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MICHIGAN
STATE HIGHWAY DEPARTMENT
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PAVEMENT ROUGHNESS SURVEYS

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PAVEMENT ROUGHNESS SURVEYS

One outstanding characteristic of the modern pavement in which the public is greatly interested is the smoothness of the surface. The public judges the quality of a road more by its smoothness than any other basis. Also people are quick to judge the efficiency of a highway administration on the general riding qualities of the Highway system. Highway engineers cognizant of this fact started to give pavement roughness serious attention more than 25 years ago. This is clearly expressed in an article by the Bureau of Public Roads appearing in Public Roads Magazine in September, 1926:

"No argument is needed to convince the user of our roads of the desirability of as smooth a surface as can be produced. A rough surface gives rise to effects unpleasant to the passenger and detrimental to the vehicle. Smooth surfaces mean greater mileage with less fatigue, with less damage to cargoes, and with lower operating costs for the vehicle. Thus the subject assumes a very considerable economic aspect.

"The highway engineer is vitally interested in building and maintaining smooth roads because of the effects already mentioned and further on account of the direct effect of surface roughness on the life of the pavement. The research of the last few years has clearly pointed out that road roughness produces impact and impact contributes to the early deterioration of any type of road surface.

"The general appreciation of the importance of this matter by highway engineers has created a demand for an instrument with which the roughness of a road surface may be measured. With such an instrument the engineer would find it possible to specify the quality demanded in new work and to obtain accurate data on the deterioration of the surface in time to apply proper

corrective measures. To be most useful such a device should not only be accurate but should supply the information rapidly and in such form that it can be used immediately. Finally, it should be mechanically simple and reliable and so designed that it can conveniently be used on an automobile."

At the present time highway engineers throughout the country are becoming very much concerned over the fact that many concrete pavements constructed since the war are abnormally rough. As a counter measure many State Highway Departments are equipping themselves with the latest roughness measuring apparatus with the view of not only evaluating the riding qualities of their existing pavements, but to accumulate data upon which eventually they can establish smoothness standards as a measure of control.

At various times in the past the Michigan State Highway Department has studied the problem of pavement roughness. But due to the difficulty and expense of acquiring suitable equipment, the work was usually short-lived. In 1947 an investigation on pavement roughness was organized by the Research Laboratory of the Department on a long-term basis as a supplement to a current research project associated with the physical behavior of post-war pavements. The project was also organized with the view of determining what construction processes were responsible for excessive pavement roughness, in order that corrective measures could be recommended.

It is the purpose of this paper to discuss the various aspects of pavement roughness and its measurements and to disclose the results of roughness surveys made on a large number of concrete pavements constructed in Michigan during 1948 and 1949. These data were recently compiled at the request of the Road Division for their immediate use in encouraging the construction of smoother concrete surfaces through the cooperation of the contractor and his personnel.

PAVEMENT ROUGHNESS AS RELATED TO HIGHWAY SERVICE

The past fifty years have witnessed three major changes in highway construction progress. The first, designated as the "Era of Dirt Roads", was terminated about 1920 with the close of the first world war. The birth of motor transportation, a product of that war, launched the succeeding "Era of Essential Highway Construction", which during the past thirty years from 1920-1950, has resulted in the complete hard surfacing of most of the primary and secondary trunk lines in the country. We are now beginning the third great period of highway advancement, which for want of a better name may be called the "Era of Refinement in Highway Construction and Service", as manifested by the appearance of rural and urban expressways and great parkway systems in metropolitan areas. In this new era now in its infancy, specific attention will be directed toward the provision of greater highway service to the public through refinement in design, construction, maintenance, and operation of the highway plant. In the future the motorist in Michigan, as he pays highway toll in the form of gasoline tax to drive many miles of highway, will expect, and rightfully so, greater safety and mobility with less driving fatigue and lower operating costs.

As may be clearly demonstrated, the smoothness or roughness of a pavement surface is intimately associated with the four factors mentioned above: - safety, mobility, fatigue, and operating costs. As stated by the Bureau of Public Roads, a rough surface is a detriment to safety and the mobility of a vehicle in negotiating the traffic stream. Furthermore, it has been proved through experimentation that rough pavements cause vibration frequencies and noises at levels which are unpleasant to the passengers, thereby ultimately resulting in fatigue that affects an individual, physically and psychologically. Excessive vibrations also cause

damage to vehicles and their cargoes. In addition, it has been proved that roughness increases the operating costs of vehicles both in maintenance as well as in gasoline consumption. Pavement roughness also presents a problem to the highway engineer because of the impact effect it produces. Impact is directly associated with load stresses considered in design requirements and it also has a marked influence on the future behavior of a highway structure.

SOURCES OF PAVEMENT ROUGHNESS

Pavement roughness may be caused by one or more of the following factors. It may be built into the road at the time of construction; it may be the result of volume changes in the base materials; it may develop from surface fatigue; or it may be the result of maintenance methods.

Initial surface roughness may be the result of improper construction practices. Poorly jointed or untamped paving forms contribute to a rough surface. Delayed finishing in hot weather produces a surface with a high roughness index. The skill of the men who hand finish behind the machine and who form the pavement joints is also reflected in pavement roughness.

Volume changes in base materials affect the surface by causing distortions in surface grade. When differential heaving occurs, sections of the slabs are lifted off from certain areas of the base, and when loads travel over these voids permanent deformations are formed in the slabs. Progressive subgrade consolidation is seldom uniformly distributed along a highway, and considerable roughness is evident in older pavements at drainage structures.

The fatiguing effect of heavy axle loads over joints and cracks tends to produce permanent relative deflection of the abutting slabs. This failure, called faulting, results in progressive and permanent pavement

roughness. It is particularly annoying to the driver because of the monotonous regularity when it occurs in a section of pavement of appreciable length. Its cause may be base soil type, lack of base consolidation, or inadequate design or installation of load transfer devices.

Many small irregularities in surface contour are caused by improper maintenance methods. Sometimes patches are poorly made or joints are sealed with a surplus of material. In general, however, maintenance tends to decrease the effect of a fault which is the result of one of the failures mentioned above.

METHODS OF MEASURING PAVEMENT ROUGHNESS

In general, apparatus so far developed for measuring road surface roughness may be classified into two major categories, designated "Profilometers and Roughometers or Roughness Indicators."

Profilometer: The term "Profilometer" refers to those instruments which produce to some scale a graphic profile along an element of pavement. The earliest devices of this type used for a reference datum fixed points on the surface of the pavement. This procedure proved slow and tedious and was generally abandoned for a more versatile machine employing a floating datum. In this latter apparatus the floating datum consisted of a long frame-work supported by a system of wheels. As in the first case, the profile of the road surface with respect to the datum, was traced on a continuous ribbon of paper to some suitable scale. This equipment also proved awkward to maneuver, the data difficult to analyze, and has, in general, been displaced by more modern methods. Principles involved in the profilometer just described are illustrated in Figure 1. Views of such instruments in use are shown in Figures 3 and 4.

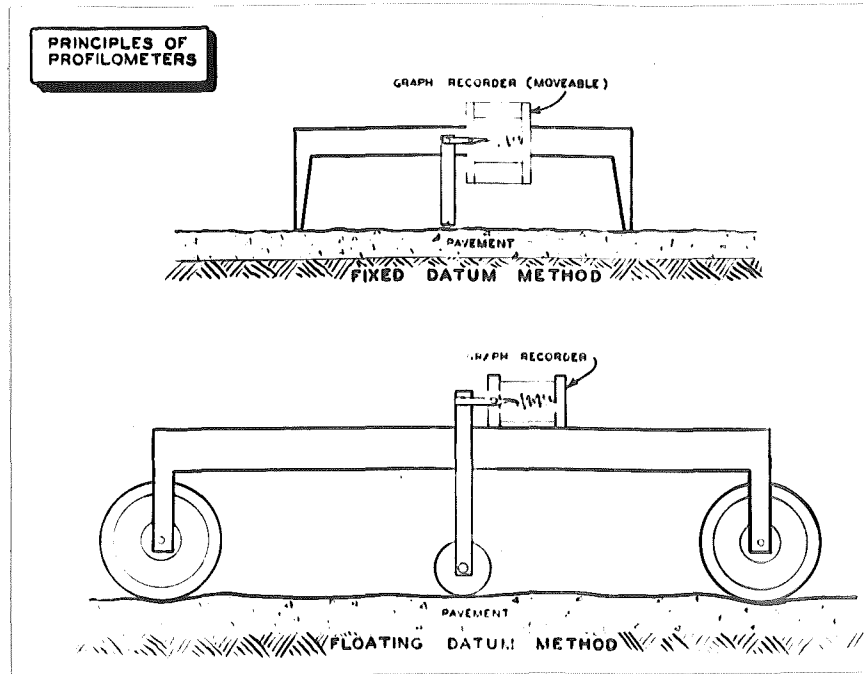


Figure 1. Principles of Profilometers

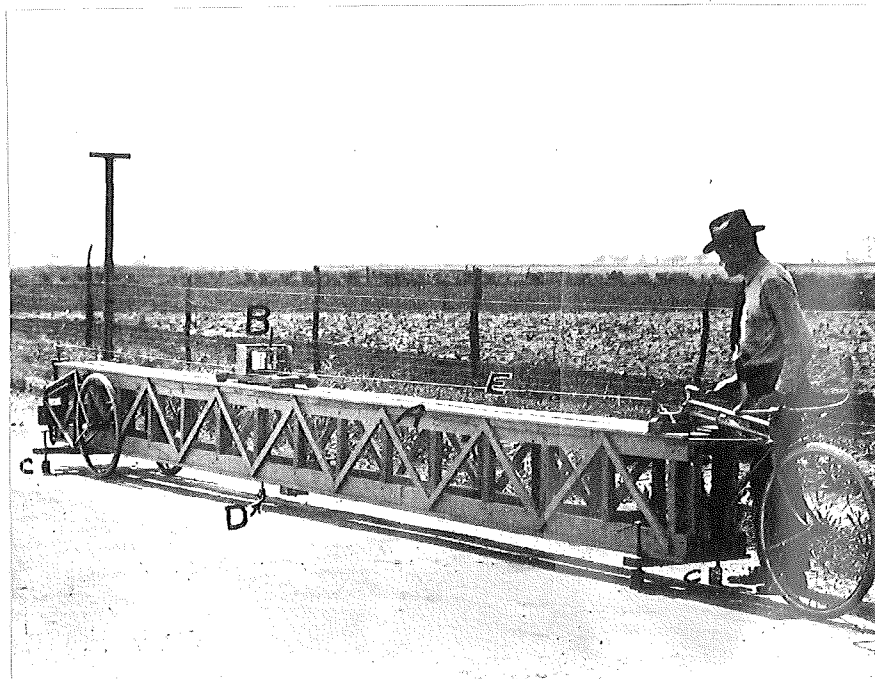


Figure 2. Early Fixed Datum Profilometer

Figure 3.
Small Profilometer
with Fixed Datum



Figure 4.
Floating Datum
Profilometer used in
California

A simpler version of the Profilometer without the continuous recorder is commonly used by inspectors on construction projects to check pavement roughness soon after construction as a control measure. See Figure 5.

Roughometer or Roughness Indicator: Roughness measuring devices in this category employ the principle of the vertically oscillating wheel with respect to a vehicle chassis or heavy frame towed as a trailer. These two methods are shown schematically in Figure 6. The fundamental principle upon which instruments of this type depend is that the vertical motion imparted to the wheel by the irregularities in the road surface bears a direct relation to the degree of roughness. The wheel motion is controlled by spring deflection and it is the spring deflection with respect to the chassis that is measured as the wheel traverses the pavement. The recorded deflection data can be translated into relative road surface roughness. The deflection data is recorded as a continuous graph or as a numerical accumulation of these movements in inches of deflection per mile of pavement.

This principle was first applied to a standard automobile in which case one of the front wheels was used as the oscillating wheel. To this wheel was attached the mechanism which operated the recording device mounted in the front seat of the vehicle. Although rather popular because of ease in operation and the readiness with which comparative data could be obtained, these indicators had certain fundamental deficiencies in that the vehicle to which the device was attached became an essential part of the roughness apparatus and therefore any changes in the vehicle condition or performance would influence the accuracy of results. A diagram of this roughometer is drawn in Figure 7. To overcome these deficiencies a trailer with a single oscillating wheel was developed during the early twenties. This unit for measuring pavement roughness has now been extensively copied and used throughout the United States.

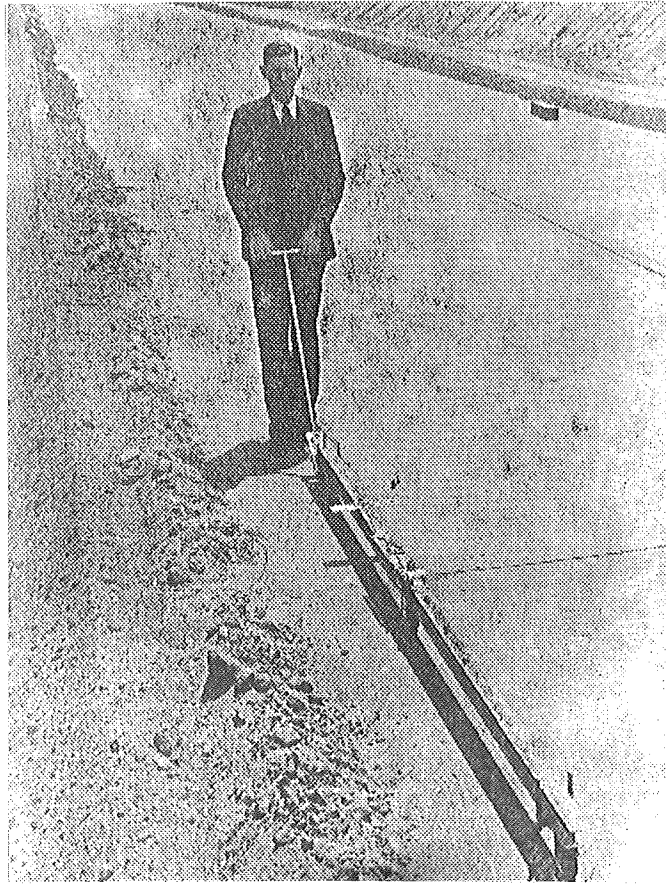


Figure 5. Simple Inspectors Profilometer used in Virginia

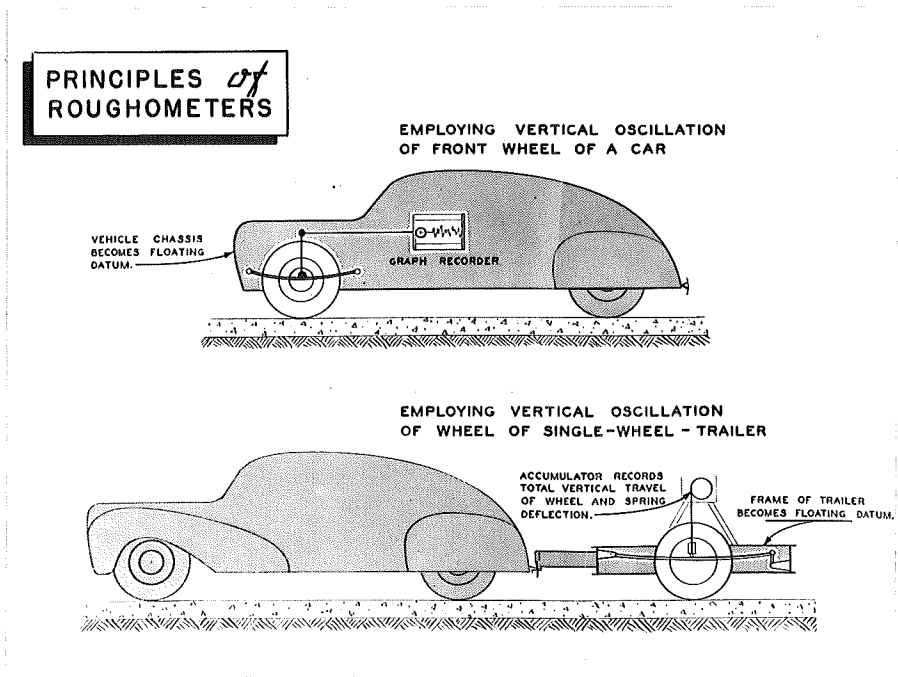


Figure 6. Two Fundamental Types of Roughometers

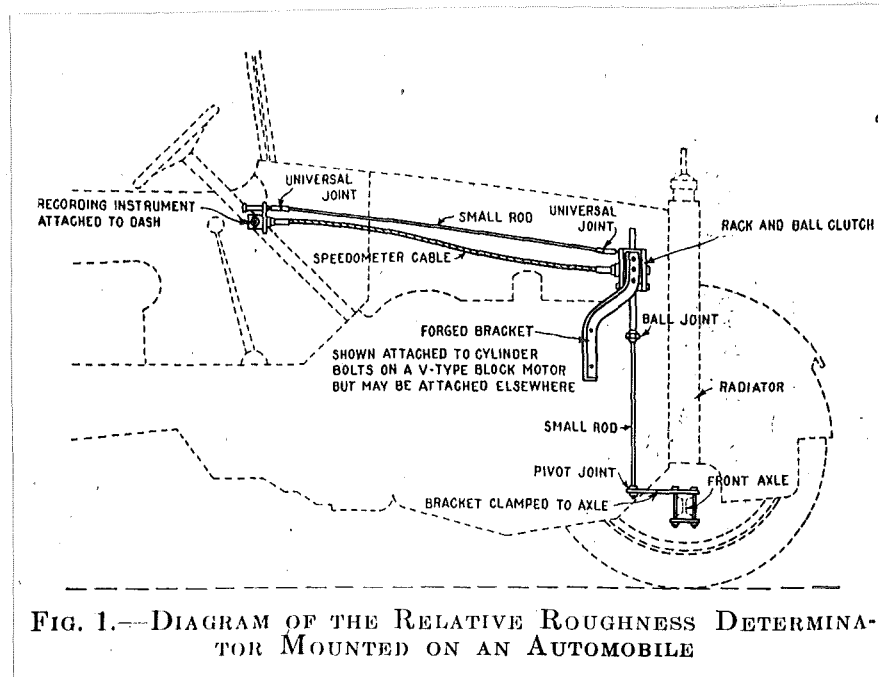


Figure 7. Roughometer with Vehicle Chassis as Floating Datum

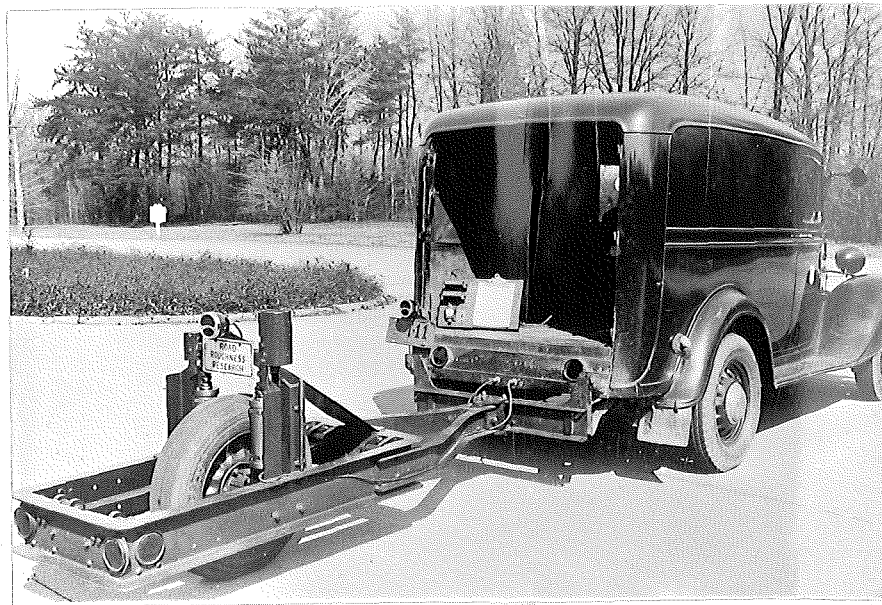


Figure 8. Bureau of Public Roads Roughness Indicator

Bureau of Public Roads Roughometer: The roughometer developed by the Bureau of Public Roads consists of a rectangular frame within which is a single automobile wheel equipped with a pneumatic tire. The axle of the wheel is attached to the center of two single leaf springs, one on each side of the wheel. The ends of the springs are fastened to the front and rear cross members of the frame through ball bearing fixtures. Over the wheel there is a cross frame or bridge on which a ball clutch accumulator unit is mounted. The accumulator is connected to the wheel axle through a drum and cord arrangement, and in this manner the total upward deflection of the springs for any given section of pavement is summarized. A view of this equipment is shown in Figure 8.

The Michigan State Highway Department Roughometer

In principle the apparatus developed and constructed by the Research Laboratory is essentially the same as that of the Bureau of Public Roads except for one new innovation. In addition to obtaining a numerical record of road roughness in inches of deflection per mile of pavement, the apparatus furnished a graphic record of the surface roughness. This has been accomplished by the addition of an electric recording system which consists of a linear differential transformer and a pen type recording oscillograph. The transformer is attached to the chassis of the trailer and the core to the wheel axle. Electrical impulses generated by the relative vertical displacement of the core with respect to the transformer are fed into the oscillograph which in turn produces a trace of the fluctuations in vertical displacement of the wheel. This trace provides a means for detailed study of any section of the pavement, it indicates the individual bump heights and also provides a means for determining bump frequency. Further electrical circuits make it possible to measure directly in a voltage meter average values of bump heights. The Michigan roughometer is illustrated in Figures 9 and 10.

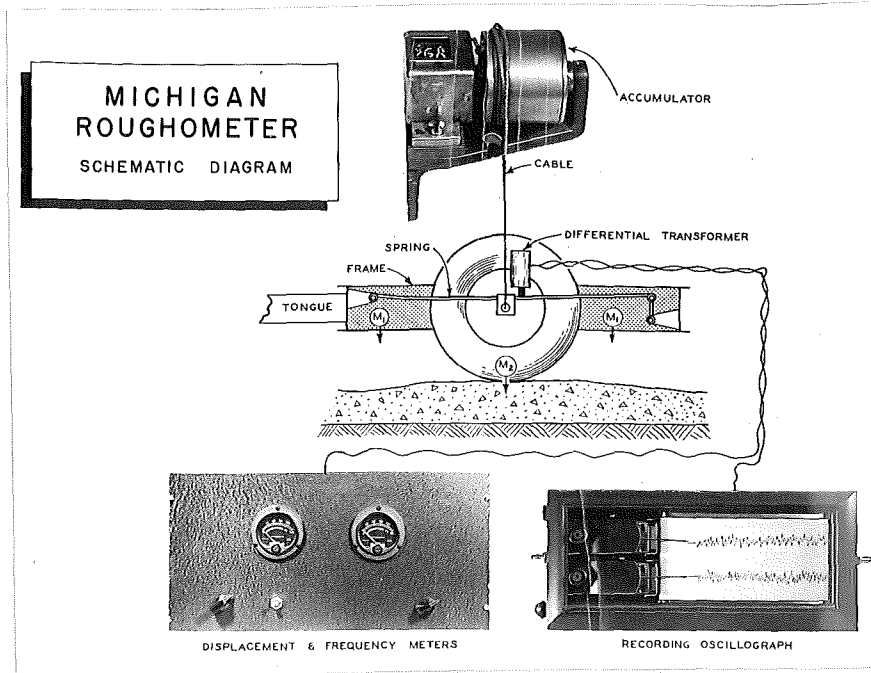


Figure 9. Diagram of Measuring Circuits in the Michigan Roughometer



Figure 10. The Michigan Roughometer

USES OF ROAD ROUGHNESS DATA

Although they do not record the true roughness profile of the pavement surface, road roughness indicators produce quick, dependable, relative surface roughness data which has many uses. In the first place, the equipment can be used as a research tool to provide data for improving the design and performance of highway structures. Second it could be a useful tool in determining when existing pavements should be resurfaced or reconstructed. Third, as is now the case, it can be useful in searching for construction factors which are contributing to pavement roughness in order that such factors may be corrected or eliminated. Fourth, the method has the possibility of providing a control for quality work and also for final acceptance of new projects, and finally, it can be used in conjunction with studies on motor vehicle operation.

RESULTS OF ROUGHNESS STUDIES IN MICHIGAN

Early Roughometer Studies in Michigan

In the late summer of 1925 the Bureau of Public Roads⁽¹⁾ made roughness surveys on 48 sections of concrete pavement in Michigan, totaling 412 miles. The roughness consisted of a 1917 Model Cadillac, equipped with recording device attached to front axle. The car was equipped with cord tires with 60 pound pressure and tests were made at 30 miles per hour with two men in the car. The average roughness factor -- inches per mile -- was 141. Records of individual projects are given below for comparing with similar records obtained on modern pavements.

TABLE 1
Roughness Readings on Michigan Pavements
Built Prior to 1925

| | | Avg. per mile | Year Built |
|--|-------------------------|---------------|------------|
| F.A. Project 27 | Petoskey to Charlevoix | 276 | 1921 |
| F.A. Project 113 | Grand Rapids to Lansing | 89.6 | 1925 |
| M-11 | Grand Rapids to Holland | 155 | 1925 |
| F.A. Project 73 | Monroe to Toledo | 86.7 | 1926 |
| F.A. Project 117 | Muskegon South on M-11 | 66.7 | 1923, 1924 |
| Average for 1948 projects (with trailer roughometer) | | 94 | |
| Average for 1949 projects (with trailer roughometer) | | 85.3 | |

Michigan Test Road Studies

In September, 1941, and again in 1949, a series of pavement surface roughness tests were conducted on the entire Test Road by personnel of the Bureau of Public Roads using their roughometer. The study was made primarily to compare the riding qualities of various sections of the pavement, especially of those having varied expansion and contraction joint spacing, and to determine change in roughness with time. In conducting the tests each section of each series was taken as an increment to compare roughness condition for the different joint spacings and concrete mixture variations. In 1941, additional tests were made on nearby projects, one of the same age as the Test Road and another project 20 years old, to afford a comparison with standard construction and to determine an expectant roughness factor. The roughness data obtained from the two series of tests are presented graphically in Figure 11.

Two factors motivate the presentation of this data here, first, the data indicate that the original roughness factor for the entire project ranged from 75 to 101 inches per mile, an indication, in general, of good workmanship and excellent riding qualities, and second, to show the increase in roughness of the pavement surfaces with time. The general increase in roughness for the entire Design Project of the Test Road is approximately 56 percent for the 8 year period or 7% per year.

Roughness of Pavements Constructed between 1946-1948

Since 1945, pavement condition surveys have been made on all important concrete pavement projects for the purpose of evaluating their physical behavior in relation to construction practices. In conjunction with this work, an attempt has been made to include roughness data as determined by the Department's new Roughometer. At this time the roughness data has not

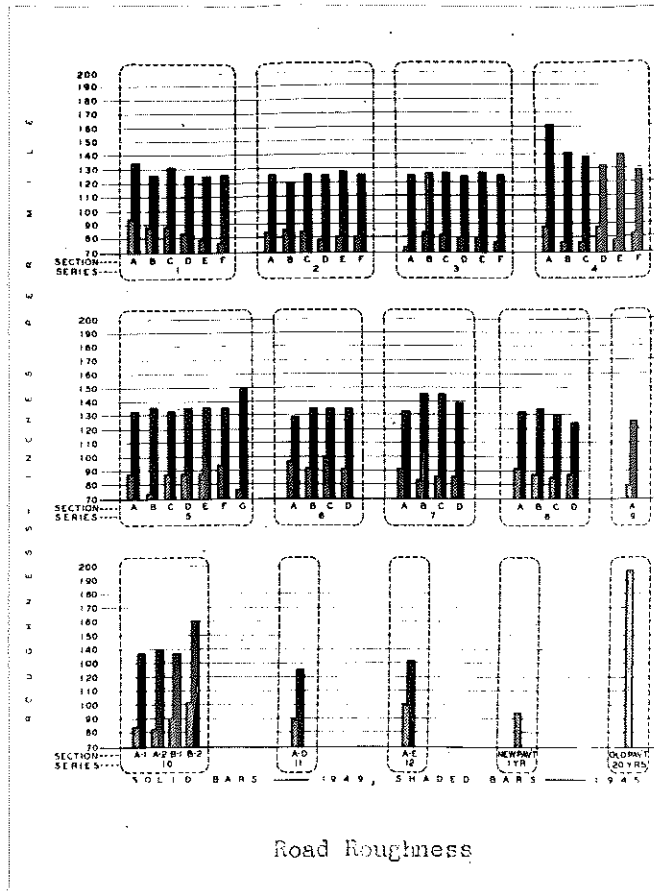
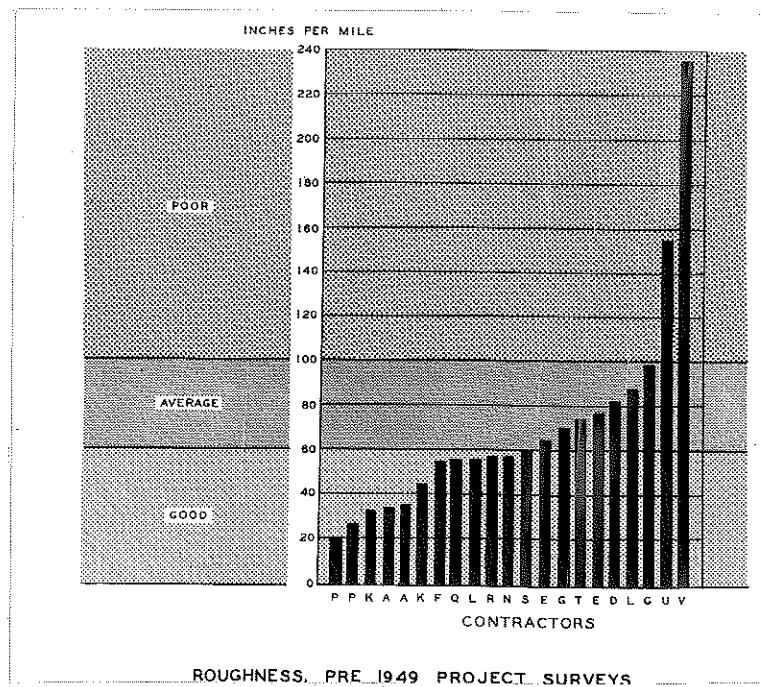


Figure 11. Comparison of Roughness Records on M-115 Test Road



12. Roughness Comparison on Projects Constructed in 1946 to 1948

been obtained for all projects included in the condition surveys but roughness values for those completed have been presented graphically in Figure 12 for comparative study. In this figure it may be observed that the projects fall into three categories of roughness, namely, good, average, and poor. The classification is dependant upon roughness value in inches per mile and the limits have been arbitrarily selected as follows: up to 60 inches per mile as good; 60 to 100 inches per mile as average; and 100 inches per mile and above as poor. Experience indicates that a new concrete pavement should have a roughness factor of 100 inches per mile or less. Roughness data from several sources indicates that this value for roughness is not too difficult to attain and should not necessarily impose any undue hardship on the part of the Contractor. The roughness data in Figure 12 further indicates that a majority of the Michigan contractors are able to achieve this degree of smoothness repeatedly.

A roughness value of 100 inches per mile for concrete surfaces has also been suggested and recommended as a possible standard by Professor Ralph A. Moyer, formerly with Iowa State College, after many studies of pavement roughness in the Central Western States.

In the winter of 1948 and 1949 the Construction Division made roughness determinations on many projects using a vehicle roughometer built by the Wayne County Road Commission from a previous design by the Dow Chemical Co. at Midland. The data obtained from their survey parallel very closely the results obtained by the roughometer equipment developed by the Research Laboratory.

Roughness of Pavements Constructed in 1949

Similar roughness studies were continued on concrete pavement projects constructed in 1949. It was not possible to cover all of the projects,

especially those completed at the close of the season because of unsatisfactory operating conditions. However, the roughness data for those projects covered are presented graphically in Figure 13. A general comparison of roughness data for pre-1949 and 1949 projects is presented in Table 2. The data presented in Figures 12 and 13 and Table 2 are based on average roughness values including both lanes of each pavement project.

TABLE 2

COMPARISON OF PRE-1949 AND 1949 ROUGHNESS DATA

| Degree of Roughness | Inches per Mile | Avg. bump Height Inches | Pre-1949 Projects | | | | 1949 Projects | | | |
|-----------------------------|-----------------|-------------------------|-------------------|-------------|----------|--------------------------|-----------------|-------------|-----------|--------------------------|
| | | | No. of Projects | Total Miles | % | Avg. in/ mi. per project | No. of Projects | Total Miles | % | Avg. in/ mi. per project |
| Good | 0 - 60 | 0 - .08 | 12 | 61 | 60 | 45 | 8 | 40 | 34 | 48 |
| Fair | 61 - 100 | .09-0.13 | 7 | 36 | 35 | 79 | 14 | 58 | 50 | 75 |
| Poor | 101 + | 0.14+ | <u>1</u> | <u>5</u> | <u>5</u> | <u>157</u> | <u>8</u> | <u>18</u> | <u>16</u> | <u>132</u> |
| Total | | | 20 | 102 | 100 | | 30 | 116 | 100 | |
| Yearly Average all Projects | | | | | | 94 | | | | 85 |

Pavement Roughness by Lanes

In the analysis of roughness data it was observed that on certain projects the roughness values for different lanes of a two lane pavement varied considerably. This discovery led to further analysis of roughness data for 1949 by individual lanes and a summary made in graphic form as shown in Figure 14. Here it may be observed that individual lane roughness for any two lane pavement varied as much as 42 inches per mile, the average ranging around 9 to 17 inches per mile. Experience indicates that this variation in lane roughness could be associated with the relative experience and ability of the two concrete finishers working on their respective sides of the pavement or it could be due to certain maladjustments in bull float or

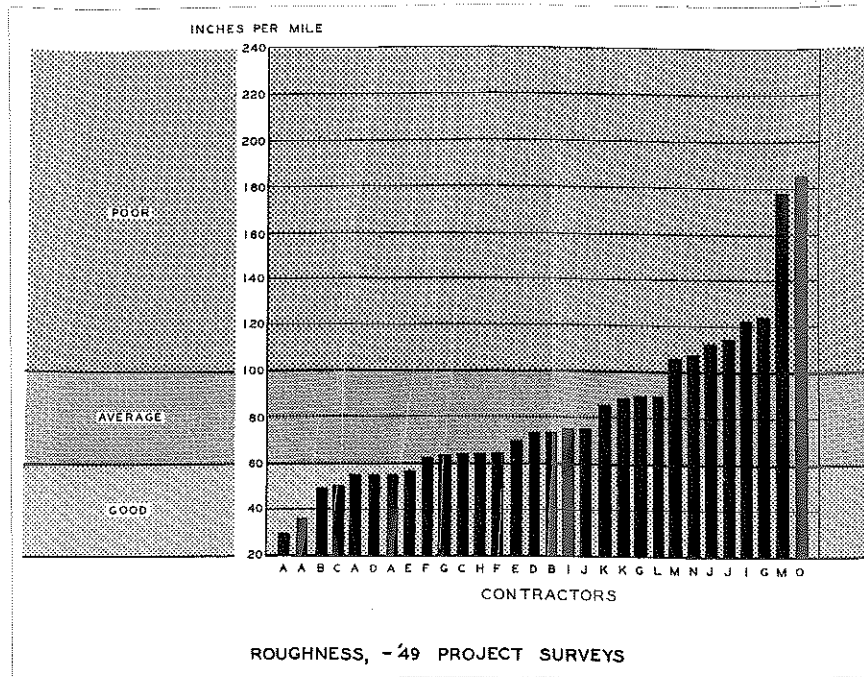


Figure 13. Relative Roughness of Projects Constructed in 1949.

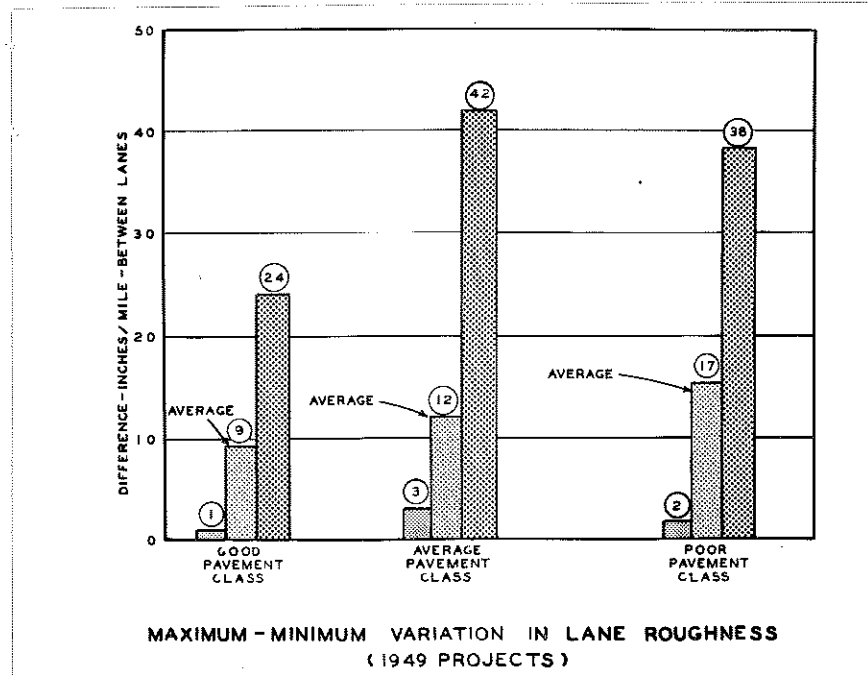


Figure 14. Variations in Lane Roughness.

finishing equipment. Other deficiencies in construction practices such as form setting and soil conditions could cause major differences in lane roughness.

Peculiarities in Pavement Roughness Patterns

Certain peculiarities in roughness pattern of different projects were disclosed by the continuous graph records. Examples of four characteristic types of pavement roughness are presented in Figure 15.

The frequency of modulation in all cases ranged from 500 to 700 cycles per mile. In general, low amplitude is evidence of smoothness, and high amplitude with irregular pulse is indicative of a very rough surface.

Roughness of Bridge Decks

During the course of a pavement roughness survey an occasional bridge structure or railroad crossing was encountered. In all cases the roughness pattern of these structures were markedly different from that of the adjacent pavement structure. This is clearly illustrated in Figure 16 in which are shown reproductions of graphs from several projects. This indicates the need for more detailed studies of bridge deck roughness in connection with construction practices and maintenance because of the influence of roughness on the live load stresses in bridge structures.

FACTORS RELATED TO PAVEMENT ROUGHNESS

It is believed that the construction or development of roughness in pavements can be associated with many factors appearing under one or more of the following major categories: (1) State Supervision; (2) Contractor's personnel; (3) Contractor's equipment; (4) Workmanship; (5) Materials used, and (6) Foundation conditions.

State Supervision

This includes the activities of the project engineer and paving inspector as well as other administrative officers directly responsible

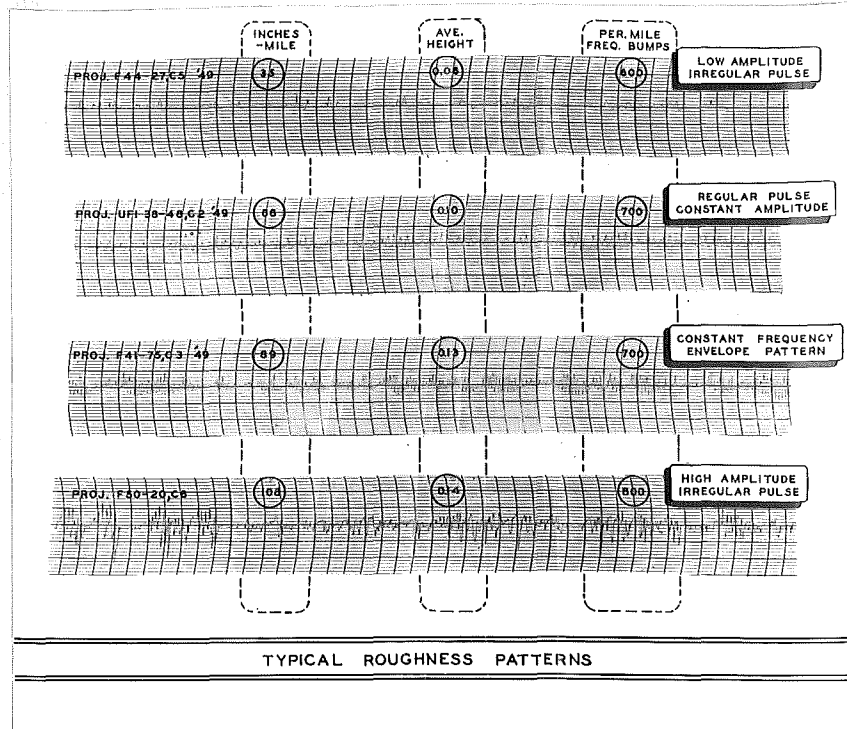


Figure 15. Typical Samples of Road Roughness

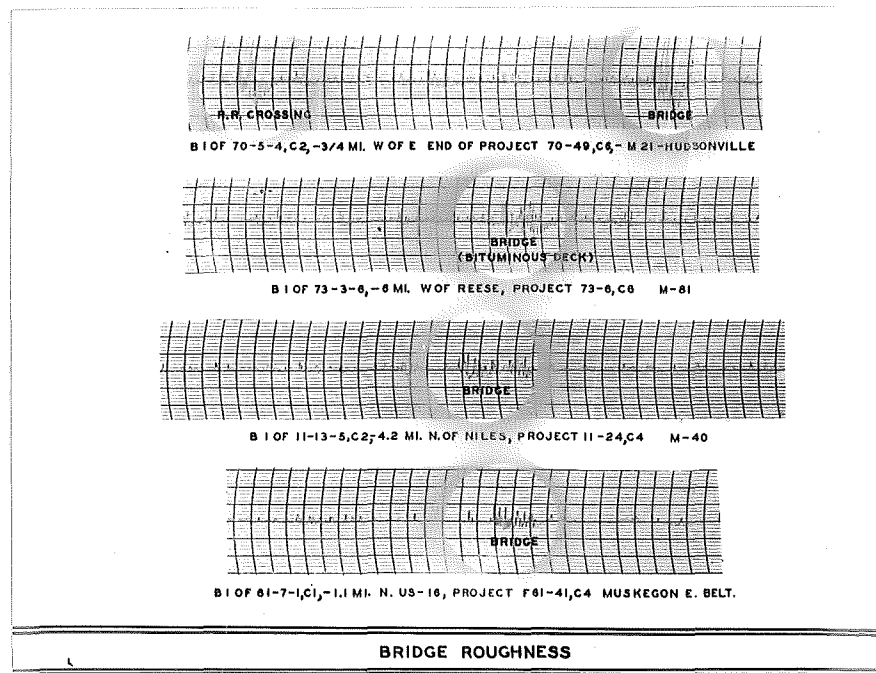


Figure 16. Samples of Bridge Roughness Records

for the final condition of the finished pavement. Conscientious supervision of all paving activities and rigid enforcement of specification requirements are mandatory to insure a quality product. In 1926, Commissioner Charles M. Ziegler⁽²⁾ then District Engineer said: "It is the responsibility of the field engineer and, through him, of the inspector to see that the materials are so handled and mixed, and the resulting concrete placed and finished strictly in accordance with the plans and the intent of the specifications. The specifications generally represent the best known practices at the time of the handling and combining of these materials to get the required grade of construction. The amount of money involved in the materials, labor and profit in the construction of a cement concrete pavement are sufficient to employ the highest class of workmanship. The field engineer in charge of construction should, therefore, be selected with care. He should be a good capable man of sound judgment, honest and conscientious. He must have good reliable inspectors and sufficient engineering organization under him so that his instructions will be carried out accurately and so that he will have enough time for the general supervision of the work. The inspectors must be selected for their intelligence, integrity, experience and personality. Good inspection is necessary to a smooth-functioning organization, which in turn, is necessary for a good and uniform quality of work."

Contractor's Personnel

It is believed that the overall experience, attitude, and efficiency of the contractor's personnel has more to do with the production of smooth pavements than any other single factor. Proper supervision of these men by competent superintendents is also a necessity. A reliable contractor with an experienced organization is necessary for the best results. The

contractor and his organization must be honestly interested in producing a good job. Unless he is making a fair legitimate profit on his labor and money invested, he will be working under a handicap and in spite of all the efforts of the engineer to maintain the standard of good construction the organization will not function properly, and the general quality of the work aimed at is liable to suffer.

Contractor's Equipment

The contractor's equipment must be first class and adequate for handling all phases of the work. The make, age, and physical condition of the contractor's spreading and finishing equipment and its adjustment can no doubt influence the quality of a pavement surface. Condition of the paving forms and consolidation of the soil beneath them are also of vital importance. Some form of standardization or specification may be necessary in the future to assure adequate equipment which, when operated by experienced personnel, will build smooth surfaces.

Workmanship in general

The quality of workmanship in all phases of the work associated in particular with the setting of the forms, placing, spreading, and finishing of the concrete as well as the final jointing practices no doubt has a profound influence on the riding qualities of the finished surface. Good workmanship can be expected only from artisans interested in their work and not from itinerant workers who are concerned only with the pay check.

Materials Used in the Surface

Physical characteristics of the ingredients such as aggregate and cement may undergo autogenous volume changes in the setting up period which could contribute in a certain extent the inherent roughness of the surface. Such changes may take place during and immediately after final finishing operation and therefore could not be corrected by the finishers while in a workable condition.

Foundation Conditions

There can be no argument but that non-uniformity in soil conditions and lack of proper consolidation can contribute materially to the subsequent roughness of any pavement surface. Steps should be taken to insure that proper foundation conditions are realized before pouring operations start. Although the selection of the base material upon which the slab is laid is fundamental, the drainage and consolidation methods are of equal importance. Too often the advantage of granular base material is offset by failure to give it any treatment after cutting it to grade.

Further evidence of negligence in base consolidation is shown in the crack pattern appearing on condition survey maps. Breaks are often found over under-drains and adjacent to drainage structures. More stringent regulation of backfill consolidation will remedy this fault.

SUMMARY

Highway pavements must be built and maintained with a minimum of surface roughness. Safety, driver fatigue, vehicle wear, structural deterioration, and the psychological effect on the public are factors which make smooth highways necessary.

A satisfactory instrument for measurement of road roughness is the roughometer. The independent floating datum type pioneered by the Bureau of Public Roads has proven reliable, and the Michigan indicator was patterned after that model. An additional feature of the Michigan roughometer is a continuous oscillograph record of road roughness.

Road roughness indices may be used to improve highway design methods, to determine the need for resurfacing, to aid in the search for construction factors contributing to rough pavements, and, to control the quality of pavement finishing.

Michigan studies have shown some improvement in "built in" smoothness in highways since 1925. They have also shown that surface roughness progresses with age, the increase in index being about 7% per year on the M-115 test road.

The effect of machine finishing on improved riding quality is shown by the fact that bridge decks universally show high roughness indices.

It is believed that smoother pavements can be built when construction is controlled by more rigid state supervision, improved contractor's personnel, workmanship by qualified artisans, and high quality machinery. Control of foundations and surface material quality is essential to lasting smoothness.

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- (1) J. T. Voshell, District Engineer, Bureau of Public Roads, The Roughometer and Its Utilization, 12th Annual Conference of Highway Engineers, Univ. of Michigan, 1926.
 - (2) C. M. Ziegler, "Fundamentals of the Mixing and Laying of Cement Concrete," Proceedings of 12th Annual Conference of Highway Engineers, University of Michigan 1926.