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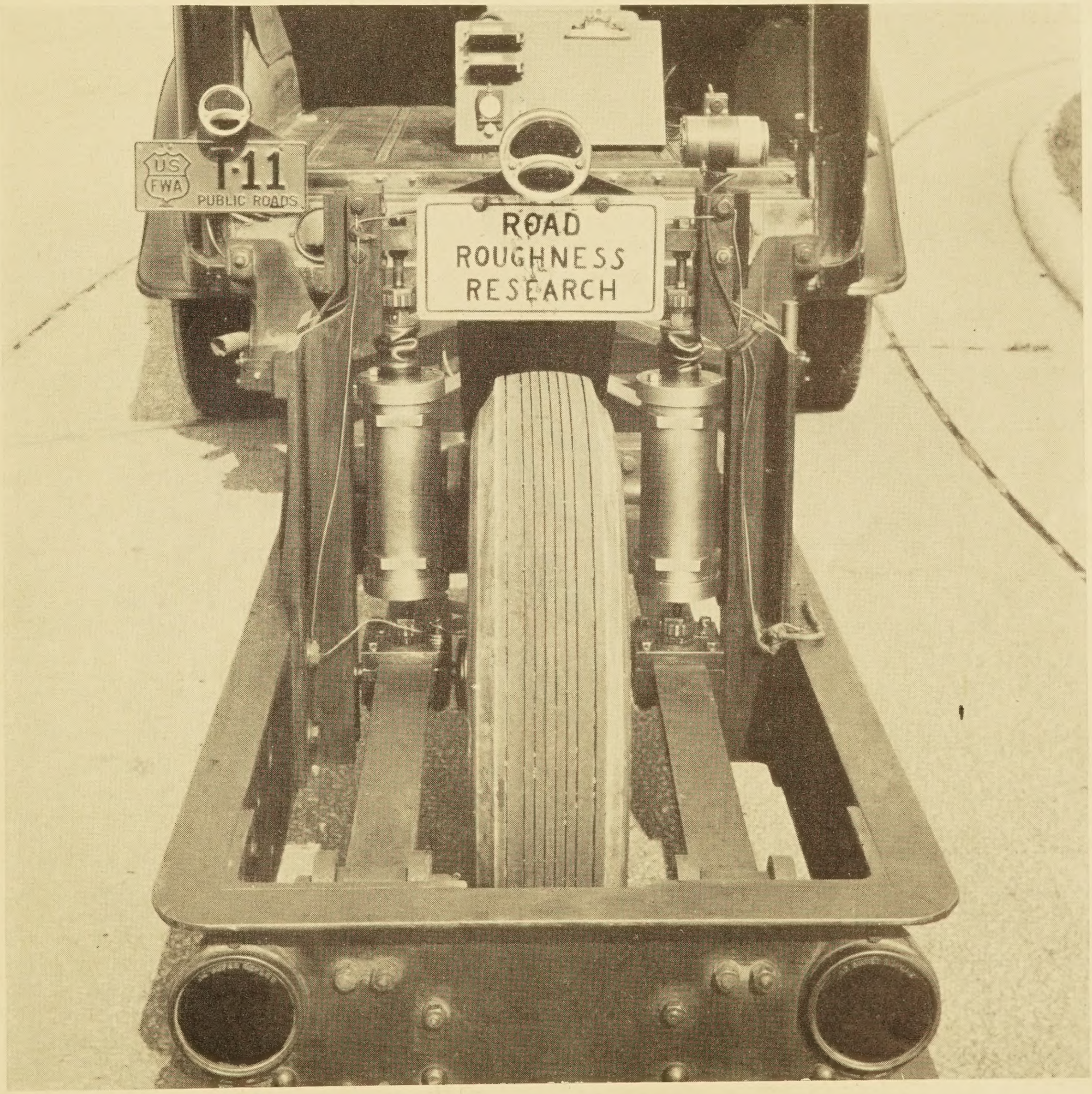

EQUIPMENT FOR MEASURING ROAD SURFACE ROUGHNESS

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D. M. BEACH, *Editor*

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

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STANDARDIZABLE EQUIPMENT FOR EVALUATING ROAD SURFACE ROUGHNESS[a]

BY THE DIVISION OF TESTS, PUBLIC ROADS ADMINISTRATION

Reported by JAMES A. BUCHANAN, Engineer of Tests, and ARTHUR L. CATUDAL, Assistant Highway Engineer

Various methods have been employed for determining the smoothness or roughness of road surfaces. This report discusses these methods and certain inherent characteristics that have precluded their general acceptance. Equipment is described that operates on the principle of the measurement of the vertical movements of a wheel suspension with respect to its supported frame. In earlier applications of this principle it was recognized that the difficulties that were encountered were caused by the use of apparatus that made use of the motor vehicle and its load as a component part. This led to an investigation of the use of a special vehicle capable of standardization in all of its parts.

The new equipment is in the form of a single wheel semitrailer, attachable to any towing vehicle. The vertical movements of the wheel with respect to the frame are measured by a newly designed, overrunning clutch integrator with improved operating characteristics. The performance of the apparatus and the recommended standard operating procedure are given in detail. Many hundred miles of operation without mechanical failure indicate adequate mechanical design. The device is simple to operate 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 surfaces is sound and that the present equipment is superior to that developed earlier in two important respects: First, the use 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.

ONE ATTRIBUTE of the modern pavement in which the riding public is greatly interested is the smoothness of the surface. Because of this general public interest, great care is taken by highway engineers to construct and to maintain surfaces that are as smooth as possible, from the standpoint of riding quality. 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. Apparatus for indicating road surface roughness falls into one or the other of two general 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, 2, 4, 8, 16, and even 32 wheels having been employed in the various designs. Usually, the profile of the road surface, with respect to the datum, was traced 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.

VEHICLE SPRING DEFLECTION MEASURED AS INDEX OF ROAD SURFACE ROUGHNESS

The other class of instrument made use of the fact that irregularities of surface contour cause the wheels of motor vehicles to oscillate vertically with respect to the vehicle chassis. Since this motion is permitted by 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. The recorded data were 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 somewhat 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—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 instrument.[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 labora-

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[a] Paper presented at the Twentieth Annual Meeting of the Highway Research Board, December 1940.

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

[2] An Instrument for the Measurement of Relative Road Roughness. PUBLIC ROADS, vol. 7, No. 7, Sept. 1926.

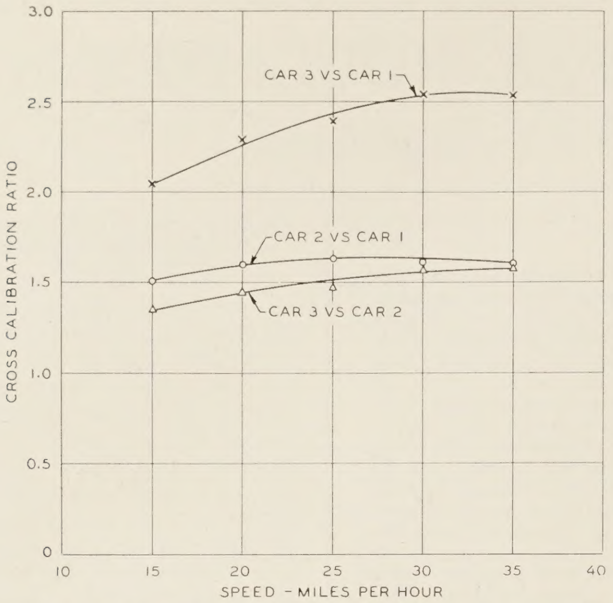

FIGURE 1.—VARIATION OF CROSS CALIBRATION RATIO WITH SPEED. (EACH VALUE IS THE AVERAGE OF 4 DETERMINATIONS.)

tory tests in which all of 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 calibration 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 in this report to describe in detail the work that was done. A few generalized comparisons will show the significance of the results of the study.

When 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 are 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 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 data three cars closely spaced were driven on the same path over 15 successive miles of road at a constant speed of 25 miles per hour, 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 roads representing a wide range of surface roughness. In this figure the road roughness values were those indicated by the instrument on car 3.

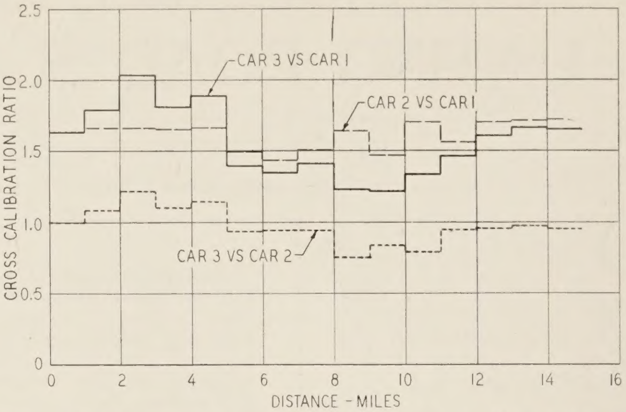

FIGURE 2.—VARIATION IN CROSS CALIBRATION RATIO FOR INSTALLATIONS ON THREE DIFFERENT CARS OPERATED AT 25 MILES PER HOUR OVER SECTIONS OF VARIED ROUGHNESS.

NEED FOR STANDARDIZABLE EQUIPMENT EMPHASIZED

Tests were made also with road surfaces whose natural roughness was increased by placing on the surface a series of artificial obstructions of fixed dimensions, shape, and spacing. These tests were made to determine the relation between the constant artificial roughness and the effect on the roughness values obtained for three different vehicles operated at the several speeds shown. The purpose of the procedure was to obtain values for the road surface roughness 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 obtained. Each graph shows the range in the values of the increase in roughness created by a series of 10 obstructions placed 50 feet 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 indicated roughness caused by the artificial obstructions was affected by characteristics of the car and by the roughness of the road surface on which the obstructions were placed, as well as by the speed and other controllable test conditions.

The difficulties encountered were recognized as being caused by the use of apparatus of 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 being used, with the result that an improved integrator has also been developed. 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 this report is primarily concerned.

The design of the standardizable vehicle for evaluating road roughness is quite simple.[4] 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

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[3] The Dana Automatic Roughometer for Measuring Highway Roughness—discussion by L. W. Teller. Proceedings Highway Research Board, 12th Annual Meeting (1932).

[4] Plans and specifications for the apparatus will soon be available and will be sent upon request to anyone wishing to construct this type of roughness indicator.

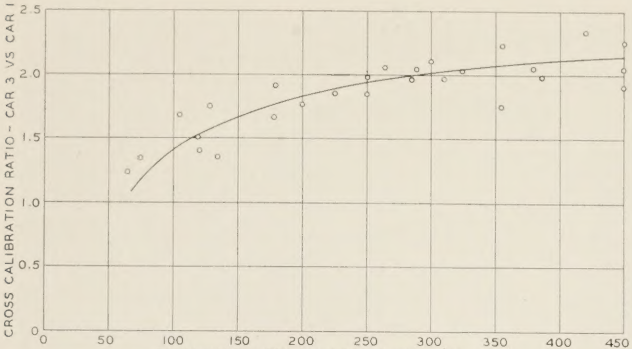

Figure 3.—Variation in Cross Calibration Ratio With Surface Roughness.

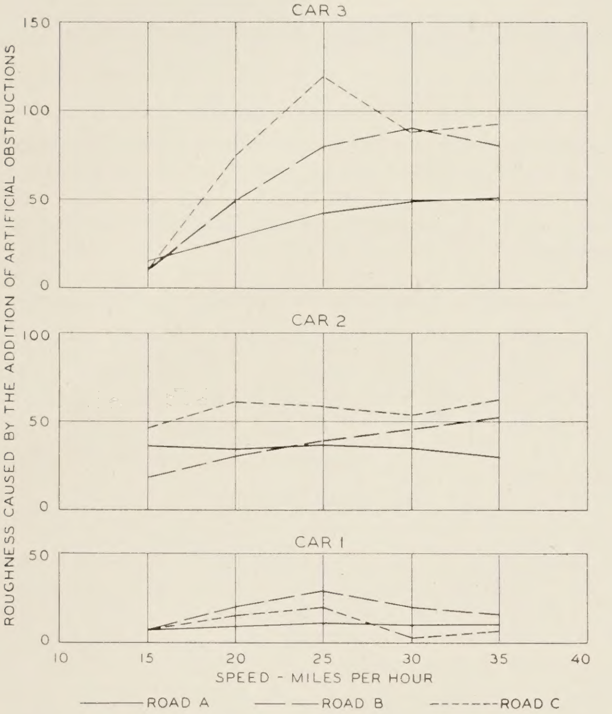

Figure 4.—Range of Increase in Roughness Caused by the Addition of the Same Artificial Obstructions to Three Different Roads Using Three Different Cars. (Each Value Is the Average of 4 Tests.)

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 appearance, as seen from the side, in figure 6.

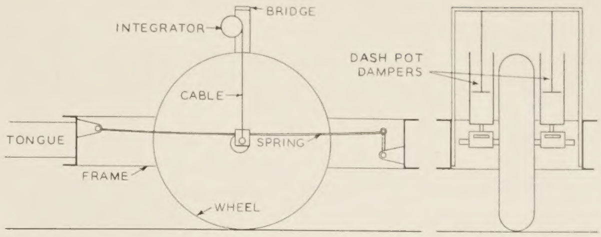

Figure 5.—Schematic Drawing of the Essential Elements of the Trailer.

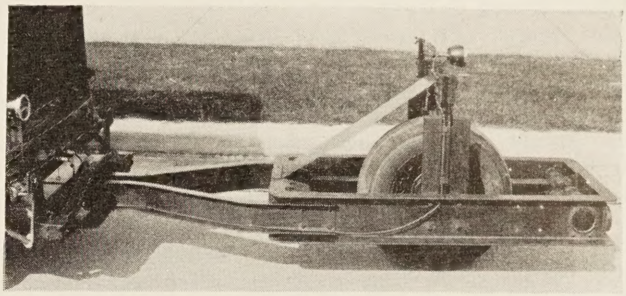

Figure 6.—Side View of the Trailer.

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 pounds, the reaction under the wheel being 580 pounds and that at the towing hitch being 160 pounds. 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 2-wheel trailer, because the former would respond to the contour of but one path.

A survey of tire equipment in use at the time of the design showed that the 5.50–17-inch 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-inch 4-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 attached to a disk wheel. If the time should come when this disk wheel is no longer commercially available, it would be relatively simple to make one by welding a suitable flat disk 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 (S A E 4140).

DAMPING SYSTEM CONTROLS SPRING OSCILLATION

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.

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 a 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 dash pot arrangement in which an appreciable volume of low-viscosity liquid was displaced through fixed ports. The liquid could not be corrosive or 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 [2] 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 vertical 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 was 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.

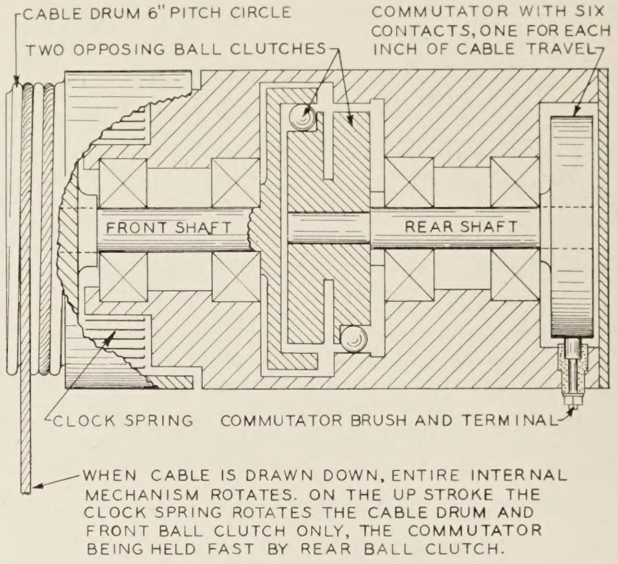

Figure 7.—Schematic Section of Integrator Elements.

NEW CLUTCH DESIGNED FOR ROUGHNESS INDICATOR

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 electrical 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. It is 3-strand, 12 wires to the strand, each wire being 0.005 inch in diameter. It is rated at 175 pounds breaking strength, is a type used for deep-sea fishing, and is readily obtainable. 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 circumference of the groove is 6.00 inches 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 had 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 obtain 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 inches in diameter. The eight balls are ⅛ inch in diameter and they operate on a wedge angle of 15°.

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 would occur; if too tight clutch slippage would result. In the

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[2] An Instrument for Measuring Relative Road Roughness. PUBLIC ROADS, vol. 7, No. 7, Sept. 1926.

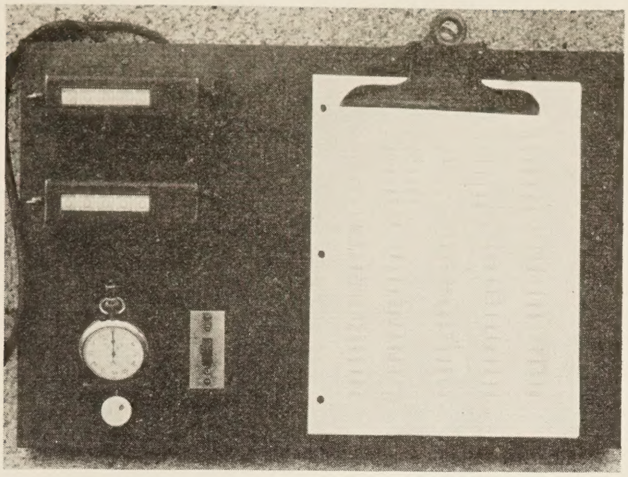

FIGURE 8.—CLOSE-UP VIEW OF THE INSTRUMENT BOARD.

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 disk 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 inches in circumference, each impulse to the electrical counter marks the accumulation of 1 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 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 alinement of the essential 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 (cover illustration) at the right-hand end 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 8. The magnetic counters operate on 6 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.

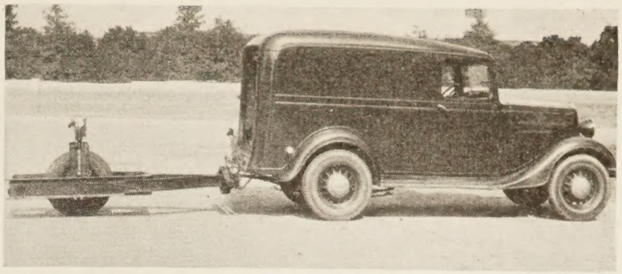

FIGURE 9.—GENERAL VIEW OF TRAILER AND TOWING VEHICLE.

STUDIES MADE OF VARIOUS OPERATING CHARACTERISTICS

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 is carried in the towing vehicle. The entire equipment is shown in figure 9.

In the development of equipment such as that described, it is necessary to investigate the operating characteristics as affected by certain constructional details and by the conditions under which the equipment must operate in the field. These studies included investigation of 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 study of the effect of tread design, tread wear, and inflation pressure. As shown in figure 10, the first two were found to be not critical. Although almost any 6.00–16-inch, 4-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 11, and the technique adopted for testing requires an inflation pressure of 30±0.5 pounds per square inch. 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.

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

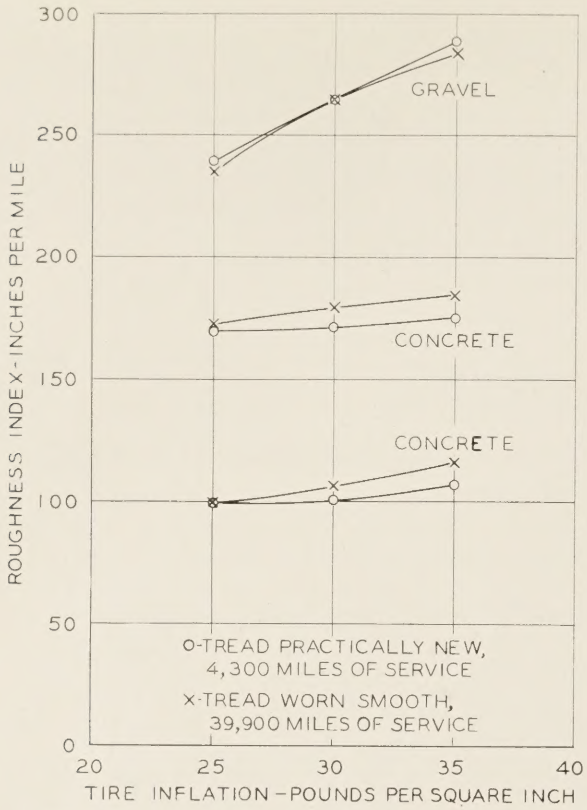

Figure 10.—Effect of Tread Wear on Roughness Index. (Each Value for Concrete Represents the Average of 12 Tests; for Gravel the Average of 6 Tests.)

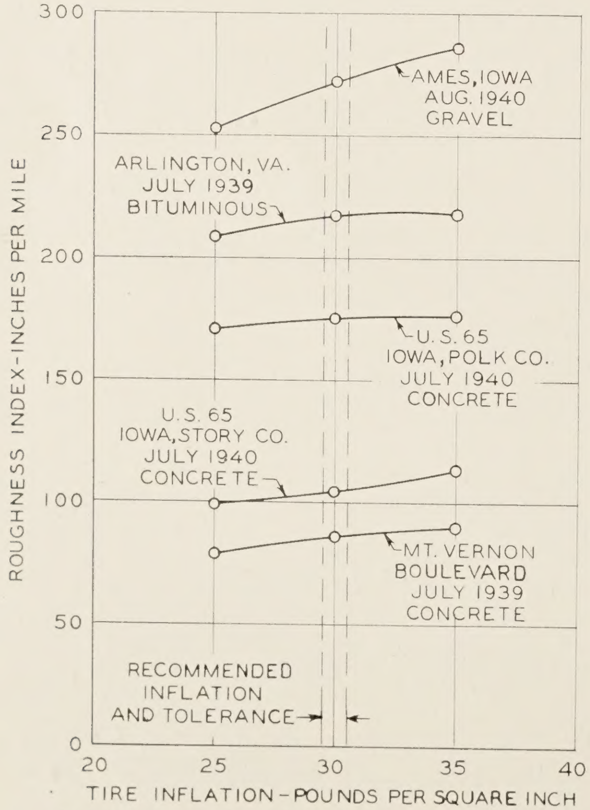

Figure 11.—Effect of Tire Inflation on Roughness Index; Nominal Speed 20 Miles Per Hour. (Each Value Is the Average of 6 Tests.)

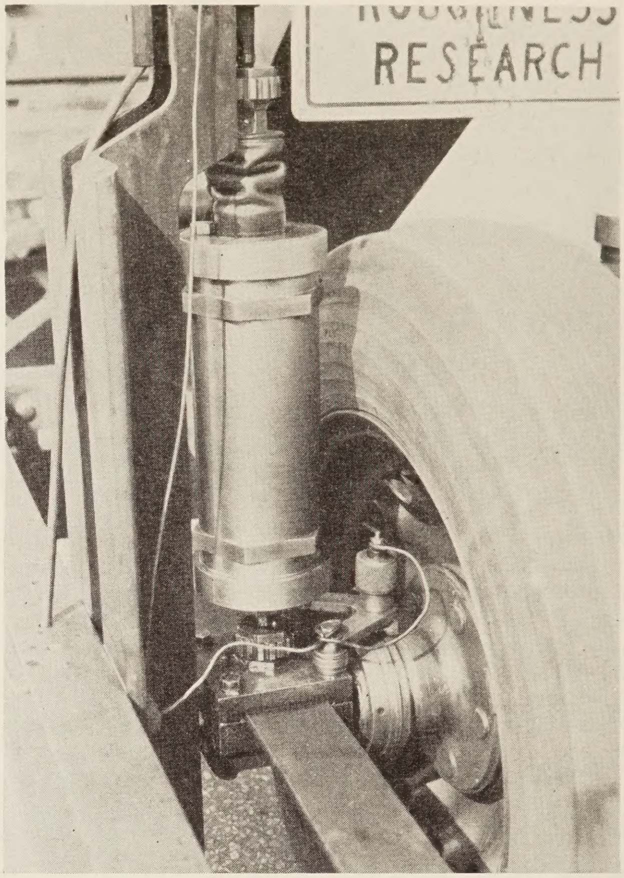

Figure 12.—A Close-Up View of One of the Damping Units and the Revolution Counter Contactor on the Wheel Hub.

on the damping action and also be designed so as to be exactly duplicable. The principle of a dash pot 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 dash pot with a piston 3 inches in diameter. In the head of the piston are two bypass ports through which the oil flows. The ports are 0.25 inch 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 water and dirt by a collapsible leather sleeve. The close-up view shown in figure 12 shows the appearance of the unit.

The influence of oil viscosity on the integrator readings is shown by the data in figure 13. They 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 that had a viscosity that would remain within the limits of 40 to 100 seconds (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

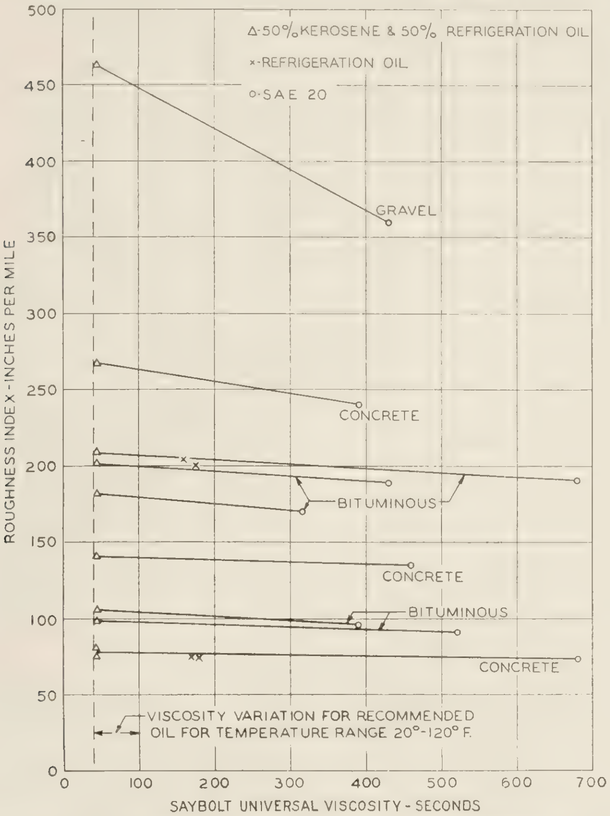

Figure 13.—Effect of Oil Viscosity on Roughness Index; Tire Inflation 30 Pounds Per Square Inch, Nominal Speed 20 Miles Per Hour. (Each Value Is the Average of 5 Tests.)

found that a light refrigeration oil mixed with an equal volume of kerosene satisfied the requirements. Figure 14 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 seconds (Saybolt Universal Viscosity).

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 thicknesses 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 inches wide by $\frac{11}{32}$ inch thick. The deflection rate is approximately 100 pounds per inch.

TESTING SPEED OF 20 MILES PER HOUR FOUND MOST SUITABLE

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.

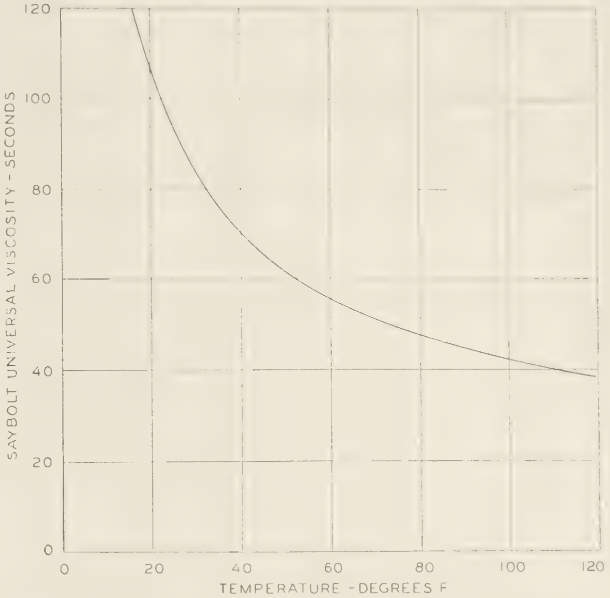

Figure 14.—Viscosity Curve for the 50–50 Blend of Kerosene and Refrigeration Oil Used in the Damping Units.

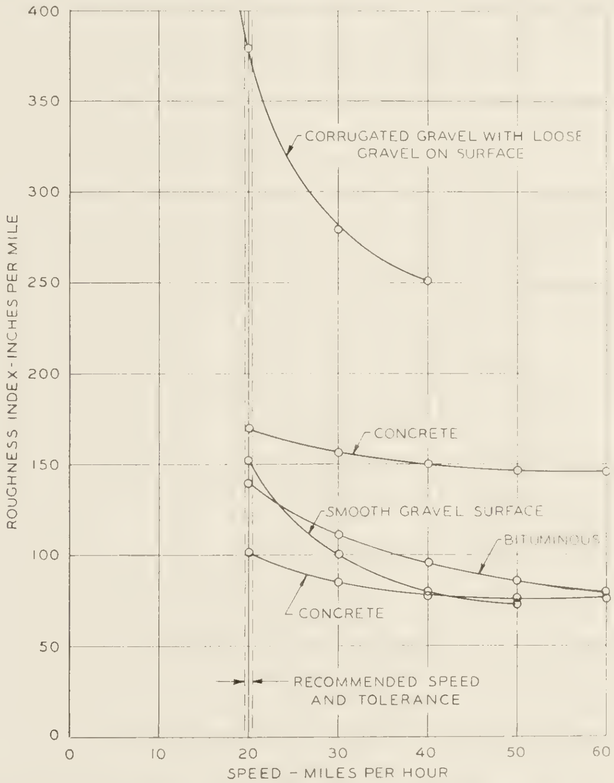

Figure 15.—Effect of Speed on Roughness Index; Tire Inflation 30 Pounds Per Square Inch.

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 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 of the experience and data thus far available a testing speed of 20 miles per hour appears

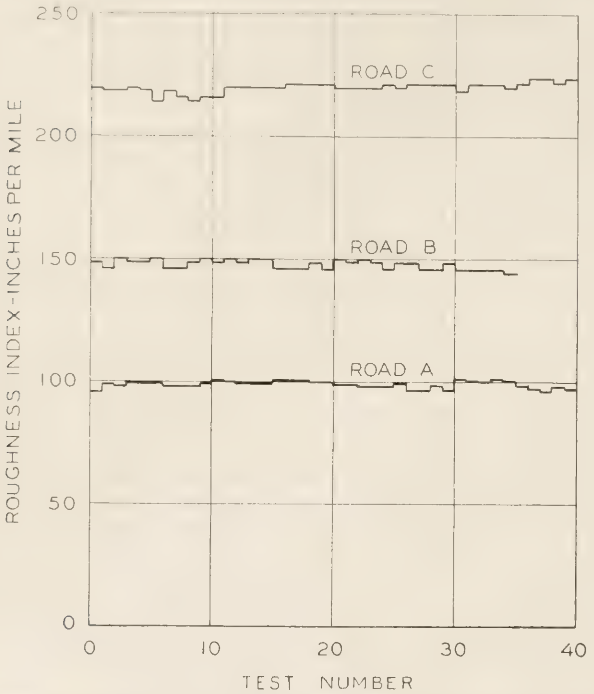

Figure 16.—Variation in Indices for Repeated Tests on Three Different Roads.

to meet these requirements best. In figure 15 are shown the relations 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 ±½ mile per hour will not cause material variation in the roughness index at the 20-mile per hour 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 they can be obtained more precisely with the stop watch 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 can be easily determined and, in conjunction with elapsed time from the stop watch, average speeds can 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 15, 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.

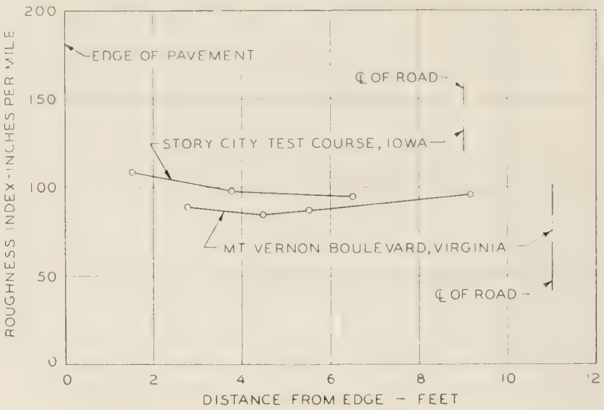

Figure 17.—Variation of Roughness Along Various Elements of Two Roads.

The influence of the characteristics of the towing vehicle on the action of the trailer was investigated by duplicate tests, using first a light passenger car with a 109-inch wheel base, and second a ½-ton panel body truck with a 113-inch wheel base. When attached to the passenger car the kingpin of the trailer was 33 inches back of the rear axle, while with the truck this distance was 64 inches. Test data obtained on six 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 indices 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.

Table 1.—*Effect of type of towing vehicle on roughness index*

Type of road surface	Roughness index [1] when towing vehicle was—	
	Passenger car	Light truck
	In. per mile	*In. per mile*
Concrete	101	100
Bituminous	119	120
Concrete	159	160
Bituminous	214	216
Do	233	230
Concrete	289	289

[1] Each value is the average of 5 tests expressed to the nearest unit.

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 16 are data obtained on three different roads in tests in which five measurements per day were made on a number of different days. For roads A and C the total period covered by the data in this figure is 8 working days but for road B the days on which the repeat measurements were made were spread over a period of about 4 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 17. 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.

(Continued on page 243)

SOME IMPORTANT CONSIDERATIONS IN THE DESIGN AND USE OF SOIL PRESSURE CELLS[a]

BY THE DIVISION OF TESTS, PUBLIC ROADS ADMINISTRATION

Reported by A. C. **BENKELMAN**, Associate Research Specialist, and R. J. **LANCASTER**, Assistant Highway Engineer

Soil pressure cells have been used for many years in studying the problem of road subgrade support and pressure distribution. The results obtained in some cases have been such as to cast serious reflection upon the accuracy of the pressure-measuring devices used.

This report describes an exploratory series of tests that concern the performance characteristics of the pneumatic pressure cell, one of the more common types of soil pressure measuring devices. The tests serve to emphasize the fact that if a pressure cell is rigid and the soil in which it is placed is compressible, the accuracy of the pressure indication will depend upon the physical dimensions of the cell as well as upon the relation between the size of the pressure-sensitive area and the size of the total facial area exposed to pressure.

The investigation suggests the possibility of so designing the cell that the error in pressure intensity indication caused by cell thickness can be compensated for by suitably proportioning the active and inactive areas of the cell face.

THE DESIGN of most engineering structures must, of necessity, take into consideration the quality and the nature of the support offered by the soil on which the structure is to rest. Usually, the uniformity of the support is more important than the actual unit-supporting value, although both are of interest. Many and varied have been the theories proposed and the experiments performed in attempting to evaluate soil support; and, in order to provide experimental data, soil pressure measuring devices of numerous types, sizes, and characteristics have been designed and used.

For some time the Public Roads Administration has been studying the problem of pressure measurement in soils in connection with its possible application to the development of rational methods for designing nonrigid road surfaces. As a part of this study it is necessary to investigate the accuracy, consistency, and other characteristics of some of the devices that have been proposed and to determine the importance of some of the design features that affect the accuracy with which soil pressures can be measured.

This report describes certain preliminary or exploratory tests in which the attempt has been made to develop information concerning the factors that affect the performance of one type of pressure-measuring device, the pneumatic cell developed by the Public Roads Administration many years ago.[1]

That little importance has been attached to the external features of design of soil pressure cells is evident from even a casual survey of the literature on the subject. Apparently, the over-all size of such devices has been governed more by the space requirements of the internal pressure measuring element than by other considerations. Moreover, in some cells the pressure-receiving face is separate and distinct from the side walls and base section; in others, it is integral with these parts.

The data presented in table 1 indicate the extent to which the dimensional and structural features of some of the more recent designs for soil pressure cells vary. While the list is not complete, it serves to indicate that in the design of soil pressure cells no great consideration has been given to the possibility that the physical dimensions might seriously affect the accuracy with which they would indicate soil pressure.

EXTERNAL DESIGN FEATURES OF PRESSURE CELLS IMPORTANT

It is only reasonable to expect that the introduction into a soil mass of assumed homogeneity of a foreign object having radically different elastic properties will disturb the distribution of pressure in the vicinity of the object. It is, therefore, rather surprising that so little attention has been paid to this point in the design of pressure-measuring equipment.

Kögler and Scheidig[2] first called attention to the difficulties of measuring soil pressures accurately with a pressure cell. They pointed out that a cell more rigid than the soil would indicate pressures greater than those present in the soil and, conversely, a cell more compressible than the soil would give pressures less than those in the soil. This fact was also recently recognized by Goldbeck.[3] There can be little question as to the correctness of this reasoning and the natural inference is that if a device is to indicate true soil pressure, it must possess in itself the same elastic properties as those of the surrounding soil. In other words it must deform in all directions to the same extent as the soil.

TABLE 1.—*Variations in dimensions of various soil pressure cells*

Type of cell	Thickness	Diameter	Rim width (inches)
	Inches	*Inches*	
Pneumatic [1]	1.25	5.50	1.0.
Vibrating wire [2]	2.67	5.52	About ¼.
Carbon disks [3]	.25	.50	Thin bakelite ring.[4]
Rubber diaphragm [5]	.62	4.00	0.25.
Dynamometer [6]	8.50	8.00	Not indicated.

[1] A. T. Goldbeck, Measurement of Earth Pressure. Proceedings, Highway Research Board, vol. 18, 1938, part II.

[2] I. F. Morrison and W. E. Cornish, Measurement of Earth Pressure. Canadian Journal of Research, vol. 17, sec. A.

[3] M. G. Spangler, Wheel Load Stress Distribution Beneath Flexible Type Pavements. Proceedings Conference on Soil Mechanics and Its Application, Purdue University, July 1940.

[4] Thickness somewhat less than that of measuring element.

[5] F. Kögler and A. Scheidig, Druckverteilung im Baugrunde, Die Bautechnik, No. 29, July 1, 1927.

[6] W. H. Evans, Dynamometer for Measuring Earth Pressures. Engineering, vol. 149, No. 3876, April 1940.

With the possible exception of the rubber diaphragm cell, the cells listed in table 1 are essentially rigid in character. This means that the pressure indicated by them is apt to exceed the true pressure in the soil in which they are installed. The extent to which the indicated pressure might deviate from the true pressure probably would vary as some function of the thickness or of the cross-sectional area of the cell.

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[a] Paper presented at the Twentieth Annual Meeting of the Highway Research Board, December 1940.

[1] An Apparatus for Determining Soil Pressures, by A. T. Goldbeck and E. B. Smith. Proceedings, American Society for Testing Materials, 1916.

[2] Druckverteilung im Baugrunde, F. Kögler and A. Scheidig. Die Bautechnik, No. 31, July 15, 1927.

[3] Studies of Subgrade Pressures under Flexible Road Surfaces. Proceedings, Highway Research Board, vol. 19, 1939.

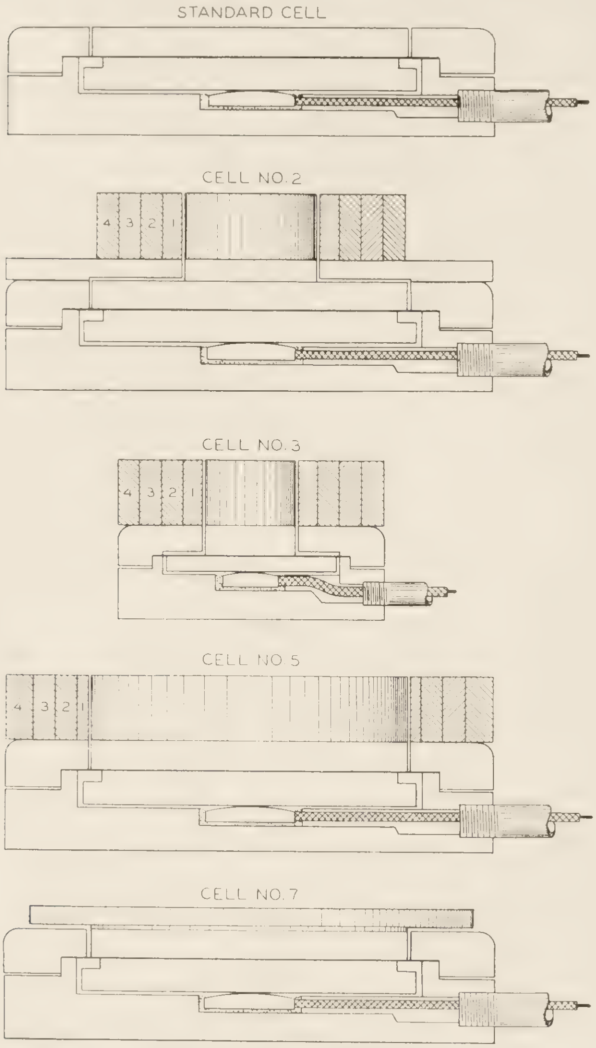

Figure 1.—Pneumatic Soil Pressure Cells and Attachable Sections.

In connection with this aspect of the problem, it is of interest to speculate upon just what sort of forces are imposed upon a rigid-type pressure cell when it is embedded in a compressible soil. It seems probable that they are analogous to those that resist the penetration of a rigid bearing block into the soil. It has been found that the pressure existing over the plane of contact between a bearing block and the supporting soil is not of uniform intensity. In the case of cohesive soils, the intensity is greater near the edges of the area of contact and in the case of granular soils it is greater in the interior portion of the area. This explains the observed fact that the resistance offered to the penetration of a circular bearing block into a cohesive soil varies inversely as the diameter of the area while, for a granular soil, it varies more or less directly as the diameter of the area.

Thus, if it is assumed that the forces imposed upon a pressure cell are essentially the same as those resisting the penetration of a body into the soil, it would be expected that the pressure indicated by cells of different size would vary with the area and would be different for cohesive and granular materials.

In this discussion it has been assumed that the cell is of tangible thickness and that the pressure-receiving face is not encompassed by a rim section. It seems reasonable that the presence of a rim around the pressure-responsive area would disturb the pressure-area relationships because it would tend to alter the distribution of pressure on the central area.

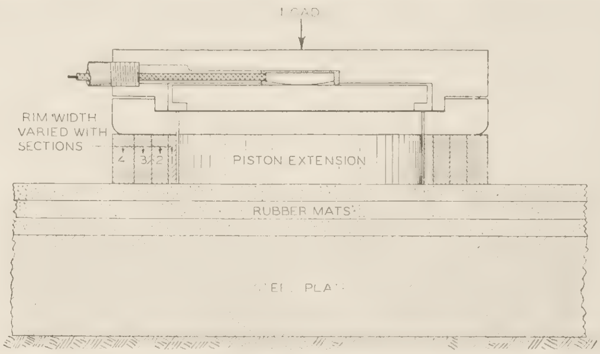

Figure 2.—Test Set-Up For Studying Effect of Width of Rim of Pressure Cell When Supported by Rubber Cushions.

Another point to be considered when cells with a rim around the pressure face are being used is that difficulty may be experienced in seating the cell upon the soil in such a manner that the same intimacy of contact exists over both the rim and the pressure-sensitve face. If uniform bearing on the two sections is not obtained, the indicated pressure might be considerably in error.

5 PNEUMATIC-TYPE PRESSURE CELLS STUDIED

In planning these exploratory tests, consideration was given to the several points mentioned in the above discussion. Pressure cells of the pneumatic type developed by the Public Roads Administration, but modified with the detachable rim and piston sections as shown in figure 1, were used in the study. Detachable pistons, not shown in figure 1, were also used on cell No. 7. In all cases the diameter of the pistons was the same as that of the pressure-sensitive area, referred to in the text and tables that follow. The important dimensional features of these cells are given in table 2.

Table 2.—*Dimensions of pneumatic-type soil pressure cells used in study*

Cell	Pressure-sensitive area		Cumulative width of attachable rim section			
	Diameter	Perimeter-area ratio	1	2	3	4
	Inches	*Inches*	*Inch*	*Inch*	*Inch*	*Inch*
Standard	3. 57	1. 12	-----	-----	-----	-----
No. 3	1. 00	4. 00	0. 25	0. 50	0. 75	1. 00
No. 2	1. 50	2. 67	. 25	. 50	. 75	1. 00
No. 5	3. 57	1. 12	. 16	. 41	. 66	. 97
No. 7	5. 05	. 79	-----	-----	-----	-----

It will be noted that the diameter of the pressure-sensitive areas varied from 1 to 5.05 inches and the perimeter-area ratios from 4.0 to 0.79. The construction made it possible to study the performance of these cells in a number of different ways. For example, they could be placed face down on a soil, or any other plastic material, and loaded; or they could be installed in a container that could be filled subsequently with a soil and loaded in any manner desired. In tests of the first type, the effect of variations in the width of the rim section was studied. In tests of the second type the cells proper were set flush with the base

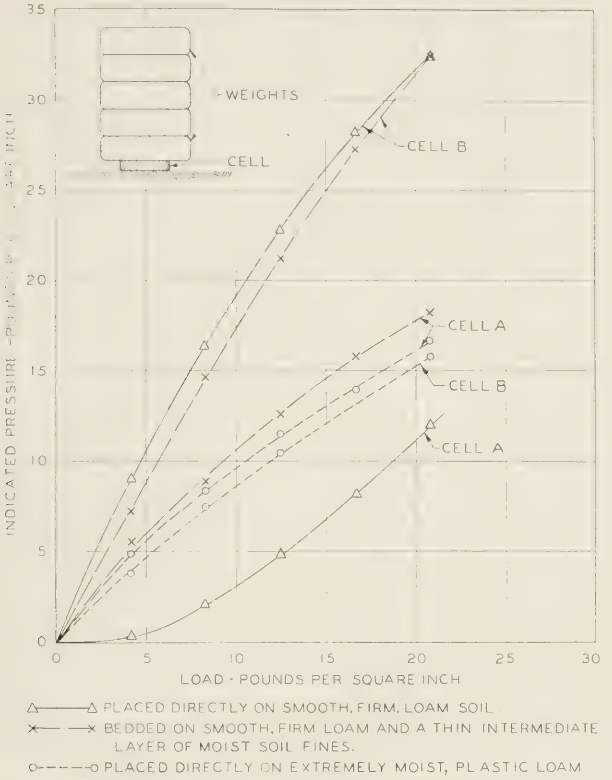

Figure 3.—Results of Pressure Cell Tests on Soil in the Field.

section of a cylindrically shaped soil container and, by means of the attachable parts, studies were made of the effect of thickness and facial area of the cells as well as of the effect of variations in the width of rim. In these latter tests the type and condition of the soil through which load was transmitted to the cells could be varied as desired.

The first series of tests concerned the performance of cells 2, 3, and 5 when placed face down upon rubber cushions and loaded individually as shown in figure 2. Two types of rubber mats were used: Ordinary soft sponge mats, ⅜ inch thick, and firm fabric-reinforced mats about ¼ inch thick. In the test a load was applied to each of the cells in suitable increments and the indicated pressures were noted, first with only the piston extensions bearing on the test materials, and second with the several rim extensions added one at a time.

The difference in performance of the cells when in contact with the two grades of supporting material was striking. In the case of the soft, yielding sponge rubber, the pressure intensity indicated by the cells was always equal to that computed for the load and the contact area in question. This was true regardless of the width of the rim around the pressure-recording piston. In other words, the pressure intensity over the contact plane remained uniform.

When the firm fabric mat material was employed an entirely different condition resulted. With this material difficulty was experienced in obtaining the same intimacy of contact beneath the central piston and the surrounding rim sections before the load was applied to the cells. This meant that in one instance more of the load was transmitted to the test material through the piston section; in another more through the rim section. This difficulty made it impossible to develop definite information regarding pressure distribution between such a material and the pressure cells when their size and rim width was changed. In contrast, the sponge rubber behaved much like a fluid or semifluid medium and slight differences in the relative elevation of the piston and rim section apparently did not affect the pressure intensity indications.

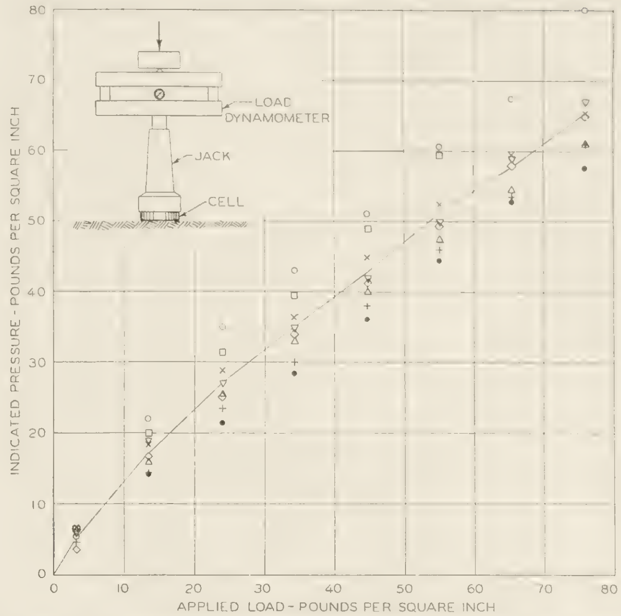

Figure 4.—Results of Pressure Cell Tests on Soil in the Field.

Another factor entering into such tests concerns the manner in which pressures are measured with the pneumatic type of cell. The piston or weighing face is subject to some outward movement when the cell is expanded and a pressure balance is obtained. If the material supporting the rim-piston face is strictly nonyielding in character, this movement, even though infinitely small, would tend to shift all the load to the weighing face. Goldbeck,[1] in a series of special tests made with damp sand soil, found that the error due to this movement was extremely small. However, it is believed that the magnitude of the error would be dependent upon the stiffness or deformation modulus of the material in question.

RIM-TYPE PRESSURE CELLS MUST BE CAREFULLY INSTALLED

Data showing the effect of variations in the seating on various soils of a cell, with its pressure rim face down, are shown in figures 3, 4, 5, and 6. The curves in figure 3 show pressures that were recorded in a test in which two of the standard cells (fig. 1) were placed face down in different ways upon different soils and loaded with dead weights as shown.

When the two cells were placed directly upon a smooth, flat surface of firm loam soil in the field, the relation between applied and indicated pressures varied widely. With an applied unit load of 20 pounds per square inch, the pressure intensity indicated by cell A was about 12 pounds per square inch and by cell B about 33 pounds per square inch. Apparently, in the case of cell A, a greater percentage of the applied load was transmitted through the rim section and less

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[1] An Apparatus for Determining Soil Pressures, by A. T. Goldbeck and E. B. Smith. Proceedings, American Society for Testing Materials, 1916.

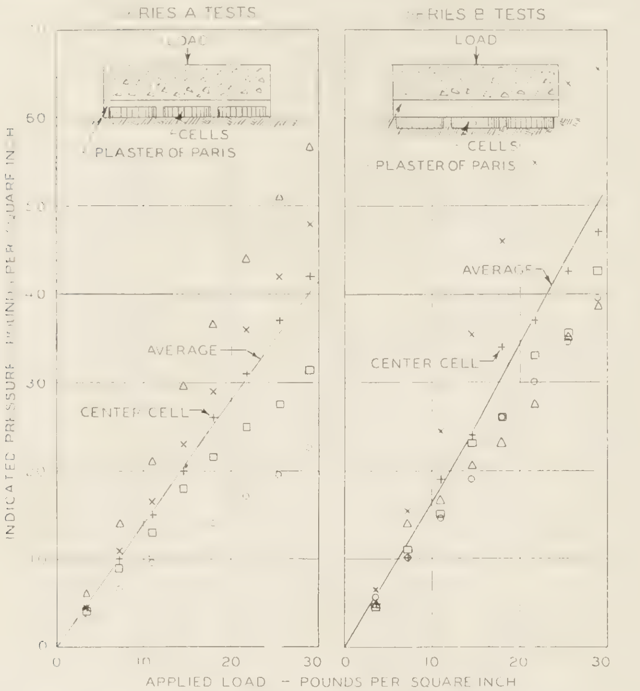

Figure 5.—Performance of Standard Cells When Placed In and Beneath Rigid Bearing Blocks.

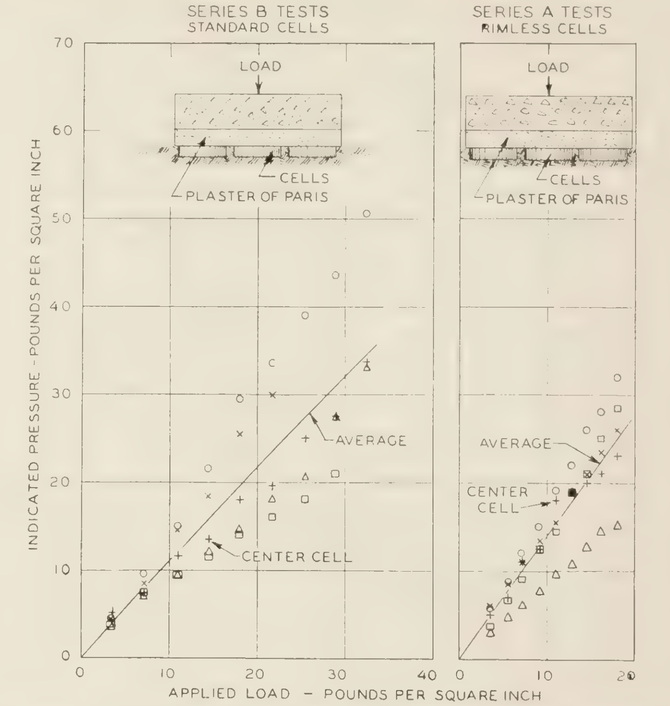

Figure 6.—Results Obtained by Testing Cells Beneath Rigid Bearing Blocks.

through the pressure-sensitive area than in the case of cell B. In an attempt to improve the degree of uniformity of contact between the cells and soil, an intermediate thin layer of the moist soil fines was introduced and this resulted in some improvement, cell A indicating a pressure of 18 pounds per square inch (for a unit load of 20 pounds per square inch), cell B showing no appreciable change.

In another test, the same two cells were placed on an extremely moist, plastic loam soil, and the pressures indicated by the two cells were in close agreement although about 20 percent less than the calculated pressure intensity. In this test, it appears that there was a concentration of pressure near the perimeter or upon the rim section of the cells.

The data shown in figure 4 were obtained in another test designed to show the effect of variations in the seating of pressure cells of the rim type on a soil. Eight of the standard cells were placed reasonably close together on a thin bed of the moist soil fines laid over a uniform soil formation and loaded in the manner indicated. As the data in figure 4 show, the indicated pressures varied considerably between cells.

The data in figures 5 and 6 further emphasize the fact that when a group of pressure cells having rims are placed face down on a soil and loaded equally, there is apt to be considerable dispersion in the pressure values indicated by the various cells in the group. In the test referred to as series A in figure 5 four identical cells were spaced symmetrically around a central cell, then a bearing block 18.75 inches in diameter was cast centrally over the group, i. e., the cells proper became an integral part of the bearing block. Series B tests referred to in the same figure differed from series A in the one important respect that the cells were set into the soil rather than cast in the bearing block. The bearing blocks in each series were loaded in the manner illustrated. The data obtained in these tests likewise show an extremely wide dispersion in the pressure values indicated by the individual cells. The average indicated pressure for a given load is somewhat greater in series B than in the series A tests. This would indicate that the soil around and between the cells did not transmit its proportionate part of the load. This point was given further study in later tests.

The possibility that much of the dispersion in pressure values indicated by different cells when tested in the same manner was caused by lack of uniformity in seating them on the soil was investigated in another group of tests, the results of which are shown in figure 6. In the series A tests referred to in this figure, cells with the rims eliminated (cell 7, fig. 1) were installed beneath the bearing block. It is to be expected that there should be less difficulty in properly seating cells without rims and, in general, the data indicate this to be the case. With the exception of data from one of the outer cells, the values for the various cells are reasonably close together, in contrast to those of series B, in which the standard rim-type cells were again used, and in which the individual pressure values are scattered to about the same degree as in the earlier tests. The fact that the average pressure indicated by the cells in the series A tests is higher than that in series B is probably due to the greater cell thickness. Other tests were made to investigate this matter more fully.

RIGID PRESSURE CELLS MAY DISTURB THE CONTINUITY OF STRESSES

The tests thus far described clearly indicate that considerable trouble may be expected in so seating a pressure cell of the rim type on a soil that the same initial intimacy of contact obtains beneath the rim and pressure-recording area. This appears to be true even though the cell is bedded on a thin intermediate layer of moist soil fines. Thus, where it is necessary to place the cell on a soil such as, for example, a prepared section of road subgrade, rather than place the soil upon the cell as in a fill, the presence of a rim might cause ap-

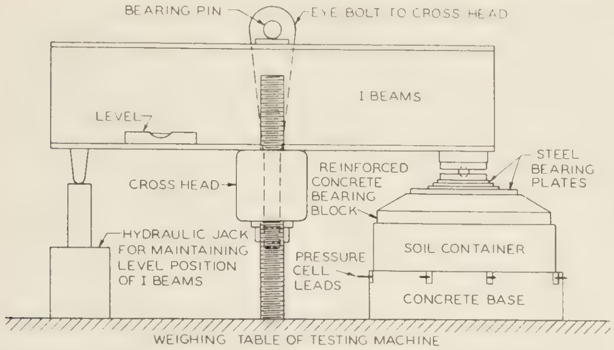

Figure 7.—Plan of Loading Set-Up for Soil Container Tests.

preciable errors in the pressure indications.

Also, the presence of a rim might affect in another way the accuracy with which the cell will indicate pressure because the soil when loaded will tend to flow around the foreign object and, under these circumstances, the pressure intensity on the object would not be uniform from edge to center. If such soil movement tends to form a concentration of pressure around the perimeter of the object, the presence of a rim on the pressure cell should serve to reduce correspondingly the pressure intensity that is indicated by the cell, and this indicated pressure intensity will be less than the average applied over the entire face of the cell. If, on the other hand, there is a concentration of pressure in the central area of the cell face, as might occur with granular material, the pressure intensity indicated by the cell may be higher than the average for the entire cell face.

Earlier in the report mention was made of certain tests in which the pressure cells were installed in a container that was later filled with soil to which load was applied. These tests were designed primarily to develop information concerning the effect on pressure indication of some of the factors just discussed. Figure 7 shows how the equipment was arranged on the table extension of the testing machine that was used to apply known forces on the soil surface.

The soil container consisted of a steel hoop or cylinder 30 inches in diameter and 8 inches high placed on a concrete base which, in turn, was supported on the table of the testing machine. The cells were arranged in the bottom of the container in the pattern shown in figure 8. Loads were applied to the soil with a concrete bearing block that covered the soil surface. Three soils varying in character from a heavy plastic moist clay to a cohesionless dry sand were used in the study. The gradings and soil constants of the materials are listed in table 3. The loam soil was used both in a dry and in a moist condition.

It is recognized that in these tests with the container, the soil through which the pressure was transmitted to the cells was restrained from lateral movement and was thus forced to behave somewhat differently than it would under normal field conditions.

The test procedure was briefly as follows: With the pressure-sensitive area of the cells flush with the surface of the base section, the container was, as a general rule, filled twice in succession with each of the four soils; the load was applied to the bearing block in suitable increments and the indicated pressures were recorded. Then, to cells 2, 3, 5, and 7 the ¾-inch piston extensions were attached and the tests repeated. This was followed by similar tests in which the rim or ring sections were added one at a time to cells 2, 3, and 5.

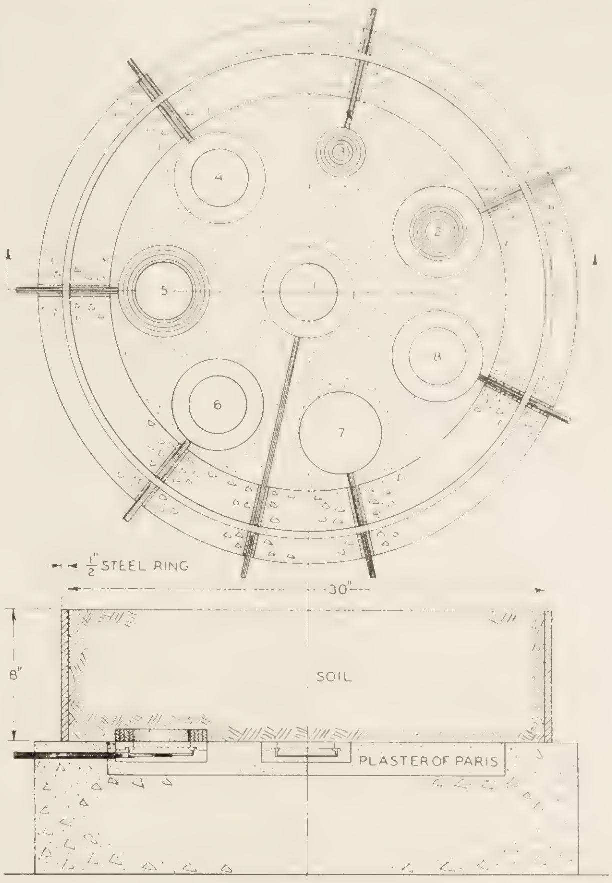

Figure 8.—Lay-out of Cells in the Test Container.

Throughout these tests the pressure-sensitive face of standard cells 1, 4, 6, and 8 remained flush with the base of the container. In the case of cell 7 the ¾-inch-thick piston extension was left in place.

Table 3.—*Gradings and soil constants of materials tested*

MECHANICAL ANALYSIS

Material	Particles larger than 2.0 mm.	Particles smaller than 2 mm. (percent by weight)					
		Coarse sand, 2.0 to 0.25 mm.	Fine sand, 0.25 to 0.05 mm.	Silt, 0.05 to 0.005 mm.	Clay, smaller than 0.005 mm.	Colloids, smaller than 0.001 mm.	Passing No. 40 sieve
Sand	0	75	22	1	2	-------	56
Loam	0	14	34	31	21	8	94
Clay	0	2	3	24	71	49	99

PHYSICAL TEST CONSTANTS OF MATERIAL PASSING NO. 40 SIEVE

Material	Liquid limit	Plasticity index	Shrinkage		Moisture equivalent	
			Limit	Ratio	Centrifuge	Field
Loam	24	6	15	1.9	18	18
Clay	78	51	15	1.9	43	29

The moisture contents of the damp loam and moist clay soil were held practically constant throughout the tests, being about 15 and 30 percent, respectively. With the exception of the moist clay, which was hand

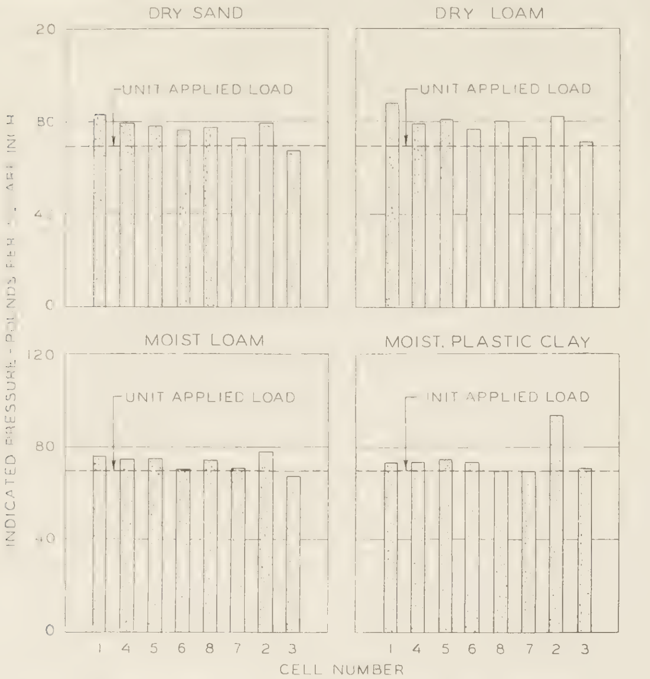

FIGURE 9.—VARIATION IN PRESSURE RECORDED BY THE CELLS WHEN FLUSH WITH THE BASE OF CONTAINER.

tamped in place in order to eliminate large void spaces in the final specimen, the soils were placed in the container without artificial compaction. After test, the compacted specimens of the moist and dry loam soil were broken up by screening through a ¼-inch mesh sieve preparatory to being used over again.

With this method of test the effect of size of the pressure-recording device, both with and without encompassing rim sections, could be studied. In contrast to the tests described earlier in the report, the use of the container permitted the soil to be placed or molded against the pressure-sensitive face of the cells. Thus the possibility of nonuniform intimacy of contact between pressure and rim sections was removed.

When these tests were planned it was thought that the intensity of the pressure transmitted through the soil to the base section, at points radially equidistant from the center of the container, would be uniform or at least would not vary to such an extent that the performance of one cell could not be compared directly with another. However, it was found that when the cells were installed flush with the base, differences of appreciable magnitude existed in the pressures indicated by the various cells. The data obtained in the tests with the cell faces flush with the base are given in figure 9. Although it was noted that the differences were greatest between cells of different size and that they were less when plastic soil was used than they were when granular types of material were employed, still no relations could be developed that would permit the direct comparison of the several individual cells.

It was decided, therefore, to use the data obtained with each cell in these tests as a basis of comparison with data obtained with the same cell in future tests in which the individual cells had been altered in various ways. For example, the cell face could be extended into the soil various distances and the effect of varying amounts of rim area could be studied, always comparing individual cell data with those obtained with the same cell set flush with the surface of the base.

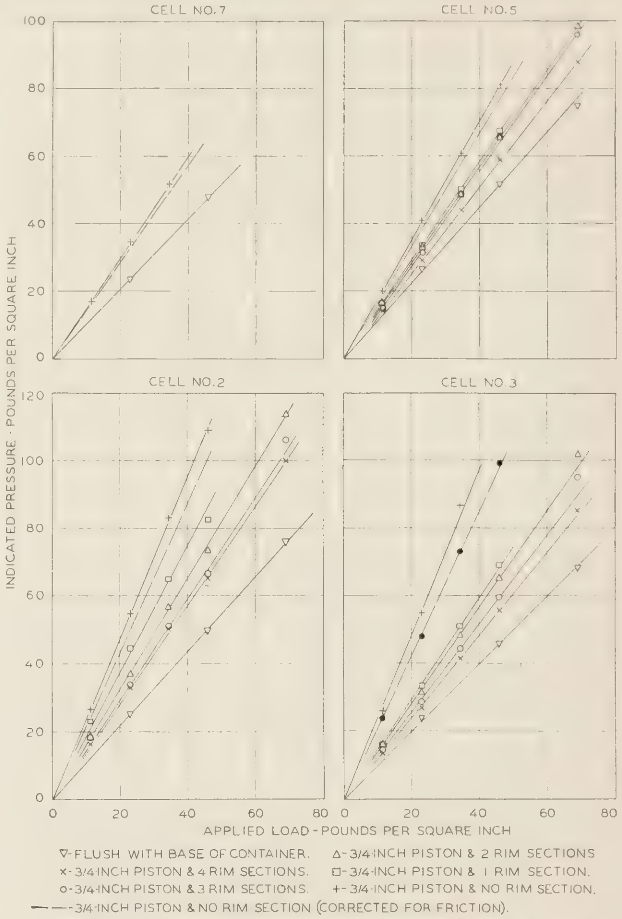

FIGURE 10.—LOAD-PRESSURE RELATIONSHIPS FOR THE MOIST LOAM TEST SOIL.

PERFORMANCE OF RIMLESS PRESSURE CELLS DEPENDS UPON THEIR SIZE AND THICKNESS

In general, the pressures indicated by the cells were found to be directly proportional to the applied load. This is evident in the typical load-pressure relationships shown in figure 10 for the moist loam soil. These data show the pressures indicated by cells 2, 3, 5, and 7 for the following physical conditions: (1) Zero thickness, or with the pressure face flush with the base section; (2) ¾-inch thickness, or with the piston extensions attached; and for the ¾-inch thickness plus (3) one rim section, (4) two rim sections, (5) three rim sections, and (6) four rim sections. Each plotted value represents the average of two tests.

In these and subsequent figures and in the test where the term "cell thickness" is used, this dimension refers to the amount of the extension of the cell piston or the cell rim into the soil in the container and does not refer to the dimension of that part of the cell that is embedded in the plaster of paris.

In connection with figure 10, attention is called to the relationship shown by a broken line for each of the cells. This represents a corrected value in which the element of friction on the lateral surface of the piston extension was eliminated. The correction was arrived at by test data obtained with cell 3, in which duplicate tests were made with and without a very thin metal sleeve surrounding the piston extension. It was considered that this sleeve served to eliminate friction between the lateral surface of the piston and the soil.

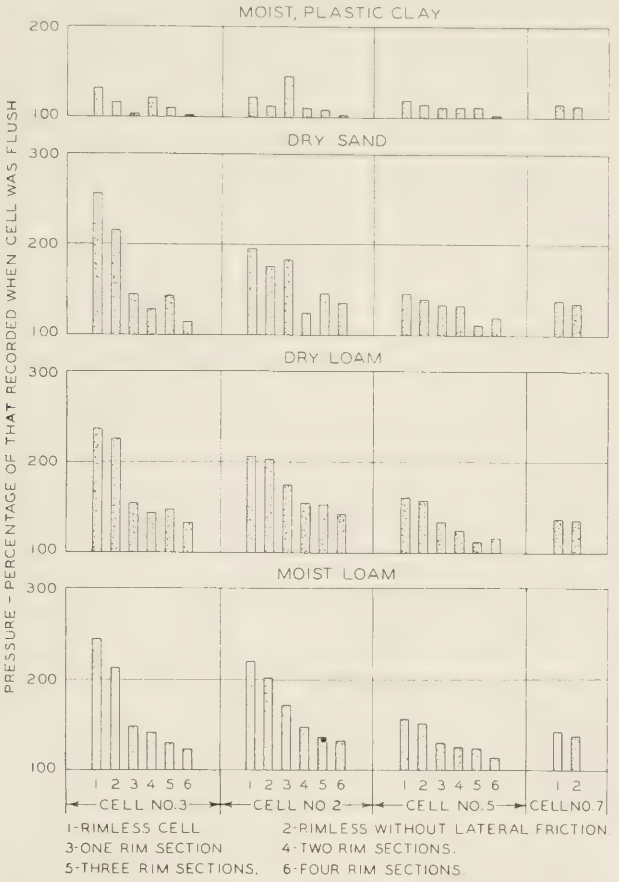

FIGURE 11.—PERFORMANCE OF CELLS WITH AND WITHOUT RIM SECTIONS.

Thus the increase in pressure due to cell thickness alone was determined. Assuming that the intensity of this lateral frictional force would be unaffected by the diameter of the cell, the values of pressure that would have been indicated by the other three cells, had not friction been present, were computed.

From such data for the four test soils, it was possible to express on a percentage basis the pressure intensity indicated by the cells when they extended up into the soil, in terms of that recorded when the pressure area was flush with the base of the container. The relationships are shown in figure 11.

With the exception of the test data obtained with the moist plastic clay soil, the trend of the data is very consistent and strongly indicates: First, that as the size of a rimless-type pressure cell is decreased, the pressure intensity that the cell will indicate, in soils that displace vertically above and around them, may be expected to increase to a marked degree; and second, that the presence of a rigid rim section around the pressure-sensitive area tends to compensate for the effect of cell thickness.

The behavior of the moist plastic clay in these tests was quite different from that of the other three soils. Its moisture content was such that apparently the material behaved nearly as a fluid with essentially the same pressure intensity present throughout the confined mass of soil. It was observed in all of the tests with this soil that some of the material, in contrast to the other soils, actually flowed out through the ⅛-inch clearance space between the bearing block and the walls of the container.

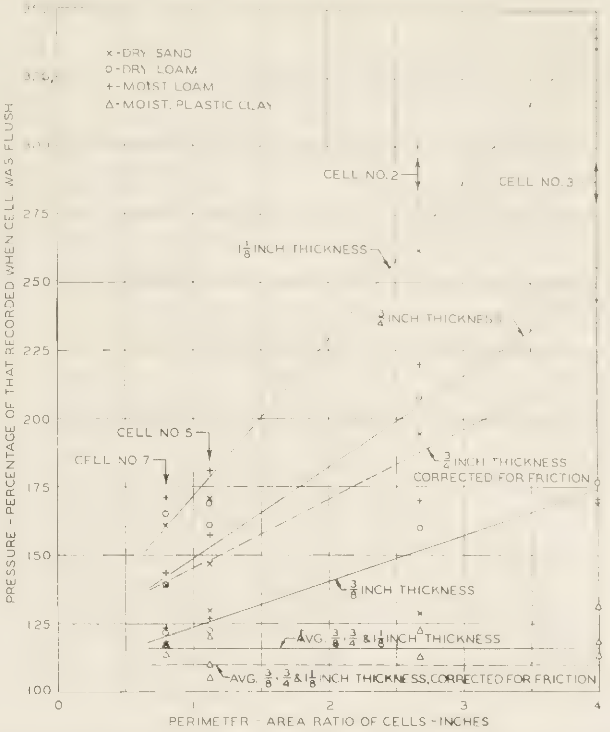

FIGURE 12.—EFFECT OF SIZE AND THICKNESS OF CELLS OF THE RIMLESS TYPE.

Figure 12 shows a portion of the same data plotted so as to indicate the effects of the physical dimension of cells of the rimless type on the manner in which they performed under the described conditions of test. In this graph the pressure intensity, expressed as a percentage of that obtained with the cells set flush, is plotted against the perimeter-area ratio of the recording units, for cell thicknesses or piston extensions of ⅜, ¾, and 1⅛ inches, respectively. It was considered advisable to include more than one thickness of cell unit in order properly to evaluate this factor. The relationships shown are considered indicative rather than absolute. However, the indications are believed to be significant.

RIM SECTIONS ON RIGID PRESSURE CELLS COMPENSATE FOR EFFECT OF CELL THICKNESS

It is evident that for the dry sand, dry loam, and moist loam the physical dimensions of the cells, as measured by the thickness and by the perimeter-area ratio, are quite directly related to the accuracy with which they will indicate pressure intensities. In the case of the plastic clay, on the contrary, the physical dimensions of the cells apparently do not affect the accuracy of the pressure indication as is shown by the horizontal line which averages the test values obtained with the plastic clay. It is to be noted that when this value of 117 percent is corrected for lateral friction, it remains somewhat greater than the pressure (100 percent) indicated by the cells when flush with the base of the container. It may be assumed that for this soil the increased pressure intensity indicated by the cells, with the piston extensions in place, was largely due to lateral friction.

The fact that tests with moist loam, dry loam, and dry sand soil gave similar values was not entirely unexpected. In these tests the body of soil as a whole

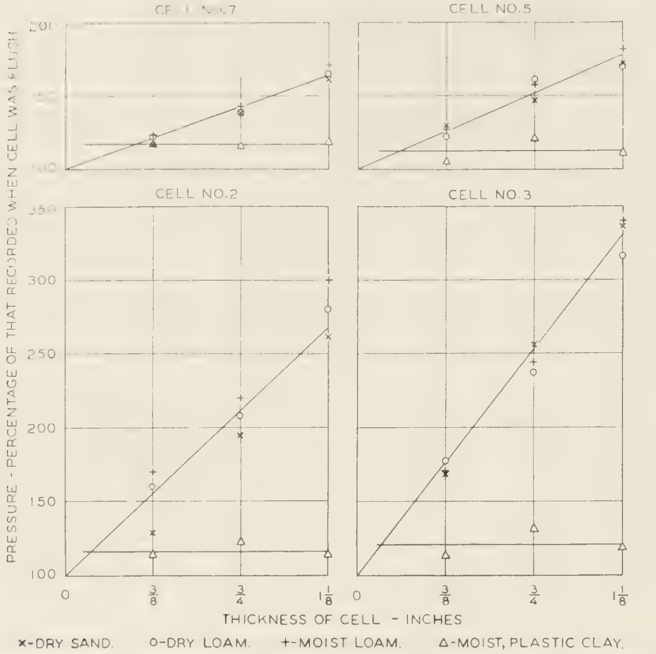

Figure 13.—Effect of Thickness of Cells of the Rimless Type.

could move or displace only in the vertical direction. Had the tests been made in a way such that the material could behave in a natural manner, i. e., displace laterally, the cells in dry sand might have behaved somewhat differently than in the loam soil. It is known that the resistance offered by granular soils to the displacement of loaded bodies varies more or less directly with the size of the loaded area, the displacement under the same unit load decreasing as the size of the area is increased. From this, one would expect that, under normal conditions, the pressure recorded by cells in granular soils would increase as the pressure-sensitive area of the cell was increased, which is contrary to the relation found by the tests made in the rigid container.

Some further evidence indicating that the restraining effect of the container was responsible was obtained from a limited series of tests made in a container whose side walls were not strictly rigid. With this type of container when dry sand was used, the pressure indicated by cells of ¾-inch thickness decreased as their areas were decreased. In fact, for the smallest cell, 1 inch in diameter, the pressure recorded was less when the cell thickness was ¾ inch than when the pressure-sensitive area was flush with the base of the container.

In spite of the fact that the tests were made in a container that restrained the soil body from lateral movement, it is believed that the data shown in figure 12 clearly indicate that, unless a soil is so plastic that it behaves essentially as a fluid, the accuracy of cells of the general design studied may be affected to an important degree by both the thickness and the diameter.

It was remarked earlier in the report that the pressure intensities that rigid cells might indicate when embedded in and surrounded by soil might possibly vary in a manner similar to that which obtains under rigid bearing areas of different sizes. The data obtained in these experiments, as well as data obtained by Housel [4] and other investigators, indicate that this relationship exists.

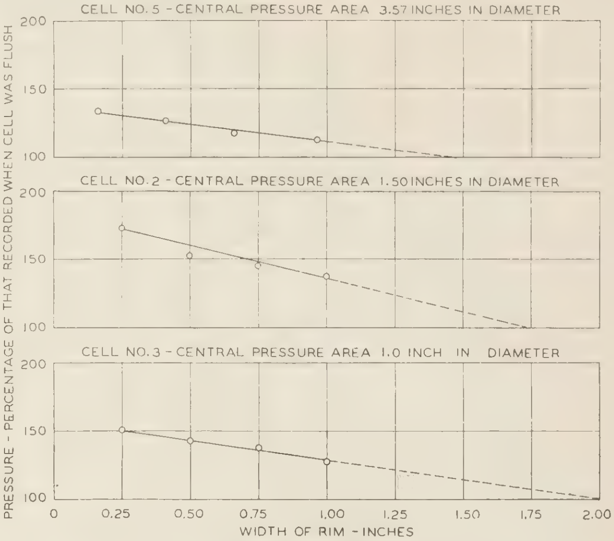

Figure 14.—Effect of Width of Rim for Cells of Different Size.

Referring again to the data given in figure 12, it is of interest to note that the slope of the pressure intensity-perimeter area ratio curves increases as the thickness of the cell unit increases. In other words, as the cell thickness is increased, the differential in soil movement is greater and the effect of diameter (as measured by the perimeter-area ratio) becomes more pronounced.

In his tests with rigid bearing areas, Housel [4] found that as the displacement of the bearing plate was increased, the slope of the pressure intensity-perimeter area ratio curves increased. It is believed that the same soil reaction is responsible in both experiments.

In figure 13, cell thickness is plotted as a direct function of the pressure indicated by each of the four cells for each of the soils tested. It is evident that, unless the soil is so plastic as to behave as a fluid. the indicated pressure intensity varies directly with the thickness of the cell. This effect of cell thickness is a very important one since for practical reasons the cell must have thickness and only in special cases can it be installed so that this thickness does not exert an influence.

The result of increasing the effective rim width of the three cells of variable size, but of a constant ¾-inch thickness, is shown in figure 11. These data show that as the width of rim was increased the pressure intensity indicated by the cell approached that indicated by the same cell when set flush with the base; in other words, that which would be shown by a cell of negligible thickness. This suggests the possibility of determining the width of rim necessary to compensate for the errors in pressure indication that are caused by the cell thickness of ¾ inch.

In figure 14 the data for each of the three diameters of cell (1.0, 1.5 and 3.57 inches, respectively) are arranged for this purpose by averaging the values plotted in figure 11 for the dry sand, dry loam, and moist loam soils for the ¾-inch thickness corrected for side friction. Figure 14 indicates: First, that it is possible to adjust the rim width to compensate for cell thickness in cells of this type; second, that the rim width required for such compensation increases as the over-all cell diam-

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[4] A Practical Method for the Selection of Foundations Based on Fundamental Research in Soil Mechanics. Department of Engineering Research, University of Michigan, bul. 13, 1929.

eter is decreased; and third, that for cells of this thickness the rim width required is appreciable.

SUMMARY

In appraising the significance and utility of the knowledge obtained in this study, it should be remembered that the tests having to do with the influence of the dimensional features on cell performance were made with soil that as a body was not free to move laterally and that was of rather limited depth. How the cells might have performed in the same soils had there been no planes or barriers of discontinuity was not indicated by these tests, but it is probable that some differences would have been found.

The question is intimately related with the state of initial density of the material. Increasing the density of a soil by artificial compaction will reduce its movement under load, although some movement is to be anticipated in even the densest soil materials. To indicate the true pressure developed in a soil by an external force, a pressure-measuring device, particularly a cell of the rimless type, must either possess the same load-displacement characteristics as the soil itself or it must have no tangible thickness. In this connection it appears reasonable to assume that a slight amount of differential movement around a pressure cell in a compacted soil would impose as much additional pressure on the cell as would a relatively large movement in an uncompacted soil.

It seems impracticable to attempt to design pressure-indicating cells that will display the same load-displacement characteristics as the soil because these are neither constant nor known. The design of a cell that has no tangible thickness likewise presents practical difficulties. It appears that the problem of measuring pressures can best be approached by systematic study of the design features of cells that satisfy practical requirements as to dimensions and materials to the end that these may be used with a full knowledge of their accuracy and other characteristics. It is believed that this exploratory study of the performance of cells of a single type, limited as it is, has served a useful purpose and has produced significant results.

It has been shown that when cells equipped with a rigid rim are placed on a soil, even with the greatest care, it is difficult to obtain the same initial intimacy of contact between the soil and the active and inactive areas of the soil face. As a result there is apt to be a rather wide variation in the pressure intensities indicated by identical cells installed in the same way on the same soil medium.

The tests indicate further that when cells of this type are used, the actual magnitude of the pressure intensity that the cell may indicate depends upon the amount of plasticity possessed by the soil. Where the soil used is so plastic as to act like a fluid under pressure, the cells give an accurate indication of pressure intensity.

The accuracy of the indication of pressure intensity given by cells of this type is apparently affected to an important degree by the physical dimensions and by the external design features such, for example, as the relation between the size of the pressure-sensitive area and that of the total facial area exposed to pressure.

It appears possible to design the cell so that, for given test conditions, the error in pressure intensity indication caused by the cell thickness can be compensated for by suitably proportioning the active and inactive areas of the cell face.

As stated at the beginning, this report describes the results of certain exploratory tests. The data obtained are not offered as conclusive. They do, however, point to the importance of a knowledge of the performance of pressure-measuring equipment if dependable data are to be obtained.

(Continued from page 234)

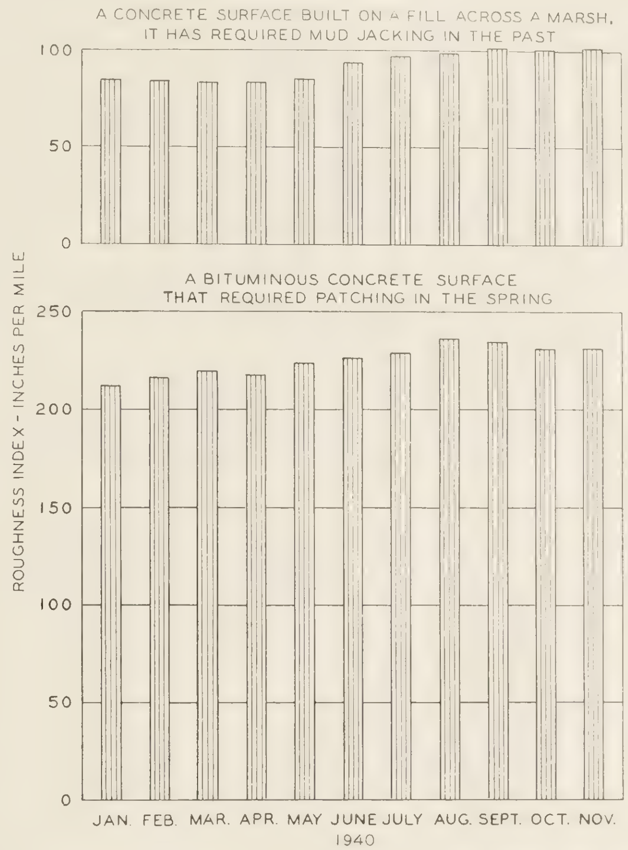

FIGURE 18.—PROGRESSIVE CHANGE IN ROUGHNESS OF TWO ROAD SURFACES WITH TIME.

SUMMARY

The equipment that 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 roughness of the various pavements in a highway system. For example, figure 18 shows how the surfaces of two pavements compared month by month over a period of 11 months. 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 roughness available, the interest of construction and maintenance crews can be aroused and a desirable competitive spirit stimulated.

REPORT OUTLINING NATION'S HIGHWAY NEEDS STILL AVAILABLE

Copies of the report "Toll Roads and Free Roads" are available from the Public Roads Administration of the Federal Works Agency. This publication is divided into two parts as follows:

1. It reports the findings of an investigation of a proposal to build six toll highways, three spanning the country from east to west, and three from north to south.
2. It presents a master plan for future highway development, based on factual information obtained in highway planning surveys.

Initial distribution of "Toll Roads and Free Roads" has already been made. However, an ample supply of this particular publication is still available for free distribution to highway engineers, libraries, colleges, and others. Requests for "Toll Roads and Free Roads" should be addressed to the Public Roads Administration, Washington, D. C.

SIMILAR EQUATIONS DERIVED BY INDEPENDENT WORKERS

In the article "Soil Displacement Under a Loaded Circular Area," by L. A. Palmer and E. S. Barber appearing in the December 1940 issue of PUBLIC ROADS, reference to an earlier article by the late Dr. John H. Griffith of Iowa State College was unfortunately not made. The authors derived their equation 5 without knowledge that Dr. Griffith had presented essentially the same expression as his equation 3 on page 32 of Bulletin 101, volume 30, No. 1, Iowa Engineering Experiment Station, Iowa State College, under the title "Physical Properties of Earths." Equation 5 in the report by Palmer and Barber is

$$V=\frac{p}{C}\left[(2-2\mu^2)\ (a^2+z^2)^{1/2}-\frac{(1+\mu)z^2}{(a^2+z^2)^{1/2}}+(\mu+2\mu^2-1)z\right]\text{-----}(5)$$

where V is the vertical displacement of an earth particle at any depth, z, on the axis of symmetry under a uniformly loaded circular area at the ground surface; μ is Poisson's ratio; a is the radius of the loaded circular area; p the unit load; and C is the modulus of deformation obtainable from plotted stabilometer test data.

In Dr. Griffith's equation 3, a modulus of elasticity, E, was used in place of the C in the above equation. Dr. Griffith did not indicate values for μ or E nor did he mention any possible laboratory means of determining these values. Aside from this difference, his expression is the same as the above equation 5.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF JANUARY 31, 1941

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			*BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 2,858,664	$ 1,421,234	95.1	$ 5,233,779	$ 2,603,570	189.8	$ 977,800	$ 486,350	32.9	$ 3,818,639
Arizona	1,054,331	739,348	47.7	1,968,869	1,313,364	83.1	428,157	266,227	9.7	1,759,129
Arkansas	4,865,206	2,231,305	124.5	1,276,678	636,963	50.9	296,709	147,722	8.0	1,738,999
California	5,812,677	2,948,188	110.0	8,206,550	4,363,159	127.1	1,835,549	942,990	35.5	4,528,248
Colorado	2,172,320	1,183,569	188.7	2,001,971	1,147,250	81.0	798,749	450,175	89.6	3,386,286
Connecticut	1,936,006	938,685	16.2	1,187,936	580,855	11.3	699,855	338,145	7.5	1,313,013
Delaware	1,085,086	541,827	24.0	1,107,587	527,071	8.5				1,530,883
Florida	2,512,745	1,248,025	62.5	1,830,844	923,710	59.4	618,194	309,097	25.6	3,687,669
Georgia	3,033,370	1,508,949	184.7	7,077,312	3,539,156	277.3	1,730,704	865,352	79.9	6,926,356
Idaho	1,529,343	916,941	151.0	1,040,215	640,970	56.9	505,148	311,354	12.5	2,296,138
Illinois	6,435,116	3,184,386	146.0	6,775,176	3,387,423	132.3	2,746,200	1,373,100	90.0	5,364,167
Indiana	5,063,556	2,493,378	117.6	6,438,874	3,113,291	90.0	2,072,267	962,200	42.3	2,689,881
Iowa	5,486,851	2,563,365	188.6	3,861,243	1,731,009	119.4	1,153,219	470,421	66.9	2,546,581
Kansas	3,651,486	1,801,155	301.2	5,761,217	2,899,371	346.6	2,811,870	1,393,916	167.8	5,237,218
Kentucky	2,756,915	1,373,701	85.2	3,012,306	1,511,833	81.1	931,557	465,779	37.3	4,329,017
Louisiana	1,183,855	586,339	16.0	12,581,978	3,339,976	63.2	969,534	477,079	34.9	4,251,218
Maine	1,319,269	641,968	29.1	734,950	381,115	20.5	841,245	420,622	1.1	1,067,035
Maryland	1,019,901	505,992	24.2	3,121,923	1,556,361	27.2	494,303	247,151	5.9	2,032,567
Massachusetts	1,669,600	831,974	19.9	2,360,660	1,179,910	16.1	61,470	30,705	.4	4,307,283
Michigan	6,132,119	2,904,437	215.1	8,131,410	4,053,105	197.0	775,610	387,805	24.3	3,051,351
Minnesota	5,941,448	2,902,882	448.1	4,305,316	2,149,276	244.1	1,642,752	820,446	69.9	5,138,495
Mississippi	1,916,346	777,748	94.7	7,202,034	3,358,161	353.3	1,160,300	557,350	85.1	2,785,895
Missouri	3,412,475	1,690,301	169.0	7,823,951	3,649,255	194.0	4,325,104	1,967,383	124.7	5,293,489
Montana	4,086,764	2,313,548	283.3	2,202,220	1,242,712	116.7	692,624	390,848	40.7	4,944,690
Nebraska	4,643,695	2,217,388	548.3	3,838,524	1,946,325	445.3	1,861,780	930,889	197.5	3,764,135
Nevada	1,545,941	1,322,120	79.6	1,038,047	903,974	43.9	381,593	293,814	23.8	1,750,673
New Hampshire	1,445,362	707,199	36.4	419,795	209,610	9.0				1,401,951
New Jersey	1,525,860	751,438	9.4	5,681,620	2,840,810	39.3	1,882,890	941,365	15.2	1,754,615
New Mexico	2,043,679	1,243,663	172.8	1,521,249	928,805	67.0	373,787	225,318	10.9	2,336,740
New York	11,443,080	5,610,806	198.8	11,258,818	5,601,260	137.8	692,127	275,809	12.0	4,993,656
North Carolina	4,326,497	2,161,479	232.2	4,492,562	2,231,595	184.2	1,166,250	582,630	58.9	3,193,427
North Dakota	1,951,966	1,049,687	191.2	2,532,510	1,426,041	197.4	2,549,484	1,295,325	217.0	4,645,532
Ohio	4,729,002	2,363,683	61.6	11,961,842	5,956,727	100.8	8,024,590	3,933,132	69.3	4,778,415
Oklahoma	2,403,776	1,274,725	112.6	2,825,034	1,454,589	82.2	1,833,026	954,127	77.2	5,694,541
Oregon	3,099,420	1,852,951	152.6	2,409,715	1,289,526	44.5	875,385	460,203	36.8	2,068,943
Pennsylvania	5,703,638	2,821,970	76.0	13,417,474	6,655,924	109.7	2,377,674	1,145,858	19.1	4,672,511
Rhode Island	1,028,203	511,131	10.2	1,195,010	596,687	10.9	4,760	2,380		1,256,946
South Carolina	1,730,969	835,385	120.6	1,940,197	919,075	133.8	1,979,190	864,790	61.3	2,799,238
South Dakota	3,145,039	1,766,352	530.9	3,897,733	2,458,183	462.9	883,560	509,000	153.7	3,506,320
Tennessee	2,438,142	1,210,196	57.1	3,059,792	1,529,896	108.4	2,349,672	1,174,836	57.5	4,785,322
Texas	7,312,763	3,586,840	463.9	9,387,080	4,638,106	442.5	4,878,879	2,401,940	155.5	9,118,009
Utah	985,953	714,222	73.1	913,421	683,969	39.7	543,279	293,840	13.4	1,672,175
Vermont	1,187,876	589,160	36.6	758,933	379,569	20.1	450,599	225,285	12.9	576,523
Virginia	2,306,123	1,068,350	64.8	3,746,689	1,777,135	70.3	798,797	396,585	10.4	2,717,689
Washington	3,110,393	1,603,560	78.2	3,134,689	1,665,335	33.8	229,841	122,100	2.5	1,832,528
West Virginia	1,989,390	991,108	74.2	3,035,284	1,511,440	63.2	1,374,486	684,810	20.2	1,930,086
Wisconsin	5,220,652	2,552,603	179.1	2,015,484	997,835	88.9	937,327	464,953	23.0	5,384,677
Wyoming	1,793,781	1,100,281	196.2	980,178	619,650	120.0	605,717	387,171	41.7	1,593,691
District of Columbia	533,627	266,813	5.0	602,937	269,909	.8	134,400	67,200	.9	614,339
Hawaii	110,831	51,536	1.7	713,726	377,860	10.2	138,944	69,472	2.5	1,953,237
Puerto Rico	519,644	257,240	10.9	1,370,673	677,010	20.3	179,616	88,630	2.0	1,047,259
TOTALS	155,210,751	78,731,131	6,916.4	203,394,015	100,375,711	6,033.7	56,076,573	32,873,679	2,387.7	165,867.425

* INCLUDES APPORTIONMENT FOR THE FISCAL YEAR 1942

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF JANUARY 31, 1941

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			* BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 190,944	$ 95,263	9.4	$ 1,308,357	$ 654,158	60.7				$ 640,736
Arizona	144,270	83,190	17.3	217,025	156,676	7.0				475,609
Arkansas	416,160	179,101	14.8	306,339	152,958	20.6	$ 148,414	$ 73,800	12.2	311,721
California	831,102	451,771	37.3	726,179	493,962	10.2	586,137	287,457	11.6	895,657
Colorado	45,873	25,854	1.6	252,726	141,919	5.3	35,799	20,176	2.9	411,324
Connecticut	370,531	179,413	4.6	105,456	49,907	1.8	194,675	87,585	4.3	186,667
Delaware	128,160	56,367	12.7	46,219	22,675	2.8				350,778
Florida	12,030	6,015		604,373	302,186	14.7	550,715	241,531	5.8	329,157
Georgia	147,586	73,258	18.6	823,559	396,780	64.7	297,409	148,705	32.6	1,381,851
Idaho	153,024	94,195	24.0	166,859	99,425	6.7	72,833	4,293	3.5	324,457
Illinois	1,695,358	827,554	80.6	939,350	454,675	28.2	541,100	245,750	39.0	697,818
Indiana	476,372	229,757	31.0	163,864	87,389	8.1	219,571	109,785	10.0	1,230,526
Iowa	2,272,828	1,077,776	487.0	638,984	303,790	176.9	262,187	113,000	77.9	492,184
Kansas	320,172	159,770	49.0	913,408	459,612	46.8	175,115	87,558	51.8	1,574,625
Kentucky	792,145	268,935	65.5	569,227	138,095	18.2	373,349	106,751	21.6	552,479
Louisiana	98,857	49,429	10.9	199,072	99,481	14.9				717,587
Maine	298,852	142,635	17.0	40,606	20,303	1.5				157,657
Maryland	128,300	64,150	5.5	98,390	49,195	4.5	36,000	18,000	4.3	531,665
Massachusetts	456,347	225,862	10.3	220,045	113,703	3.6				702,518
Michigan	1,443,931	712,804	112.3	597,780	298,890	35.9	537,720	268,860	39.5	720,827
Minnesota	734,528	358,911	103.9	667,878	333,939	102.2	449,535	224,768	45.4	1,156,016
Mississippi	272,962	136,481	12.5	660,552	326,126	37.0	325,700	140,365	14.4	743,870
Missouri	732,486	363,341	96.5	112,644	56,322	10.4	286,710	120,187	27.0	1,142,650
Montana	641,506	362,577	80.3	90,699	51,181	3.7	263,163	145,257	55.2	852,529
Nebraska	493,800	240,550	88.0	648,882	324,218	79.1	62,260	31,130	17.3	545,812
Nevada	196,240	166,314	40.9	175,048	152,379	14.3				238,859
New Hampshire	143,639	68,883	3.4	71,533	34,946	3.6				219,539
New Jersey	319,476	159,633	10.6	322,057	162,940	11.4	75,810	37,905	.2	685,061
New Mexico	94,763	59,142	13.1	634,137	343,277	28.8	92,695	49,568	3.7	326,218
New York	2,027,620	970,482	67.9	1,347,060	673,530	40.0	205,000	62,297	.6	851,636
North Carolina	946,392	471,070	82.2	378,303	191,763	40.1	56,100	24,500	3.1	609,631
North Dakota	42,880	24,583	.3	169,224	90,702	3.6				1,278,769
Ohio	1,656,279	827,346	56.0	1,807,235	902,358	57.5	220,375	110,187	11.3	1,266,827
Oklahoma	667,352	353,621	47.8	216,680	114,450	12.4	231,100	121,589	11.7	1,209,791
Oregon	372,237	205,770	56.4	190,645	84,674	13.4	250,561	126,040	22.9	413,125
Pennsylvania	1,569,327	777,140	55.9	924,097	461,140	17.6	321,936	146,468	6.7	775,751
Rhode Island	245,259	122,207	3.6	90,306	47,016	.9				126,404
South Carolina	569,763	209,926	79.0	350,840	116,990	16.9	361,867	158,700	45.6	307,042
South Dakota				28,926	19,392	9.0				1,543,134
Tennessee	151,200	72,135	8.7	287,466	143,733	10.0				1,235,745
Texas	1,187,474	579,866	176.4	1,264,264	627,228	103.5	187,956	91,650	25.6	1,646,880
Utah	88,404	49,100	9.5	185,785	123,660	22.1	55,085	27,543	2.5	294,647
Vermont	338,432	108,810	13.1	193,984	56,235	7.6				97,105
Virginia	387,164	181,027	24.8	556,520	259,546	19.7				508,533
Washington	469,256	245,605	28.2	286,980	153,439	12.2	128,257	68,700	16.2	403,637
West Virginia	310,127	154,327	16.7	118,300	59,150	4.2	43,400	21,700	2.1	600,264
Wisconsin	331,132	164,511	7.4	658,495	330,305	23.2	497,948	184,628	20.2	863,672
Wyoming	429,615	253,344	42.8	153,530	95,100	9.1				289,633
District of Columbia	120,324	60,162	1.4	2,192	1,096					111,865
Hawaii	275,662	137,588	8.6	2,192	2,192					244,452
Puerto Rico	88,612	43,260	4.3	213,612	104,380	9.7	55,188	27,140	2.1	167,407
TOTALS	26,326,753	12,930,811	2,249.6	21,747,884	10,939,186	1,256.3	8,201,670	3,733,573	650.8	33,441,747

* Includes apportionment for the fiscal year 1942

U. S. GOVERNMENT PRINTING OFFICE 1941

PUBLICATIONS of the PUBLIC ROADS ADMINISTRATION

Any of the following publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C. As his office is not connected with the Agency and as the Agency does not sell publications, please send no remittance to the Federal Works Agency.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1931. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1933. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1934. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1935. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1936. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1937. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1938. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1939. 10 cents.

HOUSE DOCUMENT NO. 462

Part 1 . . . Nonuniformity of State Motor-Vehicle Traffic Laws. 15 cents.

Part 2 . . . Skilled Investigation at the Scene of the Accident Needed to Develop Causes. 10 cents.

Part 3 . . . Inadequacy of State Motor-Vehicle Accident Reporting. 10 cents.

Part 4 . . . Official Inspection of Vehicles. 10 cents.

Part 5 . . . Case Histories of Fatal Highway Accidents. 10 cents.

Part 6 . . . The Accident-Prone Driver. 10 cents.

MISCELLANEOUS PUBLICATIONS

No. 76MP . . The Results of Physical Tests of Road-Building Rock. 25 cents.

No. 191MP . . Roadside Improvement. 10 cents.

No. 272MP . . Construction of Private Driveways. 10 cents.

No. 279MP . . Bibliography on Highway Lighting. 5 cents.

Highway Accidents. 10 cents.

The Taxation of Motor Vehicles in 1932. 35 cents.

Guides to Traffic Safety. 10 cents.

An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.

Highway Bond Calculations. 10 cents.

Transition Curves for Highways. 60 cents.

Highways of History. 25 cents.

DEPARTMENT BULLETINS

No. 1279D . . Rural Highway Mileage, Income, and Expenditures, 1921 and 1922. 15 cents.

No. 1486D . . Highway Bridge Location. 15 cents.

TECHNICAL BULLETINS

No. 55T . . . Highway Bridge Surveys. 20 cents.

No. 265T . . . Electrical Equipment on Movable Bridges. 35 cents.

Single copies of the following publications may be obtained from the Public Roads Administration upon request. They cannot be purchased from the Superintendent of Documents.

MISCELLANEOUS PUBLICATIONS

No. 296MP. . Bibliography on Highway Safety.

House Document No. 272 . . . Toll Roads and Free Roads.

Indexes to PUBLIC ROADS, volumes 6–8 and 10–20, inclusive.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y . . Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).

Report of a Survey of Transportation on the State Highways of Vermont (1927).

Report of a Survey of Transportation on the State Highways of New Hampshire (1927).

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).

Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).

Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

UNIFORM VEHICLE CODE

Act I.—Uniform Motor Vehicle Administration, Registration, Certificate of Title, and Antitheft Act.

Act II.—Uniform Motor Vehicle Operators' and Chauffeurs' License Act.

Act III.—Uniform Motor Vehicle Civil Liability Act.

Act IV.—Uniform Motor Vehicle Safety Responsibility Act.

Act V.—Uniform Act Regulating Traffic on Highways.

Model Traffic Ordinances.

A complete list of the publications of the Public Roads Administration, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to Public Roads Administration, Willard Bldg., Washington, D. C.

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF JANUARY 31, 1941

STATE	COMPLETED DURING CURRENT FISCAL YEAR					UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					* BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	NUMBER: Grade Crossings Eliminated by Separation or Relocation	NUMBER: Grade Crossing Structures Reconstructed	NUMBER: Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	NUMBER: Grade Crossings Eliminated by Separation or Relocation	NUMBER: Grade Crossing Structures Reconstructed	NUMBER: Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	NUMBER: Grade Crossings Eliminated by Separation or Relocation	NUMBER: Grade Crossing Structures Reconstructed	NUMBER: Grade Crossings Protected by Signals or Otherwise	
Alabama	$ 28,328	$ 28,328			4	$ 750,688	$ 730,611	7	1		$ 189,293	$ 189,293	2		8	$ 1,129,534
Arizona	198,347	190,981	3		2	179,037	178,688	1			13,255	13,255			2	362,838
Arkansas	651,975	651,441	6	1	8	681,768	677,936	7			341,631	341,466	3		9	473,309
California	445,134	445,134	4		8	1,028,139	847,540	7	1		754,038	754,038	2		13	1,403,058
Colorado						288,868	288,868	1			349,978	349,978	2		3	823,777
Connecticut	622,002	611,366	5	1		166,222	165,415	2								614,980
Delaware	68,080	68,080			13	132,406	132,406	5		3	2,332	2,332			1	560,165
Florida	207,524	203,025	2		2	102,816	102,291	1	1		142,649	142,649			26	1,508,766
Georgia	182,417	182,322	4	1	13	1,083,508	1,083,508	10	6		249,272	249,272	1	2	5	2,169,769
Idaho	259,459	256,029	5		23	27,239	27,239			4	30,422	30,422			10	569,399
Illinois	1,700,569	1,630,832	9	1	42	1,343,252	1,114,152	4	1	90	185,043	176,949	1		31	2,896,334
Indiana	675,332	673,532	3	2	79	611,442	611,442	5		14	451,341	418,441	3	1	8	1,032,980
Iowa	476,834	449,274	4		81	164,783	136,372	2		13	292,461	291,381	3	1	10	1,462,325
Kansas	691,995	691,888	9		15	453,190	452,712	4	1	5	383,372	383,372	10	1	8	1,226,875
Kentucky	574,050	572,380	8		11	638,550	638,550	7		1	377,956	339,556	2		3	605,766
Louisiana	95,496	95,496	1			345,122	291,627	2			632,768	575,037	11		2	1,131,893
Maine	159,759	158,841	1	1	6	132,646	132,646	1	1							398,661
Maryland	180,997	180,993	1		2	485,009	453,216	2	2	7	7,200	7,200			1	973,714
Massachusetts	16,588	16,588		1		342,715	332,292	1			90,040	89,740	1			2,319,006
Michigan	1,157,264	1,122,764	8	1	35	1,431,235	1,431,235	2	5	2	157,807	157,807	2		6	1,125,379
Minnesota	1,131,064	1,122,664	8	2	13	983,368	983,368	9	4	6	149,645	149,645		2	2	1,510,210
Mississippi	260,760	260,760	3	1		598,234	598,234	8		1	86,900	86,900	1		3	803,304
Missouri	1,208,389	1,208,389	6	5	1	1,709,501	1,254,081	5	1		215,040	161,640		2		1,461,573
Montana	427,675	427,675	5		2	88,047	88,046	1			9,155	9,155			3	609,220
Nebraska	424,946	423,276	3	1	10	813,918	813,918	13	1		130,928	130,928	1		13	512,622
Nevada	71,422	71,422	1		19	69,039	69,039	1			72,643	72,643	1		6	156,383
New Hampshire	100,989	100,953	3			149,458	148,638	3		1						429,450
New Jersey	280,886	280,886	2		4	585,098	585,098	3	1		531,926	403,881	2		1	1,173,741
New Mexico	242,979	242,979	2		6	183,821	175,247	3								651,420
New York	1,207,716	1,173,326	7	5		3,037,233	2,986,562	5	15		893,345	853,094	2	2	8	3,562,126
North Carolina	550,228	550,165	8	2	20	644,889	644,649	6	4	5	167,670	167,670		2	29	1,237,284
North Dakota	429,932	428,538	5		22	385,790	385,790	4		1						892,264
Ohio	814,523	792,761	6		17	2,140,570	2,081,380	9	3		865,625	850,163	5			2,890,830
Oklahoma	519,818	517,444	9	1	33	428,397	424,981	4		1	113,688	113,688			37	2,319,290
Oregon	208,639	117,537	3			335,392	272,981	3			5,790	5,790			2	521,531
Pennsylvania	1,387,269	1,377,793	13	2		2,021,009	2,017,181	14			846,854	846,854	7			3,746,923
Rhode Island	8,222	7,406				206,703	206,703		1							175,628
South Carolina	431,762	431,359	4	3	17	100,017	100,017	1		5	263,196	263,196	2	1	32	1,094,416
South Dakota	129,470	129,470	2	1	4	528,394	527,534	14			144,650	128,700	4		1	1,017,377
Tennessee	244,886	241,169	2	2		166,727	166,727		2		162,270	153,270	3	1		2,005,864
Texas	1,271,717	1,266,908	11		9	1,346,378	1,332,513	14	1		217,310	163,350	2		2	2,744,973
Utah	32,086	31,875			9	100,628	99,886	2		35	73,389	73,389			29	341,000
Vermont	111,265	111,095		1	6	145,570	145,570		1	6						312,120
Virginia	196,544	195,098	2	2	5	679,220	679,000	5	2	2	138,847	138,847	1	1	9	870,779
Washington	266,537	263,586	4	1	6	533,933	532,433	3	4	4	11,529	11,529			4	455,273
West Virginia	9,310	9,310			2	440,042	434,422	5			2,820	2,820			1	1,200,243
Wisconsin	834,596	819,760	6	4	7	452,980	423,971	3		4	143,882	143,668	1		16	1,724,962
Wyoming	1,986	1,982				560,904	560,903	6			4,997	4,997			2	299,298
District of Columbia	56,868	56,868	1			2,193	2,193									275,206
Hawaii	4,810	4,810			1	200,913	200,906	2		1						388,597
Puerto Rico						584,007	579,336	11								582,439
TOTALS	21,259,444	20,896,558	189	42	557	30,611,008	29,350,053	228	59	211	9,902,957	9,448,005	75	16	346	58,754,874

* INCLUDES APPORTIONMENT FOR THE FISCAL YEAR 1942