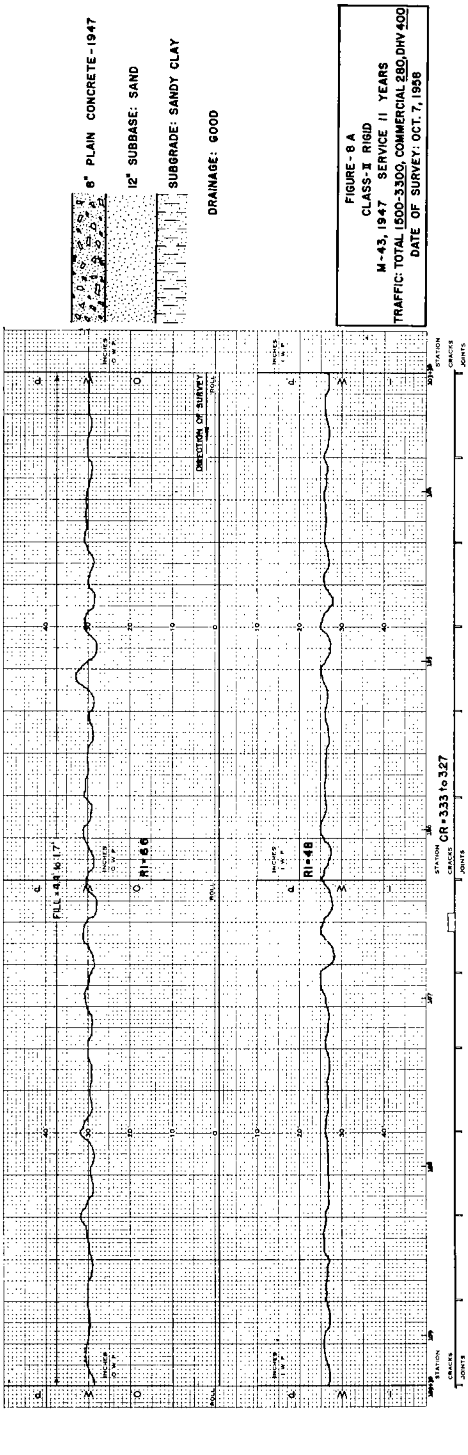


FIGURE-8 A
CLASS-II RIGID
M-43, 1947 SERVICE 11 YEARS
TRAFFIC: TOTAL 1500-3300, COMMERCIAL 280, DHV 400
DATE OF SURVEY: OCT. 7, 1958

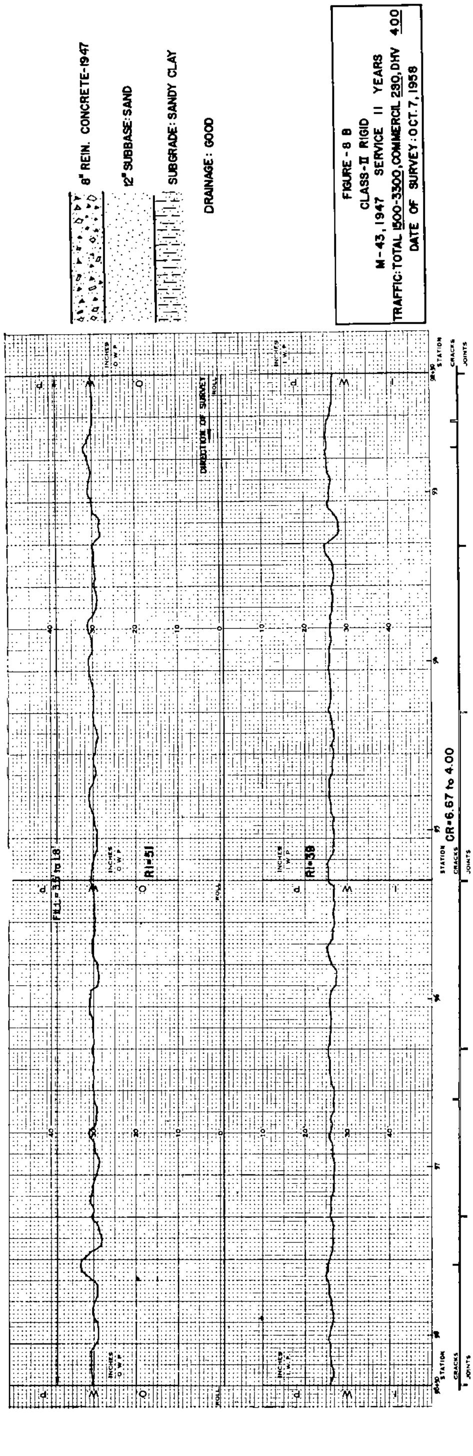


FIGURE-8 B
CLASS-II RIGID
M-43, 1947 SERVICE 11 YEARS
TRAFFIC: TOTAL 1500-3300, COMMERCIL 280, DHV 400
DATE OF SURVEY: OCT. 7, 1958

differential in roughness index is not large, but is probably a measurable difference, being somewhat more than the probable error in recording roughness, although not enough to indicate any marked difference in behavior.

Figures 9A and 9B, Class III and Class II, Rigid.—The two pavements in Figures 9A and 9B differentiate between comparable reinforced concrete pavements on poorly drained clay in Figure 9A and in a deep cut through a sandy glacial moraine in Figure 9B. On the basis of the roughness index the Class III pavement would be rated poor to very poor and the Class II pavement would be rated good. Although there is a considerable difference in the period of service and in the traffic, this is not considered sufficient to be the major factor in service behavior. These two sections were selected as representative of concrete pavements subjected to fairly heavy traffic on important truck routes. The reductions in structural continuity parallel the differences in pavement roughness. (Note that there is probably a reclassification involved in the foregoing, in that the pavement in Figure 9B is on a natural sand subgrade and not a 12-in. sand subbase: State Route 59, Class II both sides of cut.)

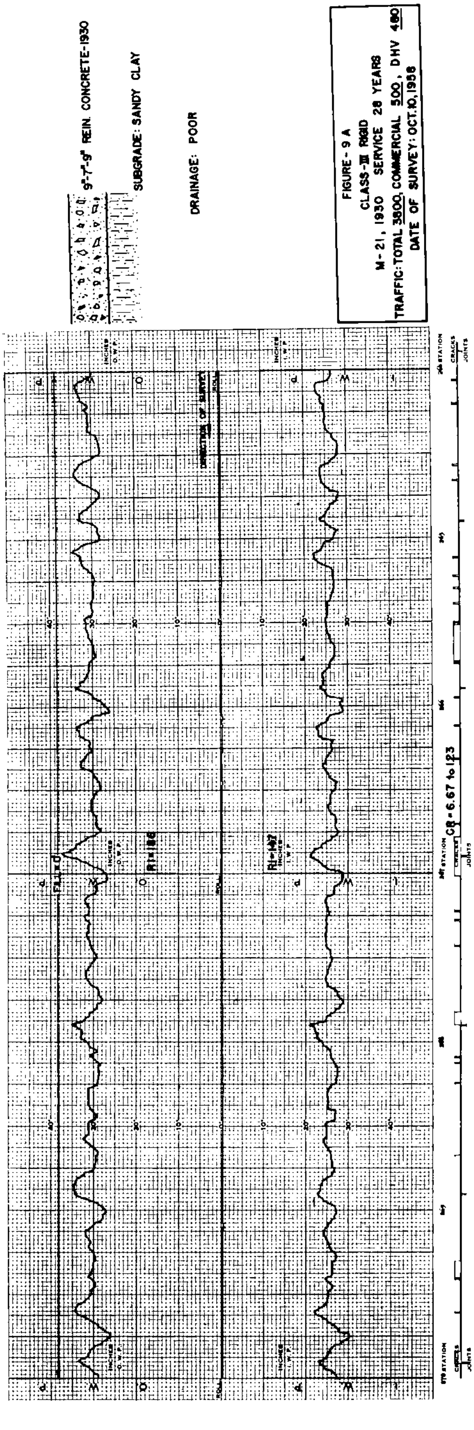
Figures 10A and 10B, Class III, Rigid.—The two pavement sections shown in Figures 10A and 10B make one of the most interesting comparisons provided by the pavement profiles presented in this report. Both sections are taken from US 41, running north out of Menominee into the Upper Peninsula, and are only 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. There is a startling differential in roughness index in these two sections; the rough section is entirely outside the rating scale, whereas the smooth section would be rated good or very good. This contrast is directly the result of a difference in subgrade soil and drainage. The rough section is a swamp fill following peat excavation, the backfill material being a heavy sandy loam. The water table is close to the surface and in this area of deep frost penetration the combination of circumstances promotes severe frost action. The smooth section, on the other hand, is on a sidehill cut and fill, the subgrade material being a light sandy loam sufficiently granular to supply more adequate internal drainage. This, in combination with the sidehill surface drainage, has produced very good performance over a service period of 22 years. Similar differentials are shown in the change in structural continuity, although to some extent the small amount of cracking in the good section is the result of the 30-ft joint spacing.

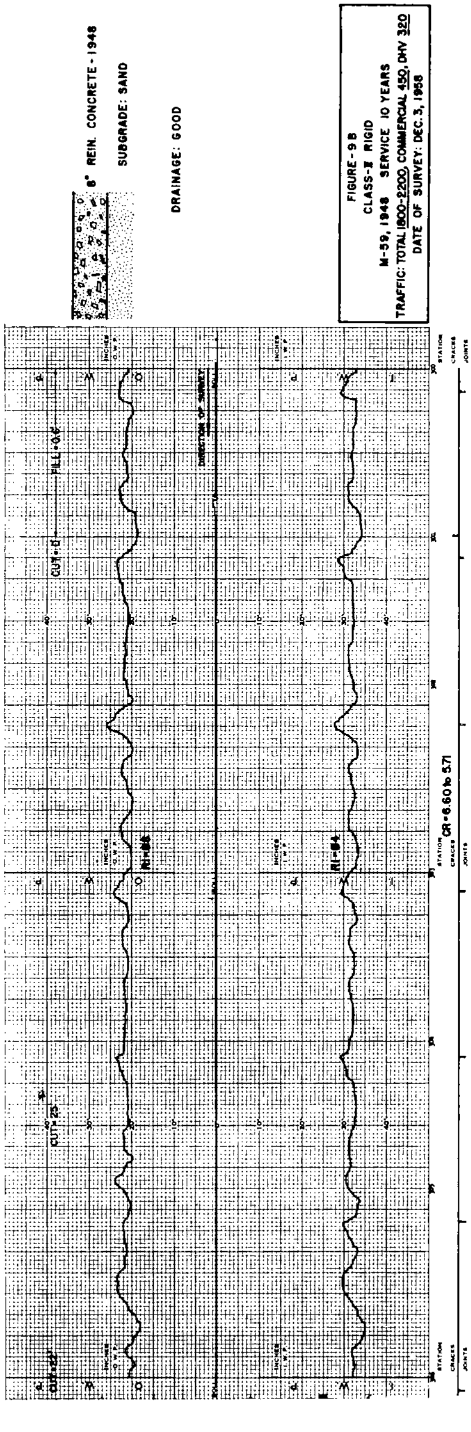
Flexible Pavements

As part of the pavement performance surveys conducted during 1958 it was arranged to obtain typical profiles of the four different classifications of flexible pavement for comparison with the rigid-type pavement and to test the applicability of pavement profile surveys and pavement roughness as measures of performance.

Figures 11A and 11B, Class I, Flexible Pavement.—The two pavement sections shown in Figures 11A and 11B are representative of high-type bituminous construction, which on the basis of performance is being given increased consideration in the state. Figure 11A has a service period of only 3 years, but the subgrade and structural components of the pavement are so closely similar to the pavement section in Figure 11B that they should give comparable performance over longer periods of time. Both are on superior subgrades of sand outwash with excellent drainage characteristics. In both cases the gravel bases were constructed first and subjected to traffic for a sufficient period to be thoroughly compacted before adding the bituminous wearing course.

In terms of riding quality, both would be rated as exceptionally smooth, indicating excellent construction practice as well as completely adequate carrying capacity. It may also be pointed out that


9"-7"-9" REIN. CONCRETE-1930
SUBGRADE: SANDY CLAY
DRAINAGE: POOR
FIGURE - 9 A
CLASS-III RIGID
M-21, 1930 SERVICE 28 YEARS
TRAFFIC: TOTAL 3800, COMMERCIAL 500, DHV 480
DATE OF SURVEY: OCT.10,1958
DIRECTION OF SURVEY


8" REIN. CONCRETE - 1948
SUBGRADE: SAND
DRAINAGE: GOOD
FIGURE - 9 B
CLASS-II RIGID
M-59, 1948 SERVICE 10 YEARS
TRAFFIC: TOTAL 1800-2200, COMMERCIAL 450, DHV 320
DATE OF SURVEY: DEC.3, 1958
DIRECTION OF SURVEY

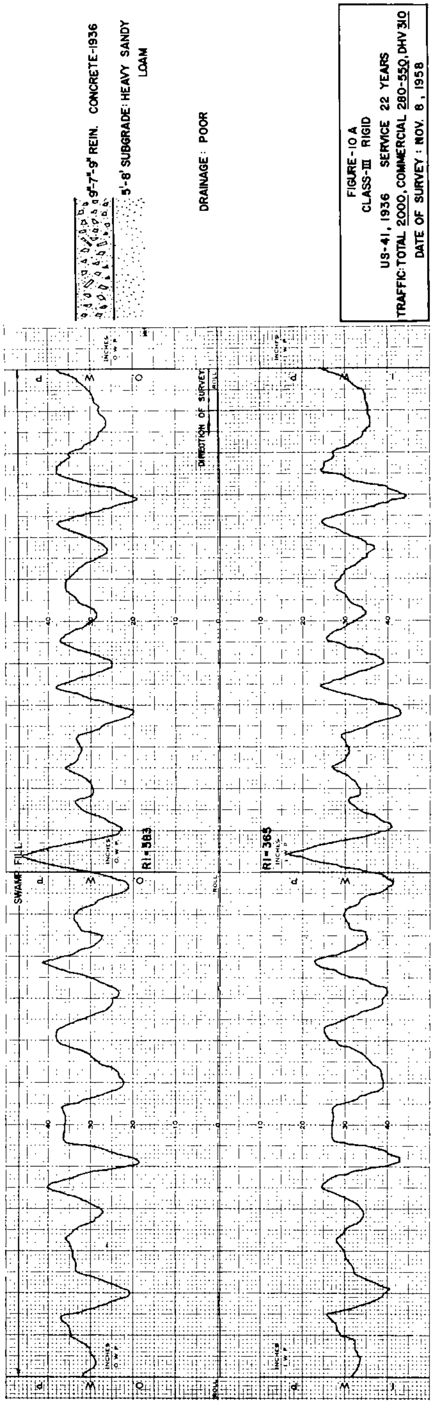


FIGURE-10 A
CLASS-III RIGID
US-41, 1936 SERVICE 22 YEARS
TRAFFIC: TOTAL 2000, COMMERCIAL 280-550, DHV 310
DATE OF SURVEY: NOV. 8, 1958

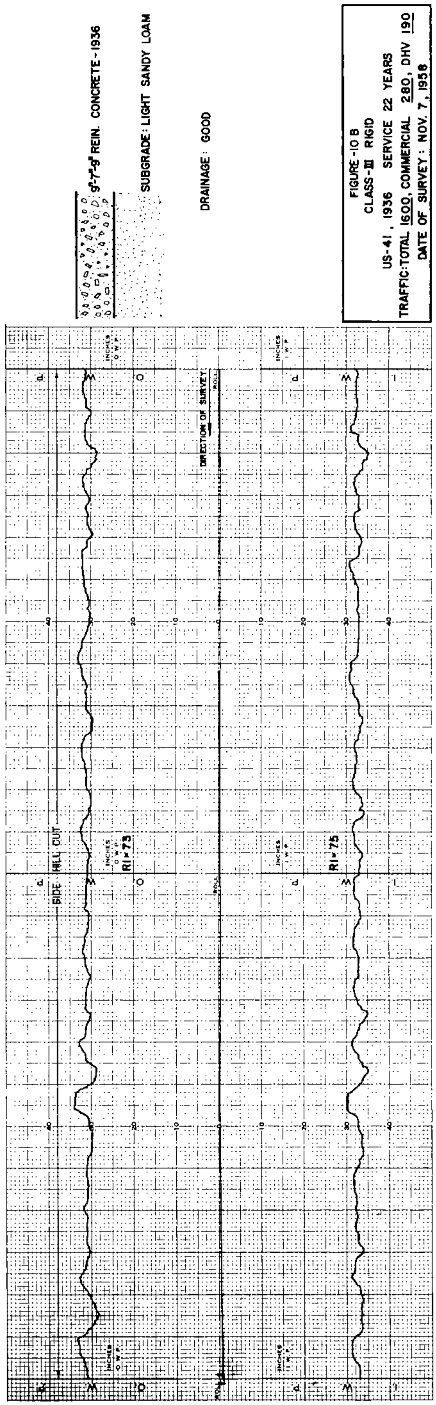


FIGURE-10 B
CLASS-III RIGID
US-41, 1936 SERVICE 22 YEARS
TRAFFIC: TOTAL 1600, COMMERCIAL 280, DHV 190
DATE OF SURVEY: NOV. 7, 1958

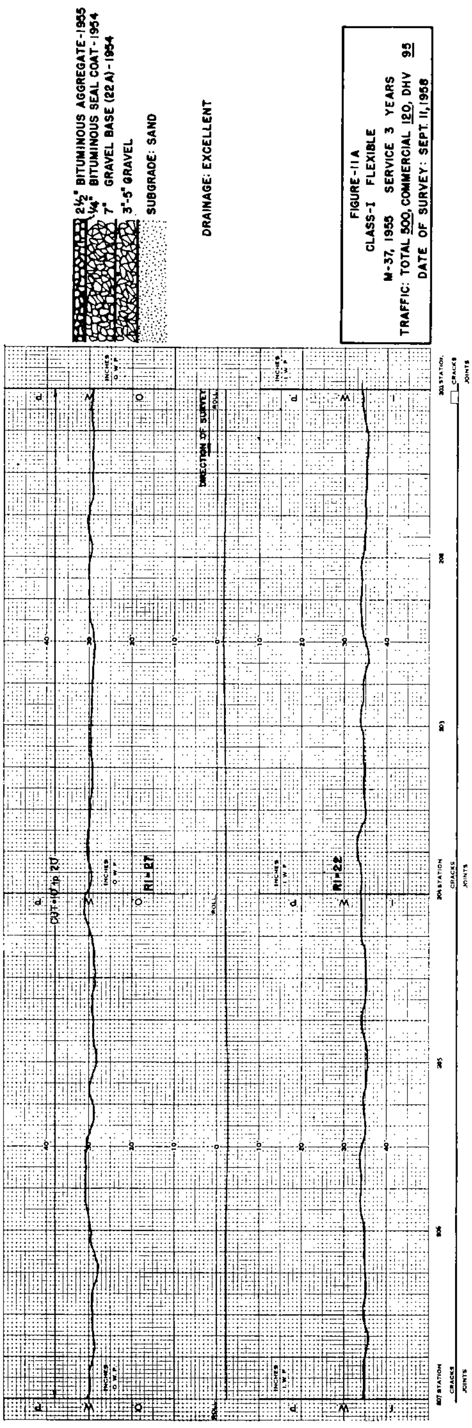


FIGURE-11A
CLASS-I FLEXIBLE
M-37, 1955 SERVICE 3 YEARS
TRAFFIC: TOTAL 500, COMMERCIAL 120, DHV 95
DATE OF SURVEY: SEPT. 11, 1958

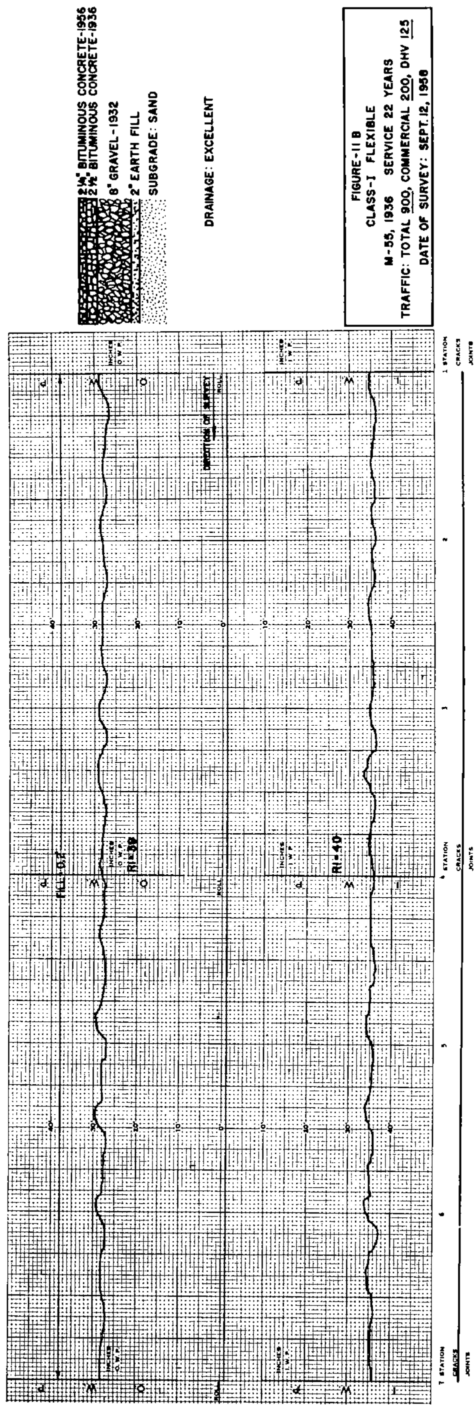


FIGURE-11 B
CLASS-I FLEXIBLE
M-55, 1936 SERVICE 22 YEARS
TRAFFIC: TOTAL 900, COMMERCIAL 200, DHV 125
DATE OF SURVEY: SEPT. 12, 1958

subgrade stabilization (in one case with earth fill and in the other case with stabilized gravel) was employed to assist in 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; the pavement in Figure 11B, with a service period of 22 years, was resurfaced in 1956 because over a period of 20 years, surface abrasion and hardening of bituminous material had produced a fragile surface that had to be either sealed or resurfaced. This, combined with the necessity for widening the road from 20 to 22 ft, led to the use of the 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 reflected in increased pavement roughness.

Figures 12A and 12B, Class II, Flexible. — The two pavement sections in the Class II category have been selected from those roads built in comparatively recent years under the design practice of supplying a minimum 12-in. sand subbase over inadequate subgrades. With the raise in grade and the good internal drainage of the sand subbase, drainage conditions were changed from inadequate to good or fair. The service behavior of these pavements as measured by the roughness index is exceptional to very good. Traffic is fairly heavy on both routes and the service periods of 6 and 9 years are rather short, but sufficient to expose any serious weakness in these pavements. The section of M-57 (Fig. 12A) was part of a betterment program of an old road which had proved to be completely inadequate under increasing traffic to which it was being subjected. The section of M-50 (Fig. 12B) is also an old road which was going through a similar experience, but the selected profile happens to be on a relocation so has been built over the original natural subgrade. Although it has maintained very good riding quality, there is more evidence of permanent displacement and a considerable amount of patching in the latter pavement, probably due to the longer service period and the substantially heavier traffic.

Figure 13A and 13B, Class III, Flexible. — The two sections of pavement in Figures 13A and 13B are taken from the same road, M-100, in a section which has presented something of a problem over the years of increasing traffic. Because of weak sections in the road it has been rated as Class III, inadequate during the Spring breakup period. However, the pavement profile surveys generally indicate that some reclassification would be justified. The addition in 1953 of a 12-in. subbase and a flexible pavement with a bituminous wearing course over the old road would appear to justify at least a Class II rating; the performance over a service period of 5 years with a roughness index of 34 and 40 would, in terms of riding quality, be rated as exceptionally smooth. One of the weak sections that had been the source of difficulty was selected as the example in Figure 13B and represents the poor performance in a comparatively short stretch. The reason for this is obvious, as this section was built over a peat swamp under the old road, and the peat has never been removed, resulting in surface subsidence followed by extensive bituminous patching, a combination which falls far short of producing the satisfactory riding quality. The basic difficulty is permanent; as long as the unstable peat is not removed, no amount of strengthening of the pavement will correct the defect. However, with the greater portion of this road giving quite satisfactory service, it would appear that reclassification is justified, accepting that the section over the peat swamp will always have to be provided with whatever maintenance is necessary to maintain a usable pavement.

Figures 14A and 14B, Class IV, Flexible. — The pavement sections shown in Figures 14A and 14B supply another

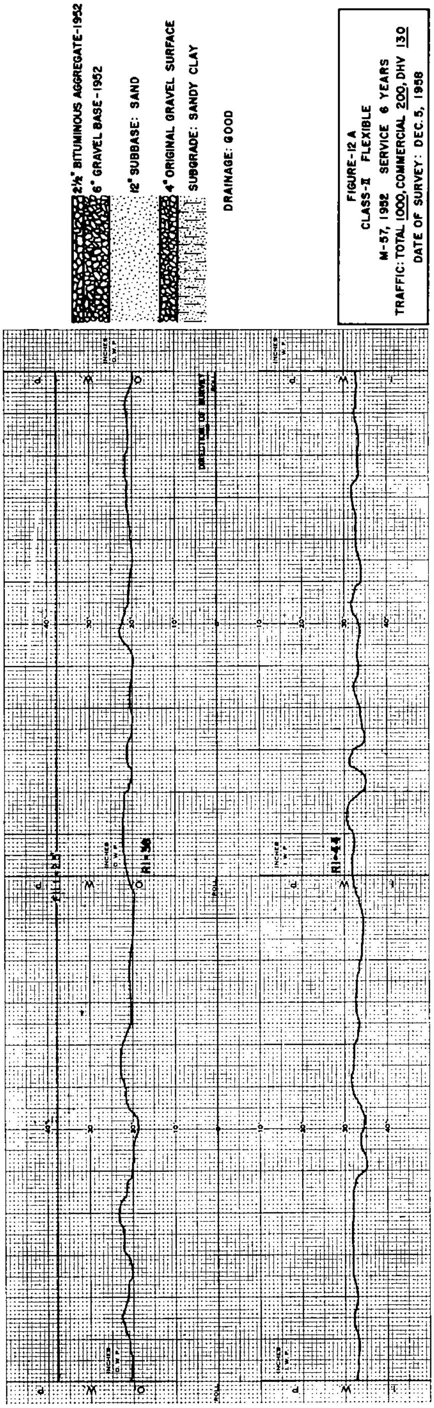


FIGURE-12 A
CLASS-II FLEXIBLE
M-57, 1952 SERVICE 6 YEARS
TRAFFIC: TOTAL 1000, COMMERCIAL 200, DHV 130
DATE OF SURVEY: DEC. 5, 1958

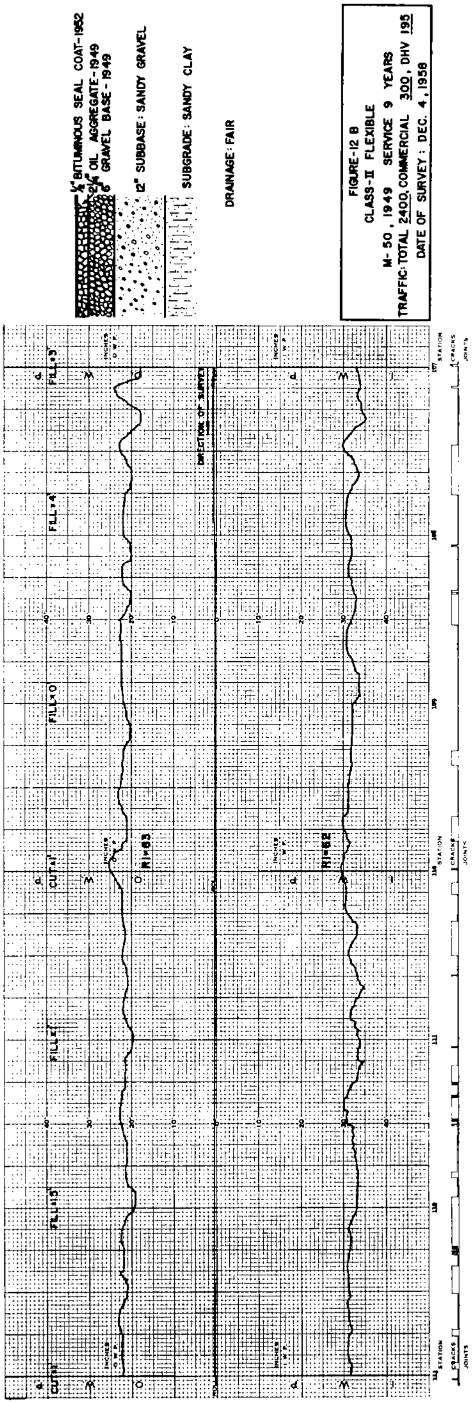


FIGURE-12 B
CLASS-II FLEXIBLE
M-50, 1949 SERVICE 9 YEARS
TRAFFIC: TOTAL 2400, COMMERCIAL 300, DHV 195
DATE OF SURVEY: DEC. 4, 1958

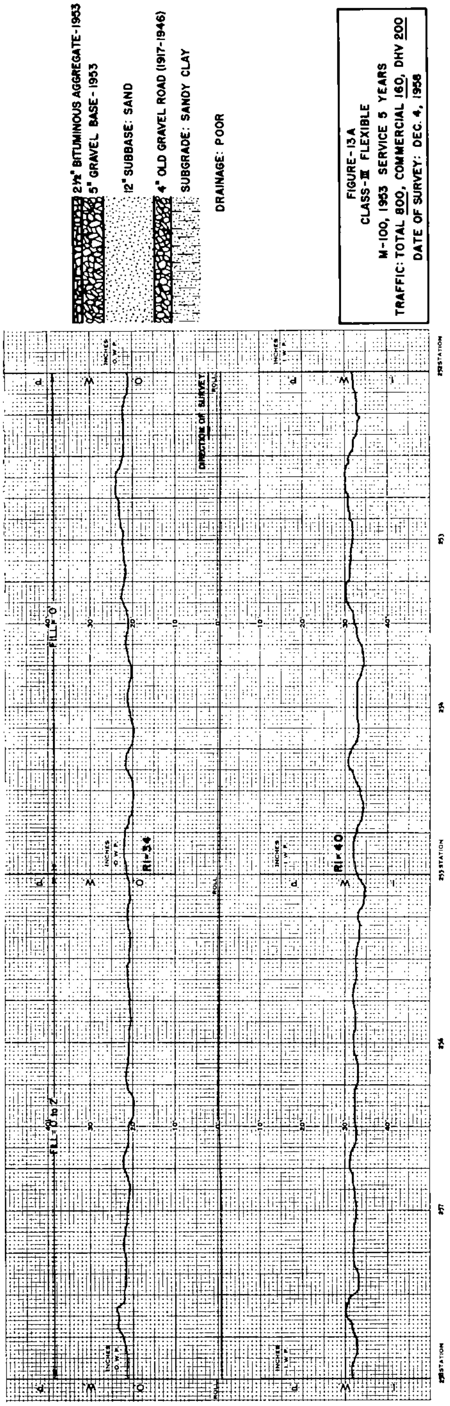


FIGURE-13A
CLASS-III FLEXIBLE
M-100, 1953 SERVICE 5 YEARS
TRAFFIC: TOTAL 800, COMMERCIAL 160, DHV 200
DATE OF SURVEY: DEC. 4, 1958

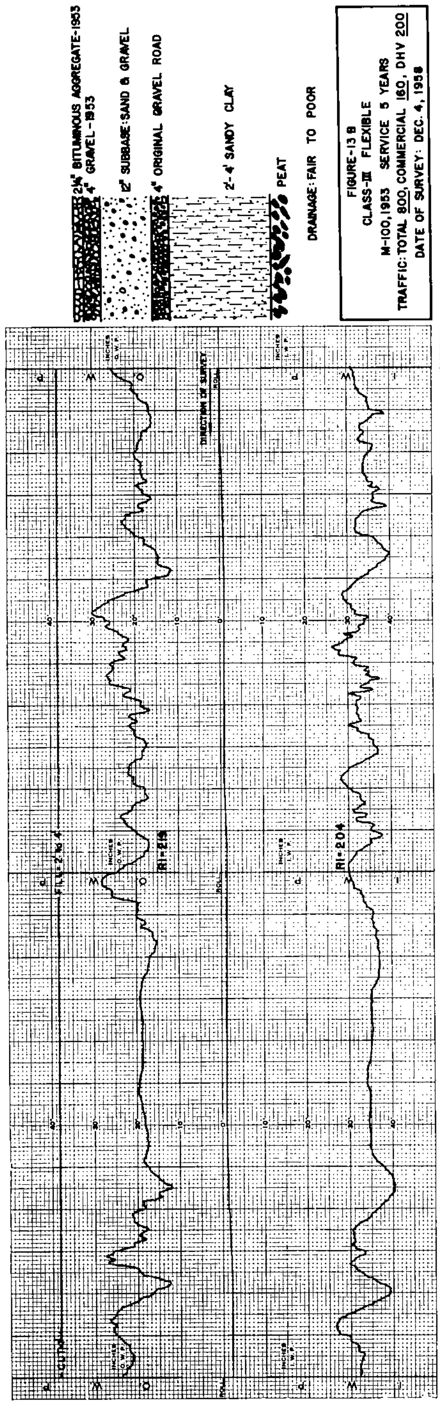
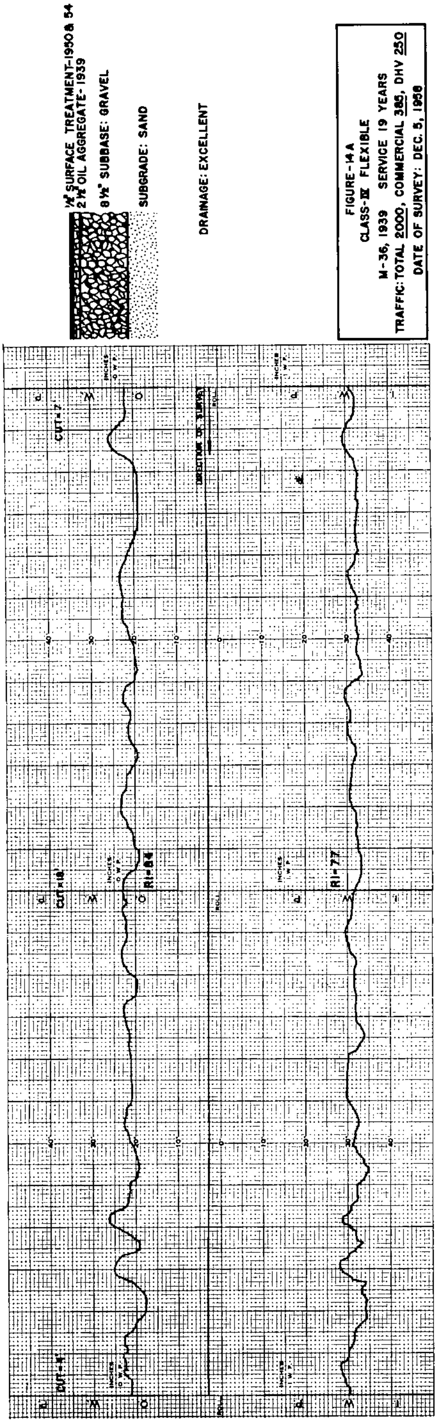
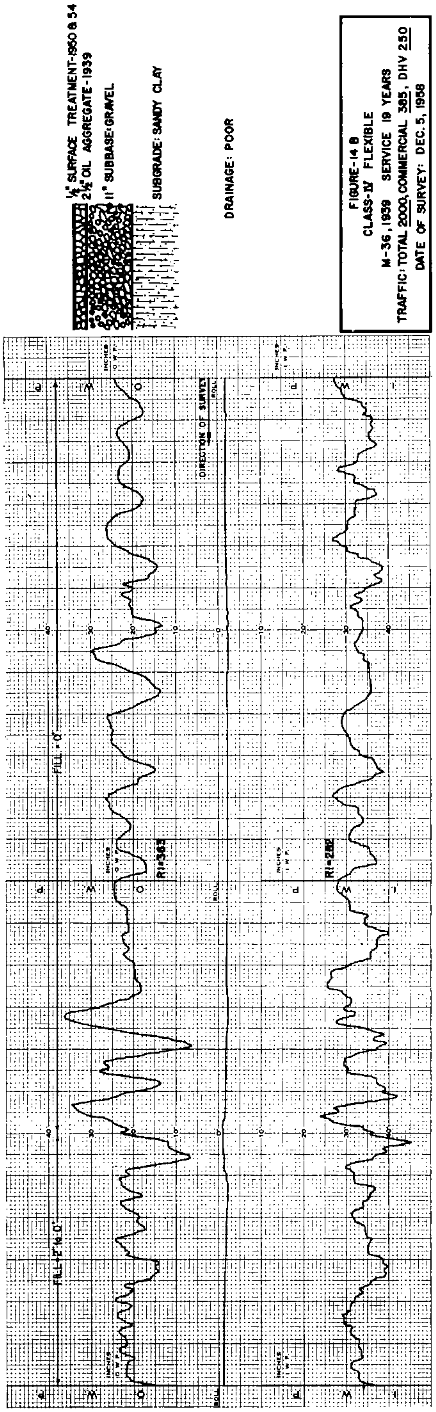


FIGURE-13 B
CLASS-III FLEXIBLE
M-100, 1953 SERVICE 5 YEARS
TRAFFIC: TOTAL 800, COMMERCIAL 160, DHV 200
DATE OF SURVEY: DEC. 4, 1958


1/2" SURFACE TREATMENT-1950 & 54
2 1/2" OIL AGGREGATE-1939
8 1/2" SUBBASE: GRAVEL
SUBGRADE: SAND
DRAINAGE: EXCELLENT
FIGURE-14 A
M-36, 1939 SERVICE 19 YEARS
TRAFFIC: TOTAL 2000, COMMERCIAL 385, DHV 250
DATE OF SURVEY: DEC. 5, 1958
CUT-7
DIRECTION OF SURVEY
RI=84
RI=77


1/2" SURFACE TREATMENT-1950 & 54
2 1/2" OIL AGGREGATE-1939
11" SUBBASE: GRAVEL
SUBGRADE: SANDY CLAY
DRAINAGE: POOR
FIGURE-14 B
CLASS-IV FLEXIBLE
M-36, 1939 SERVICE 19 YEARS
TRAFFIC: TOTAL 2000, COMMERCIAL 385, DHV 250
DATE OF SURVEY: DEC. 5, 1958
DIRECTION OF SURVEY
FILL-0'

study in contrast of two sections taken from the same road just a few miles apart. Through this area this road has been rated Class IV, inadequate at all times of the year on the basis of visual inspection and general performance. It is an old road built over a period of years by county forces, and later State Highway Department forces when the road was taken over as a trunk line. 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 some new words would have to be added to the rating table for 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

Three final examples have been selected to present some special pavement sections for which the profile data have particular interest.

Figures 15 and 10B.—The pavement in Figure 15 is of particular interest because it represents the effect of short 20-ft slabs 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 a 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-in. sand subbase was added on top of the grade to protect the 9-in. plain concrete from quite certain pumping action. The small reduction in continuity ratio indicates that the crack control was excellent, but the riding quality produced was still outside the tentative roughness scale. However, the most interesting feature on this pavement is the characteristic saw-tooth pattern that has been produced by the tilting and faulting of the short slabs, illustrating another valuable type of information from pavement profiles. From the standpoint of design the absence of load transfer at the joints is probably the critical weakness. For purposes of comparison the results shown in Figure 15 can be compared with Figure 10B, the smooth section in US 41 where there are 30-ft joints, but with load transfer provided. Expansion joints at 60 ft are supplied with a Trans-Lode expansion joint base and the reinforcing is carried through the 30-ft dummy joints.

Figures 16A and 16B.—The last two pavement sections (Figs. 16A and 16B) are examples of new pavements constructed in 1958, with profiles that give some measure of the high quality of the pavement construction being produced. Figure 16A is on a divided-lane highway (M-20, between Bay City and Midland) with a 12-in. granular subbase consisting of 9 in. of sand and 3 in. of selected gravel used as subgrade stabilization. This pavement would be rated as exceptionally smooth, with roughness indexes of 40 and 27 in the two wheel tracks. Figure 16B is an example of a heavy-duty flexible pavement constructed on the Muskegon-Grand Haven expressway and 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 profile 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.

CONCLUSION

The studies described in this paper were undertaken in the belief that some

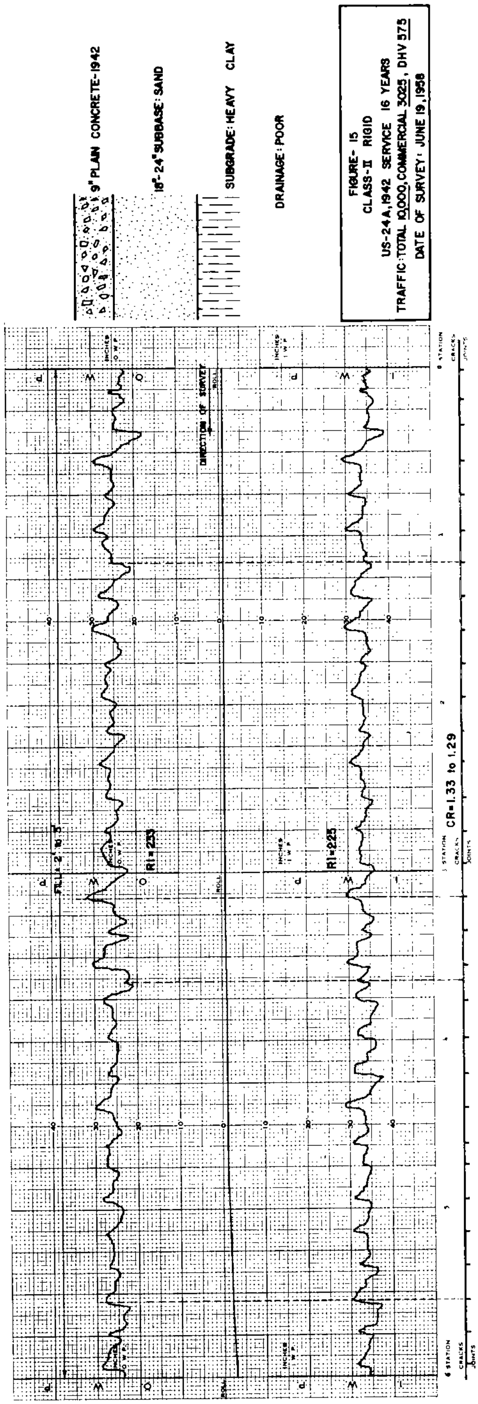


FIGURE-15
CLASS-II RIGID
US-24A, 1942 SERVICE 16 YEARS
TRAFFIC: TOTAL 10,000, COMMERCIAL 3025, DHV 575
DATE OF SURVEY: JUNE 19, 1958

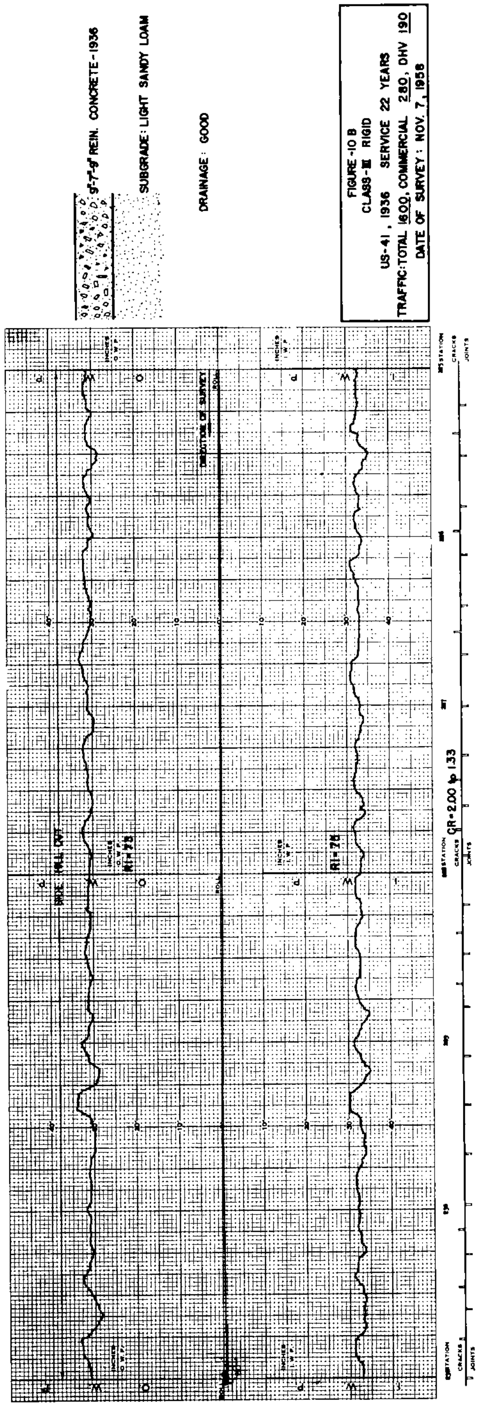


FIGURE-10 B
CLASS-III RIGID
US-41, 1936 SERVICE 22 YEARS
TRAFFIC: TOTAL 1600, COMMERCIAL 280, DHV 190
DATE OF SURVEY: NOV. 7, 1958

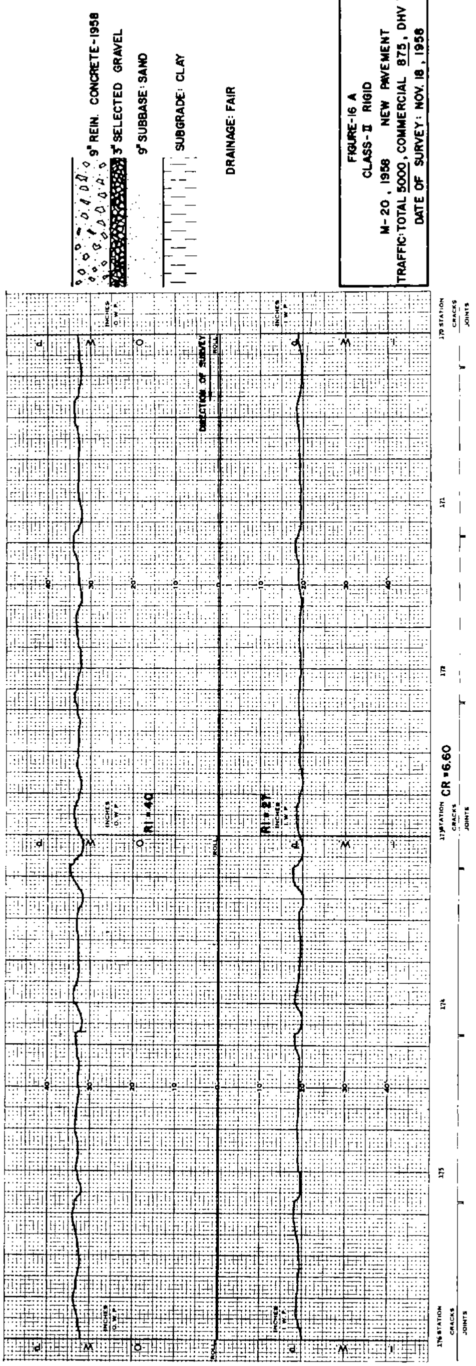


FIGURE-16 A
CLASS-II RIGID
M-20, 1958 NEW PAVEMENT
TRAFFIC: TOTAL 5000, COMMERCIAL 875, DHV 785
DATE OF SURVEY: NOV. 18, 1958

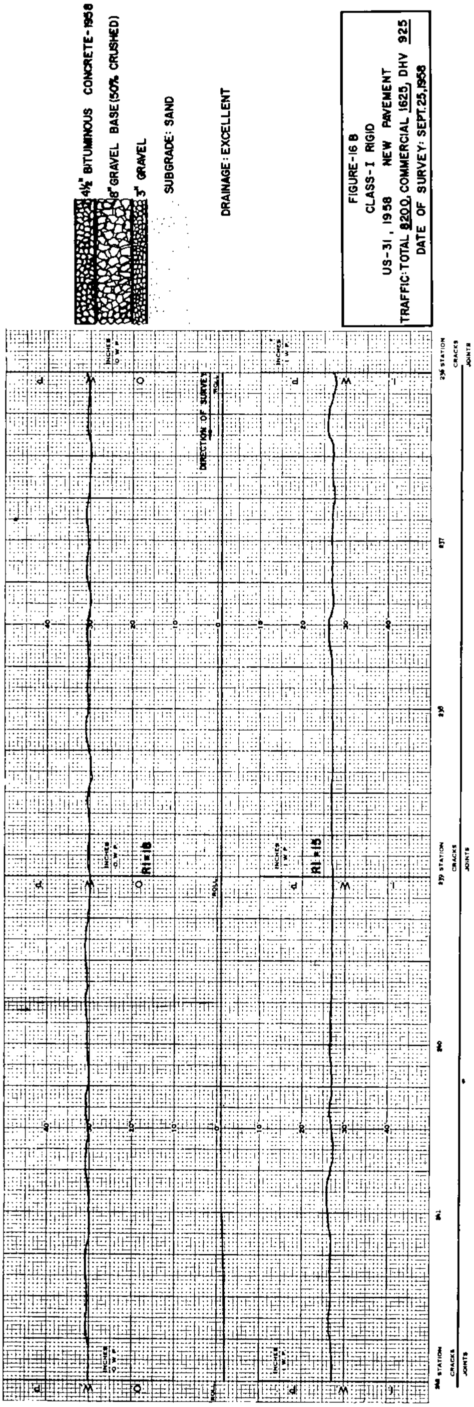


FIGURE-16 B
CLASS-I RIGID
US-31, 1958 NEW PAVEMENT
TRAFFIC: TOTAL 8200, COMMERCIAL 1625, DHV 925
DATE OF SURVEY: SEPT. 25, 1958

of the perplexing problems in pavement design could be most effectively resolved by a searching examination and careful analysis of existing roads in their natural environment and under normal conditions of traffic and loading. It was further felt that these roads already subjected to years of actual service would reflect relative strength or weakness of the total pavement structure in a way that could not be duplicated in any short period of time under simulated service conditions.

The major problems presented by such an investigation were (a) to select some basis for evaluating pavement adequacy, and (b) to devise procedures and design and build equipment for observing and recording whatever quantitative measures had been selected. Guided by the results of previous investigation, the present project has now been in progress for a little more than a year. The truck profilometer has been designed and built and more than 1,800 miles of pavement profile have been run.

Another phase of the investigation — the 30-year development of Michigan pavement design standards from pavement performance surveys — has been reviewed and recapitulated in an integrated adequacy evaluation of the state trunkline system. As a direct result of this evaluation, Spring load restrictions were relieved in 1958 on a network of about 50 percent of the state trunkline system. This action saved for industry and agriculture a substantial part of an estimated annual cost of load restriction amounting to some $20,000,000. The studies of pavement design standards and performance surveys have been combined to focus the objective of the program on more accurate classification and more precise measures of pavement performance.

The examples presented seem to indicate that a reasonably accurate pavement profile does reveal the direct correlation between service behavior under normal traffic and loading, and soil conditions, drainage and climatic environment, with quite unmistakable clarity, and serves to identify those factors responsible for differences in behavior.

The measurement of pavement roughness by the profilometer equipment used appears to be sufficiently accurate to provide a satisfactory degree of reproducibility and measures significant differentials in the pavement profile as distinguished from normal experimental error.

The correlation between pavement roughness and the structural continuity of rigid pavements appears to be consistent and mutually supporting as a measure of pavement performance and the quantitative values associated with these two factors do reflect the influence of controlling variables in service behavior.

REFERENCES

1. Hogentogler, C. A., Mullis, I. B., and Benkelman, A. C., "Subgrade Studies of the U.S. Bureau of Public Roads." *HRB Proc.,* 6:113 (1926).
2. Burton, V. R., "Survey of Soils and Pavement Condition in Progress in Michigan." *Pub. Roads,* 7:No. 4 (Aug. 1926).
3. McLaughlin, W. W., and Stokstad, O. L., "Design of Flexible Surfaces in Michigan." *HRB Proc.,* 26:39 (1946).
4. Housel, W. S., "Report on the Evaluation of Service Behavior of Plain vs. Reinforced Concrete Pavement." Univ. of Michigan Research Inst. Report 2053-1-S, for Wire Reinforcement Inst. (May 1954).
5. Housel, W. S., "Pavement Performance as Related to Design." Proc. 4th Ann. Michigan Highway Conf., Univ. of Michigan (1955).

DISCUSSION

F. N. Hveem and Bailey Tremper, *respectively Materials Research Engineer and Supervising Materials and Research Engineer, California Division of Highways.* — This paper covers a considerable scope and for purposes of discussion

may be divided into two parts: (a) the program of pavement evaluation being conducted throughout the state of Michigan, and (b) the use of a special profilometer for securing a graphical record and numerical evaluation of the surface roughness of the pavements. These comments are confined largely to the use of the profilometer and the information which may be secured by such an instrument.

As stated by Professor Housel, the Michigan instrument is patterned after the one now in use in California, which has been in operation for the last four years. Although there are some differences in detail, the electronic circuits and principles of operation are virtually identical. The principal differences are that the Michigan machine has a 30-ft base line whereas the base of the California machine is 25 ft. Whether or not this would make any perceptible difference in the profiles if both were operated over the same stretch of pavement is debatable. Preliminary trials in California using the hand-operated machines having 15-, 20-, and 25-ft wheelbases did not indicate any major differences in the recorded profile between the 20- and 25-ft machines.

Another difference is that the Michigan machine is arranged to record profiles simultaneously in two wheel paths. The California machine is capable of making dual recordings, but so far only one set of bogie wheels has been constructed and these may be attached to either side of the truck frame as desired.

The Michigan machine also records a trace indicating variations in the tilt or roll of the vehicle due to differences in relative elevation between the outer and inner wheel paths. Such a device has been under consideration for some time, but has not yet been added to the California machine. It would be helpful if the record of roll as produced on the Michigan machine were displayed in larger scale and possibly with greater sensitivity, so that the discomforting variations in tilt in short distances longitudinally would be shown more prominently.

Also, the Michigan machine uses a counting device for totalizing the upward or downward displacement due to pavement irregularities and this total is recorded at preselected intervals on the chart. The California machine does not yet have such an integrator.

In all other respects, the basic principles of detecting, transmitting, and recording the surface deviations, and the electronic circuits and mechanism by which the graph is produced, appear to be identical on the two machines. It may be pertinent therefore to discuss some of the considerations and purposes which influenced the design of the original profilographs constructed in California.

The recorded trace or profilogram showing the intimate detail of pavement surface irregularities can be used for at least three different purposes, as follows:

1. To provide an index of pavement performance as related to time, traffic volume, weight of wheel loads, type of subgrade support, and design of pavement.

2. To furnish a realistic standard by which to specify surface smoothness at the time of construction.

3. To provide an index of pavement riding qualities as they may affect the occupants of a motor vehicle.

These are three quite different objectives and each requires some special consideration in the design of the instrument and in the type of record produced.

Purpose 1 represents the principal aspect which the authors have discussed in their report. Such a survey means that a considerable mileage of pavement must be recorded and mobility of the apparatus is essential: on heavily-traveled highways, safety of the operator becomes a prime consideration.

For purposes of studying performance of pavements, there is no substitute for a visual inspection of the graph record. Examination of profilograph records brings out quite clearly that there is a wide variety in the shape of the "bumps" or irregularities. Because of the mass of detail which must be studied, there is a strong temptation for the engineer to adopt some sort of numerical scale to

express road roughness. It is a fairly simple matter to equip any of these devices with a counter, actuated through an overrunning clutch, which will summarize all of the movements in one direction. The engineer also likes to have a number to be used in reports or for conversation purposes in describing different pavement conditions. Unfortunately, a simple system of roughness numbers cannot differentiate between the various types of roughness and throws little or no light on the causes or mechanism. It is therefore strongly urged that roughness numbers should be used with caution, especially for the purpose of diagnosing the causes for pavement weakness which produce a change in the profile.

The second use to which profile records may be put—namely, establishing standards for construction—is somewhat less exacting. Here it is not often necessary to check substantial lengths of pavement at one time and when dealing with newly placed concrete pavement a lightweight hand-operated unit becomes the most practical device. Also, expressing the surface inequalities by means of a number has fewer objections as newly constructed pavements do not usually display the variety of surface contours that may be developed in older pavements under traffic. An examination of California pavements employing the jury system of rating indicates that there was usually good agreement as to which pavements were smooth, fair, or definitely rough.

Attempts to establish a numerical classification for profilograms representing pavements in the different categories led to the conclusion that a profilogram that does not deviate from a straight line more than 0.1 in., plus or minus, represents a pavement that is to all intents and purposes perfectly smooth for modern pneumatic-tired vehicle traffic. Therefore, a "profile index" was established by simply summarizing the height of the projections above or below a band 0.2 in. in width. In practice, a scribed transparent overlay representing 0.1 mi in length of pavement is placed on the profilogram. The central band 0.2 in. in width is made opaque. The overlay is adjusted to blank out as much of the trace as possible. Each visible deviation of the trace, whether above or below the blanking band, is then measured to the nearest 0.05 in. The total of these deviations expressed in terms of inches per mile is reported as the profile index. In California many new pavements, either of asphalt or concrete, have been constructed with current methods to profile indexes well below 5. In order to permit contractors to use a greater variety of equipment and finishing methods, several experimental contracts were awarded stipulating that concrete pavements may be finished by any means that the contractor may elect provided the profile index of the completed work does not exceed 7 when measured along each outer wheel path. If the profile index in any section 0.1 mi in length should exceed 7, the contractor is required to grind the high spots until the pavement meets the requirement.

The manufacture of a number of manually-operated profilographs for use by construction forces is now under way. These latest models will produce a profilogram record on paper showing the pavement as constructed. They will also mark an exaggerated profile trace directly on the pavement so that the exact location of the high and low spots will be readily apparent to the resident engineer and to the contractor.

Using the charts that accompany the authors' paper, the writers have computed a profile index for each section reported. Figure 17 shows the relationship between the Michigan roughness index and the California profile index. It is evident that there is a high degree of correlation between the two numerical scales. The intercept of the Michigan roughness index at zero profile index appears to be about 35 for concrete pavements and 20 for bituminous pavements. The Michigan counting device is obviously recording small deviations within the 0.2-in. band which is discarded in the computation of the profile index.

Electronic circuits used in the California device make it possible to vary

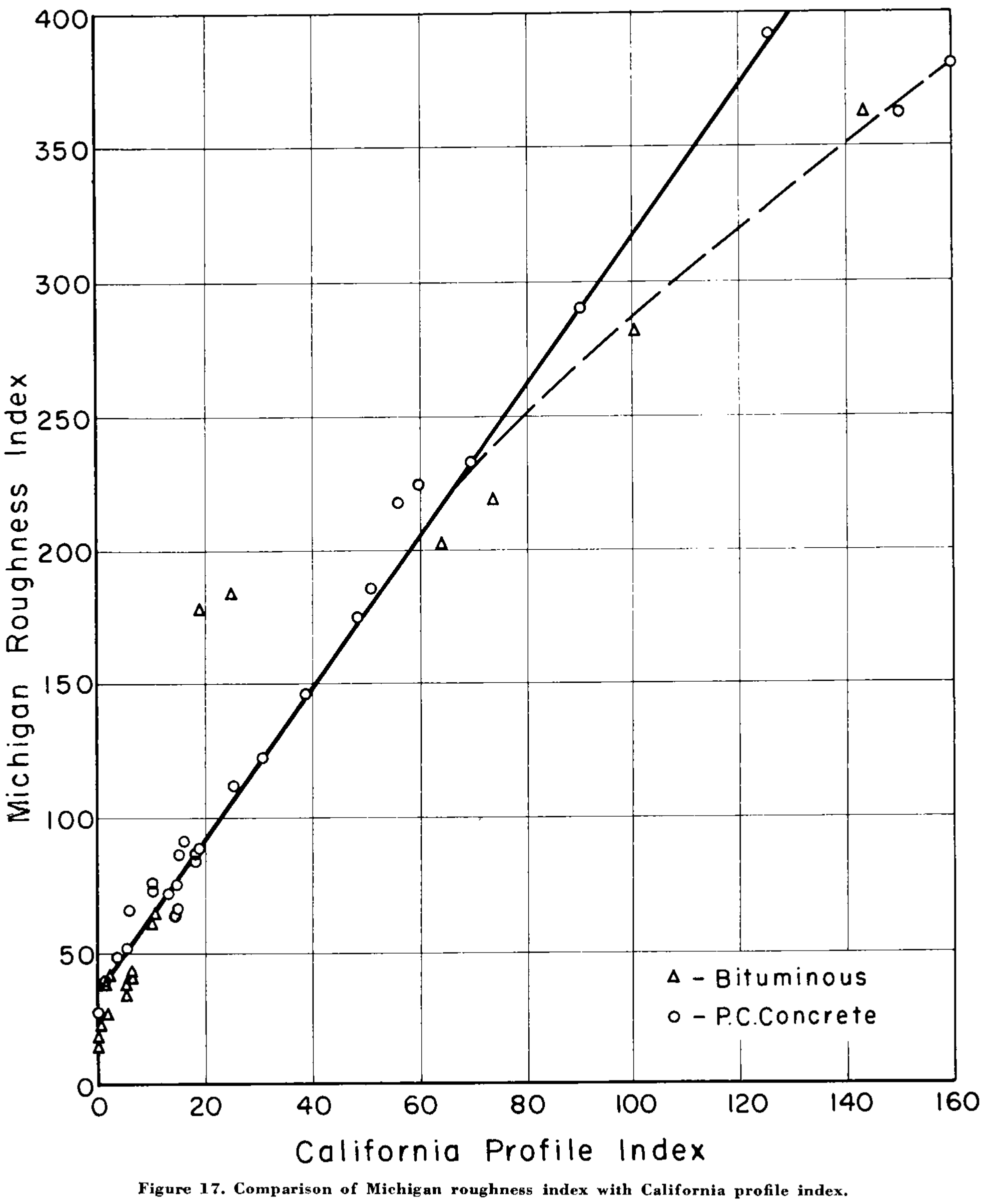


Figure 17. Comparison of Michigan roughness index with California profile index.

the degree of sensitivity within a rather wide range. The relatively smooth traces produced by the Michigan profilometer and the absence of "hash" seems to indicate that their device is being operated at a much lower level of sensitivity than has been used in California.

This matter of sensitivity becomes an important consideration when profilograms are used for studying the changes or developments in a pavement under traffic, especially in the case of concrete pavements. It is usually a matter of interest to know when the first signs of faulting or step-off are developing. An examination of profilograph records has shown that incipient faulting at the joints may be detected from the profilogram

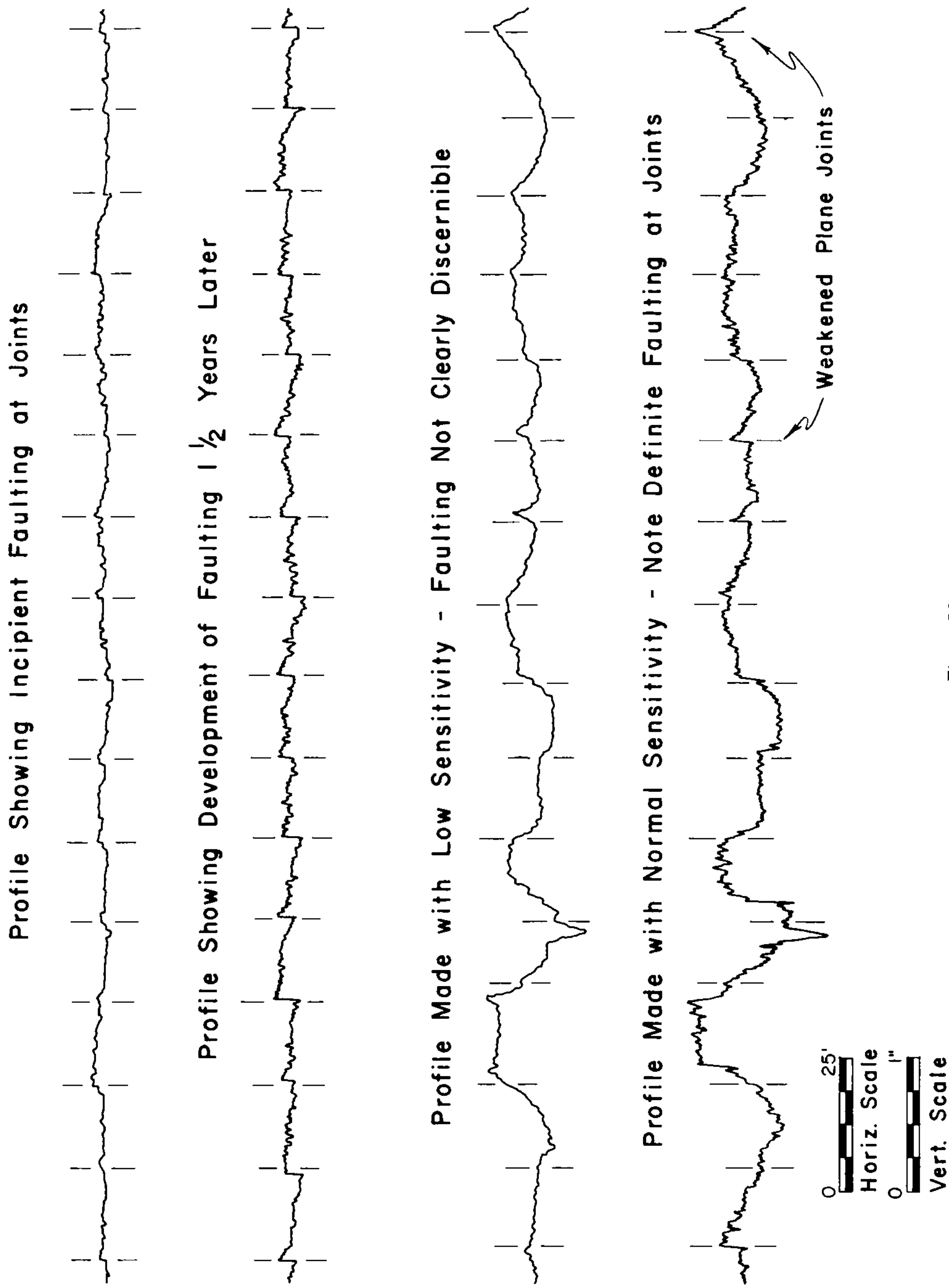

Profile Showing Incipient Faulting at Joints
Profile Showing Development of Faulting 1 ½ Years Later
Profile Made with Low Sensitivity - Faulting Not Clearly Discernible
Profile Made with Normal Sensitivity - Note Definite Faulting at Joints
Weakened Plane Joints
0
25'
Horiz. Scale
0
1"
Vert. Scale

Figure 18.

before it is readily discernible by an inspection of the pavement. Also, faulting does not ordinarily develop simultaneously in every joint and it would require a considerable amount of careful inspection of the actual pavement, whereas each joint position may be examined on the profilogram quite conveniently.

It seems impossible, however, to provide any reasonably simple automatic recorder that will register small vertical movements at the joints in the pavement and at the same time ignore all other inequalities of similar magnitude. Therefore, it has been felt necessary to accept the sawtooth pattern which typically results when the sensitivity of the instrument is such that it will record the first signs of faulting at the pavement joints. This aspect has been discussed in some detail because it, in turn, has a bearing on the action of the "bump counter" or a number such as the Michigan roughness index.

Figure 18 shows four typical profilograms which are included for comparison with the traces reported in the Michigan paper. Although they do not represent the same pavements, it nevertheless will be evident that the Michigan curves are "smoothed" out and presumably, therefore, the Michigan index does not include the number of small vertical movements that are shown on the California records. However, as indicated previously, it is evident that there is a very close parallel between the California profile index and the Michigan roughness index, even though they are arrived at differently and are based on somewhat different assumptions. It seems probable that were the Michigan machine adjusted to the degree of sensitivity used in California, the recorded roughness index would be at greater variance with the profile index and thus would require different interpretation.

It is naturally gratifying that Michigan has elected to construct a pavement profile recording device similar to the one that has been in use in California for several years. The opportunity to exchange information and to compare characteristics and performance of pavements constructed by different methods and subjected to different traffic and climatic conditions should be very valuable in establishing the factors that are essential for good pavement performance.