STANDARDIZABLE EQUIPMENT FOR EVALUATING ROAD SURFACE ROUGHNESS

J. A. Buchanan and A. L. Catudal
Public Roads Administration

SYNOPSIS

It is only natural that those interested in the building and maintenance of highways should seek to develop tools with which to measure highway surface smoothness or roughness. This report considers existing methods and certain inherent characteristics of such methods which precluded their general acceptance The standardizable equipment described in the paper operates on the principle of the measurement of the vertical oscillation of a wheel suspension with respect to its supported frame. In earlier applications of this principle it was recognized that difficulties were caused by the use of an apparatus, in which the motor vehicle and its load are a component part, and this recognition led to an investigation of the use of a special vehicle capable of standardization in all its parts

The new equipment is in the form of a single wheel semi-trailer, attachable to any towing vehicle, and is designed as a horizontal pendulum with the axle of the wheel placed at the center of percussion. The gross weight of the entire vehicle is 740 lbs. A special feature of the equipment is the incorporation of a newly-designed overrunning clutch integrator whose operating characteristics are remarkably constant. All connections to the instrument board in the towing vehicle are made electrically.

The performance characteristics and recommended standard operating procedure are given in detail Many hundred miles of operation, without mechanical failure, indicate adequate mechanical design. It is easy to use and the data are obtained rapidly with it.

It is believed that the underlying principle as a means for indicating the relative roughness of road surface is sound and that the present equipment is superior to that developed earlier in two important respects—first, the introduction of a special vehicle has removed the uncertainties of vehicle operation that were always present when an automobile was a component part of the measuring apparatus; and second, the entire equipment is so designed that it can be exactly duplicated and, to this extent, the equipment is standardizable

If there is any one attribute of the modern pavement in which the riding public is most interested it is probably the smoothness of the surface. Because of this general public reaction, great care is taken by highway engineers to construct and to maintain surfaces that are as smooth as possible. It is only natural, therefore, that those interested in the building and maintenance of highways should seek to develop tools with which to measure highway surface smoothness or roughness.

These efforts began many years ago and have continued because none of the devices that have been developed has been completely satisfactory. Generally speaking, apparatus for indicating road surface roughness falls into one or the other of two classes.

The first class comprises all of those instruments which produce, to some scale, a graphic profile along some element of the pavement surface. The earliest devices were in this category and the forms of the apparatus and the operating procedures varied widely. In some instances, both in this country and abroad, the reference datum for the profile was determined by points fixed in the road surface. This procedure was very slow and tedious and led to the development of what might be termed a floating datum, one that was determined by a wheel suspension of some sort, two, four, eight, sixteen and even thirty-two wheels having been employed in the various designs. Usually, the profile of the road surface, with respect to the datum, was traced out on a ribbon of paper to some predetermined ratio of horizontal scales. These "profilometers," as they were called, provided certain useful information as to the uniformity of the surface and the location of particularly rough areas. They were, however, awkward to maneuver, the data were difficult to analyze, and comparisons were tedious. Devices of this class were never very popular and their use has been quite generally abandoned

The other principal line of development made use of the fact that the irregularities of surface contour that cause the public reaction also cause the wheels of motor vehicles to oscillate vertically with respect to the vehicle chassis Since this motion is permitted by the vehicle spring deflection, engineers conceived the idea of measuring the spring deflection as the vehicle traversed the pavement and of using the recorded deflection data as a measure of road surface roughness. The manner in which the apparatus functioned varied rather widely but the character of the recorded data was generally either a continuous graph of the vehicle spring deflection or a numerical integration of these movements in inches of deflection per mile of pavement length. Devices of this class have been given a number of different names, the descriptive but inaccurate title of "roughometer" having been frequently applied. As a class they have been rather popular because they were easy to use and comparative data could be obtained quickly with them; but also as a class they have had one important and fundamental deficiency which has long been recognized—that the vehicle to which the device is applied becomes an essential part of the roughness indicating apparatus.

The Public Roads Administration has been interested in the problem of surface roughness measurement for many years and has experimented with devices of both classes. Various types of profilometers have been studied but, except for special uses on research projects such as small test tracks, there has been no recent development work on this class of instruments.[1] In 1926, there was published a description of one type of instrument of the second class.[2] Subsequently, the possibilities and characteristics of this particular instrument were studied by means of field and laboratory tests in which all the various factors that affect its functioning were rather thoroughly explored. In this work particular attention was given to the intercomparison of the data obtained with various vehicles equipped with the integrator units and to the possibilities of calibrating tests in which standardizable obstructions were placed upon a normal road surface and the spring deflections caused by these obstructions were recorded.

The tests were extensive and the data obtained were voluminous. However, it is neither practicable nor desirable to attempt here to describe in detail the work that was done. It is believed that a few generalized comparisons will show the significance of the results of the study.

If two cars equipped with integrator units are driven over a unit length of a given road at a given speed, two values of integrated spring deflection will be obtained. The relation between these two values may be expressed as a ratio. This ratio may change in value with car speed and the manner in which it varies will depend upon the characteristics of the

[1] Two instruments of the profilometer type are described in Bulletin of the National Research Council, vol 6, part 4, no 35, August 1923, "Apparatus Used in Highway Research Projects in the United States", pp 14–16

[2] PUBLIC ROADS, vol 7, no. 7, September 1926, "An Instrument for Measuring Relative Road Roughness."

particular cars concerned The variation of the ratio as determined for three cars and five car speeds over one road surface is shown in Figure 1

Not only does the ratio of the values obtained with two cars vary with the vehicle speed at which the particular comparison is made, but it varies also with the roughness of the road surface used for the comparison. This is illustrated by the data in Figure 2. To obtain these particular data three cars were driven simultaneously over 15 successive miles of road at a constant

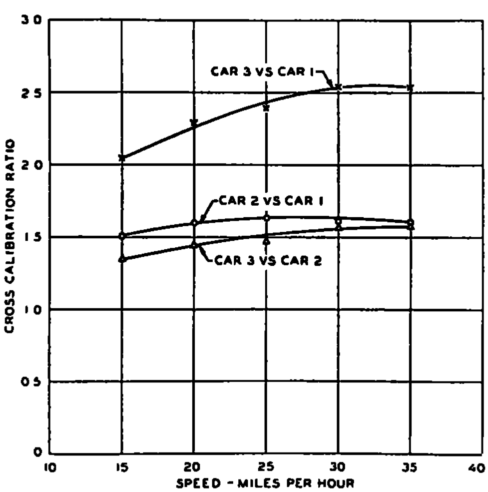

Figure 1. Variation of Cross Calibration Ratio with Speed. Each Value is the Average of Four Determinations.

speed of 25 m.p.h., integrator readings being recorded at the end of each mile. The variables present were the individual vehicle characteristics and the road roughness from mile to mile It is apparent that these variables singly and in combination can cause rather wide fluctuations in the value of the cross calibration ratio Other data bearing upon this point are shown in Figure 3, in which the ratio was determined for two cars operated at a common and constant speed over a wide range of road surface roughnesses In this figure the road roughness values were those indicated by the instrument on Car 3

Tests were made also with road surfaces whose natural roughness was increased by laying down on the surface a series of artificial obstructions of fixed dimensions, shape and spacing. The purpose of these tests was to determine the relation between the constant artificial roughness and the effect on the roughness values

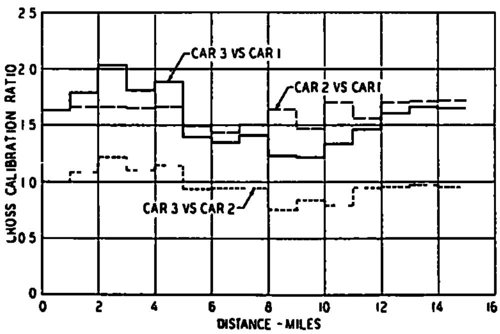

Figure 2. Variation in Cross Calibration Ration for Installations on Three Different Cars Operated at 25 M.P.H. Over Sections of Varied Roughness.

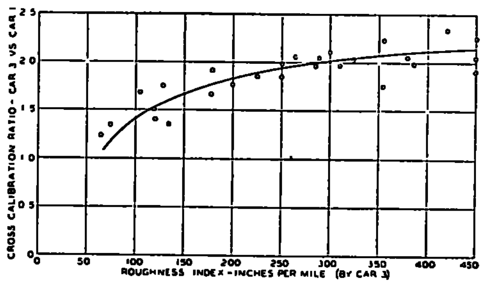

Figure 3. Variation in Cross Calibration Ratio with Surface Roughness

obtained for three different vehicles operated at the several speeds shown. The procedure was to obtain values for the road surface both with and without the artificial obstructions and, by subtraction, to obtain values attributable to the obstructions alone The data shown in Figure 4 are typical of those from these tests Each graph shows the range in the values of the increase in roughness created by a series of 10 obstructions placed 50 ft. apart on each of three road surfaces and at five vehicle speeds. The three graphs show this relation for three different vehicles The tests consistently showed that the in-

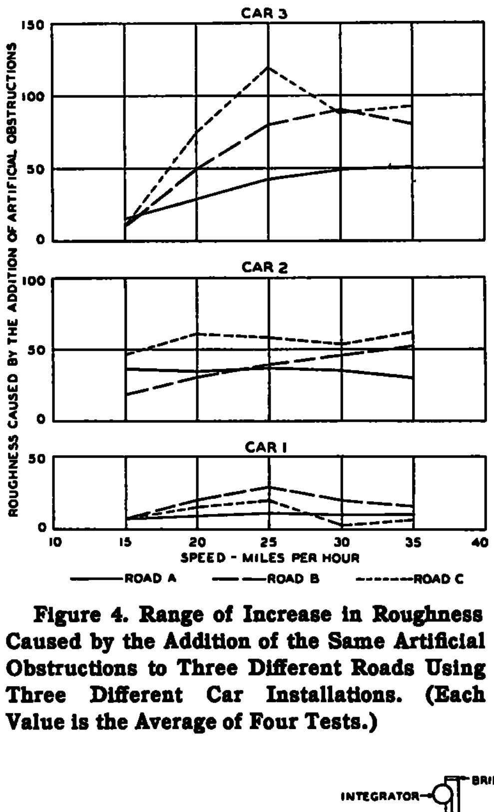

Figure 4. Range of Increase in Roughness Caused by the Addition of the Same Artificial Obstructions to Three Different Roads Using Three Different Car Installations. (Each Value is the Average of Four Tests.)

dicated roughness caused by the artificial obstructions was affected by the car characteristics and by the roughness of the road surface on which the obstructions were put down, as well as by the speed and other controllable test conditions.

These difficulties were recognized as being caused by the use of an apparatus in which the motor vehicle and its load are a component part and this recognition led to an investigation of "the use of a special vehicle, capable of standardization in all of its parts."[3]

The investigation has gone forward and the development of a standardized vehicle revealed certain weaknesses in the integrator unit with the result that a new integrator with better characteristics has been developed also. The new equipment has been given extensive field performance tests and its characteristics have been carefully studied. It is with the design and performance of this new apparatus, susceptible of exact duplication in all of its parts, that the present paper is concerned

The design of the standardizable vehicle is quite simple. It consists of a rectangular frame within which is a single wheel equipped with a pneumatic tire. The axle of this wheel is attached to the center of two single leaf springs, one on each side of the wheel. The ends of the springs are attached to the front and rear cross members of the rectangular frame through ball bearing fixtures. At the front of the frame is a tongue for connection with the towing vehicle. Over the wheel there is a cross frame or bridge on which the integrator unit is mounted and to which the pistons of two dash pot spring damping devices are attached. The essential elements of this single wheel trailer unit are shown schematically in Figure 5 and its general

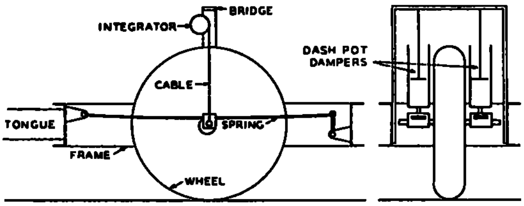

Figure 5. Schematic Drawing of the Essential Elements of the Trailer

[3] "The Dana Automatic Roughometer for Measuring Highway Roughness"—Discussion by L W. Teller, *Proceedings*, Highway Research Board Vol. 12, (1932).

appearance, as seen from the side, in Figure 6. In the early consideration of the design it appeared reasonable to assume that the chassis or frame of this vehicle should be supported on standard tire equipment and that its sprung to unsprung weight ratio and its spring characteristics should, within reasonable limits, be proportioned in accordance with automotive practice. The gross weight of the entire apparatus as shown in Figure 6 is 740 lb., the reaction under the wheel being 580 lb. and that at the towing hitch being 160 lb. It was decided that the chassis would be most convenient to handle if designed as a semitrailer that could be attached to any available vehicle. Finally, it was decided that a single wheel trailer would be more likely to repeat movements of its wheel with respect to its frame than would a two-wheel trailer, because the former would respond to the contour of but one roughness path.

A survey of tire equipment in use at the time the design was undertaken showed that the 5.50—17 in. balloon was the size in most widespread use on the then current models of automobiles. This size was selected since there was the greatest likelihood of its being available as a stock item of manufacture for many years in the future. However, during the development period it became evident that a tire of somewhat greater cross section would have certain advantages. A resurvey of possible sizes was made and the 6.00—16 in. four-ply balloon tire was adopted. This is the size now in use and, as it still is one of the most popular, it probably will remain in production for many years.

The tire is mounted on a standard drop center rim attachable to a disc wheel. If a time should come when this disc wheel is no longer commercially available, it would be relatively simple to produce one by welding a suitable flat disc to an unmounted rim. The hub is turned especially for this vehicle and is therefore exactly duplicable. The hub has a flange for the attachment of the wheel and is carried on the shaft by a pair of adjustable roller bearings. The axle or shaft is made of preheat-treated chrome molybdenum steel (SAE 4140).

As mentioned previously, the frame of the trailer is supported on the axle by a pair of leaf springs placed longitudinally, one on each side of the wheel. These springs are pivoted at the forward end and shackled at the rear, as shown in Figure 5. In the early work with roughness indicators installed on automobiles, one of the difficulties encountered was the lack of constancy in the spring action caused by variations in interleaf friction in the springs and in the friction of the spring shackles. In designing the standardizable vehicle, therefore, it was decided to employ single leaf springs and to use ball bearing spring mountings. Standard grease seal ball bearings of good quality, in specially designed fittings, are used.

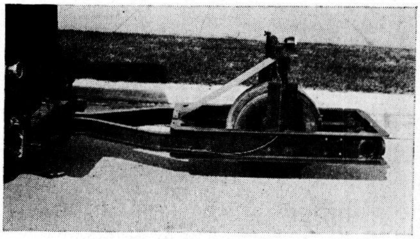

Figure 6. Sideview of the trailer

The frame is constructed of standard steel channels and may, therefore, be exactly duplicated. It is rectangular in plan with heavy angle corner connections. The wheel is located centrally in the frame and over the wheel is the steel frame or bridge that carries the instruments and provides connections for the damping devices. At the forward end of the frame a pair of channel sections forged to form Y-shaped tongue, is attached to the frame. The towing connection is provided at the end of this tongue. A molded lead counterweight is secured to the forward end of the frame, its mass and location being such that the center of percussion of the entire trailer, when suspended from the towing hitch as a pendulum, is in the plane of the axle. The hitch to the towing vehicle maintains the trailer in an upright position but provides freedom of motion by means of a universal or gimbal joint device that can be attached to any towing vehicle.

Because of the absence of friction in the spring suspension, there naturally was a marked tendency for the spring weight system of the trailer to oscillate in its own period when disturbed and some damping system to control this was necessary. It was further necessary that the damping system be consistent in its action under all conditions of temperature, that it be exactly reproducible and that it be as simple as possible. After some investigation and trial of existing devices available commercially, it was decided that none was likely to be satisfactory and that the damping requirements for this particular test vehicle would best be met by a simple dashpot arrangement in which an appreciable volume of low viscosity liquid was displaced through fixed ports. The liquid could not be corrosive nor subject to freezing and its viscosity should be affected to the least degree possible by changes in temperature, evaporation or chemical change, such as oxidation. After extensive investigation, a satisfactory liquid was found, it being a mixture of a light mineral lubricating oil with a certain proportion of kerosene. The characteristics of this liquid will be discussed later.

During the development of the standardizable vehicle, the characteristics of the relative roughness indicator[4] were being carefully studied also. It was found that improvement was desirable in four important particulars, which were:

1. The rack and pinion mechanism for translating the verticle reciprocating motion of the vehicle axle into the oscillating rotary motion that actuated the overrunning clutch was a source of error through lost motion.
2. There existed a measurable amount of slippage in the three-ball clutch as designed.
3. The adjustment of the friction brake on the ball clutch was difficult to maintain and sometimes caused uncertain performance.
4. The mechanical counter required a rather long flexible shaft to connect the counter with the ball clutch unit. Not only was such a mechanical connection poorly suited for use with the trailer because of its length and frictional resistance but it was inconvenient as a connection between vehicles that required separation.

In order to overcome the deficiencies just enumerated, a new clutch unit was designed. It consists of a drum and cable connection to the axle, a pair of opposed ball clutches and a single brush and commutator for operating an electric counter. This unit is shown schematically in Figure 7.

The drum and cable arrangement was substituted for the rack and pinion in order to eliminate lost motion. The cable selected is of stainless steel, light and strong yet very flexible.[5] The lower end is fastened to the axle with an adjustable connection. The upper end is wrapped around a spiral groove on a drum on the integrating unit which is supported by the chassis. The pitch

[4] "An Instrument for Measuring Relative Road Roughness" PUBLIC ROADS, Vol. 7, No. 7, September 1926

[5] The cable is 3 strand, 12 wires to the strand, each wire being 0 005 in. in diameter. It is rated at 175 lb breaking strength. It is a type used for deep sea fishing and is readily obtainable.

circumference of the groove is 6 in. and within the drum is a clock spring that maintains a continuous and practically constant tension on the cable.

After careful study the principle of the ball clutch was retained but significant changes in the design were made The early design comprised three balls in cylindrical tangential races, spring pressed against an annular inner race. The parts were relatively massive for the working radius of the clutch and it was somewhat difficult to secure perfectly formed and polished races. The new clutch has a plain cylindrical outer race, while the inner race has eight steps that provide the wedge planes for eight spring-pressed steel balls The outer race is 1.4 in in diameter The eight balls are ⅛ in. in diameter and they operate on a wedge angle of 15 deg.

In the earlier instrument a brake was provided to keep the driven part of the clutch element from following back the return movement of the driving part. This brake consisted of a wire loop held under tension against a grooved drum. The adjustment of the tension could be critical; if too loose follow-back occurred; if too tight clutch slippage resulted. In the new design the brake was abandoned and a second ball clutch identical in detail but reversed as to rotation was introduced, effectively locking the action against follow-back

In order to record the progress of rotation of the driven element of the clutch and thus integrate the spring deflections that had occurred at any desired time, a commutator disc was built into the new instrument to operate electrically the remote recording unit. This eliminated the long drive shaft with its attendant disadvantages and made possible a simple wired connection between the integrating unit on the trailer and the recording instrument in the towing vehicle. The commutator is fitted with six equally spaced contacts and a single brush. Thus one revolution of the commutator causes six closures of the electrical circuit that actuates the counter. Since the pitch circle of the cable drum that drives the commutator is 6 in. in circumference, each impulse to the electric counter marks the accumulation of one inch in the vertical movement of the axle with respect to the trailer frame.

The new instrument is entirely enclosed and sealed against dust and water. The internal parts are lubricated at assembly and screw-closed oil ports are provided

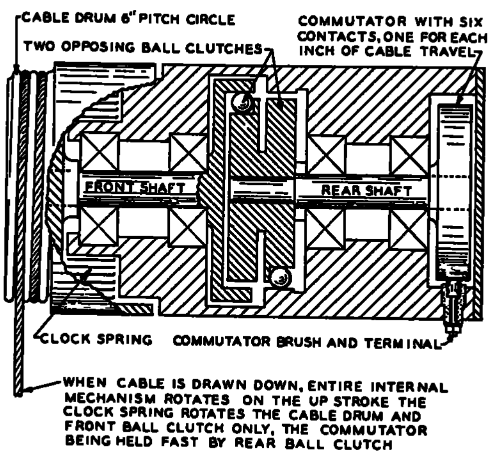

Figure 7. Schematic Section of Integrator Elements

for the introduction of specific quantities of lubricants during service, the procedure being to oil the clutch every 2,000 miles, allowing excess oil to drain out. Since most of the parts are lathe turned, accurate alignment of the eseential elements is insured. Both the driving and driven shafts rotate in ball bearings, the outer bearings in each case being provided with seals on their outer faces. The entire unit is rugged and compact, being about the size of a large drinking glass. It may be seen in the photograph taken from the rear of the trailer (Fig. 8) at the right hand of the transverse bridge frame

Completing the equipment is the instrument board carried in the towing vehicle. On it are mounted the counter that records the road roughness units, a second counter that records wheel revolutions of the trailer as a measure of distance traveled, a switch controlling both counters, and a stop watch. Since this instrument board provides a convenient place for data sheets, the operator usually holds the board in his lap and sits at any point of vantage in the towing vehicle. The appearance of the instrument board is shown in Figure 9.

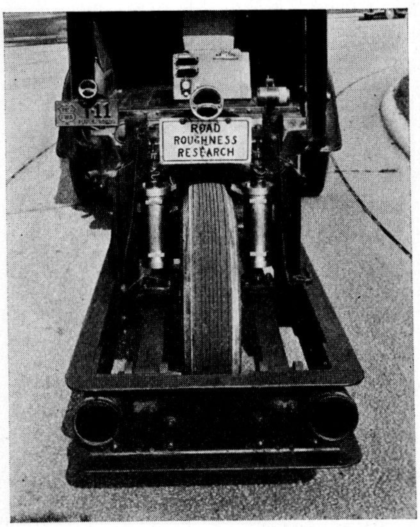

Figure 8. Rear view of trailer

The magnetic counters operate on six volts and the storage battery of the towing vehicle is a convenient source of power. Weatherproof extension wire and plug connectors are used throughout and a circuit breaker protects the system against overload.

The trailer is remarkably stable on the road at all speeds used in testing. It has good maneuverability both in backing and turning. It is fitted with approved side and rear reflector plates and a combination stop and tail light controlled by the corresponding circuits in the towing vehicle. As a further safeguard a red warning flag may be carried in a socket at the rear. A kit of emergency flares, lamps and warning flags are carried in the towing vehicle. The entire equipment is shown in Figure 10.

In the development of equipment such as that described, it is necessary to investigate the operating characteristics

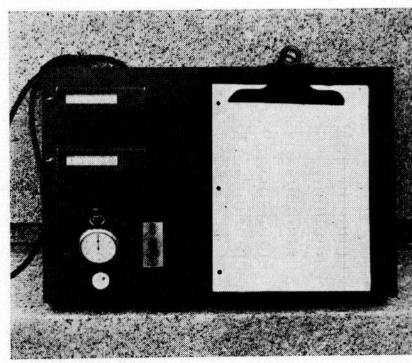

Figure 9. A close-up of the instrument board

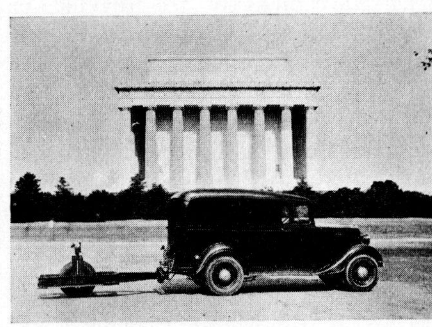

Figure 10. General view of trailer and towing vehicle

as affected by certain constructional details and by the conditions under which the equipment must operate in the field. These studies included the spring damping equipment, the vehicle springs, tire equipment factors, the operating speed, effects of temperature and the number of observations necessary to establish satisfactory data. As a result it is possible to specify the apparatus and technique that will give a high degree of consistency of performance.

The complete investigation of the influence of the tire equipment on the magnitude of the roughness values obtained included the tread design, tread wear and inflation pressure. As shown in Figure 11, the first two conditions were found not to be critical. Although almost any 6.00—16 in. four-ply tire will serve, it is believed preferable to use an all-rib tread design for the sake of uniformity and to replace the tire before the grooves entirely disappear through wear. A patched tire or one that has become otherwise unbalanced should not be used. The inflation pressure, however, is important, as shown by the data in Figure 12, and the technique adopted for testing requires an actual inflation pressure of 30 ± 0 5 lb. per sq. in. It has been found by experience that after the trailer has been run for about the first 10 miles, some adjustment of the pressure is necessary but that during subsequent running little readjustment is ordinarily required. A calibrated pressure gage of the Bourdon tube type, with suitable fittings, is recommended for the measurement of air pressure as the ordinary commercial tire gages are not sufficiently reliable. A small air pump is carried in the towing vehicle

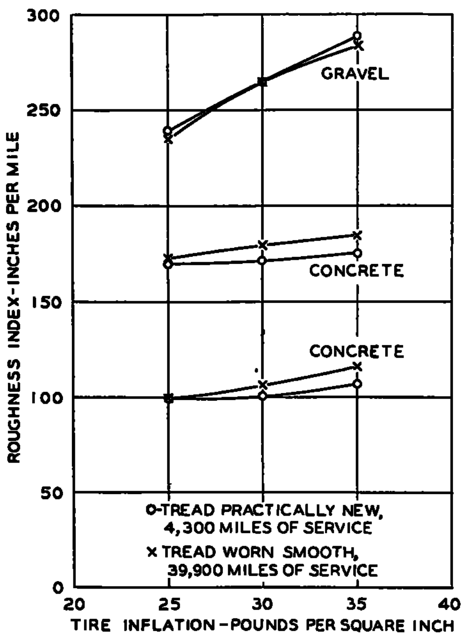

Figure 11. Effect of Tread Wear on Roughness Index. (Each Value for Concrete Represents the Average of Twelve Tests; Gravel the Average of Six Tests.)

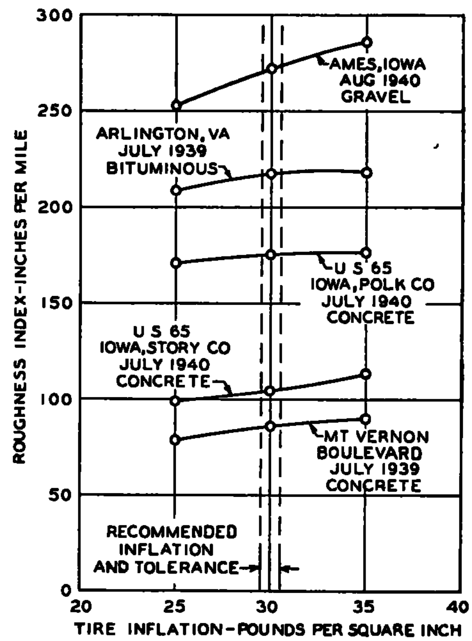

Figure 12. Effect of Tire Inflation on Roughness Index; Nominal Speed 20 Miles per hour. (Each Value is the Average of Six Tests.)

As stated previously, it is essential that the damping equipment used on the vehicle springs be of a type such that temperature changes will have a negligible effect on the damping action and also be designed so as to be exactly duplicable. The principle of a dashpot displacing a relatively large volume of low viscosity liquid was adopted because practical tolerances in the dimensions of pistons and ports and the viscosity changes due to the working temperature of the oil are less critical for such a design. As finally developed, the damper is a simple double-acting dashpot with a piston 3 in. in diameter. In the head of the piston are two bypass ports through which the oil flows. The ports are 0.25 in. in diameter and of specified length. Surge is effectively suppressed by ported baffle plates. The damper is connected to the trailer through ball thrust joints and each piston rod is protected against

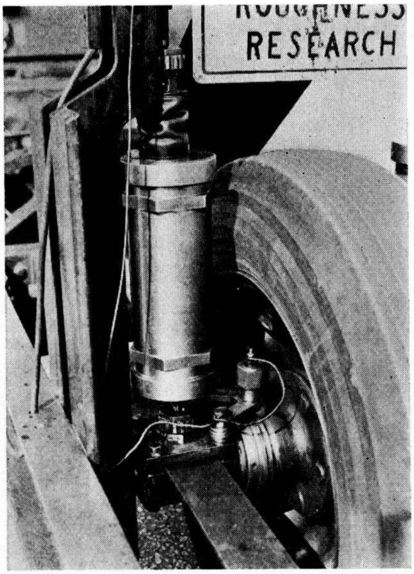

Figure 13. A close-up of one of the damping units and the revolution counter contactor on the wheel hub.

water and road dirt by a collapsible leather sleeve. The closeup photograph in Figure 13 shows the appearance of the unit.

The influence of oil viscosity on the integrator readings is shown by the data in Figure 14. These were obtained from tests with three fluids, of which an S.A.E. 20 lubricating oil was the heaviest. Attention is called to the wide range in roughnesses covered by the data. The study included many other fluids and from the data it was concluded that if one could be found which had a viscosity that would remain within the limits of 40 to 100 sec. (Saybolt Universal Viscosity) for the temperature range encountered in field testing, its use would prevent significant changes in the integrator readings when wide changes in air temperature occurred. The fluid must also meet other requirements as mentioned earlier. By trial it was found

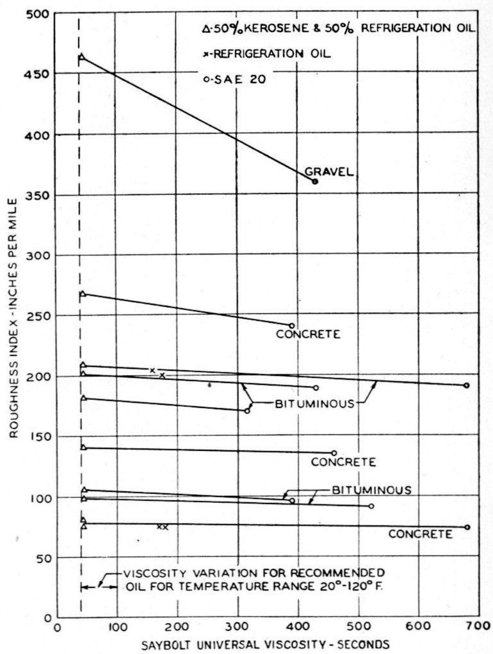

Figure 14. Effect of Oil Viscosity on Integrator Readings of Roughness Index; Tire Inflation 30 Pounds per Square Inch Nominal Speed 20 Miles per hour. (Each Value is the Average of Five Tests.)

that a light ice machine oil mixed with an equal volume of kerosene satisfied the requirements. Figure 15 shows the relation between viscosity and temperature for the oil blend now being used and it will be noted that over the temperature range +20 to +120°F. the viscosity range is about 100 to 40 sec. (S.U.V.).

During the development period various leaf springs were used, all obtained commercially with specifications that covered the dimensions and essential properties. It has been found that the commercial tolerances on width and thickness are sufficiently close for specifications for springs for this work. While some variation in the load deflection rate is permissible, it is very desirable that the two springs selected for a given installation be closely matched for load deflection characteristics The springs now in use are fabricated from silicon manganese spring stock 2½ in. wide by

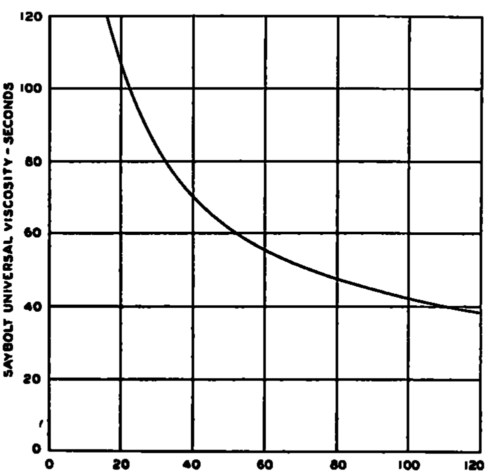

Figure 15. Viscosity Curve for the 50-50 Blend of Kerosene and Sherwood No. 125 Machine Oil Used in the Damping Units.

$\frac{11}{32}$ in. thick. The deflection rate is approximately 100 lb. per in

The speed at which the vehicle is operated affects the magnitude of the integrated spring deflections for a given road. Therefore, the speed at which the equipment is to be operated must be carefully selected and closely controlled. In selecting the speed for testing, the following conditions were considered:

1. The speed should be such that interference with or by traffic would be a minimum.
2. The speed should be within the range used by general traffic.
3. The speed should be such that minor variations will not affect the integrator values to a material degree.
4. The speed should be slow enough to permit the operator to take adequate notes.

Although the trailer has been operated and will function at speeds as high as 60 miles per hour, a much lower speed than this is necessary to meet some of the requirements stated above. On the basis

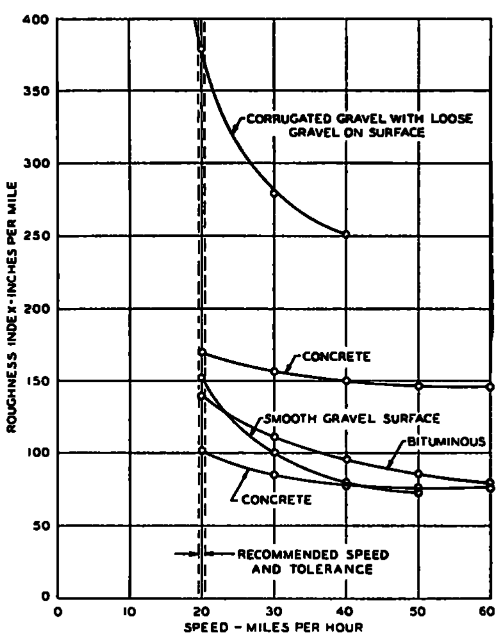

Figure 16. Effect of Speed on Roughness Index, Tire Inflation 30 Pounds Per Square Inch.

of the experience and data thus far available a testing speed of 20 miles per hour appears to best meet these requirements. In Figure 16 are shown the relation between speed of the trailer and the magnitude of the roughness index for a number of typical road surfaces varying in type and degree of roughness. According to these data, a variation in vehicle speed of plus or minus one-half mile per hour will not cause material variation in the roughness index at the 20-m.p.h. speed.

At this speed many miles of pavement can be tested in a day.

The vehicle speed and distances can be determined from the towing vehicle speedometer indications but may be obtained more precisely with the stopwatch and revolution counter on the instrument board. A simple switch operated by a cam on the hub of the trailer wheel closes the circuit of the second magnetic counter once for each revolution of the wheel. From the counter, distances traveled may be easily determined and, in conjunction with elapsed time from the stopwatch, average speeds may

TABLE 1

EFFECT OF TYPE OF TOWING VEHICLE ON ROUGHNESS INDEX

Type of road surface	Type of towing vehicle	
	Passenger car	Light truck
	Roughness index	
	in per mile	*in per mile*
Concrete	101	100
Bituminous	119	120
Concrete	159	160
Bituminous	214	216
Bituminous	233	230
Concrete	289	289

Note Each value is the average of five tests expressed to the nearest unit

be quickly computed Also this feature enables the operator to test any desired lengths of pavement without roadside markers, to calibrate the towing vehicle speedometer, and to check the operation of the towing vehicle.

It may be noticed that the effect of operating speed, as determined with this standardizable vehicle and shown in Figure 16, is somewhat different than the effect found with the earlier instrument on a conventional automobile (see Fig. 1). This is to be expected since the spring weight characteristics of the trailer differ from those of the automobile, the spring action is different and the character of the damping provided in the trailer is quite unlike that in the automobile.

The influence of the characteristics of the towing vehicle on the action of the roughness trailer was investigated by duplicate tests, using first a light passenger car with a 109-in. wheel base, and second, a half ton panel delivery model truck with a 113-in wheel base. When attached to the passenger car the kingpin of the trailer was 33 in. back of the rear axle, while with the truck this distance was 64 in. Tests data obtained on six

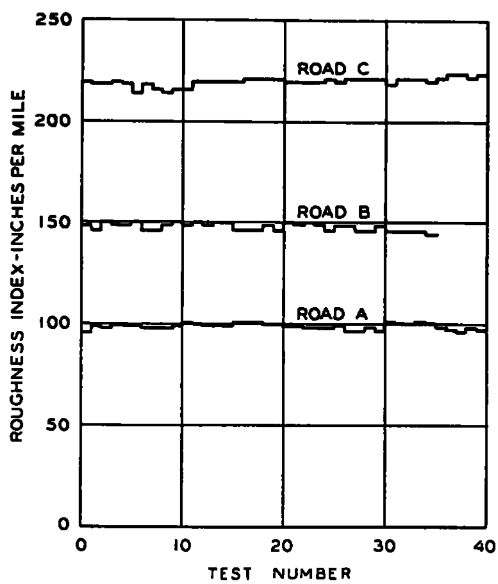

Figure 17. Variation in Indices for Repeated Tests on Three Different Roads

roads that covered quite a wide range in surface roughness are given in Table 1. It is evident that there is no significant difference in the roughness indexes for the various roads when the trailer was attached to these two vehicles. This is as would be expected from the dynamics of the trailer design.

When operated according to the standardized technique that has been described, remarkable repeatability is obtained for a given track or path on a given road. In Figure 17 are data obtained on three different roads in tests in which five measurements per day were made on a number of different days. In the case of roads A and C the total period

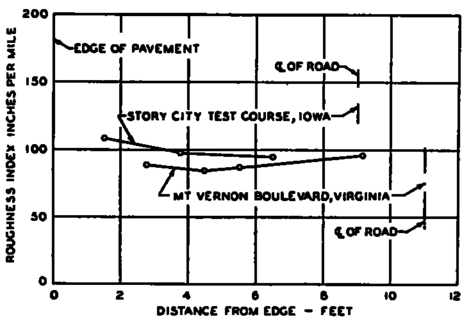

Figure 18. Variation of Roughness Along Various Elements of Two Roads

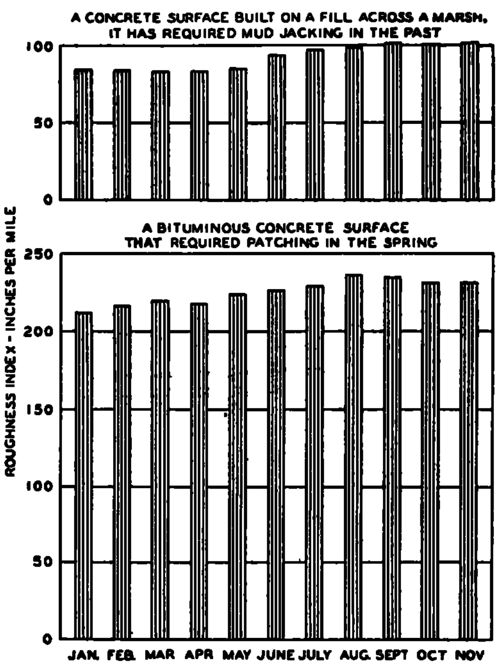

Figure 19. Progressive Change in Roughness of Two Road Surfaces with Time

covered by the data in this figure is eight working days but in the case of road B the days on which the repeat measurements were made were spread over a period of about four months. In considering the matter of consistency, two facts should be kept in mind. First, no two runs would follow exactly the same path although the attempt was made to do so; and second, a dispersion of one point may be caused by the fact that the commutator segments of the integrator might happen to be either in or out of the circuit at the instants of closing and of opening the main control switch at the beginning and end of the test

Different longitudinal tracks along a road may be different in roughness as is shown by Figure 18. These data were obtained in tests that were carried out to explore this particular point. It is interesting to note that the apparatus functioned with a precision such that differences of this small order of magnitude could be detected. When appreciable differences in roughness exist across the pavement, a fair average should be obtained by making a number of tests along various longitudinal elements of the road surface.

SUMMARY

The equipment which has been described is not perfect and it may be that some changes in the apparatus or in the technique of field testing may be found desirable at some future time. It is believed, however, that the underlying principle as a means for indicating the relative roughness of road surfaces is sound and that the present equipment is superior to that developed earlier in two important respects—first, the introduction of a special vehicle has removed the uncertainties of vehicle operation that were always present when an automobile was a component part of the measuring apparatus; and second, the entire equipment is so designed that it can be exactly duplicated and, to this extent, the equipment is standardizable. Many hundred miles of operation without mechanical failure indicate adequate mechanical design. The equipment is stable in operation and has shown remarkable consistency of performance. Finally, it is easy to use and the data are obtained rapidly with it.

It would appear that there are several fields of usefulness for equipment of this kind If the apparatus is constant in its performance, it permits of periodic surveys of surface condition that will give quantitative data on the smoothness of the various pavements in a system. For example, Figure 19 shows how the surfaces of two pavements compared month by month over a period of about a year The concrete pavement rests on a fill that is not completely stable and the bituminous pavement is one that requires patching from time to time. Data such, as these show the need for and result of surface maintenance operations. With means for evaluating surface smoothness available, the interest of construction and maintenance crews can be aroused and a desirable competitive spirit stimulated.

DISCUSSION ON EQUIPMENT FOR EVALUATING ROAD SURFACE ROUGHNESS

Prof. R. A. Moyer, *Iowa State College:* Mr Catudal brought the equipment to Ames last summer where it was given a good workout for several months on a wide variety of surfaces.

During the past two years we have been running road tests at Iowa State College to determine the effect of the road surface on operating costs. In this project which is conducted as a cooperative project with the Public Roads Administration, we have been interested in identifying the road surface on the basis of such characteristics as surface roughness and skidding properties. We are hoping that we may be able to correlate these measurements with the operating cost. In the paper[1] which I presented last year on this project, I reported the results of our measurements of road roughness on the concrete and gravel surfaces using a profilometer track and also a Firestone six-element sensitive recording contact accelerometer. Anyone interested in measurements of road roughness will find the data and analysis given last year a valuable reference in connection with this paper.

Mr. Catudal has presented some of the data obtained with his equipment on short sections of road surfaces near Ames. While most of the tests were run on short sections ½ mile to 5 miles in length, the equipment was also run over our entire concrete and untreated gravel test routes, each of which is 235 miles in length. The results of the runs on these routes are given in Figures 1 and 2. On the concrete route the equipment was run both clockwise and counterclockwise to determine differences in each traffic lane. Since the runs on the dusty "washboarded" gravel route were hard on the equipment and the differences between traffic lanes were not likely to be very large, runs on gravel were taken in one direction only.

It is interesting to note in Figure 1 the general uniformity in the results on the concrete route on all the rural sections and the extreme roughness of the surfaces in the cities and towns on the route. The values on the brick and asphalt surfaces in Hampton, Marshalltown and Nevada averaged about 400 in. per mile as compared to 100 or not over 150 in. per mile on the rural concrete sections. The roughness in the towns was not only confined to brick and asphalt but even the concrete pavements in Jewell and Waverly was found to be rough with

[1] Moyer, R A "Motor Vehicle Operating Costs and Related Characteristics on Untreated Gravel and Portland Cement Concrete Road Surfaces" *Proceedings*, Highway Research Board, Vol 19, p 68 (1939)

values as high as 200 in. per mile. The differences between the two traffic lanes on the concrete route were small, as might reasonably be expected.

last year, the untreated gravel roads have the common defect of developing long sections of rhythmic corrugations commonly known as "washboarding"

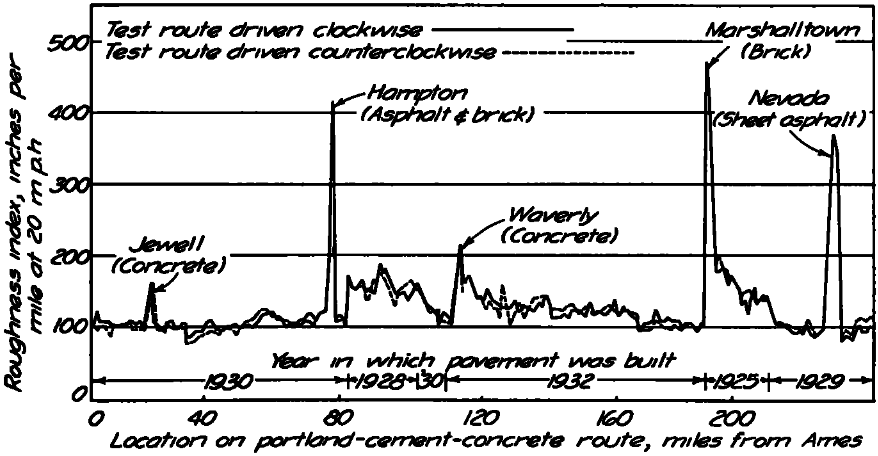

Figure 1. Road roughness in inches per mile as measured by the Public Roads Administration standardizable roughometer on the portland cement concrete test route, Project 219 of the Iowa Engineering Experiment Station in August, 1940.

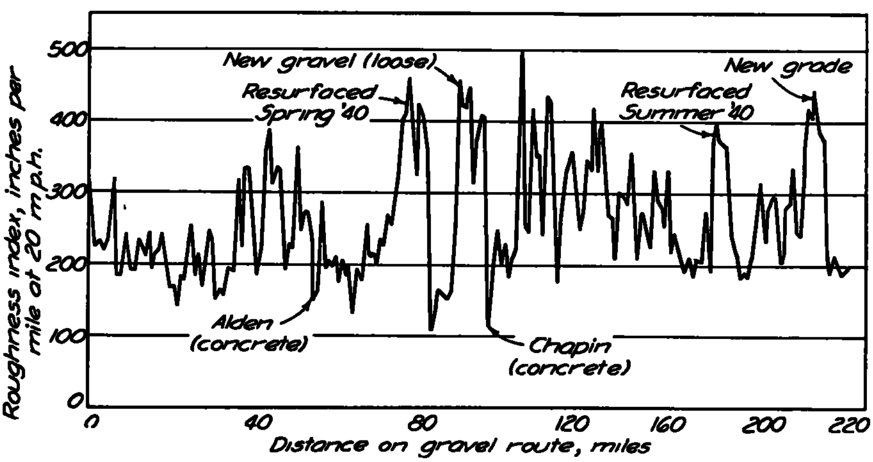

Figure 2. Road roughness in inches per mile as measured by the Public Roads Administration standardizable roughomoter on the untreated gravel test route, Project 219 of the Iowa Engineering Experiment Station in August, 1940.

The roughness of the gravel roads shown in Figure 2 varied widely and there were no sections several miles or more in length which were uniformly smooth. As was clearly brought out in the report

which make these surfaces very rough and uncomfortable when driving a car over them. The readings on the untreated gravel were rarely below 200 in. per mile and on the roughest sections frequently went above 400 in per mile as compared to the 100 in. per mile average on the best concrete and 200 in. per mile on the roughest concrete in towns.

While the detailed profile of the surface obtained with the profilometer provides an accurate record of the surface roughness, it is a rather slow and awkward method of obtaining a roughness index for long sections of road. Since the method is slow, it is necessary to use the sampling method to cover distances one mile or more in length One or two typical sections 100 ft. in length were

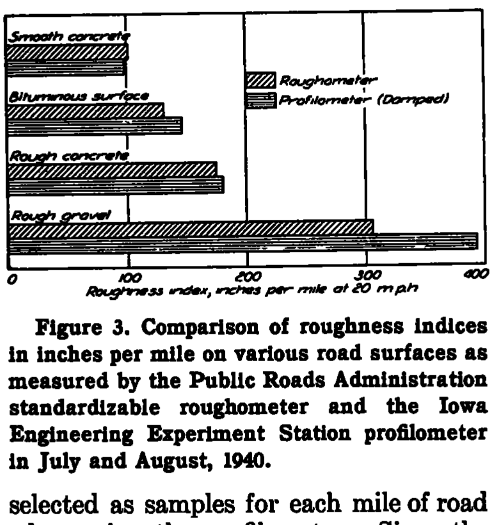

Figure 3. Comparison of roughness indices in inches per mile on various road surfaces as measured by the Public Roads Administration standardizable roughometer and the Iowa Engineering Experiment Station profilometer in July and August, 1940.

selected as samples for each mile of road when using the profilometer. Since the Public Roads Administration equipment provides a complete record over the entire length of surface in a fraction of the time required to obtain measurements with the profilometer, it is much to be preferred where measurements over long sections of road are desired in each traffic lane.

There is one distinct difference between the profilometer measurements and the P.R.A. roughness equipment measurements due to the fact that with the profilometer all the small differences in the surface profile are measured at a very slow speed with a small steel wheel, whereas the P.R.A. device is operated at 20 m.p h. and the irregularities are measured with a standard 6.00 by 16-in rubber tire. For this reason some of the minor irregularities are smoothed out by the deformation of the rubber tire or by the deformation of the road surface. An attempt was made to measure the correction factor for the tire deformations caused by various surface irregularities by using artificial obstructions of known heights on a smooth surface. The correction so obtained was called the damping factor and was found to be 2.54. As a further check on this factor, a series of tests were conducted to compare the roughness obtained with the P.R.A. device and with our profilometer track.

A comparison of the results with the profilometer and the P.R.A. equipment is given in Figure 3. The same damping factor (2.54) was applied to the profilometer measurements as was obtained for the artificial obstructions, that is, the vertical deviations from a mean path along the road surfaces in inches per mile as measured on the profilometer track records divided by 2.54 gave the values shown in Figure 3 On smooth concrete the values were found to be approximately the same by both methods but as the surface roughness increased the profilometer values were higher than the P R.A. roughometer values. The greatest difference was obtained on the untreated gravel where the values with the P.R A. roughometer averaged 306 in. per mile and with the profilometer 393 in. per mile. This large difference was not unreasonable on the flexible gravel surface on which there was a certain amount of loose gravel because on this surface both the road surface and the tire deformed, whereas on the usual hard firm surface, the only measurable deformation was provided by the tire and very little, if any, by the road.

No definite values have been established to determine the extra costs of operation which may be caused by the rough gravel surfaces but the indications are that the extra fuel, tire, and oil costs were very small, probably not more than one-fifth cent per mile, while the damaging effect on the car was no larger, if as large, as the extra fuel, oil, and tire costs on the extremely rough gravel roads.

The real value of a smooth surface lies in the extent to which it provides a comfortable ride and improves the steering and handling of the car to permit its safe operation over a wide range of speed. The data obtained in measurements with the Firestone accelerometers indicated that vertical accelerations of 25 ft. per sec. per sec. were obtained at 40 m.p.h. on the gravel roads. The computed accelerations from the profilometer records indicated values as high as 120 ft. per sec. per sec. at 40 m.p.h. It was commonly observed on the gravel roads that the front and the rear wheels were continually bouncing from crest to crest on the rhythmic corrugations and occasionally at the higher speeds all four wheels were clear from the road surface. Under these conditions the ride was extremely uncomfortable and the drivers skill in steering the car was taxed to the limit. On concrete roads speeds of 70 to 80 miles an hour are fairly common and on such roads as the Pennsylvania Turnpike, cars are being operated at speeds of 80 to 100 m.p h. Since the vertical accelerations vary as the square of the speed, it is evident that the present day road surfaces should be built to the highest possible standards of surface smoothness to permit safe operation on these surfaces at the high speeds of traffic today and the probable higher speeds in the future

On the basis of our experience with the P.R.A roughness device, I do not hesitate to recommend wide adoption of this equipment by all State highway departments to the end that equally high standards of surface smoothness will be provided on all State highways.

DR. B. D. GREENSHIELDS, *Brooklyn Polytechnic Institute:* I have been interested this morning in the academic and theoretical approach to this question of roughness. The scientific method of solving a problem in which there are a number of variables, is to keep all of these variables constant, with the exception of one, and then to vary that one and note the effect. A monkey in going through a series of aimless motions accidentally opens the door to his cage In striving to open the door again he always repeats the whole series. The scientific approach would be to successively eliminate each separate motion until the one that opened the door was found.

If one is to measure the difference in roughness of a road in Iowa and one in New York, the variables in the instruments of measuring must be eliminated or reduced to a minimum That minimum plus any difference in the method of measuring, determines the accuracy of the comparison In other words, the instruments for comparing the roughness must be standardized.

It happened that I used a roughometer several years ago, constructed to the specifications of the U S Bureau of Public Roads (*Public Roads*, Vol. 7, September, 1926). That roughometer varied in its readings with the car to which it was attached. This necessitated the use of the same car in comparing the roughnesses of any two roads.

There is a relation, and it may be quite definite, between speed, cost of car operation, comfort, and roughness. If this is true, then we have only to compare two roads in relation to one of these variables to determine the relation in the other variables. It would, of course, first be necessary to determine the limits of the relation.

MR. CATUDAL: In respect to the effect of speed on the roughness data, it will be recalled from the graphs, that for most roads the roughness indices tend to decrease with an increase of speed up to 40 m.p.h. beyond which they become practically constant. This characteristic is a function of the road surface, of the tire, spring-weight system and the damping used on the vehicle. It is apparent that this relationship would be different for different types of vehicles. As Professor Moyer pointed out in his discussion, the relation between roughness indices obtained at 20 m.p.h. and measurements of actual road surface profiles showed close agreement for the permanent types of road surfaces.

MR. BUCHANAN: With reference to the selection of the 20-mile speed: when the operator of the vehicle is making his tests, he does not want to turn out into another lane in order to pass around some slower moving vehicle. It would have a tendency to upset his tests too much. Of course he can stop behind such a vehicle but that would have a worse effect on the nature of his test information. That is one consideration and another is that he wants to make notes as he goes along—he wants, at every tenth, quarter, or half mile, to reference his readings to land marks along the road, at intersections, bridges and other points which will enable him to tie in his test results with the actual road lay-out. At 20-miles an hour he has sufficient time to do that. At 40 he would be very hard-put to keep his notes up with his observations. At the 20-mile speed he can probably cover as many miles a day in good tests (in which the data are all reliable) as he can at any of the higher speeds. With reference to the special effects which I should like to designate as wash-boarded roads· I think they are special cases. We all know they are very bad The fact that one particular vehicle can take wash-boarded roads at 50 miles an hour and another vehicle with a different passenger load could only take it at 35 miles an hour is an interesting observation—interesting principally to the driver of the vehicle. Such roads are not representative of roads throughout the country. So far as the roads with which we are really concerned are involved, the roughness effects of wash-boarding are not introduced.