HIGHWAY RESEARCH BOARD

Bulletin 264

Road Roughness and Skidding Measurements: 1960

**National Academy of Sciences—
National Research Council**

publication 777

HIGHWAY RESEARCH BOARD

Officers and Members of the Executive Committee

1960

OFFICERS

PYKE JOHNSON, *Chairman* W. A. BUGGE, *First Vice Chairman*
R. R. BARTELSMEYER, *Second Vice Chairman*
FRED BURGGRAF, *Director* ELMER M. WARD, *Assistant Director*

Executive Committee

BERTRAM D. TALLAMY, *Federal Highway Administrator, Bureau of Public Roads* (ex officio)

A. E. JOHNSON, *Executive Secretary, American Association of State Highway Officials* (ex officio)

LOUIS JORDAN, *Executive Secretary, Division of Engineering and Industrial Research, National Research Council* (ex officio)

C. H. SCHOLER, *Applied Mechanics Department, Kansas State College* (ex officio, Past Chairman 1958)

HARMER E. DAVIS, *Director, Institute of Transportation and Traffic Engineering, University of California* (ex officio, Past Chairman 1959)

R. R. BARTELSMEYER, *Chief Highway Engineer, Illinois Division of Highways*

J. E. BUCHANAN, *President, The Asphalt Institute*

W. A. BUGGE, *Director of Highways, Washington State Highway Commission*

MASON A. BUTCHER, *County Manager, Montgomery County, Md.*

A. B. CORNTHWAITE, *Testing Engineer, Virginia Department of Highways*

C. D. CURTISS, *Special Assistant to the Executive Vice President, American Road Builders' Association*

DUKE W. DUNBAR, *Attorney General of Colorado*

H. S. FAIRBANK, *Consultant, Baltimore, Md.*

PYKE JOHNSON, *Consultant, Automotive Safety Foundation*

G. DONALD KENNEDY, *President, Portland Cement Association*

BURTON W. MARSH, *Director, Traffic Engineering and Safety Department, American Automobile Association*

GLENN C. RICHARDS, *Commissioner, Detroit Department of Public Works*

WILBUR S. SMITH, *Wilbur Smith and Associates, New Haven, Conn.*

REX M. WHITTON, *Chief Engineer, Missouri State Highway Department*

K. B. WOODS, *Head, School of Civil Engineering, and Director, Joint Highway Research Project, Purdue University*

Editorial Staff

FRED BURGGRAF ELMER M. WARD HERBERT P. ORLAND
2101 Constitution Avenue Washington 25, D. C.

The opinions and conclusions expressed in this publication are those of the authors and not necessarily those of the Highway Research Board.

HIGHWAY RESEARCH BOARD

Bulletin 264

Road Roughness and Skidding Measurements: 1960

Presented at the
39th ANNUAL MEETING
January 11-15, 1960

1960

Washington, D. C.

$1.00

Department of Design

T.E. Shelburne, Chairman
Director of Research, Virginia Department of Highways, Charlottesville

COMMITTEE ON ROAD SURFACE PROPERTIES RELATED TO VEHICLE PERFORMANCE

R.A. Moyer, Chairman
Institute of Transportation and Traffic Engineering
University of California, Berkeley

L.E. Gregg, L.E. Gregg & Associates, Consulting Engineers, Lexington, Kentucky
Frank P. Nichols, Jr., Highway Research Engineer, Virginia Department of Highways, Charlottesville
E.A. Whitehurst, Director, Tennessee Highway Research Program, University of Tennessee, Knoxville
Ross G. Wilcox, Highway Engineer, Portland Cement Association, Chicago, Illinois
Ernest G. Wiles, Highway Physical Research Engineer, Bureau of Public Roads, Washington, D.C.
Dillard, Woodson, The Asphalt Institute, University of Maryland, College Park

Contents

DEVICES FOR RECORDING AND EVALUATING PAVEMENT ROUGHNESS

MEASUREMENTS OF PAVEMENT FRICTION BY A DECELEROMETER

Devices for Recording and Evaluating Pavement Roughness

F.N. HVEEM, Materials and Research Engineer, California Division of Highways

● EVER SINCE roads and highways have been constructed, the people who use them have been keenly aware of the relative degrees of comfort or discomfort experienced in traveling. This awareness has been so deeply ingrained that most languages contain metaphors such as "rough road" or "smooth road" to describe human experiences involving hardship or good fortune. There is no doubt that mankind has long thought of road smoothness or roughness as being synonymous with pleasant or unpleasant. Road surface roughness is not easily described or defined and the effects of a given degree of roughness naturally vary considerably with the speed and characteristics of the vehicle. Anyone looking at photographs of the Appian Way (Fig. 1) or the streets in Pompeii (Fig. 2) must wonder how it felt to ride in a chariot over such surfaces, especially as the chariots had steel or bronze tires and no springs. One might assume that the repair bills on chariots were fairly high, and undoubtedly the occupants had real cause to feel "shook up."

In more modern times, references to roads appear in the folk lore, in song and story and in the literature. There is the wistful song about the high and low roads that lead into Scotland, but roads were little, if any, smoother a hundred years ago thanthey were in the times of the Romans, and our hardy ancestors were not above complaining about them. The "rocky road to Dublin" is legendary, and it may be that the Irish were more concerned over such things than most because it appears than an Irishman may have been the first man to construct a device for measuring road roughness, at least the earliest reference thus far found is in a book entitled "Road Making

Figure 1. Ruins of the Roman Forum with a remnant of the Appian Way in the foreground.

Figure 2. A street in Pompeii showing stepping stones and grooves worn by chariot wheels.

and Maintenance," by Thomas Aitken. This book was published in 1900 and on page 420 there is a discussion of an instrument called the "Viagraph." It is said to be the invention of J. Brown, an engineer of Belfast, Ireland, and is described as being "a straight-edge, twelve feet long and nine inches wide, applied continuously to the road surface, along which it is drawn." This early Viagraph (Fig. 3) contained "an apparatus for recording on paper a profile of the road surface tested, and the sum of unevenness is indicated by a numerical index." The author is mildly chagrined to note this description as he "invented" a device employing the same principle in 1929 (Fig. 4). Brown goes on to discuss the gravel and macadam-type road surfaces that were characteristic of his time (in the years prior to 1900) and concludes that steam rollers offer a distinct advantage in producing a regular and smooth surface. He shows some "autograph records" of macadamized road surfaces and states that, "In the author's opinion, after experience gained in working this instrument over many miles of road and under varying circumstances, a standard of fitness or smoothness of 15-ft of unevenness, or variation from a regular plane, per mile of road might be safely adopted." Brown's device furnished virtually all the information obtainable from the most modern profilograph units today—except that he measured "roughness" in feet instead of inches per mile.

With the high speeds common to modern vehicles on highways and airplanes on landing fields, even minute deviations in the pavement surface become a matter for concern. In the last 40 yr there have been many devices developed for measuring, evaluating or locating the individual high and low spots on a pavement surface. Following Brown's Viagraph, no record has come to light of similar devices until we come to the era of the Bates road test in Illinois in 1922. A. C. Benkelman kindly furnished photographs of a Profilometer built by the State of Illinois at that time (Fig. 5). Judging from the photograph, this was a most impressive instrument in which the frame was supported by 32 bicycle wheels mounted in tandem. According to reports, this particular model was not too successful and undoubtedly was unwieldy and difficult to handle. It does, however, represent a most elaborate example of the principle which is still being used; namely, a series of wheels mounted on short beams or "eveners" to produce a mechanical integration; that is, the center point of the main

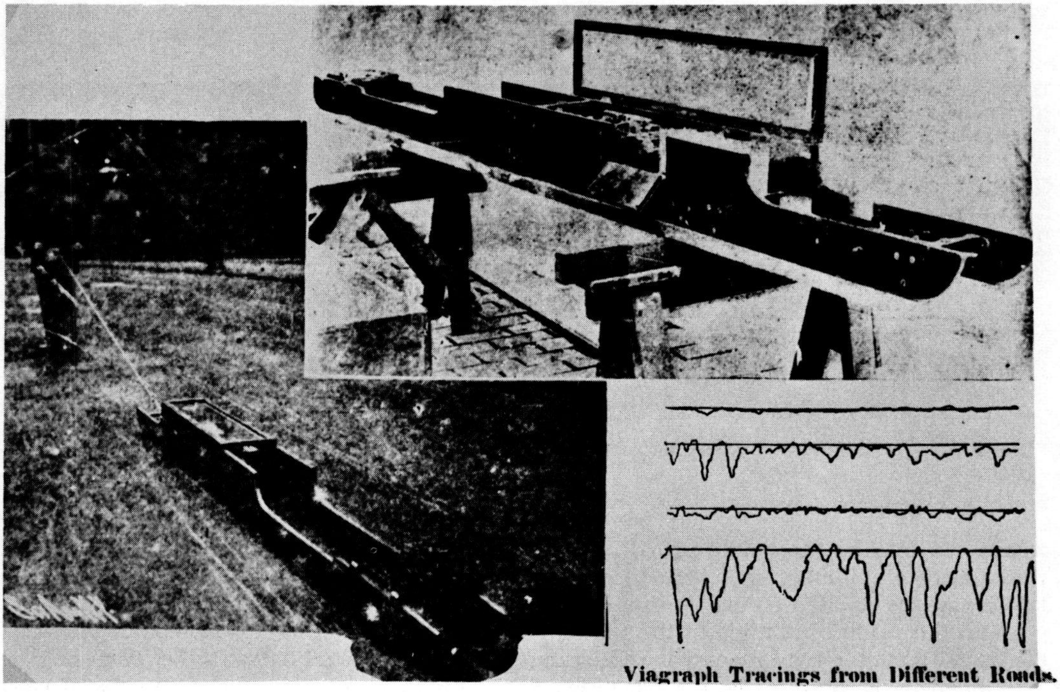


Figure 3. Brown's Viagraph constructed prior to 1900.

frame parallels in elevation at all times a point representing a mean elevation between the high and low spots of the pavement contacted by the series of wheels. By this means, a datum plane is produced to serve as a "plane of reference" for the recording

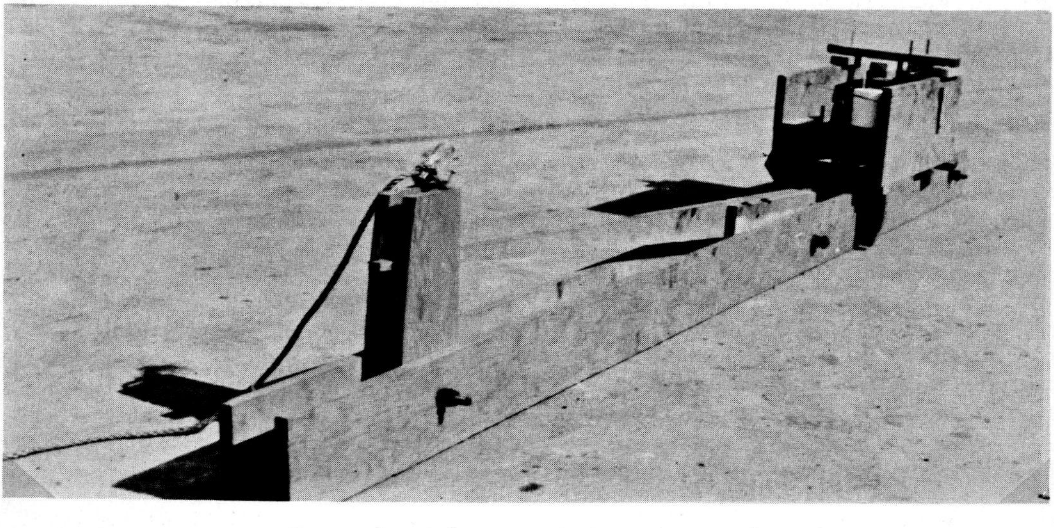


Figure 4. A "poor man's Profilograph."

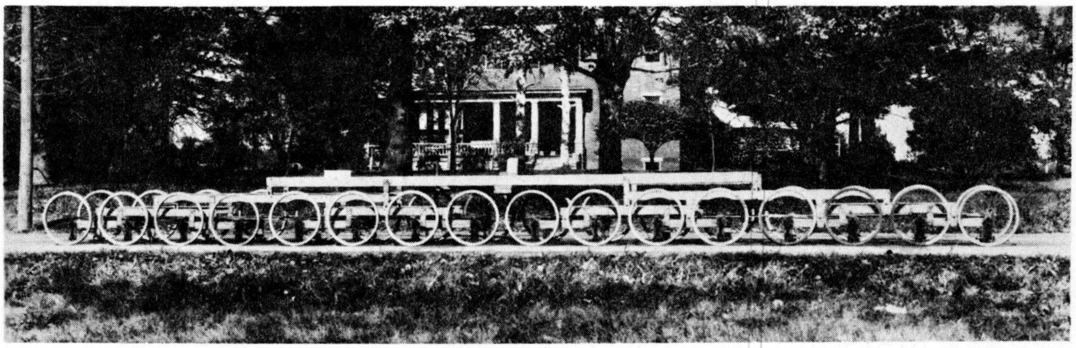


Figure 5. Profilometer constructed by the State of Illinois for the Bates test road, circa 1922.

wheel that follows the actual profile of the pavement. All of the straightedge types, of which Brown's pioneer model is an example, measure the profile in terms of depth below the peaks or high points on the road surface within the length of the straightedge.

With the rapid expansion of the motor vehicle and increasing awareness of riding qualities, another type made its appearance. One of the earliest was the "Via-Log" developed in the State of New York (Fig. 6). The Via-Log consisted of means of recording a profile on a strip of paper, the stylus being actuated by the vertical movements of the front axle of an automobile with reference to the frame of the car. In order to produce a reading, the car had to proceed at appreciable speed (20 mph or more).

Public Roads magazine for September 1926 reports on a variant of this instrument for the measurement of relative road roughness. It is described as consisting of a "rack which is attached in a vertical position to the front axle of the vehicle, Fig. 31. Meshed with this rack is a spur gear which is supported by the frame of the car. Movement of the front axle with respect to the chassis, caused by deflection of the body spring, thus produces translation of the rack and rotation of the gear. This gear is connected through a flexible shaft to a mechanical counter on the instrument board of the automobile." Modifications and developments of this type have been used for many years in California and by other states and agencies. Constant difficulty was encountered in securing uniformly reproducible readings and results obtained with the same apparatus mounted on different automobiles gave widely different results.

The Bureau of Public Roads continued to work on the problem and in Public

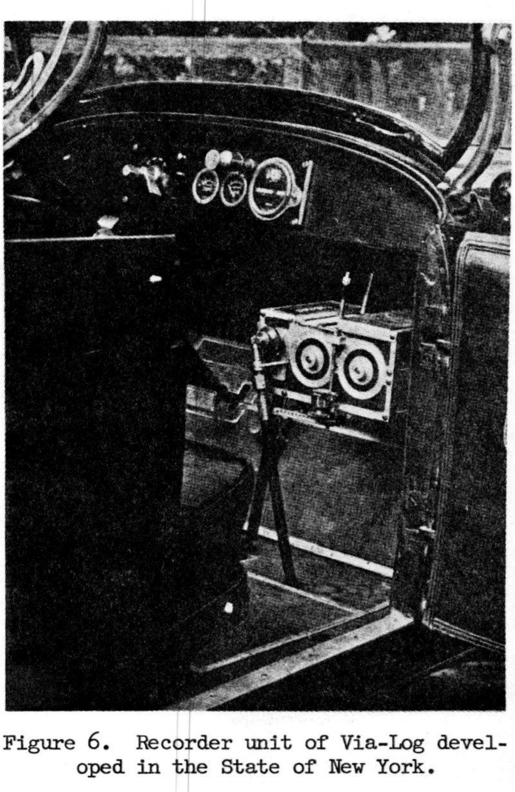


Figure 6. Recorder unit of Via-Log developed in the State of New York.

Figure 7. BPR Road Roughness Indicator, outrigger trailer carrier and tow car.

Roads for February 1941 reported on a trailer unit (Figs. 7, 8). In principle, this device is similar to those mounted on an automobile except that carefully selected springs, means for damping, and the weight of the unit can be standardized and thus produce an instrument that is not subject to variations such as exist between automobiles of different size and make. This road roughness indicator is probably the one most widely used in recent years, having been duplicated by several states and other agencies. Figure 9 shows traces of the record produced by one of these units operated by R. A. Moyer of the University of California. However, it is subject to the same criticism as applies to recording devices actuated by the front axle of a car. One might quote from and article on "Independent Wheel Suspension" by Maurice Olley, Special Problems Engineer, Cadillac Motor Car Company; "Frequently analysis of a

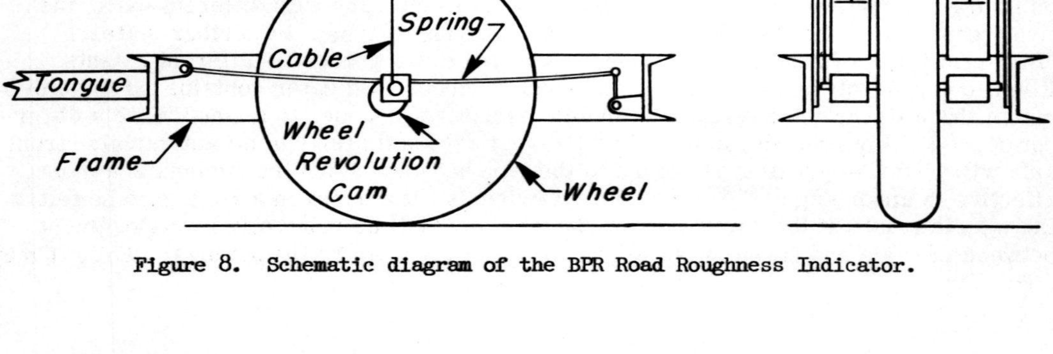


Figure 8. Schematic diagram of the BPR Road Roughness Indicator.

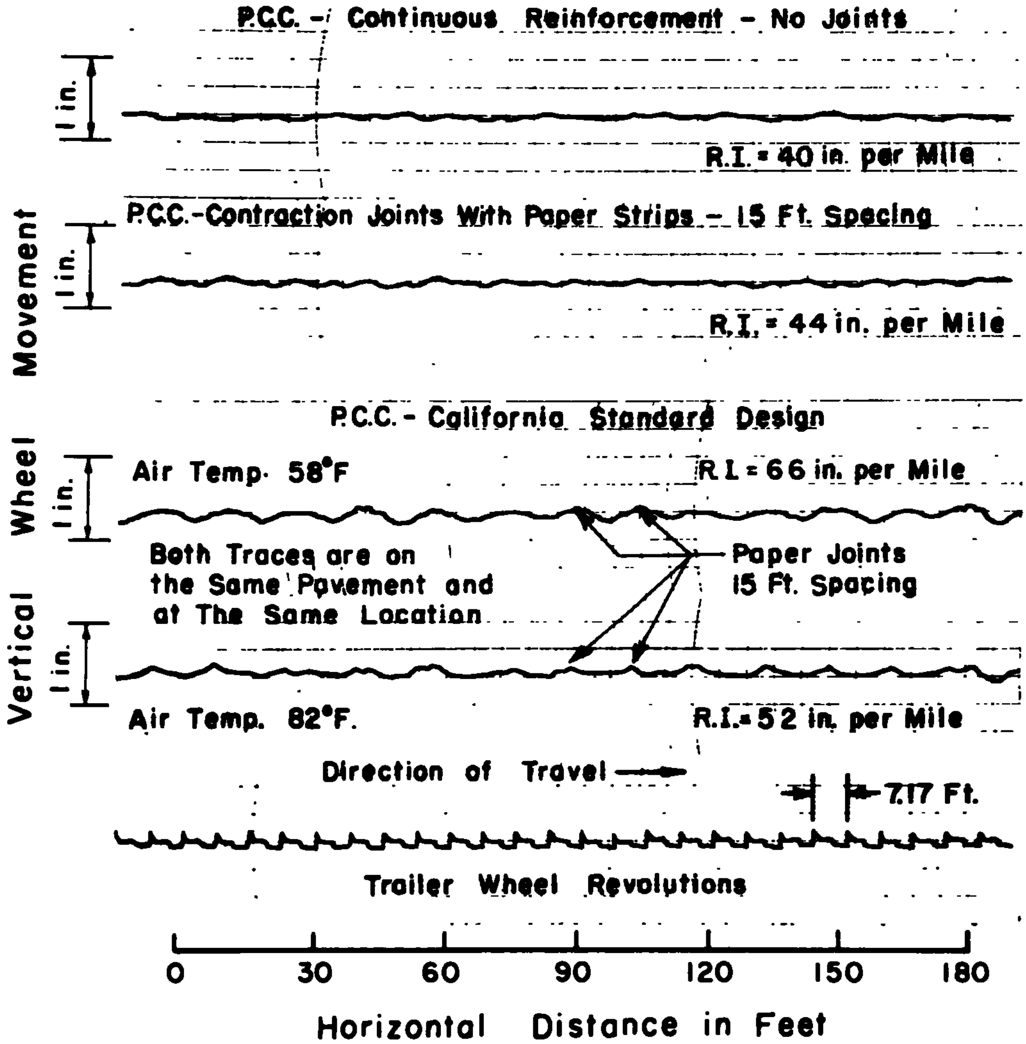


Figure 9. Roughness oscillograph records for P.C.C. pavement. Recorded by BPR Roughness Indicator.

car on the road shows that the average road at normal speeds disturbs the passage of the car by acting as an excitation for the natural frequencies of the car itself. The motion of the car, in other words, is never a true picture of the road surface but is made up of the car-frequencies excited by that particular road surface." Olley goes on to discuss the effects of the main frequencies which vary with different cars, the tire frequencies, and the frequencies of the unsprung masses. He further states, "Different types of road excite frequencies of the three groups to different extents." It will be apparent then that the Bureau road roughness indicator contains all the elements that exist in the average automobile except, of course, to a considerably different degree. Any recorder actuated by the vertical oscillations of an automobile front axle will show the greatest response to the type of bump which the springs are most effective in absorbing or "ironing" out. Obviously, if a bump on a road is to be felt the wheels must lift the car frame and hence there will be relatively less movement between the axle and frame when the shock is not taken up by the springs. While it may be true that rough roads will cause a greater number of vertical movements than will smooth ones, nevertheless a very distorted picture can be obtained from measurements of this type.

A fairly comprehensive resumé of road profile measuring devices was prepared by H. Petersen of the Road Research Institute, Technical University, Hanover, Germany, which was published in Strasse in 1939. Many of the following examples or illustrations are taken from Petersen's compilation.

Undoubtedly, the most simple (although slow and painstaking) method of gauging road roughness is by means of a straightedge laid on the surface of the road which means, of course, that the straightedge rests on the peaks of high points and the depths of the valleys or depressions are measured from the bottom of the straightedge, a wedge being a convenient means for accomplishing this purpose (Fig. 10).

In considering the general problem, it is evident that a true profile of a pavement surface can only be plotted in terms of absolute or relative elevations above some base elevation (sea level, for example). Such profiles are commonplace tools used by engineers for planning and establishing grade lines for roads and are generally developed by plotting elevations from level notes. However, such a process becomes very time consuming and requires painstaking care to produce even an approximately accurate intimate profile of a pavement surface as it will be necessary to take readings every foot or so along the pavement with a high degree of accuracy. However, one or two devices have been built that record the road profile with reference to a carefully leveled beam (Fig. 11).

A modification of the simple straightedge is to equip the straightedge with a center wheel that rises and falls as the straightedge is dragged along the surface of the pavement (Figs. 3, 4, 12). This is the principle of Brown's pioneer Viagraph and such a device can produce a reasonably accurate record and need not be difficult to construct. However, a straightedge or glider is tiresome and annoying to drag over the surface of a pavement and this drag becomes aggravated if the straightedge is of substantial length.

A third alternative which is an expedient "invented" by many individuals is to equip a beam with one fixed wheel at either end with a center wheel that rises and falls with the inequalities actuating a pointer or a stylus to record this vertical movement on a strip of paper (Figs. 13, 14). Many profilometers utilizing this principle have been developed but all have one primary weakness. First, a single bump on an otherwise true surface will be recorded on the graph three times as two depressions and one bump, and if a summarizing counter is used the amount of vertical excursion will be approximately twice that of the true profile. Moreover the aberrations produced by this type of device will vary with the pattern of the road inequalities. A certain sequence of waves can be described for which the recorder will produce a straight line on the graph (Fig. 15). These three wheeled machines will exaggerate some "bumps" and minimize others.

Figure 16 is an example of a three-wheel device with a rather elaborate recording mechanism which was reported on page 12 of a California Highways and Public Works, December 1939. This Viagraph was designed by Claran F. Galloway of the Los Angeles County Road Department.

Meanwhile, developments were proceeding abroad. Most of the devices utilize the principle illustrated by the Mailander Wave Measurer developed by the Illinois Division of Highways (Fig. 17). Other examples utilizing this principle are shown in Figures 5, 18, 22, 30, 38, 41, 43, 45. Through the courtesy of Raymond Peltier, Director of Research and Testing, Central Laboratory of Bridges and Roads, Paris, France, information has been furnished on developments in France. Two of the French machines are of interest. One (Fig. 18) is a large unit equipped with marking devices which delineate by a series of stripes all of the depressions or low spots on an old pavement. These markings serve as a guide to the repair crews who place thin localized patches to cover the markings and hence improve the riding quality by leveling up the surface. Figure 19 is a very ingenious design which utilizes the multiple wheel principle but in a novel fashion. Here the frame of the machine is carried on two center wheels and the individual bogie wheels are interconnected by a continous cable running over pulleys. These small individual wheels are free to rise or fall, adjusting themselves to the con-

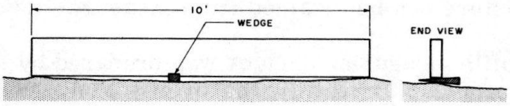


Figure 10. Long straightedge and measuring wedge.

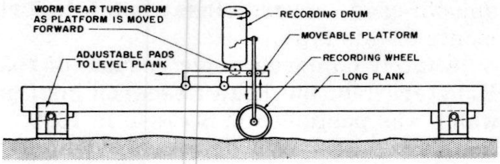


Figure 11. Measuring and recording apparatus of Kohler-Fuesz.

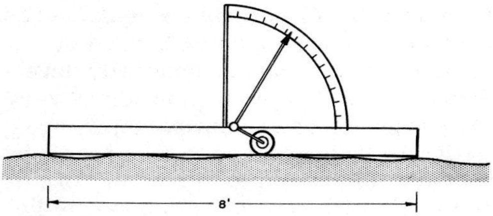


Figure 12. Stuttgart wave measurer.

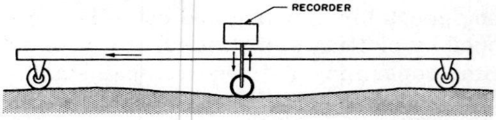


Figure 13. Portable "Unevenness Measurer" —Galloway (Los Angeles Street Dept.).

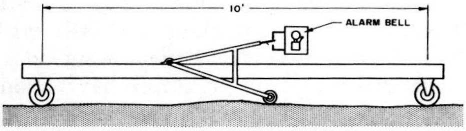


Figure 14. Bumpometer—Illinois Division of Highways.

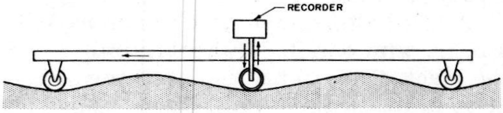


Figure 15. Illustrating the potential error produced by a device equipped with only three points of contact. The wave pattern corresponds to the spacing of the wheels and the profilograph record will be a straight line.

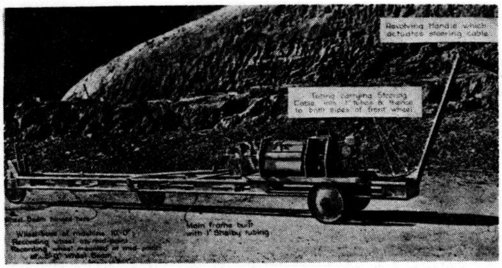


Figure 16. Viagraph designed in Los Angeles Road Department.

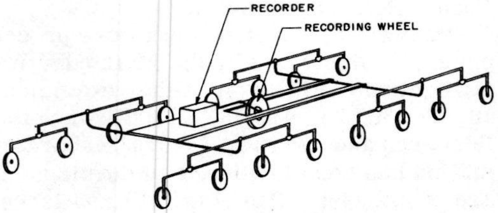


Figure 17. Schematic diagram of the "Mailander Wave Measurer" (Illinois Division of Highways).

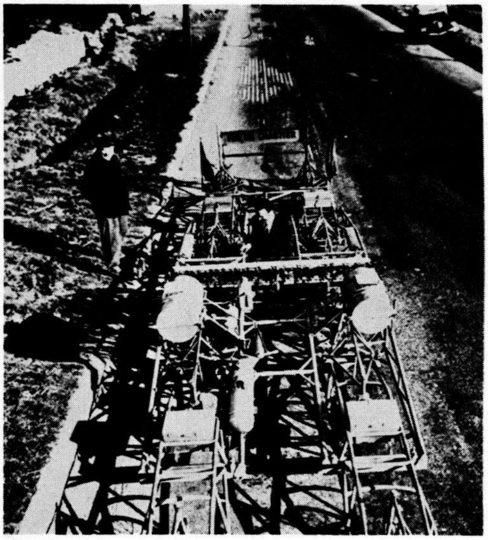


Figure 18. Viagraphe-Traceur used in France for delineating the low spots on a pavement preliminary. to placing leveling patches.

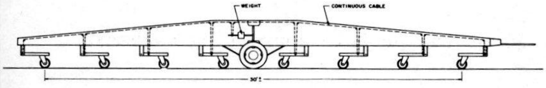


Figure 19. Schematic drawing of the Compensating Viagraphe—France.

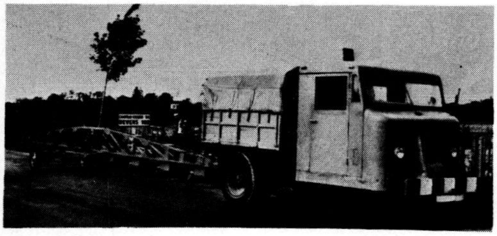


Figure 20. Compensating Viagraphe and towing vehicle—France.

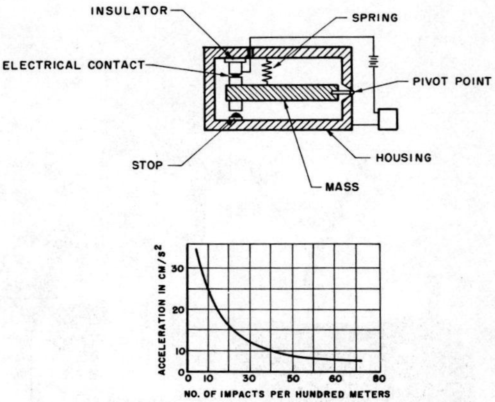


Figure 21. Maximum acceleration meter of Langer-Thome (above). Road condition curve developed by use of acceleration meter(below).

Figure 22. Multiwheel Profilometer apparatus (British Road Research Laboratory)

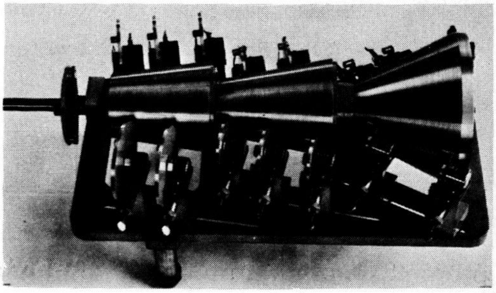
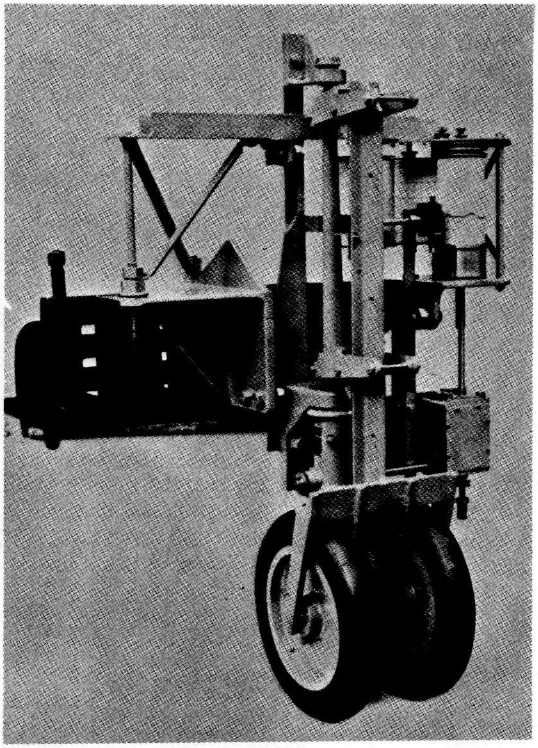


Figure 23. Multiple counter bump classifier on British machine.



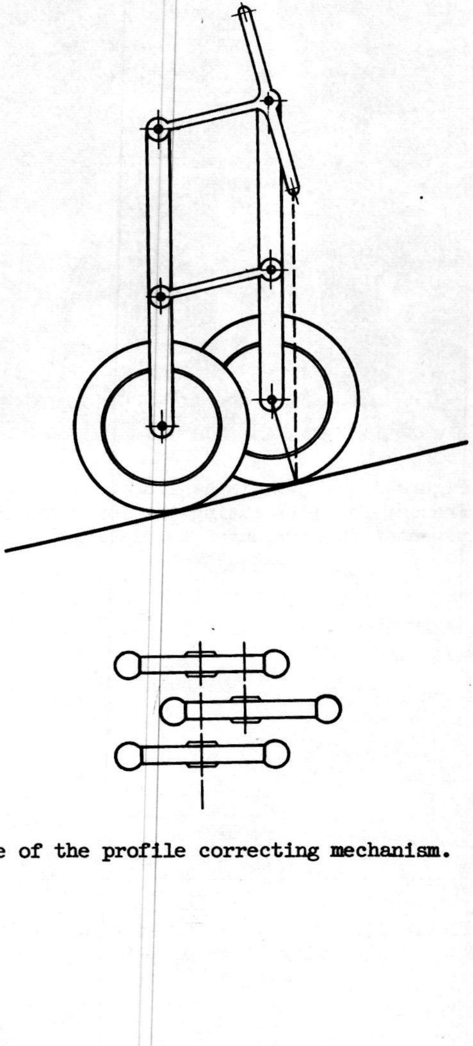


Figure 24. Diagram illustrating the principle of the profile correcting mechanism.

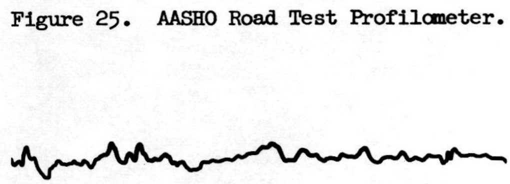


Figure 25. AASHO Road Test Profilometer.

Figure 27. Slope recorder trace of rough pavement—AASHO Road Test (not a profilogram.

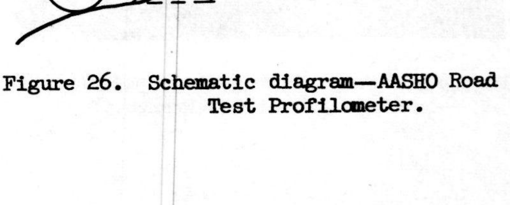


Figure 26. Schematic diagram—AASHO Road Test Profilometer.

tour of the road surface and, in effect, provide a reference datum for the vertical movements of the frame supported on the center wheels. Figure 20 is a photograph of this device shown attached to the towing vehicle. Figure 21 shows a "road condition curve" and the acceleration meter from which it was recorded and designed by Langer-Thome.

One of the more interesting and well engineered profilometers was developed many years ago by the engineers of the British Road Research Laboratory. This multiple-wheel unit employs 16 wheels but so disposed that no two wheels cross the same transverse joint or inequality at the same time (Fig. 22). Figure 23 shows the "classifier" from the British machine. This consists of a series of counters arranged to count each complete up and down movement equal to or greater than a given value. Figure 24 shows the unique three-wheeled recording unit used on the British machine.

A distinctly different principle is embodied in the "Profilometer" (Fig. 25) used on the AASHO test road. As reported by W.N. Carey, Jr., Chief Engineer for Research, it consists essentially of a trailer unit which is towed over the track by the instrument van at a speed of approximately 5 mph. As shown in Figure 26, the slope assembly S measures the angle "a" between pavement P and trailer bed T. Reference R measures angle "b" between the trailer bed and horizontal. As the trailer is towed over the pavement, two voltages are continuously generated proportional to angles "a" and "b". These voltages are added electronically to produce a voltage proportional to angle "c," the angle of the pavement from horizontal. The tangent of angle "c," (slope of the pavement on a 9-in. wheel base) is recorded as an analog in a recording oscillograph. The record includes pip marks at intervals of 1 ft on the pavement and other pips indicating the beginning and end of the test section or area of interest.

This device has reported advantages such as reasonable speed of operation, good over-all accuracy and reproducibility, and

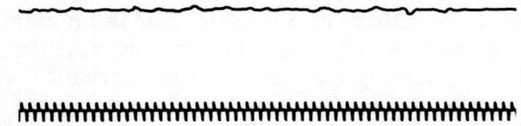


Figure 28. Slope recorder trace of smooth pavement--AASHO Road Test (not a profile).

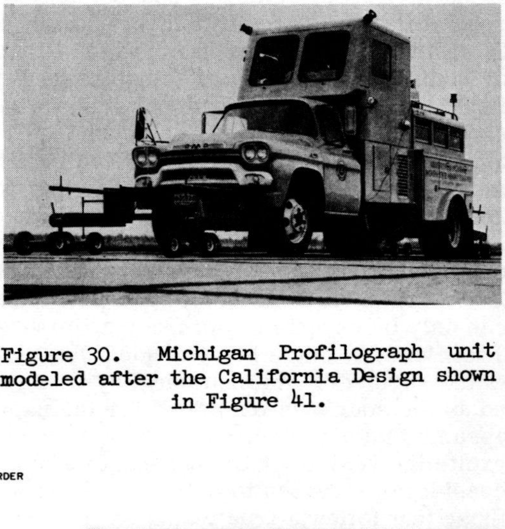


Figure 30. Michigan Profilograph unit modeled after the California Design shown in Figure 41.

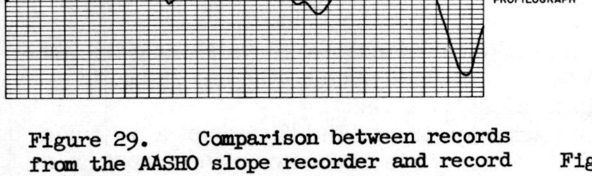


Figure 29. Comparison between records from the AASHO slope recorder and record made by Michigan Profilograph.

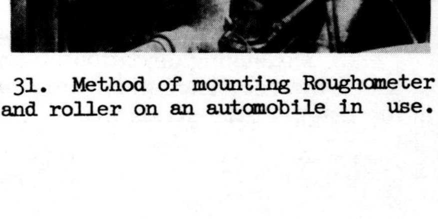


Figure 31. Method of mounting Roughometer rack and roller on an automobile in use.

the principle permits use of automatic summarization techniques to develop generalized harmonic analyses as a means of converting the wave form into a few numbers. One might judge that the 9-in. base line will introduce some error or aberrations on short wavelength bumps. Figures 27 and 28 represent some typical records produced by this instrument. The total cost is reported to be about the same as the California or Michigan Profilograph; namely, about $25,000.00. Strictly speaking, this Profilometer does not produce a profilogram directly although it is possible to reconstruct the profile by means of an electronic chart reader and digitizer. Figure 29 shows a comparison between the graphs taken with the test track Profilometer and with the Michigan machine (Fig. 30) over the same section of pavement. It will be noted that there is little apparent resemblance between the actual profile as recorded by the Michigan Profilometer and the tape record recorded by the test track unit. Carey has stated that the test track Profilometer record is actually the first derivative of the profilogram.

From the variety of devices which have been developed and promulgated by different individuals and agencies, it is evident that this problem has been approached from many different viewpoints, and it is not likely that all will agree on the relative merits or demerits of the various instruments. It seems evident, however, that there are two basic or fundamental differences in the approach. One is to record a profilogram on paper which represents a reasonably faithful picture of the intimate pavement profile. The scale, of course, must be distorted to show up the relatively slight inequalities that are involved in the term "roughness." There are several descriptive terms which are often used more or less interchangeably but which really have different connotations or meaning. One, of course, is the "profile" which represents the contour of the road surface along some single line or path. The term "profile" carries no implication as to whether or not the surface is smooth or rough. The term "pavement roughness" is also frequently used. This, of course, leaves the impression that all pavements must be rough to some degree which, of course, they are. The second approach is the attempt to measure "riding qualities" which is a term often used more or less interchangeably or confused with the word "roughness." It seems important to emphasize here that the individual who uses a road and drives a vehicle over a pavement is really not much concerned with roughness and even less with considerations of a profile, but is primarily and almost exclusively aware only of the "riding qualities." The term "riding qualities" means the response of a particular individual in a particular vehicle to the particular road surface at typical speeds of operation. The point the author wishes to emphasize is that an engineer cannot specify such a subjective attribute as "riding qualities" nor can he directly order a pavement contractor to achieve this somewhat elusive condition. By tradition, an engineer or a construction man works to line and grade and hence he can only be expected to produce a finished profile within certain limits of variation. Therefore, it might be concluded that the profile is the aspect which is of most interest to the engineer. As mentioned by Olley, the roughness of the pavement must be regarded as the source of excitation for the natural frequencies of the vehicle. Most will assume that a perfectly smooth road having neither bumps nor low spots will not excite the vehicle or the passenger and consequently will be smooth riding but there is considerable reason to believe that the most pleasant riding highway surfaces are not those that follow a true plane; on the contrary some undulation in the road surface may break the monotony and definitely add to the pleasant sensations of riding in a motor vehicle. Referring to the Profilometer developed and being used on the AASHO test road it might be said to develop some index to the excitation elements in the pavement surface.

It will appear then that the expedients or devices that have been used fall into seven classes which may be described, as follows:

1. Plotting a profile from level notes taken at frequent intervals along the pavement with rod readings to the nearest 0.001 ft. Devices such as the one shown in Figure 11 produce a record with a similar reference plane.
2. Measuring deviations from a straightedge laid on the surface of a pavement in which the reference plane corresponds to the average of the two highest spots within the length of the straightedge.

3. Profile records plotted by the movements of a center wheel in a three-point contact system. In other words, a beam equipped with a single wheel at either end and with a recording wheel in the center free to move in a vertical plane.

4. Recording vertical oscillations of a wheel with reference to a suspended weight or mass; for example, movements of the front axle of an automobile or movements of a wheel in a specially constructed device such as the U.S. Bureau of Public Roads road roughness indicator (Fig. 7).

5. Devices in which the reference plane represents the mean of a number of points of contact with the road surface in the vicinity of the point being recorded.

6. Devices to mark the pavement to delineate either high or low spots as desired. The most elaborate of this type known to the author is the "Marking Viagraphe" developed and used in France. This machine, instead of examining a single line, marks a considerable width of pavement in one operation (Fig. 18).

7. A novel device developed by the staff on the AASHO test road is equipped with two wheels 9-in. apart in tandem with electronic means for constantly measuring the slope of all inequalities on the road surface. This device does not give a direct picture of the road profile but it is stated that the data could be interpreted to give a profilogram if desired (Figs. 25,26,27,28,29).

DEVELOPMENTS IN CALIFORNIA

As stated before, the California Division of Highways became interested in means for evaluating road roughness more than 30 yr ago, and for many years construction forces, resident engineers and contractors were "kept on their toes" by the fact that pavements would be evaluated for roughness at the completion of the contract. The devices used were of the type described previously in the form of a mechanically operated counter actuated by the movements of the front axle of a car (Figs. 31,32,33). In 1950, the mechanical difficulties of the car-mounted Roughometer were overcome by the development of an electronic device (Fig. 34) but differences between cars still affect the readings.

A novel instrument developed by E. L. Seitz, Resident Engineer of the California Division of Highways (1), (Figs. 35,36,37), is the Bumpograph which was intended solely for use during the construction of asphaltic concrete pavements. When wheeled by hand over a section of pavement, the Bumpograph would mark all of the high spots with white chalk. The machine was light in weight, weighing only about 30 lb and had a wheel base of approximately 8 ft.

While serving as a resident engineer on a paving contract, the author developed a simple profile measuring device (Fig. 4) which it now appears was identical in principle to the original Viagraph ascribed to Brown of Belfast 40 yr earlier. The mechanism use, however, was much less involved than that shown for Brown's Viagraph. The straightedge was constructed of two pieces of 1- by 6-in. lumber 10 ft in length. The paper feed roller was driven by a small rubber-tired wheel and the mechanism taken from a small hand-operated churn served as a reduction gear. The stylus was a common lead pencil and the platen supporting the paper was an empty tomato can. Graph records were quite accurate and reproducible. However, the unit was somewhat noisy in operation and dragging the "sled" for any appreciable distance became a little wearing.

In 1940, after becoming associated with the Materials and Research Department, a more elaborate device was constructed (Fig. 38), which consisted of a frame 10 ft in length supported on multiple wheels at either end arranged in a pattern similar to that of the larger British machine (Fig. 22). The important feature of this first California Profilograph (2) is the fact that the frame could be broken down into relatively small pieces for ready transportation in a pickup or in the tonneau of a small sedan (Fig. 39). The selection of a 10-ft length of frame was due to the fact that California specifications for pavement finish referred to the amount of departure from a 10-ft straightedge placed on the surface. Profilograms obtained with this profilograph were compared with profiles plotted from level notes at 5-ft intervals and also comparisons were made over sections of pavement by stretching a steel piano wire and measuring ordinates with a steel scale (Fig. 40). Agreement appeared

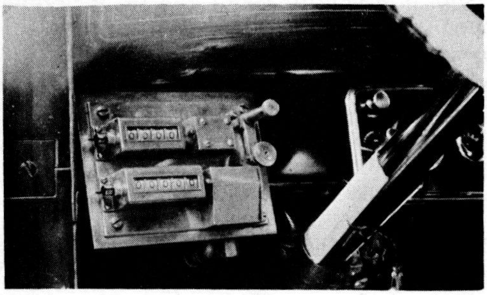


Figure 32. Roughometer head mounted on instrument board.

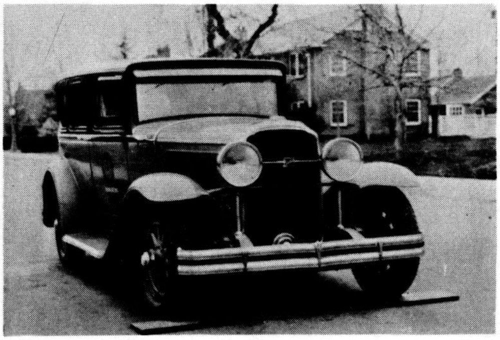


Figure 33. Testing Roughometer with 1-in. boards—1931.

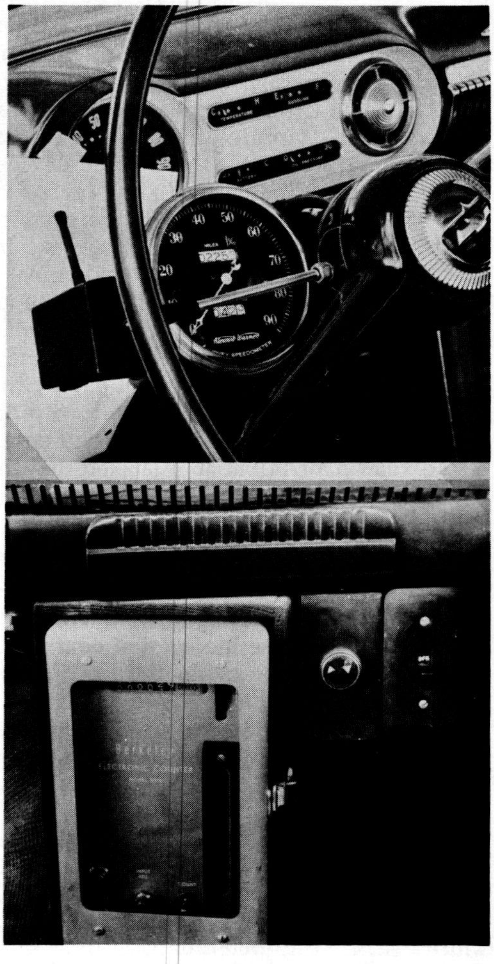


Figure 34. Electronic Roughometer assembly and recorder—1957.

to be sufficiently close for all practical purposes but unanswered questions always persisted as to the exact shape of the bumps in the pavement.

With the general increase in the speed of traffic and trend toward vehicles with a longer wheel base, it was concluded that an improved profilograph should have a longer frame and a 25-ft length was selected more or less arbitrarily. Experience in operating the hand-propelled profilograph on pavements subjected to high-speed traffic has shown that this is definitely a hazardous occupation. Therefore steps were taken to develop a unit capable of more rapid operation and which would offer reasonable protection to the operator. In order to accomplish both purposes a profilograph mechanism was incorporated into a two-ton truck. The frame of the truck was lengthened and became the principal "beam" member. The truck was equipped with a series of small bogie wheels in the front and rear making a total of ten wheels in line. Figure 41 shows this truck with the operator carried by an independently supported frame pushed ahead of the truck, this position enables him to get a close view of any cracks or defects which are registered on the profilogram by manually pressing appropriate buttons on the console. Figure 42 shows the unit with the driver in an elevated position back of the cab. This position is used whenever it is not necessary to mark cracks or joints on the profilogram. The vertical movement of the extra bogie wheels is mechanically integrated and then electrically integrated with the movement of the truck frame in order to produce a datum representing the mean

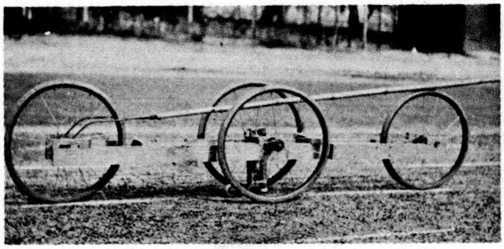


Figure 35.

Figure 38.

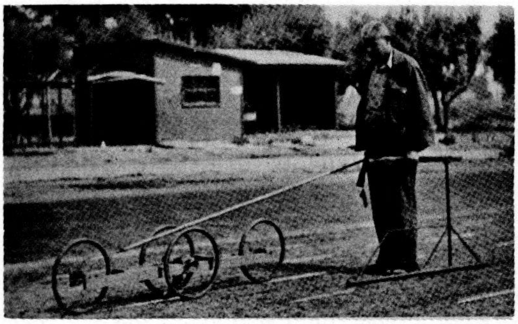


Figure 36.

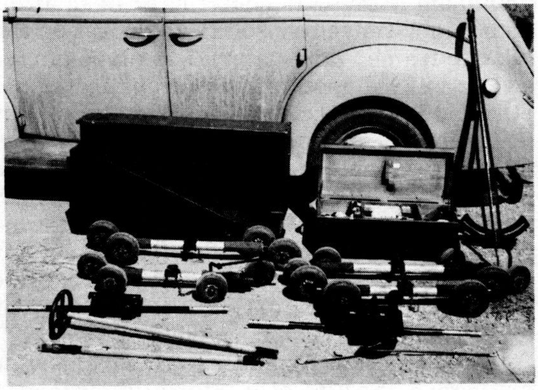


Figure 39. Multiwheel Profilograph with 10-ft base length (California Division of Highways).

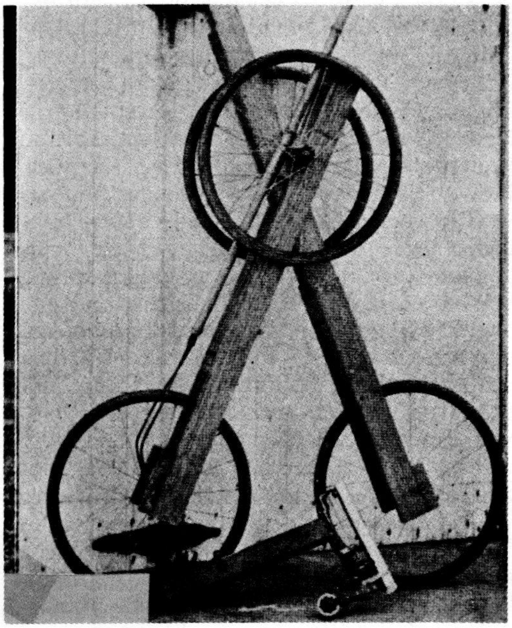


Figure 37. Bumpograph constructed by E.L. Seitz, California Division of Highways, for detecting bumps during construction of asphaltic pavement.

elevation of the high or low spots of the pavement which are in contact with the ten wheels. The "profile" is recorded from the vertical movement of a wheel attached to the truck frame at the mid-point and is always with reference to the mean elevation of ten points of contact with the road surface. This self-powered mobile profilograph was constructed in 1955 and has been operated over the length and breadth of California and was sent on one trip to Colorado to record the riding qualities produced with a slipform-type paver. This truck model has proved to be eminently satisfactory and has given little or no trouble in operation and has enabled the California Division of Highways to make records over many miles of existing highways. This unit has been duplicated with some modifications in the State of Michigan (Fig. 30) and reported by Housel and Stokstad (3). It has permitted setting up of a tentative scale for evaluating pavement roughness and relating this scale to the so-called riding qualities or the reactions to the road roughness of drivers and passengers in motor vehicles.

While the truck-mounted profilograph is invaluable for securing measurements over many miles of an existing highway system and for following the changes that take place with time and traffic, it is, of course, not suitable for use on jobs under construction. The truck is obviously too heavy for safe application on a newly constructed concrete pavement. Therefore, there is a need for a lightweight profilograph and a new model has been constructed using the same wheelbase as the truck unit and which produces a graph record by mechanical means that is virtually indentical. There had been some complaint from operators using the original small plywood unit that crosswinds at times created problems in operating the machine. Therefore, a 25-ft unit using a tubular aluminum frame was constructed in an attempt to meet this objection (Figs. 43,44). Although satisfactory so far as operation and ability to knock down and reassemble the tubular frame, this material and type of construction proved to be relatively expensive and so in 1957 another hand-propelled model was designed using a plywood frame constructed in five sections for ready knock-down and transportation (Figs. 45,46,47). This model, constructed of plywood, appears to be superior in most respects considering rigidity, ability to nest units for conservation of space in a transporting vehicle, enclosing of the operating mechanism for protection against damage and above all the lowest initial cost of construction. This instrument is intended primarily for use to check the surface roughness of newly constructed pavements. The profile of the finished pavement is recorded on a graph record or profilogram to a horizontal scale of 1 in. = 25 ft and a vertical scale of 1 in. = 1 in. which is the same as the scale established for the mobile truck-mounted unit.

Since the first roughness measurement devices were constructed, there has been an instinctive and virtually automatic move on the part of engineers to reduce the data to a number. For example, in the report of Brown's Viagraph it is shown that he recorded a profilogram and he also expressed road roughness in terms of feet per mile. It is previously noted that he thought that 15 ft of roughness per mile represented a satisfactory road. Throughout the years, engineers have converted the readings of Roughometers, Profilometers, etc., to numbers, thus California employed a unit of inches per mile to express results of a "bumpmeter" mounted in an automobile. The Bureau of Public Roads device has means for integrating the results, and Housel has added a mechanism for accumulating the total distance involved in the vertical excursions of the recording stylus to develop a "roughness index." It is true, of course, that these numbers are convenient, but unfortunately often represent an oversimplification and no single numerical scale has been devised to distinguish between large numbers of small asperities on the pavement surface as compared to a few larger and distinct bumps. The British machine uses a number of different counters but the results are not expressed by a single number. It appears that there is no substitute for a careful examination of the graph record if an engineer wishes to know what is going on during construction of a pavement or to study the nature of changes which are taking place with time and traffic. However, the use of roughness "number" becomes less objectionable and is more justifiable as a means for specifying the surface finish to be obtained during construction. Therefore, California had developed a new index which has been called the "profile index" to indicate that it is derived from the recorded profile or profilogram record. Appendix A is taken from a report by Bailey Tremper describing in some detail how the profile index was derived. No claim is made that the roughness or riding quality of a pavement is directly or completely reflected by the profile index. It should again be emphasized that strictly speaking the devices reported herein do not furnish a direct index to "riding qualities." The most elaborate attempt to actually evaluate the response of a passenger is an elaborate instrument developed in Kentucky (4). California duplicated the Kentucky machine and instrumentation but was unable to interpret the results to give consistent or meaningful indices to rideability of a road surface. However, as a practical matter, it can be shown that if the profile index is low the pavements are usually considered to be smooth and to have good riding qualities. At the present time California has established a profile index of 7 which means that the contractor is permitted deviations outside of the 0.2 in. band which will not

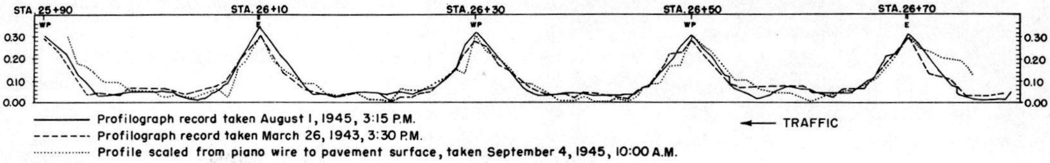


Figure 40. Relative accuracy of profilograph records compared with profile obtained by stretching a piano wire and scaling offset to pavement surface. The pavement shown is a badly curled or warped concrete pavement.

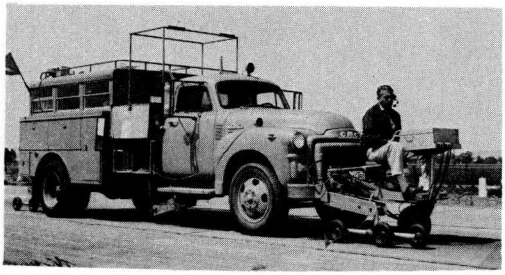


Figure 41. Mobile Profilograph constructed by California Division of Highways—1955—showing operator in position to record cracks and joints.

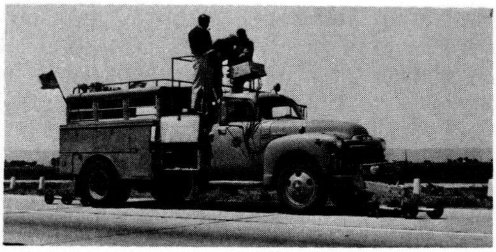


Figure 42. California Profilograph showing recording console in elevated position.

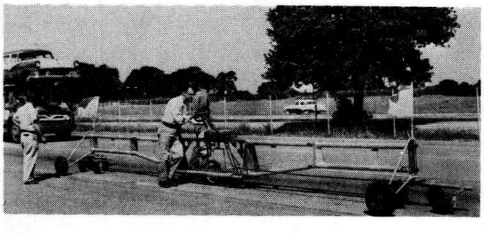


Figure 43.

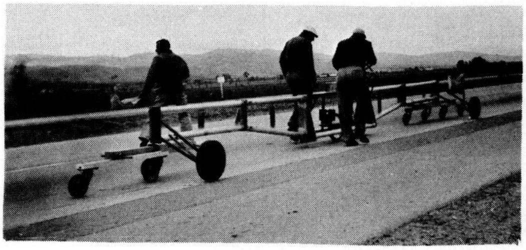


Figure 44. Hand-propelled Profilograph with unitized frame for rapid knockdown.

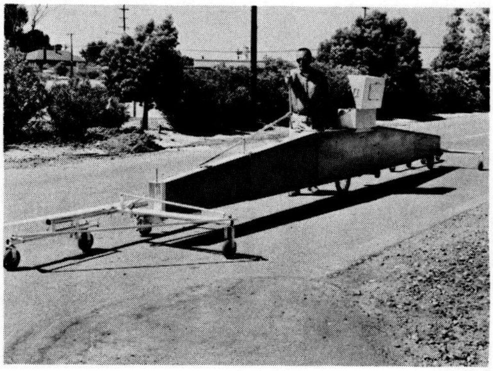


Figure 45.

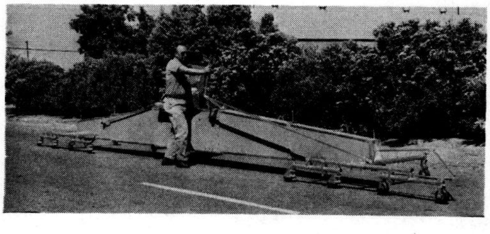


Figure 46.

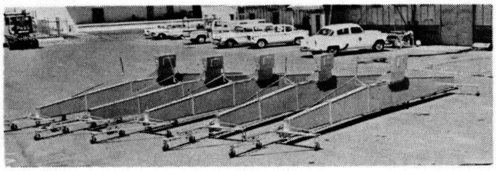


Figure 47. Most recent California model—hand-propelled recording Profilograph intended primarily for construction control.

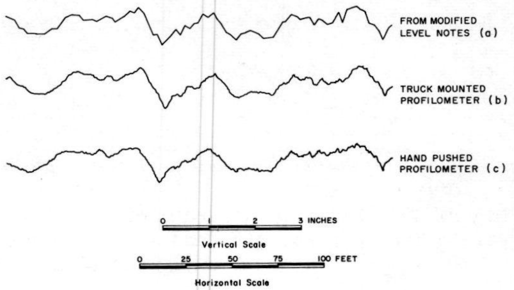


Figure 48. Comparison between three different methods of recording pavement roughness.

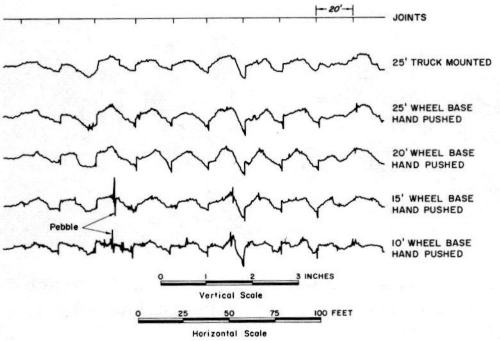


Figure 49. Profiles of a faulted concrete pavement showing influence of varying the length of wheel base on the Profilograph.

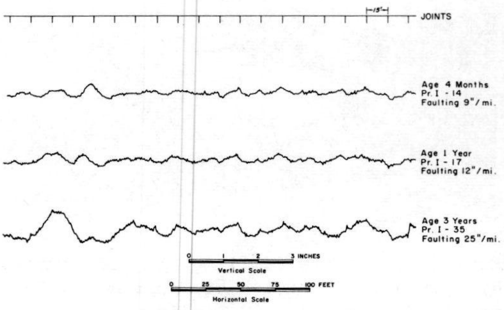


Figure 50. Shows progressive roughening of a concrete pavement.

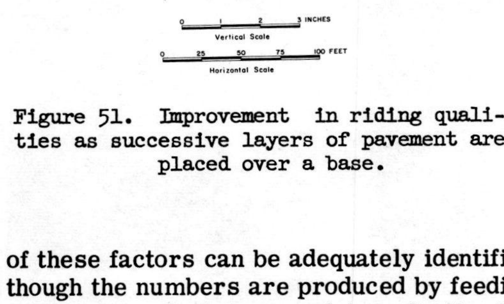
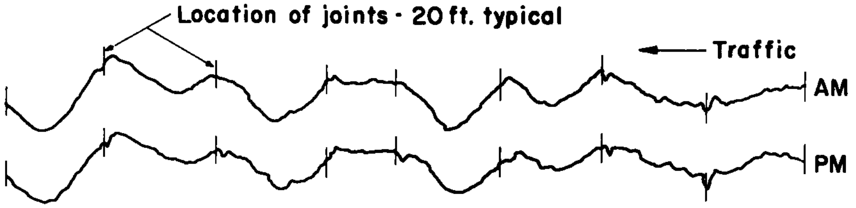


Figure 51. Improvement in riding qualities as successive layers of pavement are placed over a base.

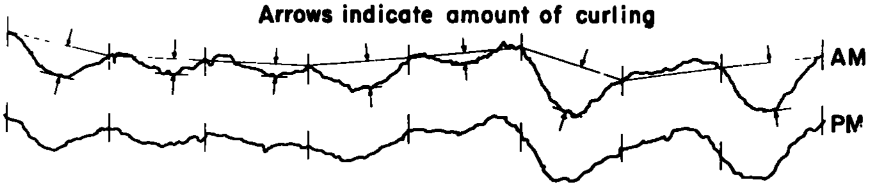
total over 7 in. per mile or in porportion for shorter distances. A copy of the Division's current specifications is Appendix B.

Although the profile index appears to be reasonably satisfactory for use in specifications, it fails to differentiate between bumps or irregularities of different shape and of different length and this numerical expression does not adequately emphasize the annoyance in terms of riding qualities generated by badly faulted concrete pavement, for example. A somewhat more elaborate system of deriving a numerical index will be necessary if it becomes important to assign numbers to existing highways or airfields. It is to be doubted that there will ever be any adequate substitute for careful visual examination of the recorded profiles which convey information on the frequency, magnitude and shape of the inequalities, and it seems unlikely that all of these factors can be adequately identified by any simple numerical expression even though the numbers are produced by feeding the profile record into one of the modern electronic calculators or data reduction "mechanical brains."

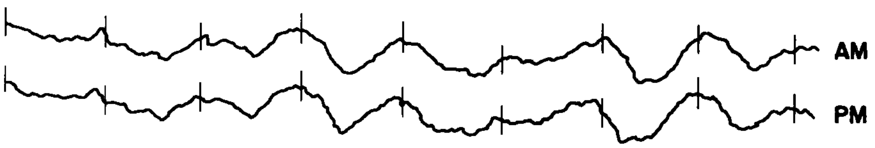
To illustrate some of the relationships and information which may be derived from pavement surface profilograms, several examples are shown. Figure 48 represents



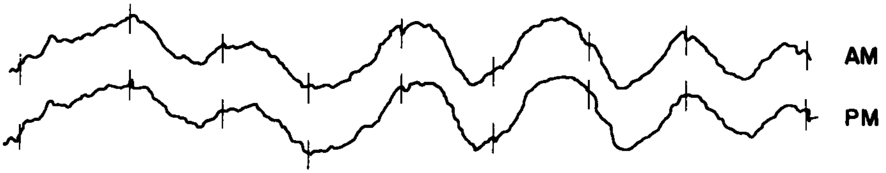
Section 19, Cement 2, 1" Aggt. 1924 Curing 124" per mile



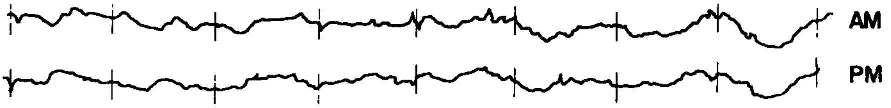
Section 22, Cement 3, 1" Aggt. 1924 Curing 108" per mile



Section 1, Cement 1, 1" Aggt. 1949 Curing 106" per mile



Section 33, Cement 2, 1" Aggt. 1924 Curing 158" per mile



Section 27, Cement 1, 2" Aggt. 1924 Curing 84" per mile

Figure 52.

three profiles taken of the same stretch of pavement plotted by different means. Profile (a) was developed from level notes with rod readings taken at 2½-ft intervals. The readings were adjusted to eliminate any effects of pavement grade or grade changes. Profile (b) is the same surface as recorded with a truck-mounted Profilometer (Figs 41, 42). Profile (c) is recorded with a hand-propelled model (Figs. 43, 44). Figure 48 and Figure 40 both show the relative accuracy of these profilograms compared to other methods of measurement. It will be obvious, of course, that the inequalities in the pavement are recorded with reference to the datum furnished by a 25-ft beam supported on multiple wheels at either end. To illustrate the effects of varying the length of the wheel base. Figure 49 shows a stretch of concrete pavement with marked faulting at most of the joints as recorded by the 25-ft truck Profilograph. The succeeding profiles represent the same stretch of pavement recorded with hand-propelled units in which the length of wheelbase has been changed successively from 25 ft to 20 ft, 15 ft and 10 ft, respectively. It will be evident that whereas there is not much difference between a 20-ft and 25-ft length, the 10-ft wheelbase does introduce some departures in the recorded profile. It will be noted, however, that the principal features are shown on all records, especially the magnitude of faulting at the joints. Figure 50 is included to show some of the changes in surface roughness which may develop in a pavement over a period of time. Here are shown three stages

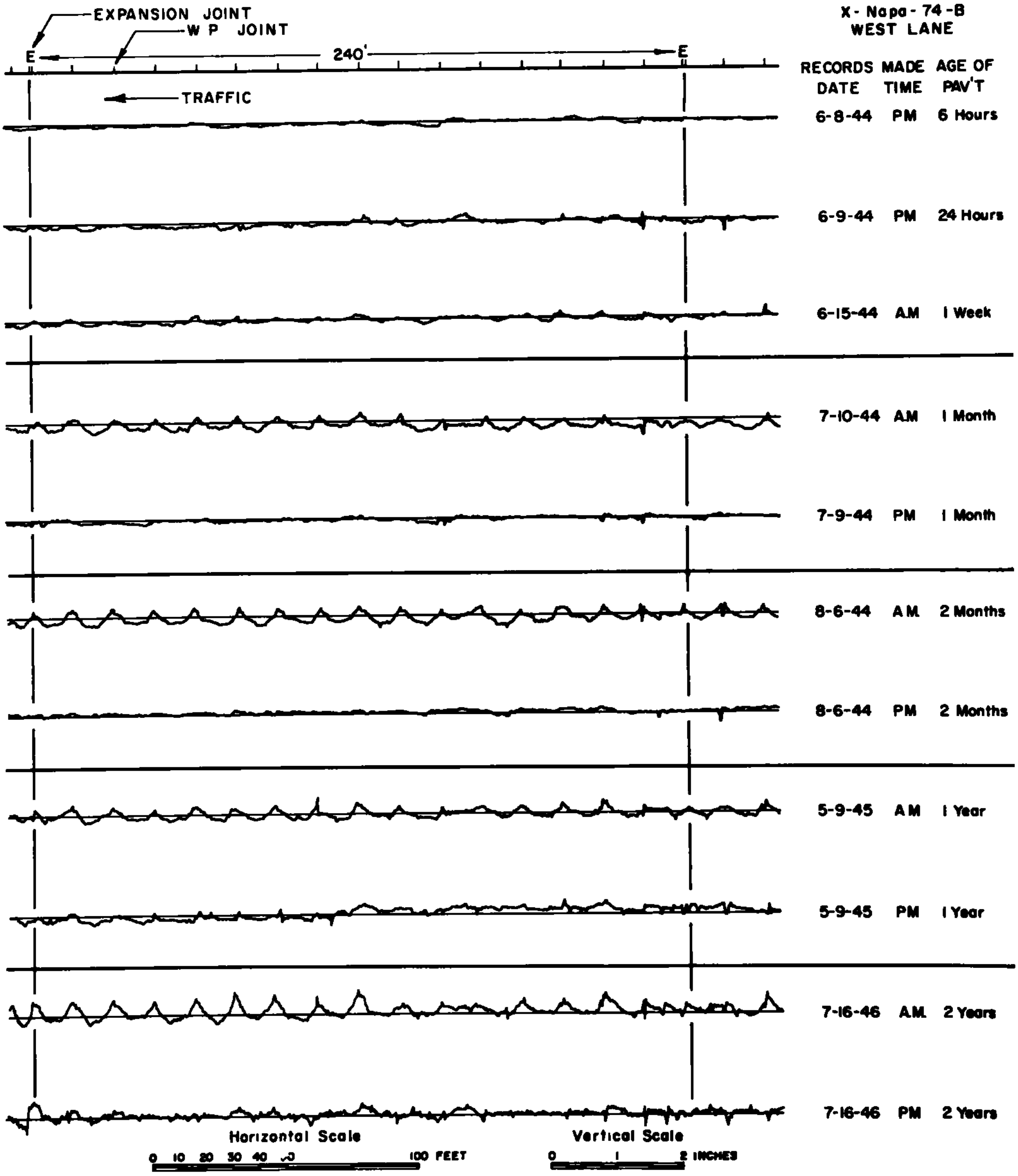


Figure 53. Profilograph records show daily cycle of curling as pavement increases in age.

in the life of a concrete pavement; namely, after 4 months, 1 yr and 3 yr. Figure 51 shows the improvement in riding qualities that develop from placing successive layers of construction. The lower graph is the surface of a cement-treated base. The lower graph is the surface of a cement-treated base. The second is the surface of the first layer or leveling course of asphaltic concrete. Third represents the second layer of dense-graded asphaltic mixture and the fourth or upper profile represents the finished surface of an open-graded wearing course. It will be observed that although most of the initial bumps were eliminated in the top course, nevertheless, the principal one which is shown is apparently the reflection of a bump in the base course.

One valuable attribute of the profilograph is the ability to detect incipient faulting. If the instrument is adjusted to give the proper sensitivity, it is possible to estimate faulting to the nearest 0.01 in. Periodic measurements make it possible to follow the increase in faulting if it occurs. Faulting can be detected on a profilogram before it is apparent from an inspection of the pavement. Profilograms provide a convenient method for recording the location of cracks and also for determining whether there is any relationship between the high or low points in the profile and the location of joints or cracks in the pavement. Profilograms have been used to measure the warping or curling of slabs as affected by variables such as the maximum size of aggregate or nature of the cement. For example, Figure 52 shows several profiles taken from the Topeka test road illustrating some of these effects. (Note that the numerical values for roughness represent a total range from high to low points and on this chart do not correspond to the profile index scale.) Profilograms have made it possible to visualize the wide variations in curling of concrete slabs that often develop between early morning and late afternoon (Fig. 53). They have also demonstrated that California pavement slabs as a rule are curled upward at the ends and it is only on warm afternoons that the slabs approach a condition of flatness. Very few examples have been found of pavements that assume a downward curl with the joints being low.

As also shown in Figure 53, profilograms furnish an invaluable means for recording the initial roughness of pavements as constructed and for following up and analyzing the changes which take place during the years following construction. It is axiomatic that if an engineer is to take steps to correct any deficiency he must understand the nature and cause of the thing he is trying to correct.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions of many individuals who have furnished information and material used in this paper and to those who have assisted in the development and use of the profilograph units constructed in this state.

Among those who have furnished helpful information are: H. Petersen, Road Research Institute, Technical University, Hanover, Germany; R. Peltier, Director of Research and Tests, Laboratoire Central des Ponts et Chaussees, Paris, France; A. C. Whiffin, Head of Special Problems Section, Road Research Laboratory, Harmondsworth, Middlesex, England; J.D. Lindsay, Engineer of Materials, Illinois Division of Highways, Springfield; W.N. Carey, Jr., Chief Engineer for Research, and A.C. Benkelman, Flexible Pavement Research Engineer, AASHO Road Test, Ottawa, Illinois; and, Ralph A. Moyer, University of California, Berkeley.

Among those who have made contributions to the work in this State are: Bailey Tremper, Supervising Materials and Research Engineer; George Pomeroy and R. E. Wilhelmy, Chief Instrumentmakers; J. L. Beatty, Charles W. Clawson, and Douglas Howard who have operated the profilographs over many miles of road. J. E. Barton, who suggested the electrical circuits making possible the compensating device on the truck-mounted profilograph; Robert Field who worked out the mechanical and electrical circuits for this unit; and Don Spellman who developed the Profile Index.

REFERENCES

1. California Highways and Public Works, p.26 (Feb. 1937).
2. California Highways and Public Works, pp. 6-9 (March-April 1944).
3. Housel, W.S., and Stokstad, O.L., "Pavement Profile Surveys to Correlate Michigan Design Practice with Service Behavior." HRB Proc., 38:149-182 (1959).
4. Gregg, L.E., and Foy, W.S., "Triaxial Acceleration Analysis Applied to the Evaluation of Pavement Riding Qualities." Kentucky Department of Highways.

Appendix A

A Report on Measuring Pavement Roughness From Profilograms—March 8, 1957

During the spring and summer of 1956, profilograms of selected pavements in nine districts were recorded with the new truck-mounted profilograph. These pavements were selected by the districts in response to a request for examples of "smooth" and "rough riding" pavements, of both portland cement concrete and bituminous types. The profiles covered 60 mi in all, representing 17 sections of each type. Some sections were 2-lane and others 4-lane and because profiles were nearly always made of the two outer lanes, the lengths given are only about one-half the total profiles obtained. All profiles represent the outer wheel track, about 30 in. from the edge of the pavement, recorded in the direction of traffic. From this group, 15 sections of portland cement concrete pavement and 11 sections of bituminous pavement were selected for study.

At the time the profiles were made, the operators recorded their personal observations as to relative roughness when driving over the roadway in a car. Disagreement in terms of personal impressions was found with only a few of the district ratings. Such disagreement however, was only to be expected since the profilograph operators were making comparisons on a statewide basis, while the districts were presumably comparing roads within their own areas. It is believed that the observations made by the Headquarters profilograph operators should be more consistent on a statewide basis and for this reason they are used in the discussion that follows.

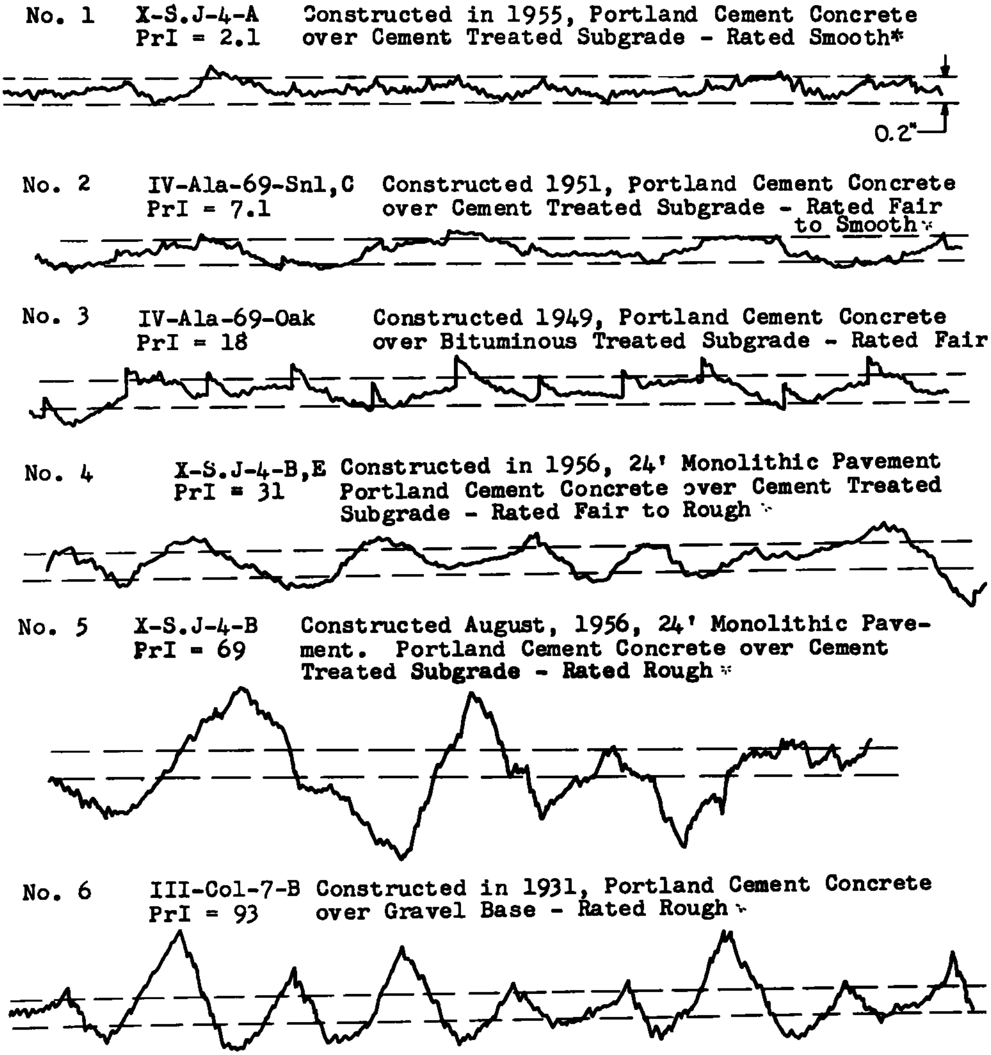
The classification as to riding comfort must necessarily be broad because in addition to the factor of personal reactions, speed and type of vehicle are other prominent variables. Nevertheless, among the pavements selected, examples were found that could be classified as distinctly either rough or smooth without much likelihood of disagreement. In the intermediate zone it is not unlikely that there would be some difference of opinion as to which pavements are smoother than others.

PROFILE ANALYSIS

Various expedients were tried seeking to convert the profilogram records to a numerical scale that would correlate with the jury classification. Some of the relationships developed are given in Table 1.

To speed up the evaluation and make use of the fact that rough roads showed short waves or "scallops" having ordinates over ⅜-in., Don Spellman conceived the idea of evaluating roads on the basis of vertical deviations only after blanking out those portions of the profile showing only minor inequalities which apparently cause little discomfort to the passengers in a motor vehicle. A "blanking" band of 0.2 in. was arbitrarily selected and a summarization of the measurements of the peaks and low points exceeding that amount were made on several profiles by selecting 1-mi sections that were typical of the job.

It was found that a minimum of 1-mi of profile was needed to obtain a reasonably



No. 1 X-S.J-4-A Constructed in 1955, Portland Cement Concrete
PrI = 2.1 over Cement Treated Subgrade - Rated Smooth*

No. 2 IV-Ala-69-Snl,C Constructed 1951, Portland Cement Concrete
PrI = 7.1 over Cement Treated Subgrade - Rated Fair to Smooth*

No. 3 IV-Ala-69-Oak Constructed 1949, Portland Cement Concrete
PrI = 18 over Bituminous Treated Subgrade - Rated Fair

No. 4 X-S.J-4-B,E Constructed in 1956, 24' Monolithic Pavement
PrI = 31 Portland Cement Concrete over Cement Treated Subgrade - Rated Fair to Rough*

No. 5 X-S.J-4-B Constructed August, 1956, 24' Monolithic Pavement. Portland Cement Concrete over Cement
PrI = 69 Treated Subgrade - Rated Rough*

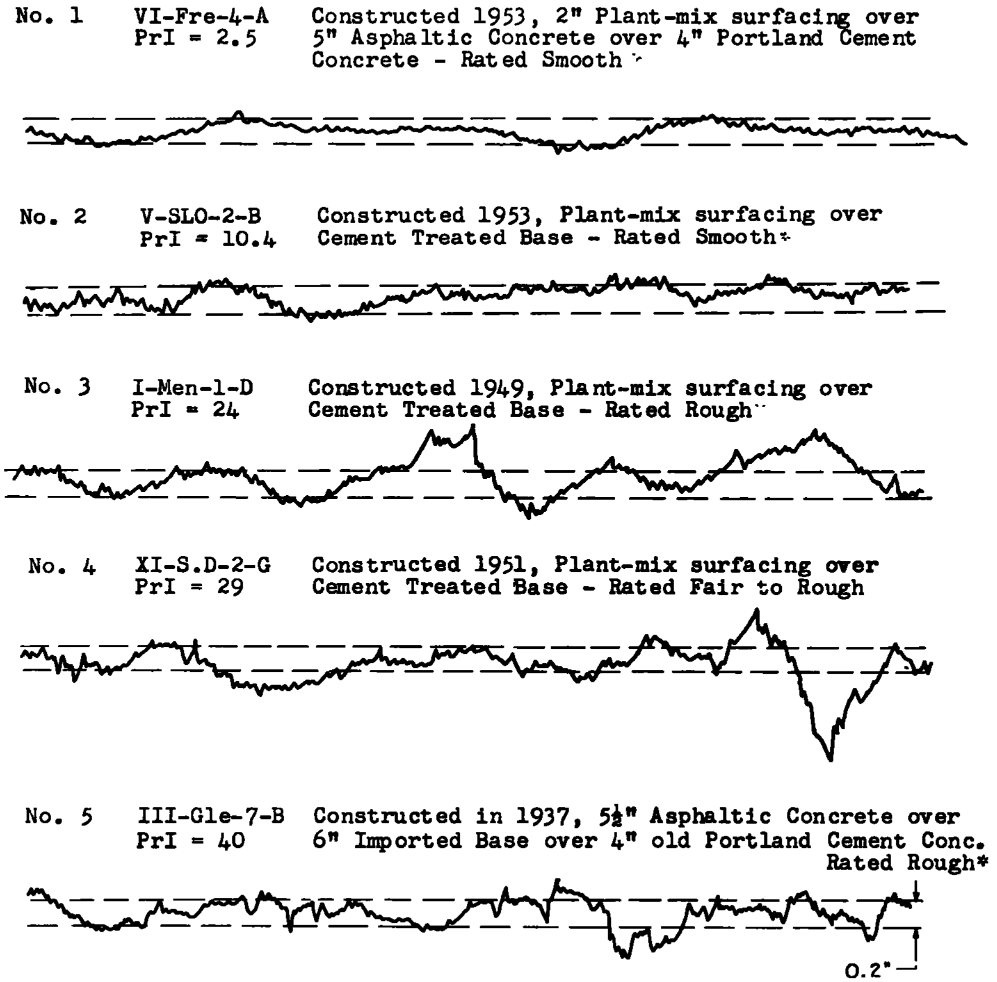
No. 6 III-Col-7-B Constructed in 1931, Portland Cement Concrete
PrI = 93 over Gravel Base - Rated Rough*

PrI = Profile Index = inches per mile in excess of 0.2"
Horizontal Scale: 1" = 25' Vertical Scale: 1" = 1"

*These ratings are drivers impression while riding in a light car at approximately 50 miles per hour.

Figure 54. Typical profiles of portland cement concrete pavements.

representative section of road. Even then some profiles exhibit wide differences in appearance from one end to the other and cannot be represented as "average." This is one distinct advantage of the profilogram record in that such varying areas can readily be seen on the graph and located on the road. The entire profile could be used in an analysis but of course this would lengthen the time required. The counts or total number of inches deviation obtained by this method varied from 2 in. to over 90 in. per mile. To avoid confusion with previously established use, the term "inches per mile" in excess of 0.2 in. will be given another name, to indicate that these values are derived from the profile. This term "Profile Index (0.2 in.)", leaves room for other terms which may correlate better with "Riding Quality." A Profile Index (0.2 in.) of 2 in. to 10 in. on a portland cement concrete pavement appears to be typical of new pavements and old ones in good condition. Counts of 40 or over would be considered rough. Other methods yet to be devised may better describe roughness or may better express "riding qualities." Figure 54 is a series of profiles representing some of the varieties of roughness developed in concrete pavements. Figure 55 shows a similar range for asphaltic types.



No. 1 VI-Fre-4-A PrI = 2.5 Constructed 1953, 2" Plant-mix surfacing over 5" Asphaltic Concrete over 4" Portland Cement Concrete - Rated Smooth*

No. 2 V-SLO-2-B PrI = 10.4 Constructed 1953, Plant-mix surfacing over Cement Treated Base - Rated Smooth*

No. 3 I-Men-1-D PrI = 24 Constructed 1949, Plant-mix surfacing over Cement Treated Base - Rated Rough*

No. 4 XI-S.D-2-G PrI = 29 Constructed 1951, Plant-mix surfacing over Cement Treated Base - Rated Fair to Rough

No. 5 III-Gle-7-B PrI = 40 Constructed in 1937, 5½" Asphaltic Concrete over 6" Imported Base over 4" old Portland Cement Conc. Rated Rough*

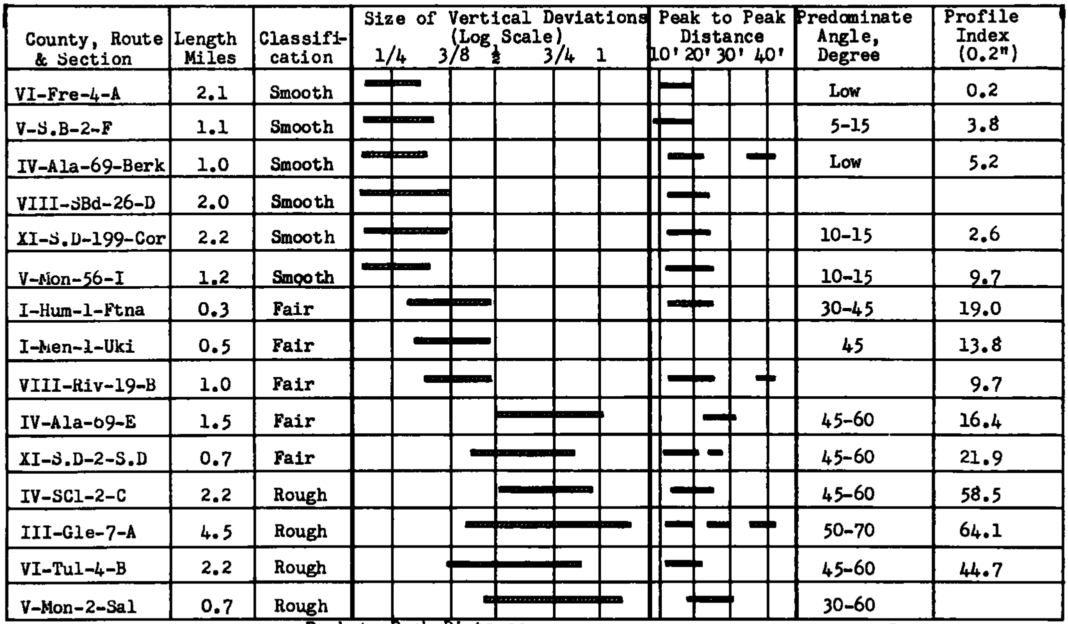
PrI = Profile Index = inches per mile in excess of 0.2"
Horizontal Scale: 1" = 25' Vertical Scale: 1" = 1"

*These ratings are drivers impression while riding in a light car at approximately 50 miles per hour.

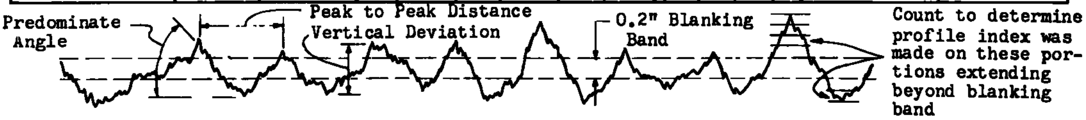
Figure 55. Typical profiles of bituminous-type pavements.

TABLE 1

PROFILE ANALYSIS SUMMARY SHEET - PCC PAVEMENTS



County, Route & Section	Length Miles	Classification	Size of Vertical Deviations (Log Scale) 1/4 3/8 ½ 3/4 1	Peak to Peak Distance 10' 20' 30' 40'	Predominate Angle, Degree	Profile Index (0.2")
VI-Fre-4-A	2.1	Smooth			Low	0.2
V-S.B-2-F	1.1	Smooth			5-15	3.8
IV-Ala-69-Berk	1.0	Smooth			Low	5.2
VIII-SBd-26-D	2.0	Smooth				
XI-S.D-199-Cor	2.2	Smooth			10-15	2.6
V-Mon-56-I	1.2	Smooth			10-15	9.7
I-Hum-1-Ftna	0.3	Fair			30-45	19.0
I-Men-1-Uki	0.5	Fair			45	13.8
VIII-Riv-19-B	1.0	Fair				9.7
IV-Ala-69-E	1.5	Fair			45-60	16.4
XI-S.D-2-S.D	0.7	Fair			45-60	21.9
IV-SCl-2-C	2.2	Rough			45-60	58.5
III-Gle-7-A	4.5	Rough			50-70	64.1
VI-Tul-4-B	2.2	Rough			45-60	44.7
V-Mon-2-Sal	0.7	Rough			30-60	



Appendix B

Standard Specifications State of California Department Of Public Works—January, 1960

Portland Cement Concrete Pavement

40-1.10 Final Finishing.—After the preliminary finishing has been completed, the edges of an initial pavement lane shall be rounded with an edging tool having a 0.04-ft radius. Transverse contact joints, expansion joints, and joints adjacent to an existing pavement shall be rounded with an edging tool having a 0.02-ft radius.

When a straightedge 10 ft long is laid on the finished pavement surface, and parallel with the centerline of the highway, the surface shall not vary more than 0.01 ft from the lower edge of the straightedge. Upon completion of the pavement, if any high points are in excess of 0.01 ft, they shall be removed by abrasive means.

In addition to the requirements in the preceding paragraph, the pavement surface shall be tested by a profilograph in accordance with the methods in use by the Laboratory of the Division of Highways.

The profile index, as measured by the profilograph, for any $\frac{1}{10}$-mile section shall not exceed the rate of 7.0 in. per mile along any line parallel to the edge of the pavement. Any deviations, which priduce a profile index rate of more than 7.0 in. per mile in any $\frac{1}{10}$-mile section shall be reduced by abrasive means to provide the required profile index. Such abrasive means shall not produce a polished pavement surface. If the daily average of the profile indexes, measured along lines approximately 2.5 ft from the edges of each traffic lane, before grinding, exceeds the rate of 7.0 in. per mile for any three consecutive working days, the paving operations shall be discontinued until suitable equipment and methods are provided by the contractor and approved by the engineer.

Measurements of Pavement Friction By a Decelerometer

TERRENCE M. ALLEN, Highway Traffic Safety Center, Michigan State University, East Lansing, Michigan; and
JACK H. DILLARD, Virginia Council of Highway Investigation and Research, Charlottesville, Virginia

● IN RECENT YEARS there has been an increased awareness of the problem of slippery pavements. Research has shown that the number of dangerously slick pavements is much higher than many engineers believed. Although most pavements develop sufficient friction with tires in dry weather, many become dangerously slick when wet. It has been shown that both concrete and asphalt pavements can, in some cases, become slippery in a short period of time when certain types of aggregate are subjected to heavy traffic volumes. Awareness of this problem led to the organization of the First International Skid Prevention Conference at the University of Virginia in 1958. The conference has been described (1), and present knowledge on the problem was summarized in a Proceedings of the Conference (2).

Accident rates have been shown to be related to slippery pavements, and methods have been developed for providing skid-resistant surfaces to both existing and new pavements. Pioneer work in several states and abroad has shown the feasibility of a systematic program of identifying slick pavements and applying adequate treatment to them. The need for such a program on a nationwide basis is recognized.

There is need for equipment, which should be as simple and inexpensive as possible, for measurement of the skid-resistance of pavements on a statewide basis. A decelerometer which has been used for this purpose in Great Britian appeared promising, and there was need to investigate its usefulness with American vehicles and conditions.

In connection with the Skid Prevention Conference, a correlation study was carried out in which several methods of measurement of road surface friction were compared by testing several pavement surfaces. The principal results of this study have already been reported (3, 1). A decelerometer was installed in one of the skid-test cars in the experiment, in order to compare its results to those of other methods of measurement. The purpose of this paper is to evaluate the results of this instrument in comparison with the more commonly used methods of measurement of pavement friction.

THE DECELEROMETER AS A DEVICE FOR MEASURING FRICTION

The British Road Research Laboratory evolved a test procedure for a commercially available portable decelerometer (4, 5, 6), which is simple, reliable, requires no maintenance, and can be purchased in the United States for under $200. This meter is of the damped pendulum type which has a scale reading directly in g's. If the wheels of the vehicle are locked, and air friction is neglected, the meter then reads the coefficient of friction directly. The meter, mounted on a heavy base, is set on the floor of the vehicle. The vehicle is brought to a speed of 30 mph on the site to be tested, and the brakes applied with sufficient force to lock the wheels. At the end of 1 sec, the brakes are released, and the decelerometer reading recorded. A ratchet device causes the meter to record the maximum deceleration reading obtained during the 1-sec interval. The British have obtained very good empirical correlations between friction measurements obtained in this manner and measurements obtained by other means.

If measurements by such a procedure are sufficiently valid, it would compare favorably with other methods of measurement, because of large advantages in simplicity, cost, convenience, and adaptability. The British procedure makes use of only one piece of additional equipment: a simple timing device to enable the driver to time the period of brake application accurately.

It would be possible for each county engineer to install such a device in a vehicle, and send it with a technician to any site suspected of being slippery. With measurement equipment available locally, advantage could be taken of rainy weather to cover areas systematically without the need for a tank truck to wet the pavement surface. Even state police officers could use such an instrument to reliably refer slippery sites to the highway department for further testing.

Also, because the instrument can be installed in any vehicle simply by setting it on the floor, it might be useful for studying the coefficients of friction obtained for various types of heavy vehicles both loaded and empty.

An interesting relationship derived by the Road Research Laboratory would make possible further uses. Granting certain assumptions, the distance a vehicle would skid of a complete stop from a speed V could be estimated from a brief measurement of the instantaneous deceleration at a speed $\frac{2}{3}$ V. (This relation will be discussed in detail later in this paper.) Use of such a brief skid would be much safer than a complete skid, and would make possible tests involving vehicles or sections of roadway such that a complete skid would be impractical.

However, a number of questions regarding the performance of such an instrument for pavement-friction measurements remain unanswered. Differences between British and American vehicles may be sufficient to invalidate the empirical correlation obtained in Great Britain, and further knowledge of its characteristics would be necessary before adapting it to other purposes. This study, therefore, endeavored to determine the applicability of the British procedure to the vehicle and pavements used in the Skid Prevention Conference correlation study, and to gain a better understanding of the behavior of this instrument in an American vehicle.

PROCEDURE

The procedure has been described in a previous paper (3). In brief, tests were made on four pavements with coefficients of friction ranging from poor (approximately 0.25) to excellent (approximately 0.65). A Tapley decelerometer of the type used by the British, and fully described by them (5), was mounted in a vehicle used to measure pavement friction by the stopping-distance method. It was mounted on the floor of the space normally occupied by the back seat. A movie camera recorded readings of the decelerometer, a speedometer, and a distance-meter for each of the 48 skids. This made it possible to compare the decelerometer directly with the stopping-distance method, inasmuch as observations for both were obtained simultaneously from the same vehicle.

RESULTS

Readings of the camera film were made, and results with standard tires are shown in Figure 1. (Results of the series of runs with regular tires were not included, because the pattern was essentially the same; the two sets of curves differed slightly in height.)

In Figure 2, an average curve for each site is shown. In addition, a corrected curve is shown which takes account of the tilt of the vehicle (and the pendulum decelerometer) caused by the elasticity of the car's suspension system. As explained in the previous paper, the correction for tilt was made assuming that tilt was a linear function of deceleration as measured by the decelerometer. Although this assumption probably does not hold exactly, it was felt that the deviation from the actual value of tilt would result in a negligible change in the corrected curve.

Examination of the decelerometer curves seems to show what might be expected for the deceleration of a fully braked vehicle—the deceleration increases sharply as the brakes are applied, reaching a maximum at the moment of impending skid, then quickly declining as the brakes lock. The curves then show the increase in coefficient with decreasing speeds which is characteristic of wet pavements. The curves for the excellent site, however, do not seem consistent with such an explanation, The low point at about

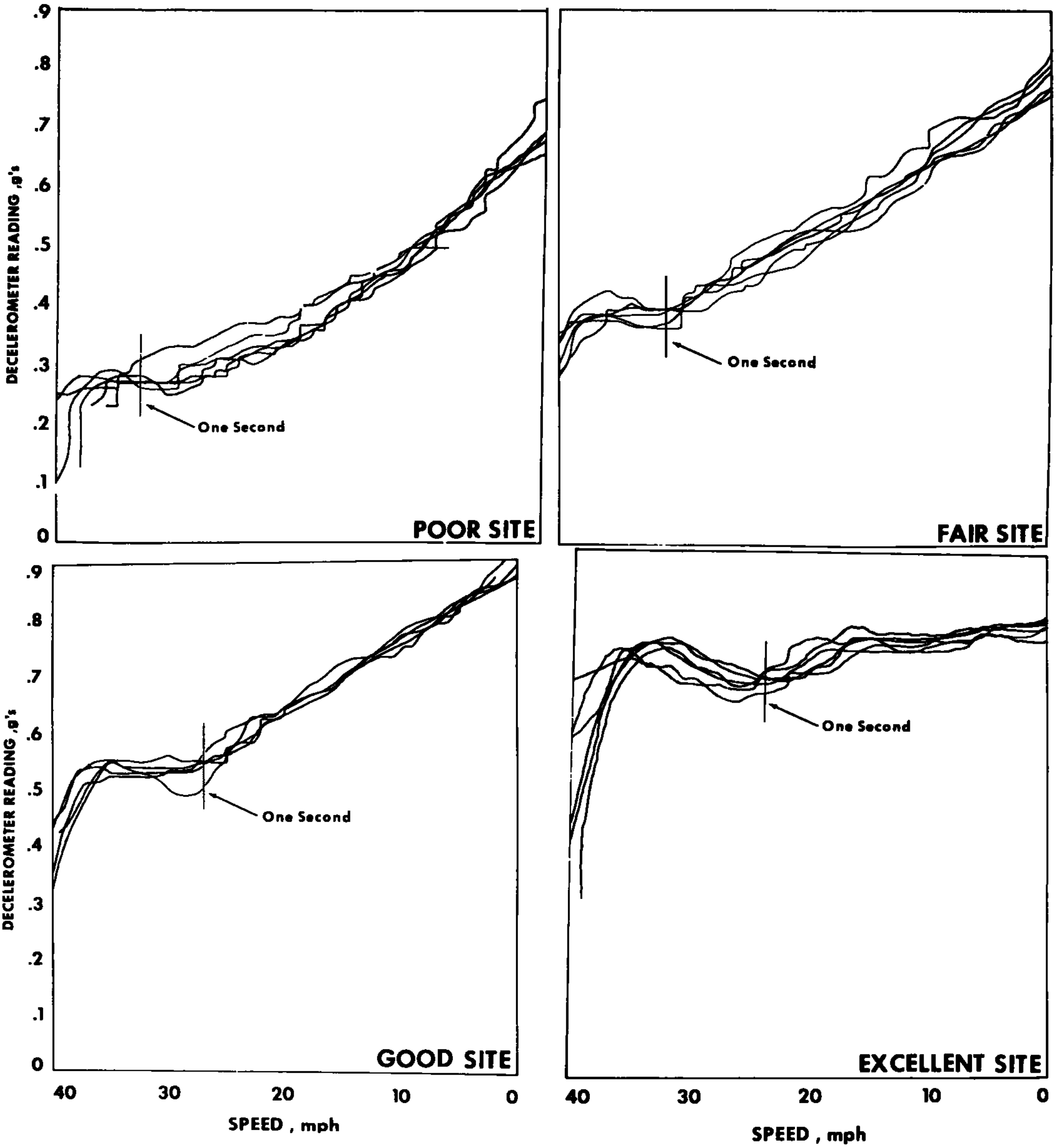


Figure 1. Instantaneous decelerometer readings during skids from 40 mph.

1 sec does not fit such a trend, and the curve as a whole suggests a damped oscillation. The question arises as to whether the fluctuations in decelerometer readings represent real fluctuations in deceleration, or merely fluctuations in the readings of the instrument.

The answer to such a question requires knowledge of the instrument. In their description of this decelerometer, Starks and Lister (5) point out that the pendulum is damped so that about 0.8 sec is required for a full reading to be obtained after a sudden deceleration of one g. Another factor, however, may also be affecting results. Lister (7) and Petring (8) have pointed out that vertical accelerations may also affect decelerometer readings once the pendulum is out of the vertical plane. The most desirable position for the instrument is at the center of tilt of the vehicle, so that tilt of

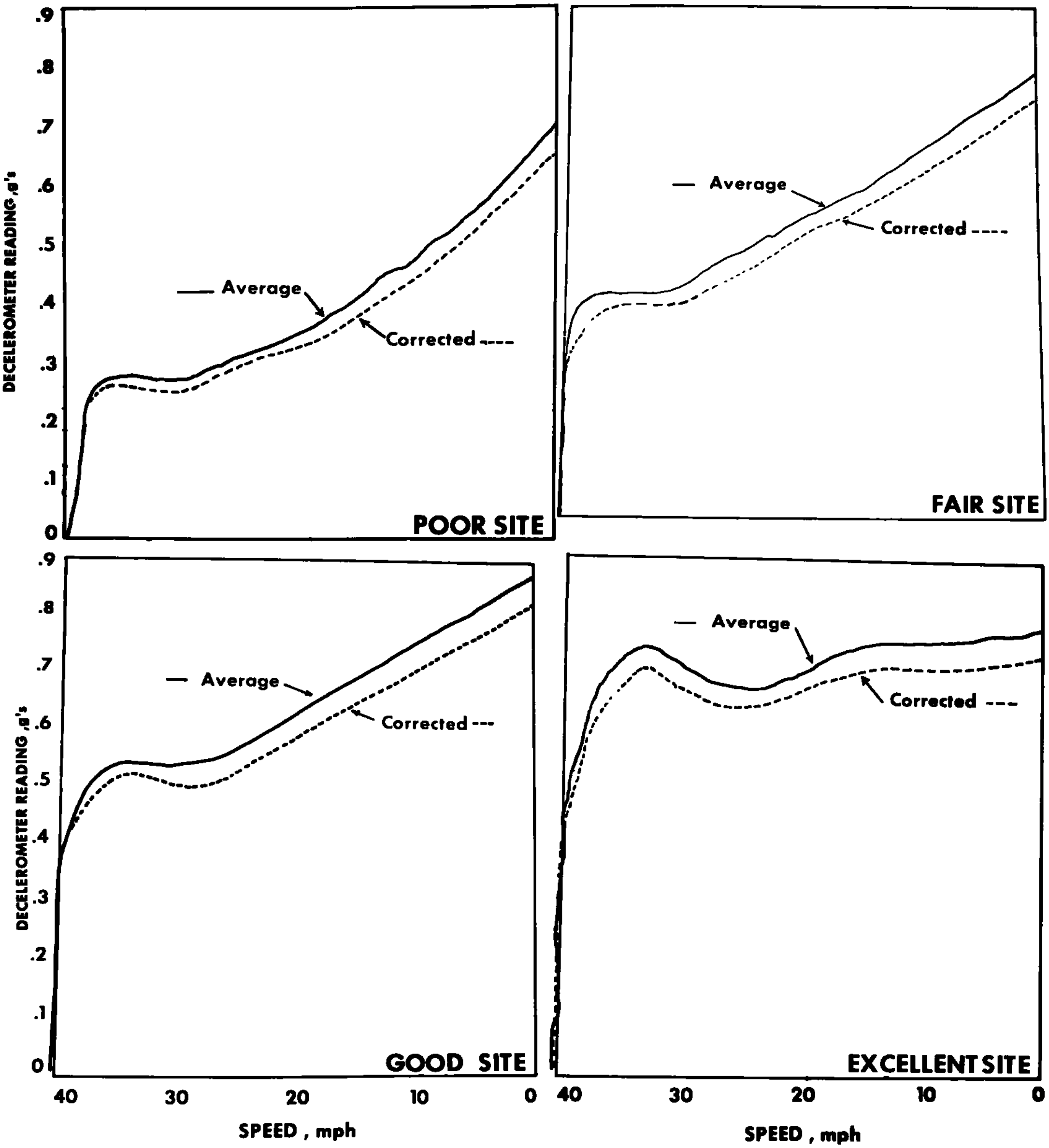


Figure 2. Average instantaneous decelerometer reading, with and without correction for tilt of vehicle.

the vehicle will not induce transient vertical forces. In this study the meter was behind the center of tilt, a sufficient distance that such vertical forces could have affected results significantly. Even with such a high damping factor, it is possible that irregularities in the curves, and even the peak at the first ½-sec of the skid, may be an artifact of the measuring instrument.

However, it is also possible that real irregularities in the deceleration of the vehicle occurred. The data on distance and speed, which were also recorded on film, were examined. However, distances could be read only to the nearest foot, and speeds only to the nearest mile per hour. Such accuracy was not sufficient for accurate evaluation of the transient accelerations in question. However, the data suggest that substantial fluctuations in deceleration did occur. Whether these might be caused by changes in weight distribution on front and rear tires as a result of the elastic action of the suspension system can be speculated upon.

The One-Second Maximum Method

The first comparison to be made was between the decelerometer results by the British method with results of other machines. The British method, by means of a ratchet in the decelerometer, retains the highest reading obtained during the first 1-sec period after the brakes are applied. The speed at which one second has elapsed is indicated for each site in Figure 1. It is noted that there is a tendency for the curves to dip, which is stronger for the higher friction pavements, and that the bottom of this dip occurs at about 1 sec. If the individual curves are examined, it can be observed that in most cases the decelerometer reading had reached a maximum and declined by the time 1 sec was reached. The maximum for each curve was recorded and the corrected values averaged. Figure 3 compares these averages with results of the trailers and the skidding cars. For the low-friction sites, results compare well with the results of the locked-wheel trailers. As expected, they fall below results obtained for the stopping distance vehicles. For the high-friction sites, the data suggest that the decelerometer 1-sec results are higher compared to the trailers. For the "excellent" site, decelerometer results were fully as high as the stopping-distance results. This is not surprising, however, inasmuch as there is for this site no strong trend for coefficients to be higher at lower speeds.

If the decelerometer 1-sec maximum method is evaluated in terms of its results, in the same manner that the other methods were evaluated, one could conclude that results seemed about as valid as results by the other methods. The previous paper (3) emphasized the large and consistent disagreements in the measurements obtained by the different machines. As long as the different methods of measurement show such a high degree of disagreement that it is not possible to determine what the "correct" value might be, it is difficult to evaluate the accuracy of any one method. Certainly the decelerometer does not appear noticeably less accurate than the other methods, and a case might be made that its accuracy is better than some.

However, it is possible to criticize these measurements on a theoretical basis. The tendency for results to be rather high for the high-friction site could also be due to the transient peak which occurred during the first second of the skid. Inasmuch as such a sharp peak was obtained in spite of the high damping factor, it seems clear that the height of the peak would be greatly affected by changes in damping factor. Even though the meter is reported to have its damping factor accurately compensated for temperature changes, reliance on such an instrument in the presence of such large transients would need to be preceded by considerable investigation. The British (9) have found their method satisfactory for most British vehicles, but have questioned whether it would be suitable for the "soft" suspension systems of American vehicles. Results of this study suggest that at least for the decelerometer so mounted in the vehicle used (1958 Chevrolet), which

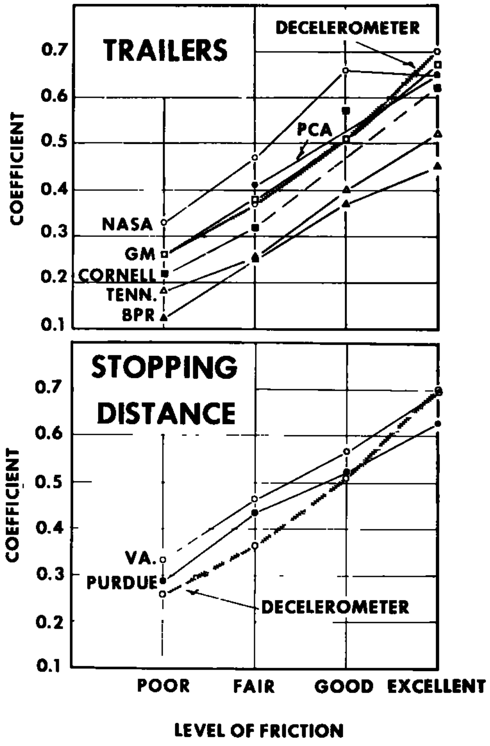


Figure 3. Decelerometer results by the one-second maximum method compared to trailer and stopping-distance measurements.

does not seem to have an atypical suspension system for American cars, transients are of such large magnitude as to cast doubt on the use of this method for precise measurements. Further research is needed to determine the effect of these transients on the accuracy of measurements.

The $^2/_3$ V Relation

R.J. Smeed of the Road Research Laboratory (4) has pointed out that under the assumption of a simple relationship between coefficient of friction and speed, the coefficient obtained by the stopping-distance method from an initial speed V can be predicted from measurement of the coefficient of friction at a speed $^2/_3$ V.

Comparisons were made between the decelerometer reading at $^2/_3$ V and the coefficient computed from the stopping-distance method, from the same car on the same skids. The results are given in Table 1. The discrepancies are considerable, and with the correction for tilt applied, all the decelerometer estimates are low. Examination of the curves shows that 26.7 mph nearly coincides with the dip in the curves already referred to. This is particularly true for the "good" site where the discrepancy is largest.

Explanation of the discrepancies is not difficutlt. The relation between the coefficient of friction μ and the instantaneous velocity v is expressed as a polynomial function

$$\frac{1}{\mu} = a_0 + a_1 v + a_2 v^2 + - - - + a_n v^n$$

It is shown that if the coefficients of higher powers of the polynomial are small, the stopping distance of a vehicle can be closely approximated by the familiar formula

$s = \frac{V^2}{30\mu}$ where V is the initial speed and μ is the coefficient of friction measured at speed $^2/_3$ V.

Examination of Smeed's equations shows that the approximation is perfect if there is a linear relation between speed and the reciprocal of the coefficient of friction and becomes successively poorer as the relation differs from linearity. It can be shown that the error in the approximation is given by

$$\text{Error} = \frac{V^2}{30}\left\{\frac{1}{9}a_2V^2 + \frac{14}{135}a_3V^3 + \frac{11}{81}a_4V^4 + . . . + \left[\frac{2}{n+2} - \left(\frac{2}{3}\right)^n\right]a_nV^n\right\}$$

Because each successive a-coefficient is multiplied by a higher power of the initial velocity V, the error rapidly becomes appreciable as the relation becomes more complex.

Evidence from previous research suggests that the basic relation between speed and the reciprocal of friction is sufficiently simple so that the approximation would be good. However, the present data included the transients in decelerometer readings already referred to. Because these transients produced a complex relationship, considerable error in the approximation would be expected. Only through reduction of these transients could the usefulness of the $^2/_3$ V relationship be utilized.

Variability of Decelerometer Readings

In the previous report, large differences in the variability of successive measurements at the same site were found for different machines. Comparable measures of variability were computed for the decelerometer readings. Table 2 shows these results compared to those of the other methods of measurement. Even for the most variable decelerometer index used, instantaneous decelerometer reading at $^2/_3$ V = 26.7 mph, the variability of successive measurement is about equal to that of the least variable trailers. In terms of variability, then, the decelerometer compares favorably with other methods of measurement.

TABLE 1

STOPPING DISTANCE COEFFICIENT AND DECELEROMETER READING AT A SPEED OF ⅔ V

Site	Stopping Dist. Coeff.	Decel. Rdg. at 26.7 mph Corrected	Decel. Rdg. at 26.7 mph Uncorrected
Poor	0.33	0.30	0.31
Fair	0.47	0.40	0.43
Good	0.57	0.51	0.57
Excellent	0.69	0.65	0.69

TABLE 2

VARIABILITY OF MEASUREMENTS—AVERAGE STANDARD DEVIATIONS OF REPEATED MEASUREMENTS

Trailers	
Bureau of Public Roads	0.040
Tennessee	0.037
Portland Cement Association	0.026
General Motors	0.020[1] - 0.027[2]
NASA	0.015[1] - 0.024[2]
Cars	
Purdue	0.013
Virginia	0.037
Decelerometer	
Average over whole skid	0.022
One-second-maximum	0.021
Instantaneous reading at ⅔ V	0.025

[1] Excluding one set of unusually variable readings.
[2] Including all readings.

Comparison of Stopping Distance and Trailer Measurements

It was planned to use decelerometer data to facilitate comparisons between coefficients by the stopping-distance method with those of the trailers. The deceleration of a skidding car at 40 mph should check with trailer measurements at the same site when measurements were made at 40 mph. By fitting a curve to decelerometer readings at each site by regression analysis, it was planned to make an estimate of the coefficient at 40 mph. However, the uncertainty associated with the transient changes in decelerometer readings made such a procedure unwise. Further research will be necessary for a precise comparison to be made between these two types of measurements.

FURTHER RESEARCH NEEDED

The need for further research on the use of such a decelerometer for measurement of pavement friction is intimately related to the need for research on other methods. Only when several machines consistently obtain nearly the same measurement of friction can the accuracy of any one method be evaluated. Further research on decelerometers should be correlated with research on other methods. The suitability of decelerometer measurements is also closely related to needed research on comparisons between the instantaneous deceleration of a skidding vehicle and measurements by locked-wheel trailers.

To answer the basic question raised by this study, it will be necessary to determine whether the transient changes in decelerometer readings were due to the instrument and the way it was used, or to real transient changes in deceleration of the vehicle. In order to obtain the actual deceleration, two types of instrumentation might be used: (1) a research-type decelerometer suitable for measuring such transients and not sensitive to vertical accelerations, or (2) devices capable of measuring distances to 0.1 ft and speeds to 0.1 mph. Devices for measurement of vehicle tilt would also be desirable.

If real irregularities in the deceleration of a skidding vehicle exist, they will pose serious problems for obtaining precise correlations between trailer measurements and stopping-distance measurements. If a peak in decleration occurs during the first ½ sec of the skid due to a slow locking of the wheels, consideration must be given to control of the rate of brake application, perhaps by apparatus such as that of the Purdue vehicle. If oscillations in deceleration are found to be a function of the "soft" suspension systems of American vehicles, consideration might be given to alteration of the suspension systems of vehicles to be used for testing.

SUMMARY AND CONCLUSIONS

A simple decelerometer offers an inexpensive, convenient, and adaptable means of measuring pavement friction. To evaluate the accuracy of such measurements, a Tapley decelerometer was included in a vehicle making locked-wheel stops. Results were compared to measurements of the same pavements obtained by the stopping-distance method and several towed trailers. Because the several machines obtained such large and consistent differences in measurements, it was not possible to make a precise evaluation of the accuracy of any one method. The decelerometer results appeared to be as valid as those obtained by the other more commonly used methods.

It seems clear that the decelerometer can yield results which have at least a "rough-and-ready" accuracy. In terms of reliability and consistency of results it compares favorably with other methods. In the opinion of the authors, this simple and inexpensive device, if used with a minimum of care, can yield results of considerably greater accuracy than a number of much more complex devices already in use.

However, transient changes in decelerometer readings, presumably a function of the suspension system of the American car used and/or the rate of brake application, cast some doubt on reliance on decelerometer readings for precise measurement. It is not clear whether the transient changes represent real changes in deceleration of the vehicle, or are an artifact of the instrument and the way it was used. If the transients are artifacts that can be overcome, such a decelerometer is a very promising method for measurement of pavement friction. If real transient changes in deceleration exist, there are important implications for relationships between friction measurements made by trailers and the skidding distances of vehicles. Further research is indicated on (1) the use of decelerometers, (2) the irregularities of the deceleration of skidding cars, and (3) the relations between friction measurements by the stopping-distance method and by towed trailers.

REFERENCES

1. Shelburne, T.E., "Resumé of First International Skid Prevention Conference." HRB Bull. 219, pp. 1-5 (1959).
2. "Proceedings First International Skid Prevention Conference." Virginia Council of Highways Investigation and Research (1959).
3. Dillard, J.H., and Allen, T.M., "Comparison of Several Methods of Measuring Road Surface Friction." HRB Bull. 219, pp. 21-50 (1959). Also in (2) pp. 381-410.
4. Giles, C.G., "Some European Methods for the Measurement of Skidding Resistance." In (2) above, pp. 267-296.
5. Starks, H.J.H., and Lister, R.D., "The Characteristics and Performance of a Maximum Deceleration Meter for Testing Vehicle Brakes." Road Research Lab., London, Eng. (1951).
6. Giles, C.G., and Lander, F.T.W., "Tests on the Effect of Tire Tread, Road Surface Texture, and Tire Inflation Pressure on the Braking Performance of a Vehicle Skidding with Locked Wheels on a Wet Surface." Road Research Lab., London, Eng.

7. Lister, R.D., "Methods and Equipment for the Inspection of Vehicle Brakes." Road Research Lab., London, Eng.
8. Petring, W.F., Discussion of (3) p. 295.
9. Giles, C.G., Discussion of (3) p. 296.

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY–COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.