PUBLIC ROADS

A JOURNAL OF HIGHWAY RESEARCH

UNITED STATES DEPARTMENT OF AGRICULTURE
BUREAU OF PUBLIC ROADS

VOL. 11, NO. 7 ▽ SEPTEMBER, 1930

RUNWAY WITH ARTIFICIAL OBSTRUCTIONS USED IN IMPACT TESTS AT ARLINGTON

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MOTOR TRUCK IMPACT AS AFFECTED BY RUBBER TREAD THICKNESS OF TIRES

REPORT OF COOPERATIVE TESTS BY THE BUREAU OF PUBLIC ROADS, THE SOCIETY OF AUTOMOTIVE ENGINEERS, AND THE RUBBER MANUFACTURERS ASSOCIATION

Reported by JAMES A. BUCHANAN, Associate Engineer of Tests, Division of Tests, U. S. Bureau of Public Roads [1]

> Since the tests reported in this article were conducted, a thorough investigation of the accuracy of the instruments used has been made by the United States Bureau of Standards, in cooperation with the United States Bureau of Public Roads. A summary account of this work was published in PUBLIC ROADS, July, 1930. The committee which guided the investigation recommended that the following statement regarding the accuracy of the data accompany this report:
> **The results obtained in the motor-truck impact tests are, in general, systematically from 10 to 15 per cent too low. A conservative estimate of the dispersion of the measured values of acceleration indicates that 90 per cent of the significant accelerations lie within less than 15 per cent of the mean, for tests involving artificial obstructions.**

THE experimental motor-truck impact tests which were reported in part in the June, 1926, issue of PUBLIC ROADS [2] have been continued and the scheduled tests on cushion and solid tires cut to various heights of tread rubber are now completed.

The Bureau of Public Roads, the Rubber Manufacturers Association, and the Society of Automotive Engineers have continued to cooperate in this work and the administration and test procedure in these tests are the same as in those previously reported. For specific and detailed information concerning instruments used and methods of testing, reference should be made to the earlier report.

The object of this particular phase of the impact investigations was to determine the effect of reducing the thickness of the tread rubber on the cushioning properties of typical solid and cushion tires. Briefly, the procedure followed was to equip the test truck with new tires and, under carefully controlled conditions of load and speed, to drive the truck over a test road artificially roughened with steel obstructions. For these conditions the vertical impact reactions were determined. The tires were then removed from the truck, placed in the tire cutting machine shown in Figure 1 (described later), and a definite depth of the tread thickness removed. This insured tires identical in all respects except that of the factor being studied (tread rubber thickness). These cut-down tires were then replaced on the test truck, the runs over the artifically roughened test road repeated and the impact reactions determined for this new tire condition. By continuing this program of cutting down and testing as far as was practicable with the various types of tire, data were obtained which show the relation between the loss of tread rubber and the resulting increase in impact reaction for each of the typical tires included in these tests.

APPLICATION OF RESULTS LIMITED BY CERTAIN FACTORS

There are certain limitations to these tests and it is important that they be clearly understood in order to apply properly the results obtained.

The tires of reduced tread thickness were cut down from practically new stock and the cutting process, by its very nature, made them true and round. Tires with tread thickness reduced by wear in service are likely to be worn to varying degrees along the circumference and probably have suffered more or less aging and hardening at the same time. Both of these differences would tend to make the cushioning properties of service-worn tires somewhat less than those of similar tires cut down to the same height by the process used in these tests.

The results presented in this report are based on total vertical impact reactions at the instant of impact. They do not take into consideration the horizontal or tangential component of the reaction at the road surface. From the standpoint of the pavement structure it is probable that it is the large vertical component of this force which is important.

The total vertical reactions are shown without any attempt to determine the pressure intensity or the distribution of pressure over the area of contact. The general trend of the data obtained in the impact tests indicates that, the load and other variables being equal, wide tires cause heavier impact reactions than narrow tires. It is recognized that, under given loads, different tires may have different areas of contact. Thus the total vertical reaction values are given as determined, without prejudice to those tires which through larger areas of contact may possibly tend to develop somewhat lower unit pressures. The effect of variations in unit pressures or pressure distribution over the area of contact on the stresses developed in a pavement is as yet a very uncertain matter.

Tire manufacture is in a state of constant development and improvement. Since the tires used in these tests were obtained the tendency has been to increase the height of tread rubber in both solid and cushion types. Therefore the tires included in this report are in a sense obsolete in that the most recent tires of these types have generally a somewhat greater thickness of tread rubber. Tire manufacturers state that the production of regular or low profile solid tires is decreasing, such types being superseded by high profile solid tires. However, the practical application of the data herein presented is not precluded by such changes if the actual dimensions are taken into account whe

[1] The bureau acknowledges, with appreciation, the valuable assistance of J. W. Reid, formerly with the Rubber Association, in planning the tests and securing the data.

[2] See Motor-truck Impact as Affected by Tires, Other Truck Factors and Road Roughness, Public Roads, vol. 7, No. 4, June, 1926, and also General Results of the Cooperative Motor-truck Impact Tests, Journal of the Society of Automotive Engineers, vol. 18, No. 6, June, 1926.

considering the influence of the tread-rubber thickness of any tire on the total vertical impact reaction.

It is felt that this report will be most useful if it is considered as indicating only the general trend of the relations studied.

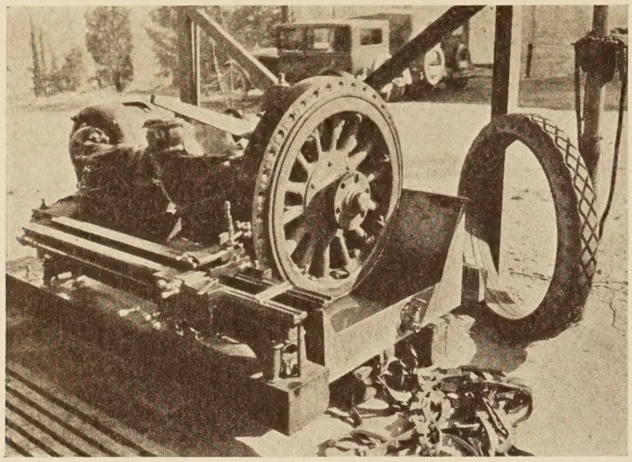

Figure 1.—Apparatus for Cutting Tires

TERMS DEFINED

To aid in a clear understanding of the matter under discussion, certain terms which appear frequently are defined as follows, reference being made to Figure 2:

Visible rubber or visible height of rubber.—The radial distance from the top of the steel flange of the rim to the extreme outer surface of the rubber, the measurement being taken at no load. In this report, visible rubber has been used to define tire height, it being the most readily determinable measure.

Over-all height or over-all sectional height.—The radial distance from the inside of the steel rim to the extreme outer surface of the rubber, the measurement being taken at no load.

Flange height.—The radial height of the steel flange of the rim, which is equal to the difference between the over-all height and the visible rubber. This flange height may be generally taken as seven-eighths inch without serious error.

Static load.—The total pressure exerted on a level surface by the tire of one rear wheel of a stationary motor vehicle.

Average impact reaction.—The impact force per rear wheel, which is the average for a series of certain representative test conditions of load, speed and obstruction (pavement roughness). It may be expressed as a pressure in pound units or as a multiple or percentage of the static wheel load.

DETAILS OF TESTS DESCRIBED

Tires.—The impact test data herein presented relate to three types of 36 by 5-inch dual cushion tire and two types of 36 by 4-inch dual solid tire equipment on the 2-ton test truck, and one type of 36 by 7 inch dual cushion tire and one type of 36 by 5 inch dual solid tire equipment on the 3-ton test truck. The tire equipments applied to the two trucks conformed with accepted practice at the time of the tests.

The cushion tires were all of the nonskid-tread designs and represented the high and low annular internal cavity and the radial external cavity types. The solid tires had smooth treads and represented the high-profile and the regular or low-profile types.

As a tire was cut down the depth of nonskid depressions was decreased or entirely eliminated and the face width of the tire increased with the depth of the cuts. In each case, the new tires were the only ones which had rounded profiles as all cuts were made from side to side parallel with the axis.

Speeds, loads, and obstructions.—The trucks were operated at various speeds from a minimum of about 3 miles per hour up to a maximum of about 20 miles per hour. The speeds varied in increments of about 3 miles per hour and it was possible to plot speed versus impact force and obtain curves from which the force at any given speed could be obtained.

Loads were applied in accordance with the capacity of the tires on the rear wheels, except in cases where trucks were empty. The capacity loads of the various tires as used in these tests were as follows:

All 36 by 5 inch cushion, 1,700 pounds per tire.
All 36 by 7 inch cushion, 3,500 pounds per tire.
All 36 by 4 inch solid, 2,000 pounds per tire.
All 36 by 5 inch solid, 3,000 pounds per tire.

The artificially roughened concrete test road at the Arlington experimental station was used to conduct these tests. On this road, which is straight and practically level, and has but slight crown, eight steel obstructions were bolted at about 30-foot intervals along a painted guide line. The obstructions listed below represent in a controlled, artificial way many of the surface roughness conditions presented by actual highways.

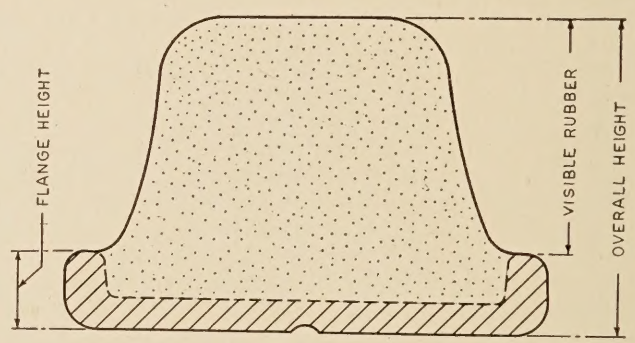

Figure 2.—Sketch Showing Method of Making Tire Measurements

No. 1. Inclined plane, 30-inch ramp, 13/16-inch rise.
No. 2. Inclined plane, 30-inch ramp, 1 15/16-inch rise.
No. 3. Rectangular obstruction, 3-inch base, 1 1/8-inch rise.
No. 4. Rectangular obstruction, 3-inch base, 9/16-inch rise.
No. 5. Rounded obstruction, 3-inch base, 1 1/2-inch rise.
No. 6. Rounded obstruction, 3-inch base, 3/4-inch rise.
No. 7. Inclined plane, 30-inch ramp, 1 1/2-inch rise.
No. 8. Rectangular obstruction, 3-inch base, 7/8-inch rise.

The impact forces developed under the various combinations of test conditions (i. e., truck, tire, load, speed, and obstruction conditions) were computed in terms of the particular static wheel load involved. From the mass of data available, 43 conditions of load, speed, and obstruction were selected as representative as set forth in detail in Table 1. The averages of these selected conditions were used in comparing the impact behavior of the various tire and truck combinations.

TABLE 1.—*Details of the 43 test conditions which are included in the averages used for comparison*

Speed (m. p. h.)	Load	Obstruction	
		Shock at—	Drop after—
7½ 12½ 17½	100 per cent tire capacity.	¾ by 3 inch rounded ⅞ by 3 inch rectangular.	¾ by 3 inch rounded. 1½ by 30 inch inclined plane. ⅞ by 3 inch rectangular.
12	Empty truck 75 per cent tire capacity. 100 per cent tire capacity. 150 per cent tire capacity.	¾ by 3 inch rounded ⅞ by 3 inch rectangular.	¾ by 3 inch rounded. 1½ by 30 inch inclined plane. ⅞ by 3 inch rectangular.
12	100 per cent tire capacity.	¾ by 3 inch rounded 1½ by 3 inch rounded 9/16 by 3 inch rectangular. ⅞ by 3 inch rectangular. 1⅛ by 3 inch rectangular.	¾ by 3 inch rounded. 1½ by 3 inch rounded. 13/16 by 30 inch inclined plane. 1½ by 30 inch inclined plane. 1 5/16 by 30 inch inclined plane. 9/16 by 3 inch rectangular. ⅞ by 3 inch rectangular. 1⅛ by 3 inch rectangular.

PHYSICAL CHARACTERISTICS OF THE TIRES DESCRIBED

Only typical data for representative tires are included in this report as inclusion of all of the data concerning the physical characteristics of all of the tires tested would add unduly to the length without adding information which would be important in the discussion which follows. Figure 3 shows static load-deflection curves for these representative tires, and Table 2 gives the physical dimensions and weights of each at the various stages of the cutting-down process. Table 3 gives data obtained in the load-deflection tests. It will be noted that Table 3 includes measured areas of contact and computed unit load values. The load per unit of area as given in this table is an average value found by dividing the total load by the area of contact. This figure is not particularly significant since actually the load intensity is variable over the entire area of contact. However, the values given are useful as they do give some idea of the unit pressures which occur under the different tires for various static loads.

TABLE 2.—*Dimensions of tires*

Type and size	Tire test No.	Visible rubber	Face width	Weight
		Inches.	*Inches.*	*Pounds.*
Hollow center cushion, 36 by 5 inches	16	3.12	3¾	140
	16a	2.00	4	120
	16b	1.50	4 3/16	111
	16c	1.12	4½	101
High profile solid, 36 by 4 inches	39	2.25	2¾	97
	39b	1.88	2¾	95
	39c	1.25	3 1/16	82
	39e	.93	3⅛	79
	39f	.62	3 7/16	72½
Regular solid, 36 by 4 inches	41	1.88	2⅞	94
	41c	1.25	3	88
	41e	.93	3⅛	80

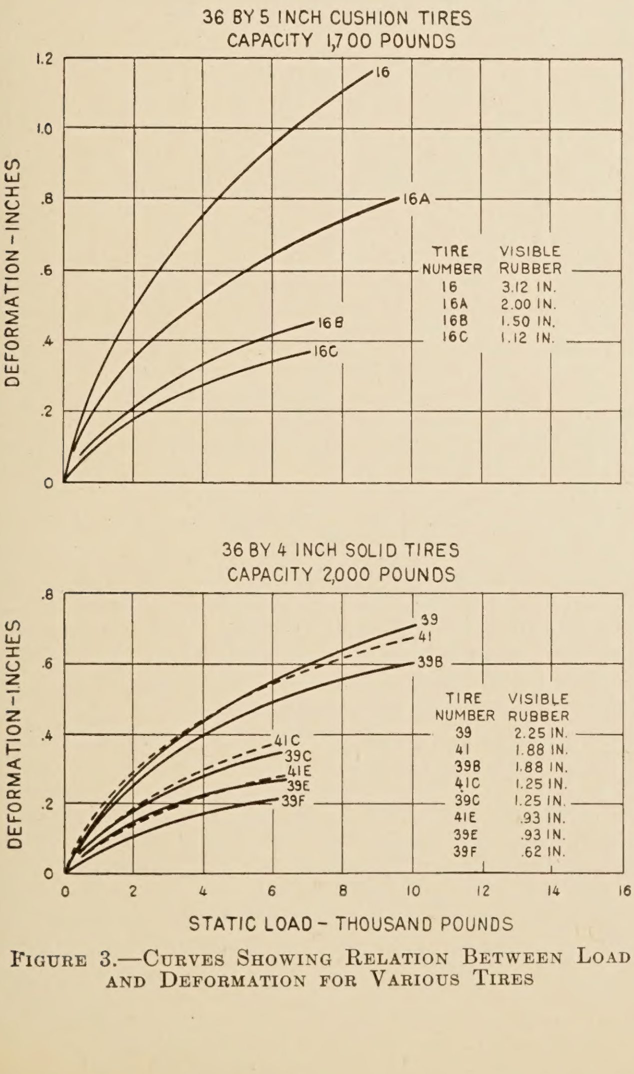

FIGURE 3.—CURVES SHOWING RELATION BETWEEN LOAD AND DEFORMATION FOR VARIOUS TIRES

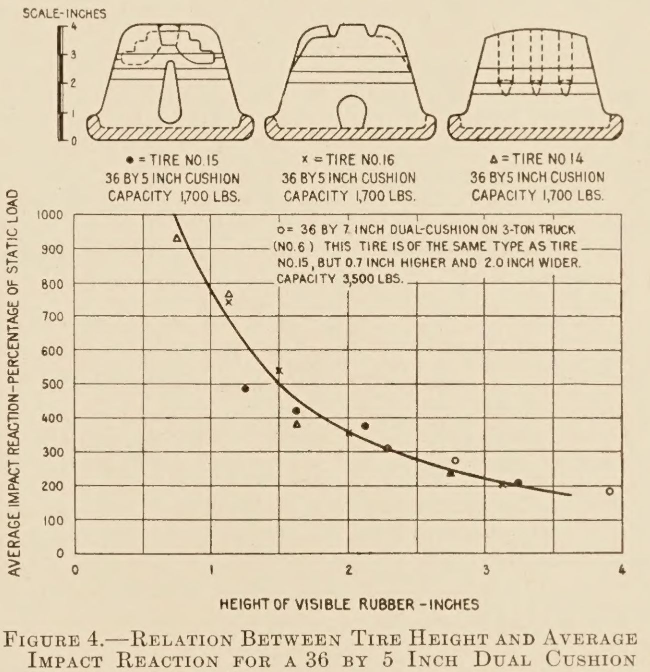

FIGURE 4.—RELATION BETWEEN TIRE HEIGHT AND AVERAGE IMPACT REACTION FOR A 36 BY 5 INCH DUAL CUSHION TIRE ON A 2-TON TRUCK

TEST DATA DISCUSSED

Representative data from impact tests on some of the tires are given in Figures 4, 5, and 6. These curves show the effect of tread rubber thickness on the magnitude of the impact reaction, other factors being the same. The ordinates selected for the presentation of the data in this form are measured values, averaged from a variety of load, speed, and artificial obstruction conditions as previously explained.

Figure 4 shows these data for the three types of 36 by 5-inch dual cushion tires on a 2-ton truck, and also

TABLE 3.—*Results of static tests*

36 BY 5 INCH HOLLOW CENTER CUSHION

Tire test No.	Static load: Percentage of capacity	Static load: Pounds	Deflection	Contact: Width	Contact: Length	Contact: Area	Average unit load: Per inch of width	Average unit load: Per square inch of area
			Inches	*Inches*	*Inches*	*Sq. in.*	*Pounds*	*Pounds*
16	100	1,700	0.42	3.35	7.83	15.28	507	111
	200	3,400	.68	3.69	9.79	22.45	922	151
	500	8,500	1.13	4.53	12.93	37.50	1,876	227
16a	100	1,700	.31	4.10	6.67	26.56	415	64
	200	3,400	.48	4.13	8.63	30.76	824	110
	500	8,500	.75	4.90	10.66	44.60	1,735	191
16b	100	1,700	.19	4.30	5.97	20.52	395	83
	200	3,400	.30	4.52	7.40	25.07	753	136
	333	5,670	.40	4.80	8.30	34.81	1,181	163
16c	100	1,700	.16	4.66	5.28	20.85	366	82
	200	3,400	.25	4.78	6.12	27.15	716	125
	333	5,670	.33	4.95	7.05	32.10	1,145	177
36 BY 4 INCH HIGH-PROFILE SOLID								
39	100	1,700	0.24	2.48	5.91	12.62	685	135
	200	3,400	.38	2.61	7.30	16.40	1,303	207
	500	8,500	.65	3.16	9.60	25.73	2,690	330
39b	100	1,700	.22	2.91	5.65	14.45	586	118
	200	3,400	.35	3.01	7.02	18.93	1,133	180
	500	8,500	.58	3.38	9.37	28.75	2,528	296
39c	100	1,700	.16	3.12	5.05	12.93	545	132
	200	3,400	.26	3.23	6.35	17.58	1,052	194
	333	5,670	.34	3.42	7.19	21.40	1,660	265
39e	100	1,700	.13	3.40	4.90	13.12	500	129
	200	3,400	.20	3.50	5.70	16.95	972	201
	333	5,670	.26	3.65	6.50	20.53	1,553	276
39f	100	1,700	.10	3.50	3.82	11.66	486	146
	200	3,400	.16	3.58	4.53	14.39	950	236
	333	5,670	.21	3.72	5.16	17.40	1,525	325
36 BY 4 INCH REGULAR SOLID								
41	100	1,700	0.26	2.72	5.82	14.04	625	121
	200	3,400	.41	2.98	7.35	18.32	1,164	186
	500	8,500	.62	3.30	9.27	26.76	2,575	318
41c	100	1,700	.17	3.08	5.27	13.64	553	125
	200	3,400	.27	3.17	6.36	17.90	1,072	190
	333	5,670	.36	3.30	7.33	21.20	1,720	268
41e	100	1,700	.18	3.18	4.90	12.59	535	135
	200	3,400	.20	3.28	5.95	16.42	1,035	207
	333	5,670	.26	3.48	6.77	19.90	1,628	285

includes limited data for a 7-inch tire on a 3-ton truck, for reasons that will be discussed later. Figure 5 shows similar data for 36 by 4 inch dual solid tires of the regular and high-profile types, on the 2-ton truck. Figure 6 shows the same type of data for 36 by 5-inch dual high-profile tires on a 3-ton truck. Figure 8 shows another grouping of the data which indicates the increase in the impact reaction (expressed as a percentage of the static reaction) as the height of visible rubber is reduced by definite percentages of its original height. The tires from which these data were obtained are indicated in this figure.

CUSHION TIRES

The data presented in Figure 4 were derived principally from the tests in which three types of 36 by 5-inch dual cushion tires were used on the 2-ton truck. The curve was derived from the points obtained from the tests on the 36 by 5-inch tires and may be said to represent fairly the average relation found for these three types of tires. This curve indicates that if 1 inch of tread rubber is lost from a new tire with an original height of visible rubber of 3⅛ inches, the magnitude of the average impact reaction is increased from 215 to 340 per cent of the static load. A further reduction of 1 inch in tread rubber thickness increases the average impact reaction to some 700 per cent of the static load.

Stated in another way, the curve indicates for these tires that, if 32 per cent of the visible height of tread rubber of the new tire is removed, the impact reaction is increased 1.6 times and that if 64 per cent of the height of visible rubber is removed the average impact reaction is some 3.2 times that for a new tire under the same conditions. Or, viewed from another angle, this curve indicates that for this "average" 36 by 5 inch cushion tire, the removal of about 1⅜ inches (about 44 per cent) of the original tread rubber thickness will cause the impact reactions to be doubled while if 1⅞ inches (about 60 per cent) of tread rubber is removed the impact reaction is trebled, and quadrupled if 2¼ inches is removed (about 72 per cent).

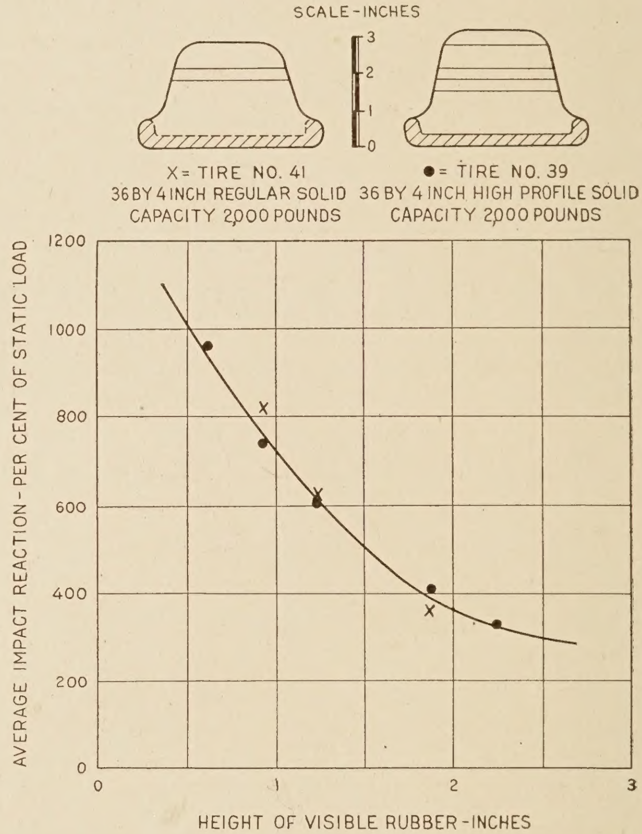

FIGURE 5.—RELATION BETWEEN TIRE HEIGHT AND AVERAGE IMPACT FOR A 36 BY 4 INCH SOLID TIRE ON A 2-TON TRUCK

Figure 4 shows three points representing data obtained from tests on dual 36 by 7-inch cushion tires. Although the number of tests made on cut-down cushion tires larger than 5 inches was very limited, the data obtained are valuable since when compared with those obtained with the 5-inch tires, as in Figure 4, there is no indication that the relation between the height of visible rubber and the magnitude of the impact reaction (expressed as a percentage of static load) is different from that established for the 5-inch tires. While the 7-inch tires were not run at the same load in pounds as the 5-inch tires, the loads expressed as a percentage of tire capacity, the speeds, and the obstructions were all practically the same.

SOLID TIRES

Figure 5 shows similar data for the dual 36 by 4-inch solid tires of the regular and high-profile types when used on the 2-ton truck. From these data it appears that if 2⅛ inches be taken as the height of visible rubber of a 36 by 4-inch new solid tire, the average impact is doubled if 1 inch of tread rubber (47 per cent) is removed, and trebled if 1⅝ inches (76 per cent) is removed.

From the data on 36 by 5-inch high-profile tires on a 3-ton truck (fig. 6), it is indicated that if 2⅜ inches be taken as the normal height of visible rubber, the impact reaction of a new tire is doubled if about 1⅛ inches (47 per cent) of tread rubber is removed and trebled if about 1⅝ inches (68 per cent) is removed.

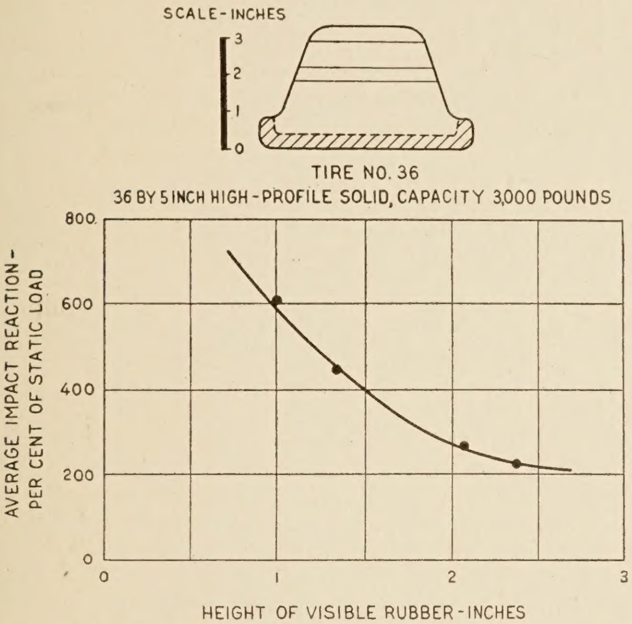

Figure 6.—Relation Between Tire Height and Average Impact Reaction for a 36 by 5 Inch Dual Solid Tire on a 3-Ton Truck

The data presented in Figures 4, 5, and 6 bring out clearly the very important influence of tread-rubber thickness on the cushioning properties of tires of both the cushion and the solid types.

CUSHION TIRES VERSUS SOLID TIRES

Before attempting a comparison of the relative cushioning properties of tires of the cushion and solid types, there are certain points concerning their use which should be thoroughly understood. Reference is made to the full discussion of the effect of tire width contained in the earlier report in which it was brought out that, in general, a wide tire tends to cause heavier impact reactions than a narrow tire, other conditions being the same. This conclusion is of immediate importance since in practice when a solid tire is replaced by a cushion tire it is necessary to increase the width because of the differences in the rated carrying capacities of the two types. For example, a 5-inch cushion tire is, in practice, considered to be the replacement size for a 4-inch solid tire. The rated capacity of a 5-inch cushion tire is 1,700 pounds, of a 4-inch solid tire 2,000 pounds and of a 5-inch solid tire 3,000 pounds. Briefly, when we replace a solid tire with one which by its construction has better cushioning properties we are forced to use a wider tire and in so doing must sacrifice at least some of the benefits gained.

A comparison of Figures 4 and 5 might lead to the conclusion that there is no real difference between the behavior of a cushion tire and that of a solid tire of the same height. Let us consider this point. In the first place, it should be noted that the impact reactions are given as a percentage of static load. As the capacity loads of the tires were not the same and as the tires of both types were loaded in each instance to their respective capacity loads or to some definite percentage of capacity load, the curves do not give comparable impact reactions in pounds. They simply show the relative increase in impact reaction for corresponding losses in the thickness of the tread rubber on the particular tire types under consideration.

By virtue of the construction of a cushion tire, it may naturally be expected to yield lower impact values than a solid tire of the same width and with the same amount of visible rubber. As has been brought out, a cushion tire is not comparable with a solid tire of the same width because of the difference in carrying capacity.

Referring to Figure 7 (reprinted from the earlier report), it is shown that on a 2-ton truck an increase in tire width of 50 per cent (from dual 4-inch to dual 6-inch) caused an increase in the impact reaction of about 30 per cent (at 12 miles per hour under the given test conditions). It appears reasonable to suppose,

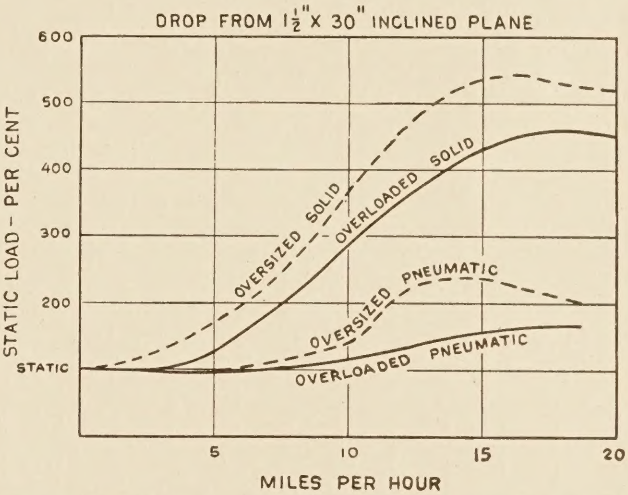

Figure 7.—Effect of Tire Size on Impact Reactions Using a 2-Ton Truck. The Overloaded Tires Carried a Load Equal to 150 Per Cent of Their Capacity and the Oversized Tires Carried the Same Load as the Corresponding Overloaded Tires. Curve Marked "Oversized Solid" Represents Dual 36 by 6 Inch New Regular Solid Tires, and the One Marked "Overloaded Solid" Represents Dual 36 by 4 Inch New Regular Solid Tires

therefore, that as the 5-inch cushion tires upon which Figure 4 is based are 25 per cent wider than the 4-inch tires upon which Figure 5 is based, the impact values of the former (the 5-inch cushion) are about 10 to 20 per cent higher than they would have been if 4-inch cushion tires could have been used.

If this reasoning is sound, it is evident that if solid tires could be replaced by cushion tires on an equal width basis, the latter would be some 10 to 20 per cent better than the former at any given height. As shown in the figures (on an equal capacity basis), there is very little difference between the two types at any given height. These data, then, indicate that the advantage of using cushion tires may be partially offset and, in the examples illustrated in Figures 4 and 5, completely offset by the disadvantage of having to use wider cushion tires in order to carry loads comparable to those which may be carried by replacement tires of the solid type. It is important to remember that this statement applies only to tires having equal heights of visible rubber.

In view of the foregoing one might reasonably ask: "Why use cushion tires?" The principal reasons may be stated as follows:

1. The average height of visible rubber for new cushion tires is about 1 inch or nearly 50 per cent greater than that of the same nominal size of regular solid tire and somewhat greater than this for the smaller size of solid tire for which the cushion is a replacement. As pointed out in the earlier report the thicker the tread (i. e., the greater the thickness of visible rubber) the greater the cushioning quality.
2. Although the use of cushion tires necessitates wider tires, the disadvantage in the use of wider tires (as brought out in the earlier report) is offset by whatever cushioning qualities may be inherent in cushion tires. Moreover, for a given force (static or impact) the load concentration on the pavement is less for wide tires than for narrow tires, and while this may not be of primary importance on the higher types of road, it undoubtedly is of considerable importance on the softer types.
3. The possible loss in height by cushion tires through wear in practical use is generally limited by the size, shape, and position of the structural cavities. It will be pointed out in the subsequent discussion that this tends to act as a safeguard to both the vehicle and the pavement.

Cushion tires of the circumferential or annular hollow-center types, such as were included in these tests, are not generally considered suitable for use at high speeds after wear of the tread has exposed the internal cavity and thus altered the structural action of the tire. The use of tires of this type is thus practically limited to the amount of wear which can take place before this condition obtains and is dependent upon the position, size, and shape of the internal cavity. In this way a type whose internal cavity becomes exposed while there is still a considerable amount of visible rubber on the tire acts as a safeguard to the highway because in such a condition of wear it is unsafe to use at speeds such as would make it objectionable from the standpoint of impact.

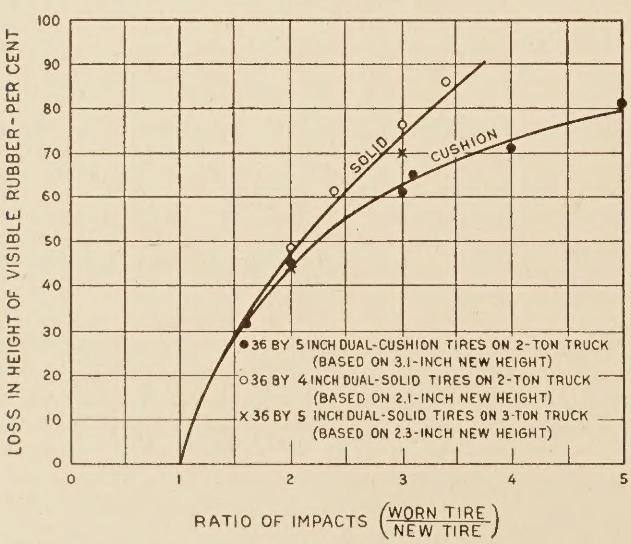

Figure 8.—Comparison of Ratio of Impact of Worn Tire to New Tire with Loss in Height of Visible Rubber

There is no apparent reason why cushion tires worn to the limit of visible rubber permitted for such tires should not assume the status of solid tires and then be worn to the limit of visible rubber permitted for

Table 4.—*Tire conditions and results of impact tests*

36 BY 5 INCH DUAL CUSHION TIRES ON 2-TON TRUCK

[For new tire, over-all height 4 inches, visible rubber 3.1 inches, average impact 215 per cent of static load]

Over-all height of worn tire	Loss in tread thickness	Loss in over-all height	Average impact of tire, percentage of static load	Ratio of impact of worn tire to new tire	Visible rubber	Loss in visible rubber
Inches	*Inches*	*Per cent*	*Per cent*	*Per cent*	*Inches*	*Per cent*
3.0	1.0	25	345	160	2.1	32
2.6	1.4	35	430	200	1.7	45
2.1	1.9	48	645	300	1.2	61
2.0	2.0	50	715	330	1.1	65
1.8	2.2	55	860	400	0.9	71
1.6	2.4	60	1,025	480	0.7	77

36 BY 4 INCH DUAL SOLID TIRES ON 2-TON TRUCK

[For new tire, over-all height 3 inches, visible rubber 2.1 inches, average impact 340 per cent of static load]

2.0	1.0	33	680	200	1.1	48
1.7	1.3	43	820	240	0.8	62
1.4	1.6	53	1,020	300	0.5	76
1.2	1.8	60	1,140	340	0.3	86

36 BY 5 INCH DUAL SOLID TIRES ON 3-TON TRUCK

[For new tire, over-all height 3.2 inches, visible rubber 2.3 inches, average impact 240 per cent of static load]

2.2	1.0	31	480	200	1.3	44
1.6	1.4	44	720	300	0.7	70

this type. If tires should be or are discarded by a truck owner as a matter of maintenance of equipment when the impact reaction has increased to a point where it is a certain number of times the impact reaction of the new tires, and this factor be taken as three, then 5-inch cushion tires would be removed after the visible rubber had been reduced to about 1¼ inches (about 40 per cent of the original visible height) and 4-inch and 5-inch solid tires would be removed after the visible rubber had been reduced to about ½ inch and ¾ inch, respectively (24 and 32 per cent of the original visible heights).

APPLICATION OF DATA TO ACTUAL PROBLEMS

The data taken from the curves to support the above conclusions have been listed in Table 4, and are shown graphically in Figure 8. Before applying the interpretations to actual problems, it is again pointed out that the impact in pounds is not the quantity used in comparing the reactions of tires. The quantity used is the increase in reaction of a given new tire when loss occurs in the height of visible rubber. Comparison of the curves representing the action of solid tires and cushion tires indicates that for a given percentage of loss in visible rubber the cushion tires show a greater percentage increase in impact reaction. This is not unreasonable when it is remembered that, for a given truck, the proper cushion tire would be about 1 inch thicker than the replacement solid tire. A given percentage loss in visible rubber would therefore mean a greater loss in inches on cushion tires than on the corresponding solid tires. A new cushion tire should cause lower impact reactions than the same size of new solid tire because of differences in height and structure, and the impact reactions should become more nearly equal as the tires approach a worn-out condition because of a gradual approach to the same physical condition of

(Continued on p. 152)

THE INTERRELATED EFFECTS OF LOAD, SPEED, TIRES, AND ROAD ROUGHNESS ON MOTOR TRUCK IMPACT[1]

Reported by JAMES A. BUCHANAN, Associate Engineer of Tests, Division of Tests, Bureau of Public Roads[2]

Since the tests reported in this article were conducted, a thorough investigation of the accuracy of the instruments used has been made by the United States Bureau of Standards, in cooperation with the United States Bureau of Public Roads. A summary account of this work was published in PUBLIC ROADS, July, 1930. The committee which guided the investigation recommended that the following statement regarding the accuracy of the data, accompany this report:

The results obtained in the motor-truck impact tests are, in general, systematically from 10 to 15 per cent too low. A conservative estimate of the dispersion of the measured values of acceleration indicates that 90 per cent of the significant accelerations lie within less than 15 per cent of the mean, for tests involving artificial obstructions. For tests on natural road surfaces the exact value of the dispersion is uncertain.

THE data obtained in the earlier motor truck impact tests shows that the magnitude of impact reaction is dependent on at least four major variables which are: Road roughness, tire equipment, wheel load, and vehicle speed. A graphic representation of the interrelationship of these four factors, based on the data obtained on the artificially roughened test road at Arlington, Va., is shown in the form of an isogram chart in Figure 1. In this figure curves of equal impact reaction show the impact force which may reasonably be expected to occur with any combination of tire equipment, wheel load and truck speed on the particular road under consideration and within the limits used in obtaining the data. The figure contains four groups of curves, each group representing one of the four representative tire types used in the tests. Figure 1 is of no practical use because it is based on a peculiar condition of surface roughness, artificially obtained, but it is significant because it indicates the possibility of conducting tests on actual road surfaces and collecting data which, when shown in a similar way, would be of considerable practical importance.

This possibility was laid before the cooperative committee in October, 1926, together with a tentative program of tests which would involve desired ranges of road surface roughness, tire equipment, wheel load, and vehicle speed, and the proposed program was authorized. The details of the test program which was followed are described in the following text.

TEST TRUCKS AND INSTRUMENTS DESCRIBED

The 2-ton and 5-ton test trucks were equipped with the coil spring accelerometer developed by the Bureau of Public Roads. This equipment had been used in previous impact tests and the method of obtaining impact forces from the data has been described in an earlier publication.[3]

The general specifications of the test trucks are given in Table 1 and the general characteristics of the truck tires and of the accelerometer elements which were used are given in Table 2.

In order to insure consistency of action, the rear springs of the trucks had been thoroughly cleaned, greased and provided with jackets during earlier work and they remained in satisfactory condition throughout the tests.

It was necessary to have the entire equipment mobile and a field office with platforms for loading and storage was built on a trailer chassis. A service truck carrying a chain hoist on a platform body was used for towing the trailer and to carry wheels, tires, gasoline, and other supplies necessary for the operation of the test trucks.

Each set of tires was mounted permanently on wheels in order that the necessary tire changes might be quickly and conveniently made merely by substituting wheels. This arrangement had the further advantage of insuring that tire installations on the trucks could be faithfully repeated regardless of the number of times the wheels were interchanged. The types selected were the same as those upon which the preliminary isogram had been based, namely, pneumatic, new cushion, new regular solid, and worn solid. These tire selections represent the range in equipment ordinarily found on the highways to-day and are briefly described as follows: Pueumatic—high pressure pneumatic cord tires on demountable rims; new cushion—new, hollow-center, pressed-on cushion tires of average height with nonskid, cushioning tread design; new regular solid—new, pressed-on, regular solid tires of average height and with smooth tread (the present tendency is to call such tires low-profile solids), worn solid--solid tires which had been cut down from new stock on a special tire-cutting machine and were thus true and round. Tires which have been worn down in service to heights corresponding to those of the worn tires as used in these tests have generally been subjected to aging and hardening influences, and service-worn tires are seldom, if ever, true and round. Figure 2 shows the tires mounted dually on wheels and ready for use. Figure 3 shows the actual cross sections of the individual tires.

Some of the details of the behavior of single tires under static load are given in Table 3. The term "visible rubber height" as herein used refers to the radial thickness of tread rubber from the outside of the steel flange of the tire rim to the extreme outer (tread) surface of the rubber, the measurement being

[1] These tests are a part of the investigation of motor truck impact being conducted by the Bureau of Public Roads and were made with the cooperation of the Rubber Manufacturers Association and the Society of Automotive Engineers.

[2] Acknowledgment is made of the assistance of J. W. Reid, formerly of the Rubber Association, in planning the tests and obtaining the data.

[3] See PUBLIC ROADS, vol. 7, No. 4, June, 1926, and vol. 11, No. 5, July, 1930.

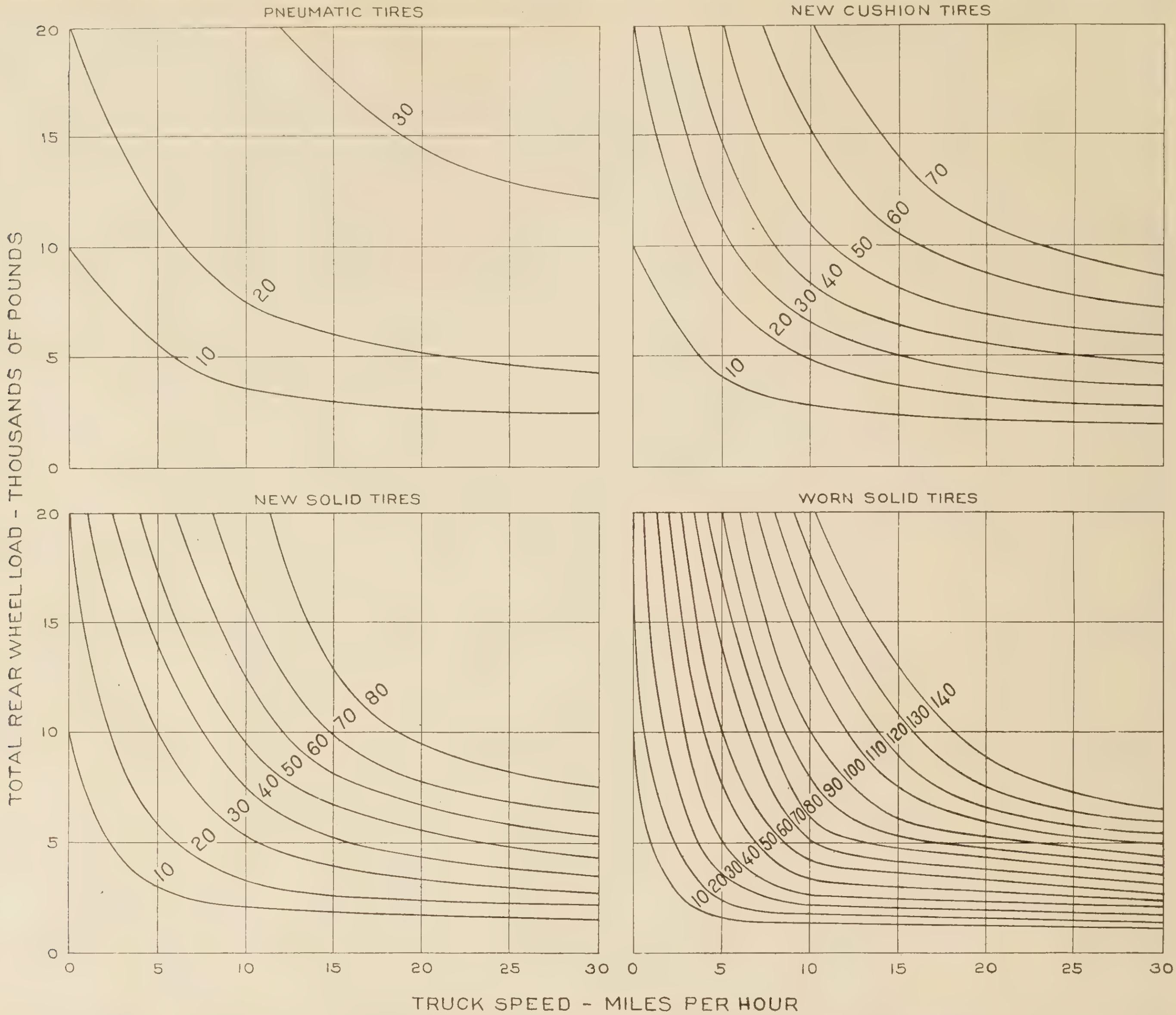

FIGURE 1.—ISODYNAMIC CURVES FOR ARLINGTON FARM TEST ROAD WITH ARTIFICIAL OBSTRUCTIONS FOR DETERMINATION OF MAXIMUM TOTAL VERTICAL REACTIONS IN THOUSANDS OF POUNDS

taken at zero load. The average static load-deflection curve for each tire type is shown in Figure 4, the deflections under a static load of 10,000 pounds being approximately 2.5 inches, 1 inch, 0.7 inch, and 0.3 inch, respectively, for the pneumatic, new cushion, new solid, and worn solid tire types.

At the beginning of the tests, the rear wheel loads were standardized at 2,500, 5,000, 7,500, and 10,000 pounds. The 2,500 and 5,000 pound loads were run with the 2-ton truck, and the 7,500 and 10,000 pound loads were run with the 5-ton truck. The light load of each truck was accurately measured on stationary platform scales and securely fastened in position. Then the heavier load (also weighed on the platform scales) was built up on each truck by adding 100-pound lead or iron weights. The positions of these extra weights were marked on the trucks so that wheel loads might be duplicated readily and with exactness. Tables 4 and 5 show the general characteristics of the loadings.

TESTS COVERED WIDE RANGE IN TRUCK SPEEDS AND CONDITION OF ROAD SURFACE

The trucks were operated over the test sections at speeds varying by small increments from the minimum up to the maximum obtainable. The average speed of each run was computed from stop-watch observations and the known lengths of the test sections (one-twentieth mile). Variations in speed were observed on speedometers mounted on the trucks. Runs varying from the average speed by more than one-half mile per hour, as registered by the speedometers, were discarded.

The highway sections used in these tests were selected as representative in type or roughness. They were marked in one-twentieth mile lengths and points were spotted on the pavements to guide the trucks over the test sections. Letter symbols were used to designate the various highways, as shown in Table 6, and the test sections were all straight, nearly level, and with but slight crowns.

FIGURE 2.—REPRESENTATIVE TIRE EQUIPMENTS SELECTED FOR TESTS

TABLE 1.—*Truck specifications (empty)*

Capacity of truck .... tons	2	5
Truck symbol	B	A
Wheel base .... feet	13.55	13.00
Normal tread width:		
Rear .... do	5.45	5.42
Front .... do	4.95	5.30
Overall:		
Length .... do	20.3	19.2
Width .... do	7.2	7.4
Inside body:		
Width .... do	6.5	6.3
Length .... do	12.0	11.5
Inside end of body to rear axle .... do	4.65	2.15
Height of body floor:		
Rear .... do	[1] 4.08	[2] 4.03
Front .... do	[1] 3.87	[2] 3.78
Tire equipment, front	([3])	([4])
Weight of truck:		
Total .... pounds	[1] 7,670	[2] 11,423
Front axle .... do	2,940	5,075
Rear axle .... do	[1] 4,730	[2] 6,348
Sprung weight, rear axle .... do	3,250	3,900
Unsprung weight, rear axle .... do	[1] 1,480	[2] 2,448
Number of leaves in rear spring	10	17
Number of leaves in front spring	9	15
Total spring thickness:		
Rear .... feet	.32	.60
Front .... do	.23	.41
Spring width:		
Rear .... do	.29	.29
Front .... do	.21	.20
Spring length:		
Rear .... do	4.47	4.47
Front .... do	3.30	3.55
Spring camber:		
Rear .... do	.14	.16
Front .... do	.23	.16
Approximate spring rate per inch, rear .... pounds	1,200	2,000

[1] Based on dual 36 by 4 inch new solid tires on rear wheels (tire No. 40).
[2] Based on dual 36 by 6 inch new solid tires on rear wheels (tire No. 37).
[3] 35 by 5 single pneumatic 65-pound pressure.
[4] 34 by 6 single nonskid solid.

TABLE 2.—*Test data*

Tire type, truck, and test symbol	Pneumatic		New cushion	
	2-ton 47–B	5-ton 49–A	2-ton 16–B	5-ton 7–A
Accelerometer:				
Spring weight combination	2a.6.H	3a.B.L	2a.6.0	3a.B.C
Free period of vibration, seconds	0.06192	0.05640	0.03351	0.03693
Calibration factor, feet per second per second per inch	429	517	1,496	1,275
Unsprung weight per rear wheel, pounds	740	1,190	820	1,380
Unsprung mass per rear wheel	23.0	37.0	25.5	42.8
Mass multiplied by calibration factor	9,870	19,130	38,150	54,570
Tire size, dual mounting, inches	36 by 6	38 by 7	36 by 5	36 by 7
Tire capacity:				
Light load, per cent	57	125	73	107
Heavy load, per cent	114	167	147	143

Tire type, truck, and test symbol	New solid		Worn solid	
	2-ton 40–B	5-ton 37–A	2-ton 39f–B	5-ton 31f–A
Accelerometer:				
Spring weight combination	2a.2.L	3a.D.L	2a.2. F	3a.D.F.
Free period of vibration, seconds	0.02539	0.02542	0.01983	0.02004
Calibration factor, feet per second per second per inch	2,655	2,654	4,604	4,523
Unsprung weight per rear wheel, pounds	740	1,224	751	1,115
Unsprung mass per rear wheel	23.0	38.0	23.3	34.6
Mass multiplied by calibration factor	61,060	100,850	107,270	156,500
Tire size, dual mounting, inches	36 by 4	36 by 6	36 by 4	36 by 6
Tire capacity:				
Light load, per cent	62	89	62	89
Heavy load, per cent	125	119	125	119

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TABLE 3.—*Tire data*

Test No.	Load: Percentage of capacity	Load: Actual	Deflection	Contact: Width	Contact: Length	Contact: Area	Average unit load: Per inch of width	Average unit load: Per square inch of area	Air pressure	Nominal size	Visible rubber height	Width: Top	Width: Bottom
		Lbs.	*In*	*In.*	*In.*	*Sq. in.*	*Lbs.*	*Lbs.*	*Lbs./sq. in.*	*In.*	*In.*	*In.*	*In.*
PNEUMATIC TYPE													
47	100	2.200	0.72	4.01	8.73	18.65	549	118	90	36 by 6	[1] 7⅛	4 1/16	6 21/32
	200	4.400	1.27	4.42	11.47	39.24	996	112	92				
	500	11,000	2.80	6.00	17.45	66.04	1,833	166	98				
49	100	3.000	.85	4.90	9.57	24.54	612	122	100	38 by 7	[1] 8	5	7 17/32
	200	6,000	1.51	5.25	12.36	46.70	1,143	129	101				
	500	15,000	3.34	7.40	18.85	80.50	2,027	186	108				
NEW CUSHION TYPE													
16	100	1,700	.42	3.35	7.83	15.28	507	111		36 by 5	3⅛	3¾	5
	200	3,400	.68	3.69	9.79	22.45	922	151					
	500	8,500	1.13	4.53	12.93	37.50	1,876	227					
7	100	3.500	.48	5.30	9.75	29.50	660	119		36 by 7	3¼	5⅜	7 1/16
	200	7,000	.74	5.77	11.60	42.42	1,213	165					
	500	17,500	1.21	6.78	14.38	62.88	2,581	278					
NEW SOLID TYPE													
40	100	1,700	.28	2.43	7.04	15.43	700	110		36 by 4	2	2¾	3 11/16
	200	3,400	.43	2.83	8.31	20.84	1,201	163					
	500	8,500	.69	3.48	10.40	30.25	2,442	281					
37	100	3,500	.45	3.83	7.80	26.75	914	131		36 by 6	2¼	4 5/16	5⅝
	200	7,000	.61	4.40	9.32	35.65	1,591	196					
	500	17,500	.89	5.38	11.53	52.75	3,252	332					
WORN SOLID TYPE													
39f	100	1,700	.10	3.50	3.82	11.66	486	146		36 by 4	¾	3 7/16	3¾
	200	3.400	.16	3.58	4.53	14.39	950	236					
	333	5.670	.21	3.72	5.16	17.40	1,526	325					
31f	100	3,500	.16	5.47	4.97	21.95	640	176		36 by 6	⅝	5 5/16	5⅛
	200	7,000	.22	5.66	5.90	27.25	1,236	258					
	333	11,670	.27	5.88	6.34	32.00	1,980	365					

[1] Over-all sectional height, fully inflated and including demountable rim.

TABLE 4.—*Load data*

	2-ton truck		5-ton truck	
Rear wheel total load ... tons	1¼	2½	3¾	5
Rear wheel, average unsprung load ... pounds	745	745	1,200	1,200
Rear wheel, average sprung load ... do	1,755	4,255	6,300	8,800
Rear axle load ... do	5,000	10,000	15,000	20,000
Front axle load ... do	3,005	4,255	7,240	8,490
Gross truck load ... do	8,005	14,255	22,240	28,490
Truck capacity ... per cent	8	164	109	171
Average ratio, Unsprung rear / Sprung rear	0.425	0.175	0.191	0.136
Average ratio, Unsprung rear / Total, rear	.298	.149	.160	.120

TABLE 5.—*Load data*

	Rear wheel load		Front wheel load
	Sprung	Total	Total
	Pounds	*Pounds*	*Pounds*
Average empty 2-ton truck	1,625	2,370	1,470
Average empty 5-ton truck	1,950	3,150	2,532

TABLE 6.—*Data on test road surfaces*

Road	Condition	Type	Direction	Location
				Washington, D. C.:
A	Fair	Sheet asphalt	W. to E.	N Street, Second to First Street SW.
B	Good	Asphalt block	N. to S.	South Capitol Street, P Street to Potomac Avenue.
C	Fair	do	S. to N.	South Capitol Street, Potomac Avenue to P Street.
D	Good	Sheet asphalt	do	First Street, O Street to N Street SW.
E	Poor	Stone [1]	do	First Street, N Street to M Street SW.
F	Fair	Macadam	E. to W.	M Street, First Street to Second Street SW.
G	Poor	do	N. to S.	Delaware Avenue, M Street to N Street SW.
H	Good	Vitrified brick	W. to E.	Alexandria, Va., King Street, railroad bridge to Little River Road.

[1] Old stone road, neither cobble nor stone block in type. It was selected because it could be relied upon to maintain its roughness during these tests.

The test road surfaces were calibrated with the relative roughness indicator [4] being developed by the bureau. This was carefully done at varying speeds, and the maximum and minimum roughness factors obtained at a car speed of 30 miles per hour were approximately 800 and 100 units per mile. The instrument was installed between the front axle and chassis frame of a large sedan automobile fully equipped with rebound snubbers and 6.50 by 20 balloon tires inflated to a pressure of 35 pounds.

Since the vehicle on which the device is mounted is an integral part of the apparatus, the data obtained with one vehicle are not directly comparable with those obtained with another. However, as the same vehicle was used to obtain data on each of a series of roads it is believed that the respective factors obtained indicate the relative roughness with reasonable accuracy.

The road sections had been selected and the impact tests substantially completed before the relative roughness indicator was available. It was later found that the surface roughness range could be adequately covered by five of the eight sections tested. Final computations were therefore made for the five roads only. The roughness calibration curves for the selected sections are shown in Figure 5.

Municipal authorities in the District of Columbia and in Alexandria, Va., were interested cooperators in the tests made within their jurisdictions. Traffic officers were assigned to assist in the work and they were extremely valuable in making it possible to conduct the tests on the public streets with safety. "No parking" signs were placed temporarily at several points to facilitate the work. Figure 6 shows the equipment used in these tests.

[4] See An Instrument for the Measurement of Relative Road Roughness, Public Roads, vol. 7, No. 7, September, 1926.

DATA CONSIDERED TO INDICATE ONLY GENERAL TRENDS BECAUSE OF LIMITATIONS OF THE TESTS

The data herein presented are based upon operations with the equipment described and it is desirable that the limitations which should be applied in their practical use be thoroughly understood.

Although the two trucks which were used are familiar commercial products, they differed from each other considerably in design and the loads on them varied widely when expressed in terms of truck capacity.

The data are influenced also by the particular tire equipments used. While these tires were selected as representative of their respective types at the time they were furnished, it is undoubtedly true that, due to the development in truck tire manufacture, better tires are being made to-day. Thus, in a sense, the tires used may be considered obsolete. Nevertheless, so far as type and condition are concerned, these tires do not depart widely from the general run of tires found in truck service at the present time. The data are applicable to current practice provided due allowances are made for changes in such major characteristics as tire dimensions.

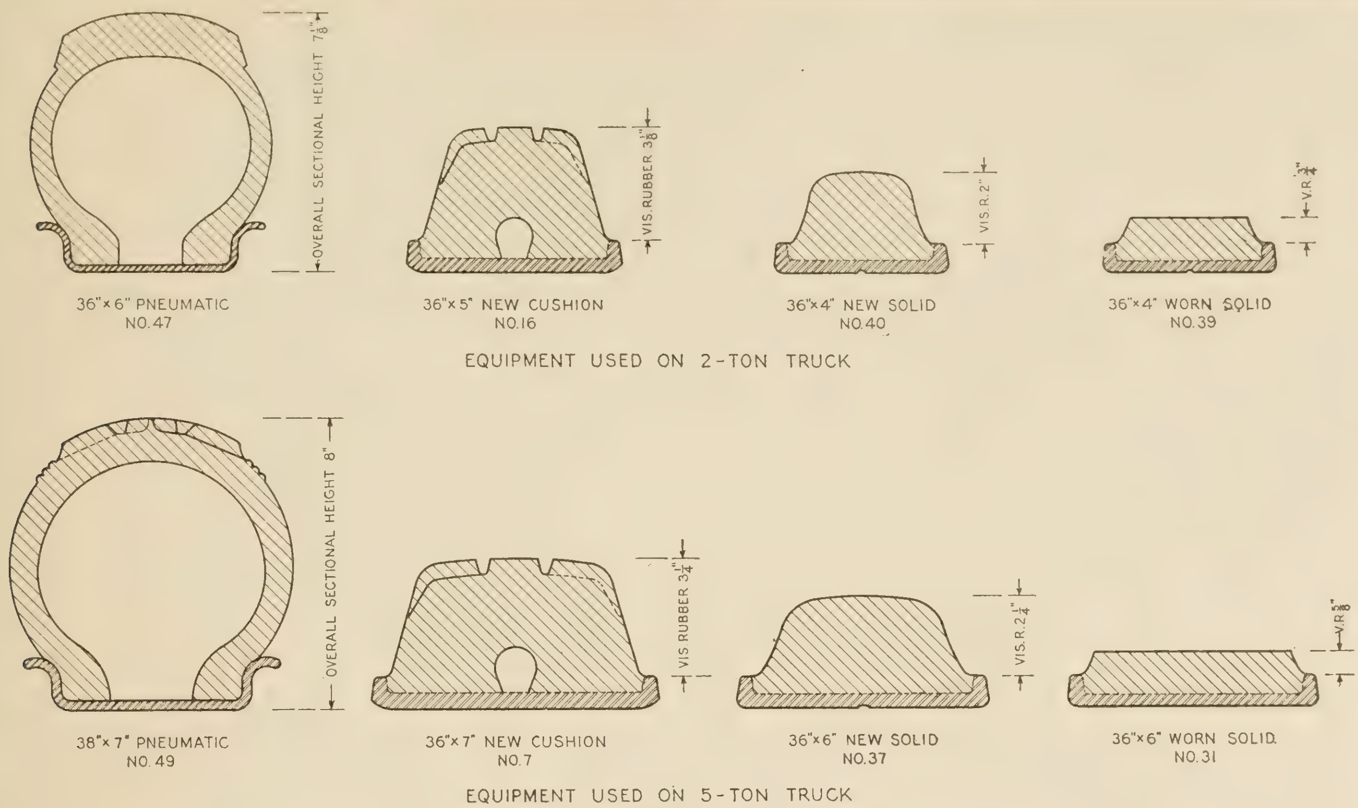

Figure 3.—Sections of the Representative Tires Selected for Tests

The principal limitation appears to be in the assignment of roughness qualities to the various road surfaces. Verbal descriptions are not adequate since, obviously, the same interpretation would not universally be made from them. Photographs were taken but were found unsatisfactory in bringing out differences. Detailed profiles might have been taken but the application of the data to actual problems would then have necessitated similar arduous processes in obtaining profiles for each and every application. The relative roughness indicator offered the most ready means for evaluating the surface roughness of the roads. It was recognized that the factors of roughness pertain only to the particular indicator installation with which they were obtained. They are relatively correct and sufficiently accurate with respect to one another to express the general differences between the various test sections.

In view of these limitations the data presented in this report are considered to indicate general trends of the interrelated effects of the four major variables under discussion.

METHOD OF EXPRESSING IMPACT VALUES DESCRIBED

It was decided that for each combination of the four variables the average of the five highest impacts occurring within the one-twentieth-mile test sections would be a reasonable and representative value to seek. For different combinations, then, of the four major variables—road, tire, load, and speed—this value represents the average magnitude of the greatest impact forces which might reasonably be expected to occur as frequently as one hundred times per mile. Although this was an arbitrary selection, it was felt that if the heavier impact reactions occurred on a given road at least as frequently as one hundred times per mile (an average of once every 50 feet) their average would be a representative criterion of that particular surface condition. Since the unsprung component of motor-truck impact is generally the major or critical quantity, it was considered sufficient to compute the unsprung impact component (determined by multiplying the unsprung mass by its acceleration) and to add to it the sprung component (determined by static weighing) in order to arrive at the total impact force developed by the rear wheel. Up to the present time, there has been no attempt to express the absolute maximum impact within the one-twentieth-mile section in terms of the average of the five highest impacts, but the data are available whenever the derivation of such an expression may be found desirable.

The impact reaction was plotted against truck speed for each of the test conditions and smooth curves were drawn through these plotted points. These curves were then read at regular intervals to obtain data for the construction of the isograms. The inclusion in this report of copies of all of the original records, the computation tabulations, and the preliminary work sheets therefrom would only make it unnecessarily extended.

EXAMPLE OF METHOD OF COMPUTATION PRESENTED

As an example of the method of constructing the isograms, the following detailed procedure is given for one of the intermediate conditions—new solid-tire equipment on the fair sheet asphalt surface.

For this, as in all of the selected combinations of tire equipment and road surface, runs for each of the four loads were made at speeds from about 3 miles per hour up to the maximum obtainable, in increments of about 3 miles per hour. For each run a record was obtained with the coil spring accelerometer used in previous

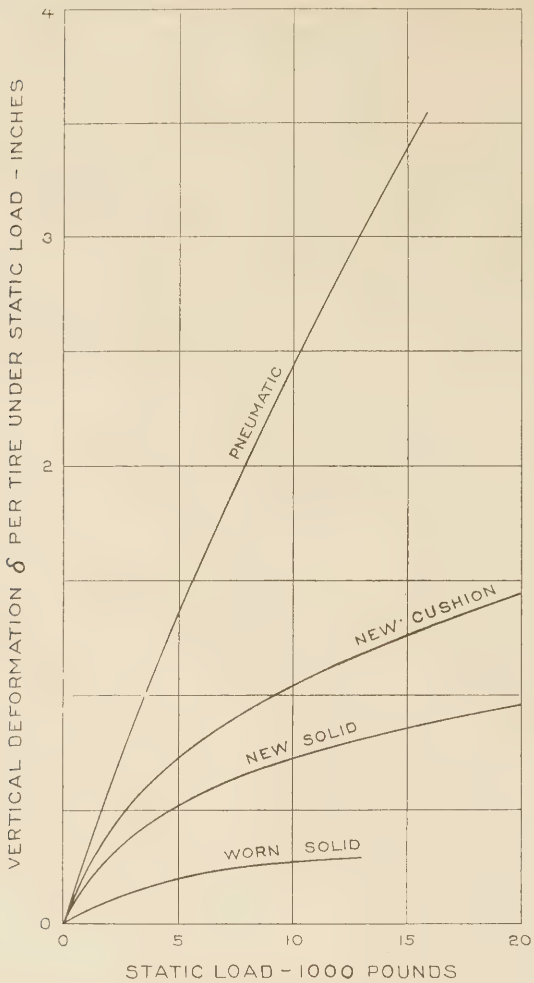

Figure 4.—Average Static Load; Deflection Curves of the Tire Types Used

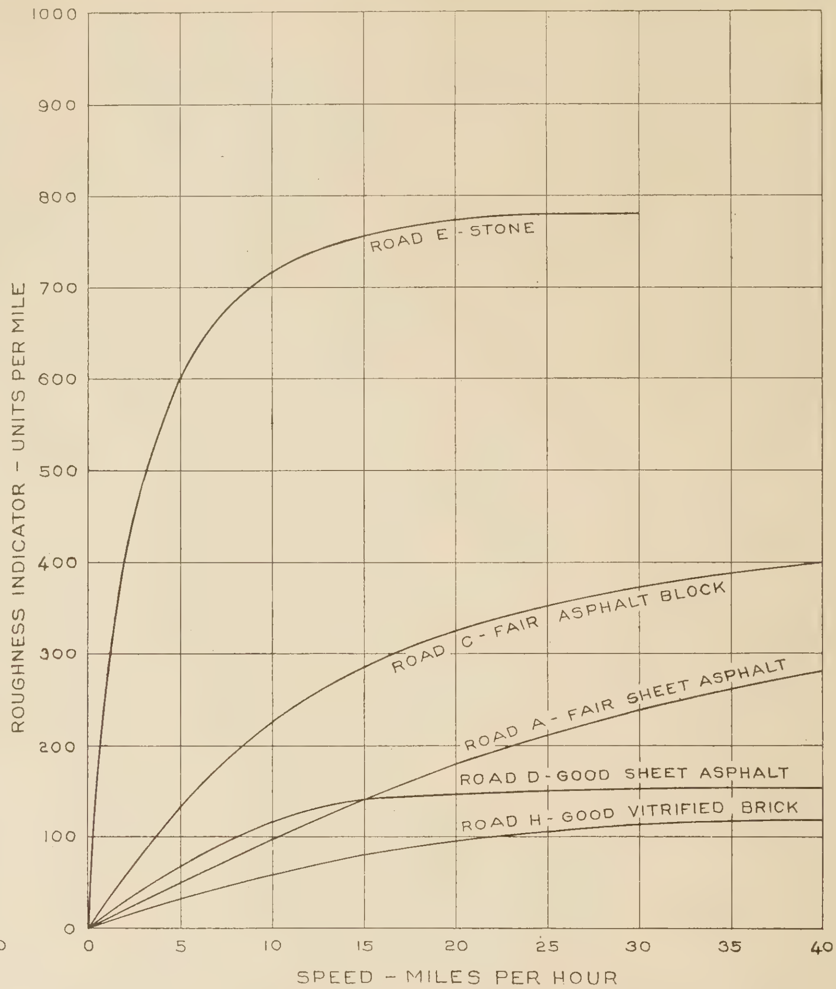

Figure 5.—Calibration of Roughness of Test Sections With Relative Roughness Indicator

impact tests. The average speed for each run was computed from a stop-watch measurement of the elapsed time during which the truck was passing over the measured test section.

The five greatest accelerometer deflections were then measured and the average deflection (of these five) obtained for each run. These data were listed as illustrated by Table 7. In the field, a rough check was obtained at this stage by plotting average accelerometer deflection against truck speed and checking any doubtful points before changing to the next test condition.

The average accelerometer deflections and truck speed were next listed on computation sheets and total forces computed, as illustrated by Table 8, according to the following formula:

$$F=S+mcr,$$

where

F = impact force for right rear wheel,
S = static total weight per rear wheel,
m = mass of unsprung weight per rear wheel,
c = accelerometer rate for the given conditions,
r = accelerometer deflection.

A preliminary work sheet was made on which impact force was plotted against speed and curves drawn through these points. Figure 7 is a typical example of a work sheet and is based on the data given in Table 8. From the smooth curves drawn on the work sheets, readings were taken at regular intervals for plotting on the isogram sheets. In Figures 8 to 12 the small cross symbols represent points so obtained and the corresponding forces in thousand-pound units are indicated by the adjacent numerals.

The portion of Figure 10 representing new solid tires is directly comparable with the typical work data above described. The construction of the actual isodynamic curves in 5,000-pound intervals was then made by a process (similar to the construction of contour maps from plotted survey computations) of obtaining points on the desired curves by interpolation and the drawing of smooth curves through the points so obtained. In Figures 8 to 12 the small filled circles indicate the interpolated points.

ISOGRAMS USED TO PRESENT DATA

A separate isogram was made for each test road according to the above method. As in the original isogram for the test road at Arlington Farm, the coordinates are wheel-load and truck speed, separate graphs being made for the four types of tire. The curves are lines of equal impact reaction and are drawn in increments of 5,000-pound reaction. It is again mentioned that the impact reaction is the average value of the greatest impact forces reasonably expected to occur as frequently as one hundred times per mile.

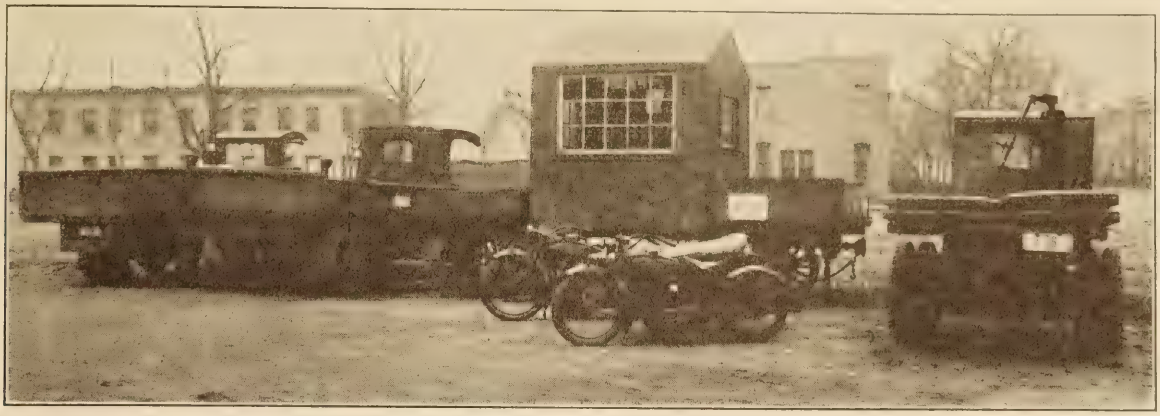

FIGURE 6.—EQUIPMENT USED IN TESTS. ON THE LEFT ARE THE 2-TON AND 5-TON TEST TRUCKS. IN THE CENTER IS THE TRAILER EQUIPPED WITH A FIELD OFFICE AND TWO LOADING AND STORAGE PLATFORMS. ON THE RIGHT IS THE SERVICE TRUCK ON WHICH IS MOUNTED A CHAIN HOIST FOR CHANGING TIRES. THE MOTOR CYCLES WERE USED BY LOCAL TRAFFIC OFFICERS

In making the selection of road surfaces for these tests it was necessary to give consideration to three conditions. First, they should include the extremes of surface condition from very smooth to very rough; second, they should furnish a sufficient number of types so that the data would cover the range between these extremes as well as possible; and, third, the pavement selected should be of such character that they would not change in condition during the tests. It would have been very difficult to fulfill all these conditions perfectly. It is believed, however, that the sections selected represent a very wide range in roughness and that all of them maintained their characteristics during the tests, but with the pavements which were available in the vicinity of Washington, it was not possible to cover the range in roughness in as uniform a manner as might be desired. Referring to Figure 5, it will be noted that there is a gap between the curves for Roads C and E. However, it is thought that the majority of pavements carrying any considerable amount of traffic will be found to have surfaces as smooth or smoother than Road C, so that the deficiency just mentioned is not so important as might appear from a cursory inspection of the surface roughness data contained in this figure.

TABLE 7.—*Typical field data sheet from tests of fair sheet asphalt using new solid tires*

2,500-POUND WHEEL LOAD														
Speed, m. p. h.	27.2	23.1	22.0	19.1	16.7	13.0	10.8	8.1	5.3	16.4	20.0	17.0	18.0	23.7
Accelerometer deflections, inches	0.205 .177 .167 .162 .158	0.160 .140 .105 .098 .088	0.152 .150 .105 .096 .096	0.180 .126 .110 .102 .092	0.066 .055 .052 .050 .049	0.047 .035 .035 .033 .032	0.056 .032 .030 .023 .023	0.016 .014 .014 .013 .013	0.011 .003 .003 .003 .002	0.075 .063 .062 .050 .050	0.174 .163 .092 .086 .085	0.096 .072 .063 .063 .058	0.127 .080 .078 .076 .075	0.162 .137 .132 .110 .098
Average deflection, inches	.174	.118	.120	.122	.054	.036	.033	.014	.004	.060	.120	.070	.087	.128
5,000-POUND WHEEL LOAD														
Speed, m. p. h.	5.3	7.3	10.4	13.4	19.2	14.6	22.5	25.0						
Accelerometer deflections, inches	0.002 .002 .002 .000 .000	0.011 .008 .008 .005 .004	0.023 .022 .018 .017 .016	0.058 .035 .033 .029 .028	0.083 .078 .078 .076 .075	0.068 .058 .041 .040 .038	0.152 .137 .130 .125 .113	0.188 .173 .130 .116 .093						
Average deflection, inches	.001	.007	.019	.037	.078	.049	.131	.140						
7,500-POUND WHEEL LOAD														
Speed, m. p. h.	5.2	8.5	9.9	13.6	15.0	20.9	14.5							
Accerlerometer deflections, inches,	0.013 .010 .007 .006 .003	0.018 .015 .013 .012 .010	0.022 .018 .016 .015 .015	0.048 .029 .028 .028 .028	0.052 .036 .034 .033 .032	0.078 .078 .073 .064 .063	0.045 .037 .032 .028 .027							
Average, deflection, inches	.008	.014	.017	.032	.037	.071	.034							
10,000-POUND WHEEL LOAD														
Speed, m. p. h.	19.6	16.7	14.1	10.0	8.0	5.7								
Accelerometer deflections, inches	0.068 .052 .046 .045 .044	0.050 .046 .045 .033 .033	0.038 .033 .032 .030 .026	0.020 .013 .013 .013 .013	0.014 .013 .008 .008 .007	0.008 .006 .006 .006 .005								
Average deflections, inches	.051	.041	.032	.014	.010	.006								

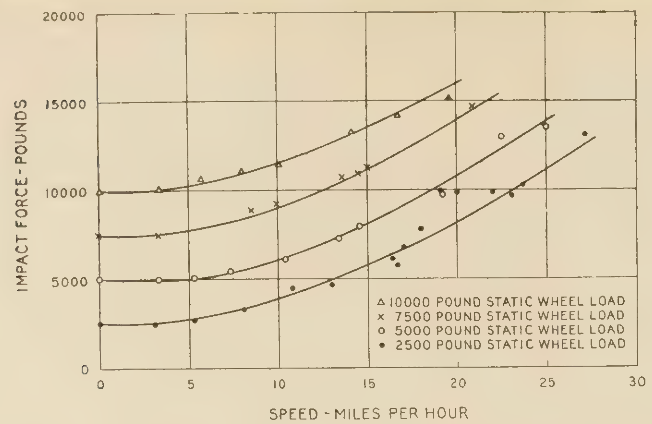

Figure 7.—Typical Work Sheet Showing Results of Tests on Road A Using Solid Tires

The isograms obtained for the five representative sections are shown in Figures 8 to 12, inclusive. In using them, the probable impact reaction (at the rate of 100 per mile of road) may be directly determined for any reasonable combination of wheel load and truck speed, whenever the road and tire conditions under consideration are identical with those of the isogram test conditions. If, however, the road condition or the tire condition (or both) should be different from those of the tests, then processes of single or double interpolation must be resorted to in applying the test data.

APPLICATION OF DATA BY PROCESS OF INTERPOLATION ILLUSTRATED

As an illustration, let us determine the impact reaction caused under the following assumed conditions.

Road: Intermediate in roughness between the sheet asphalt and asphalt block surfaces represented by Roads A and C. Let is be designated as Road X.

Tire: Intermediate in cushioning quality between new solid and worn solid equipment.

Load: 7,000 pounds per wheel.

Speed: 17 miles per hour.

So far as the assumptions as to load and speed are concerned, the reactions are read directly from the curves.

In determining the impact force for a condition which requires interpolation between two adjacent curves, it is recommended that interpolation be made through the point in question along a line approximately normal to the curves as shown on the graph for new solid tires in Figure 10. The curves were originally located by interpolations in both of the coordinate directions and the slope of the "nearest normal" determines the proportionate weights given to the load and speed influences.

In order to make the method clear, it will be illustrated by the following examples: As a simple case let it be assumed that it is desired to determine the probable approximate impact reaction for a truck equipped with new solid tires, having a rear wheel load of 7,000 pounds, travelling at 17 miles per hour over a road whose roughness is that of Road A used in

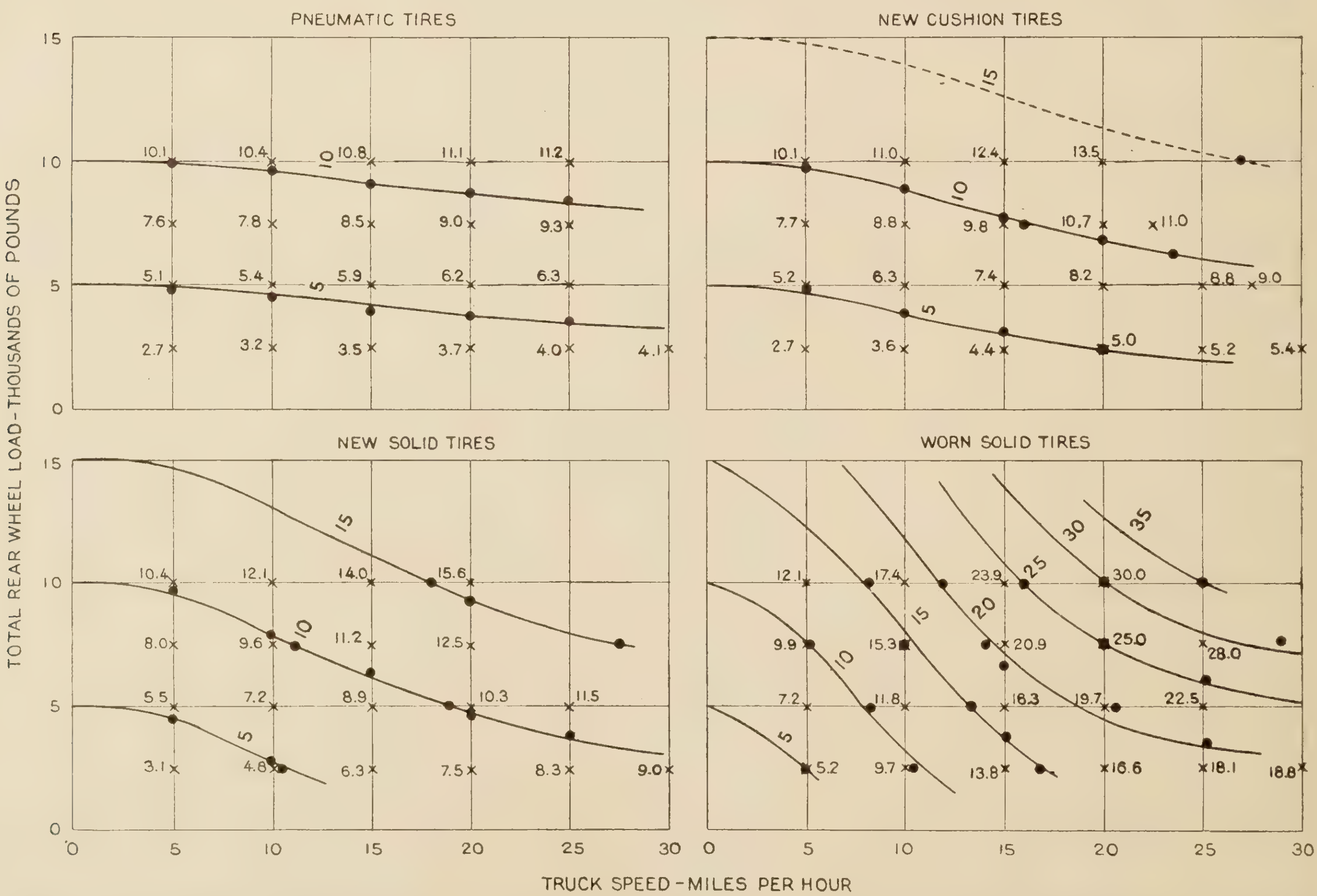

Figure 8.—Isodynamic Curves for Good Vitrified Brick Highway (Road H) for Determination of Average Total Vertical Reactions in Thousands of Pounds Occurring at the Rate of 100 per Mile

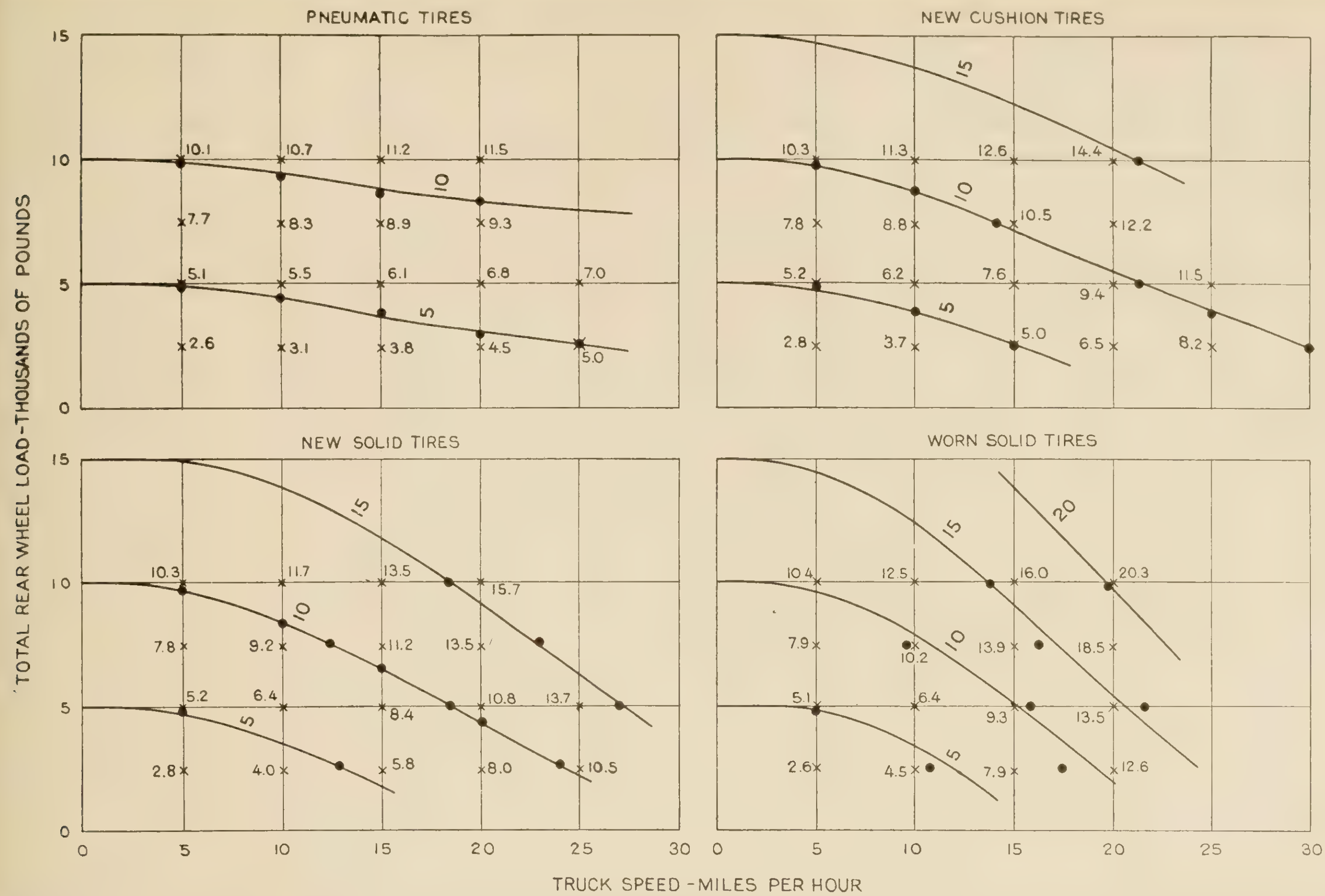

FIGURE 9.—ISODYNAMIC CURVES FOR GOOD SHEET ASPHALT HIGHWAY (ROAD D) FOR DETERMINATION OF AVERAGE TOTAL VERTICAL REACTIONS IN THOUSANDS OF POUNDS OCCURRING AT THE RATE OF 100 PER MILE

the test. Referring to Figure 10, and using the speed (17) and the wheel load (7,000) as coordinates, a point is located which lies between the impact reaction curves for 10,000 and 15,000 pounds. If a line is erected through this point approximately normal to the curves, as explained above, and an interpolation is made between the curves along this line, it will be found that the impact reaction indicated for the assumed conditions is about 11,500 pounds.

As a somewhat more difficult example let it be assumed that the roughness of Road X has been determined at the speed assumed in our example (17 miles per hour) at 250 units per mile. The simplest reasonably close interpolation between the two isogram road conditions is according to a straight line relation. At 17 miles per hour the roughness of Roads A and C are 158 and 302 units per mile, respectively. Reactions for Road X will be in excess of those for the smoother road by the proportional amount (indicated by the ratio of the road roughness differences) of the difference in reaction for Roads A and C. At the assumed speed, Road X is 92 units and Road C is 144 units rougher than Road A. Therefore, reactions for Road X are in excess of those for Road A by 92/144, or 64 per cent of the difference between the reactions for Roads A and C. The reactions are listed below.

	Road A	Road C	Difference	Correction	Road X
New solid tires	11, 500	14, 200	2, 700	1, 700	13, 200
Worn solid tires	15, 900	25, 000	9, 100	5, 800	21, 700

TABLE 8.—*Typical computation sheet showing force computations from average accelerometer deflections given in Table 7*

Instrument: 2a-2-L m=23.0 c=2,655 mc=61,060						Instrument: 3a-D-L m=38.0 c=2,654 mc=100,850					
Wheel load, 2,500 pounds			Wheel load, 5,000 pounds			Wheel load, 7,500 pounds			Wheel load, 10,000 pounds		
Deflection	Force	Speed	Deflection	Force	Speed	Deflection	Force	Speed	Deflection	Force	Speed
Inches	*Lbs.*	*M.p.h.*	*Inches*	*Lbs.*	*M.p.h.*	*Inches*	*Lbs.*	*M.p.h.*	*Inches*	*Lbs.*	*M.p.h.*
0. 004	2, 740	5. 3	0. 001	5, 060	5. 3	0. 008	8, 310	5. 2	0. 006	10, 610	5. 7
. 014	3, 350	8. 1	. 007	5, 430	7. 3	. 014	8, 910	8. 5	. 010	11, 010	8. 0
. 033	4, 510	10. 8	. 019	6, 160	10. 4	. 017	9, 210	9. 9	. 014	11, 410	10. 0
. 036	4, 700	13. 0	. 037	7, 260	13. 4	. 032	10, 730	13. 6	. 032	13, 230	14. 1
. 060	6, 160	16. 4	. 049	7, 990	14. 6	. 034	10, 930	14. 5	. 041	14, 130	16. 7
. 054	5, 800	16. 7	. 078	9, 760	19. 2	. 037	11, 230	15. 0	. 051	15, 140	19. 6
. 070	6, 770	17. 0	. 131	13, 000	22. 5	. 071	14, 660	20. 9	------	------	------
. 087	7. 810	18. 0	. 140	13, 550	25. 0	------	------	------	------	------	------
. 122	9, 950	19. 1	------	------	------	------	------	------	------	------	------
. 120	9, 830	20. 0	------	------	------	------	------	------	------	------	------
. 120	9, 830	22. 0	------	------	------	------	------	------	------	------	------
. 118	9, 710	23. 1	------	------	------	------	------	------	------	------	------
. 128	10, 320	23. 7	------	------	------	------	------	------	------	------	------
. 174	13, 120	27. 2	------	------	------	------	------	------	------	------	------

IMPACT OF PARTIALLY WORN SOLID TIRES

Reactions for tire equipments intermediate between the new solid and worn solid types may be computed by adding to the reaction for new solid tires a certain proportional amount of the difference between the reactions for new solid and worn solid tires. We are able to obtain a rational factor for such use by

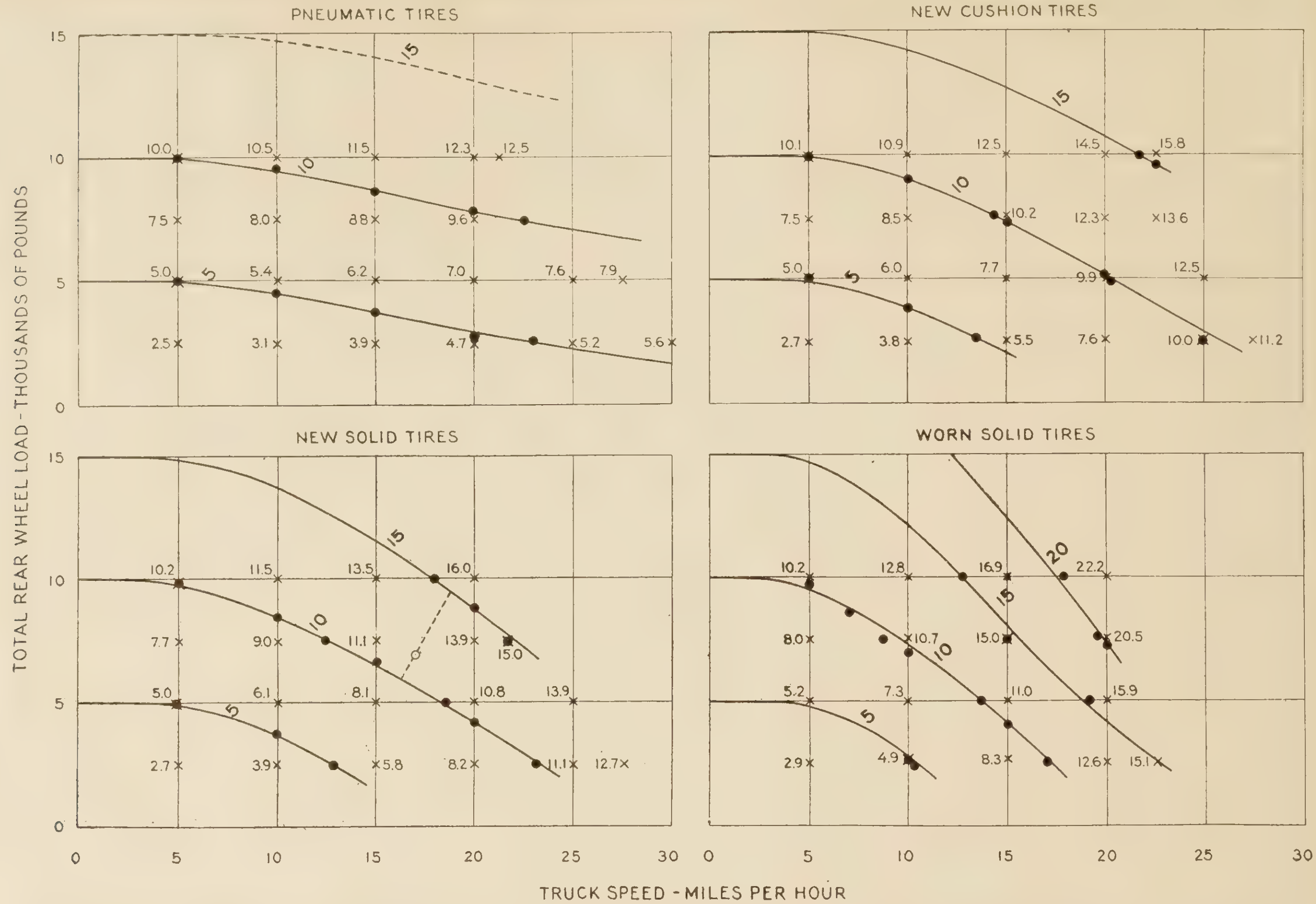

Figure 10.—Isodynamic Curves for Fair Sheet Asphalt Highway (Road A) for Determination of Average Total Vertical Reactions in Thousands of Pounds Occurring at the Rate of 100 per Mile

adapting data obtained on the artificially obstructed road in the separate research concerning the influence of tire height on impact reaction which is reported in this issue of Public Roads. This adaptation was necessary because the isogram tests involve a wide range in road roughness conditions and only two specific solid tire conditions. The influence of tire height on the proportional part of the difference between the reactions for new and worn solid tires as used in these isogram tests (which is the correction to be added to the reaction for new solid tires in order to arrive at the reaction for partially worn solid tires) has been computed from the data on cut-down tires presented in the other report and is shown in Figure 13, the limits in tire wear corresponding to the average heights of the two solid tire types used in the isogram tests. As the worn solid tires used in the tests on which the isogram curves are based had a loss averaging 68 per cent of the visible rubber on the new solid tires, the limits of loss in visible rubber in Figure 13 are 0 and 68 per cent and the corresponding proportional corrections are 0 and 100 per cent of the difference in reactions for the two types.

We are now in a position to compute the reaction on Road X, at the assumed load and speed, for a given condition of partially worn solid tire. If the height of visible rubber of this tire had been orginally, say, 2.10 inches, and in its partially worn condition was, say, 1.60 inches, then the loss in visible rubber would be 0.50 inch or 24 per cent of the original height. Referring to Figure 13 we obtain the factor 0.22 by which the difference between the reaction for new and worn solid tires is to be multiplied. This product is the correction to be added to the reaction for new solid tires to obtain the reaction for the partially worn tire. This computation is tabulated as follows:

	New solid	Worn solid	Difference	Correction	Partially worn
Road X	13,200	21,700	8,500	1,900	15,100

The reaction, then, for the conditions we have assumed for the four major variables is in round numbers 15,000 pounds, and should reasonably be expected to occur at the rate of one hundred times per mile or once in every 50 feet

In the report on tests on cut-down tires, it is indicated that for a given height of visible rubber there is substantially no difference in impact reactions for cushion tires and replacement sizes of solid tires. It is, therefore, suggested as reasonable that cushion tires be regarded as solid tires after the visible rubber has been worn to the height corresponding to that of the replacement regular solid tire. In general, this wear would be about 1 inch.

It is not essential to consider worn solid tires with less visible rubber than those used in the tests covered by this report because such tires are generally unfit for further service. Usually they are neither true nor round, have considerable variations in cross-sectional rubber, and have undergone aging and hardening.

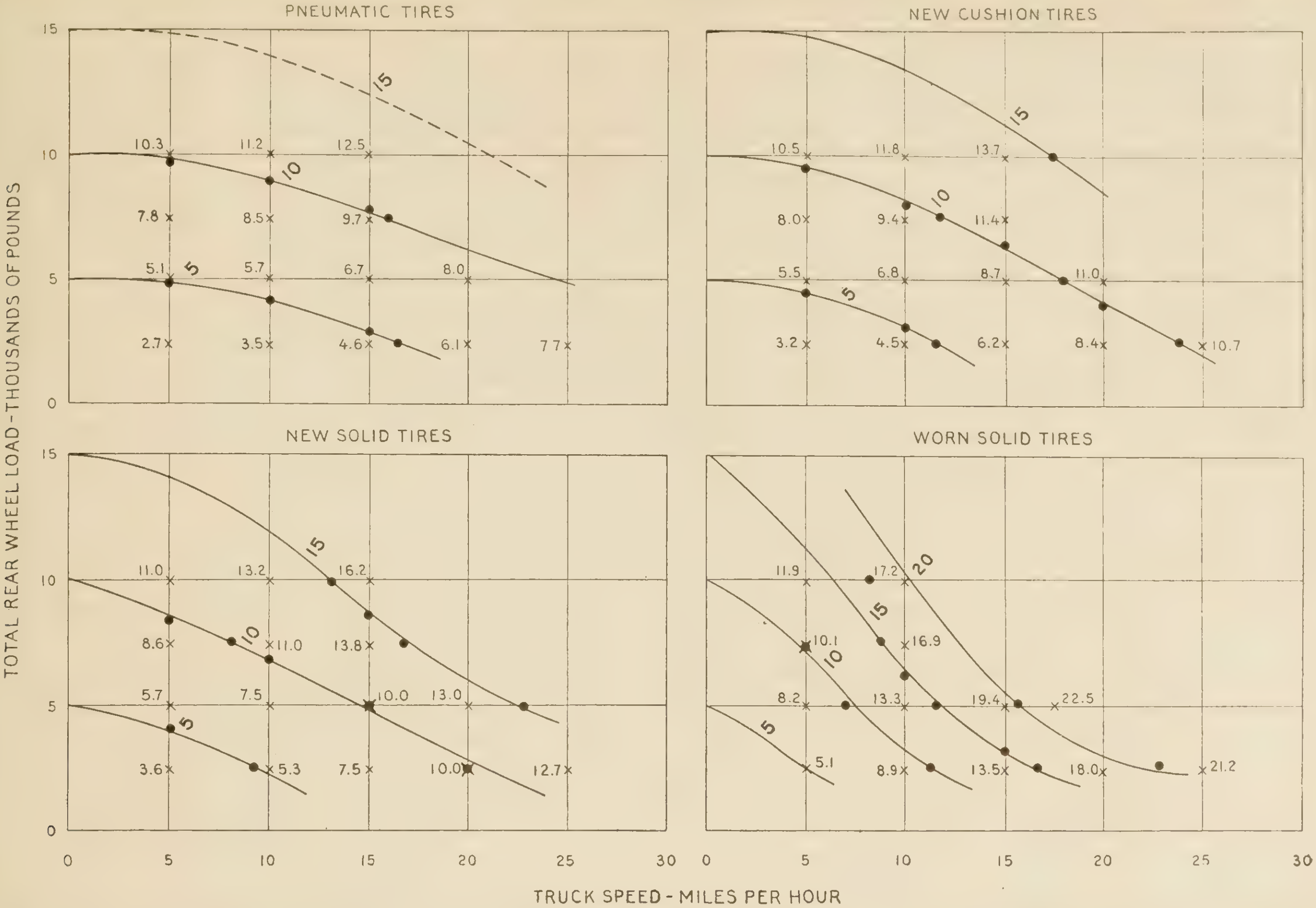

Figure 11.—Isodynamic Curves for Fair Asphalt Block Highway (Road C) for Determination of Average Total Vertical Reactions in Thousands of Pounds Occurring at the Rate of 100 per Mile

The worn tires, it has been pointed out, represent a loss in visible rubber amounting to about 68 per cent of that of new regular solid tires, the average residual height of visible rubber being about 0.68 inch.

As the worn tires of these tests were obtained by cutting new tires down to the desired height, they were of live rubber, true and round. For this reason, the results obtained with tires designated as worn are considered to represent conservatively the reactions for this general class.

In determining the factor to be used for any partially worn solid tire, according to the relation shown in Figure 13 and under present conditions of operating practice, it appears reasonable to assume, in general, that the height of visible rubber of new solid tires is the average height of the new regular solid tires used in these tests. This height is 2.2 inches.

ISOGRAM DATA SUGGEST BASIS FOR REGULATING VEHICLE SPEED ACCORDING TO TIRE EQUIPMENT

In the effort to control motor truck traffic on the highways so that its destructive impact effect will be minimized, a number of States have enacted laws which limit the speed of motor vehicles according to the tire equipment. Up to the present, however, there has been little or no information available as a rational basis for such laws. In the study of the data obtained in the present series of tests it was found possible to establish speed differentials which, when applied to the various types of tire used, would yield impact reactions of approximately the same magnitude and thus, for the first time, at least tentatively relate the variables of vehicle speed and tire type.

The data are by no means exhaustive for a study of this kind since the establishment of differential speed relations was not one of the foreseen objects of the tests. The values given in the following discussion and in Table 9 should not be considered as conclusively established, but they may be regarded as tentative differentials for relating in a general way the main tire classifications.

For the purposes of this comparison, the speeds at which each type of tire would cause the same impact reaction as that caused by the pneumatic tire at a maximum speed were tabulated for all the roads and for wheel loads ranging from 3,000 to 10,000 pounds, by 1,000-pound increments. The average speeds, when expressed as a percentage of that for pneumatic tires, appear in round numbers, as follows:

	Per cent
Pneumatic tires	100
New cushion tires	55
New solid tires	45
Worn solid tires	25

The above tabulation indicates, as a general average for the conditions of these tests, that the impact reactions with pneumatic tires at a maximum speed will be reproduced by other tire equipments at the respective percentages of the speed at which the pneumatic tire is operated. The relations for a convenient range of the variables involved have been listed in Table 9. For general use the classifications of tires should be as few as is practicable. The suggested

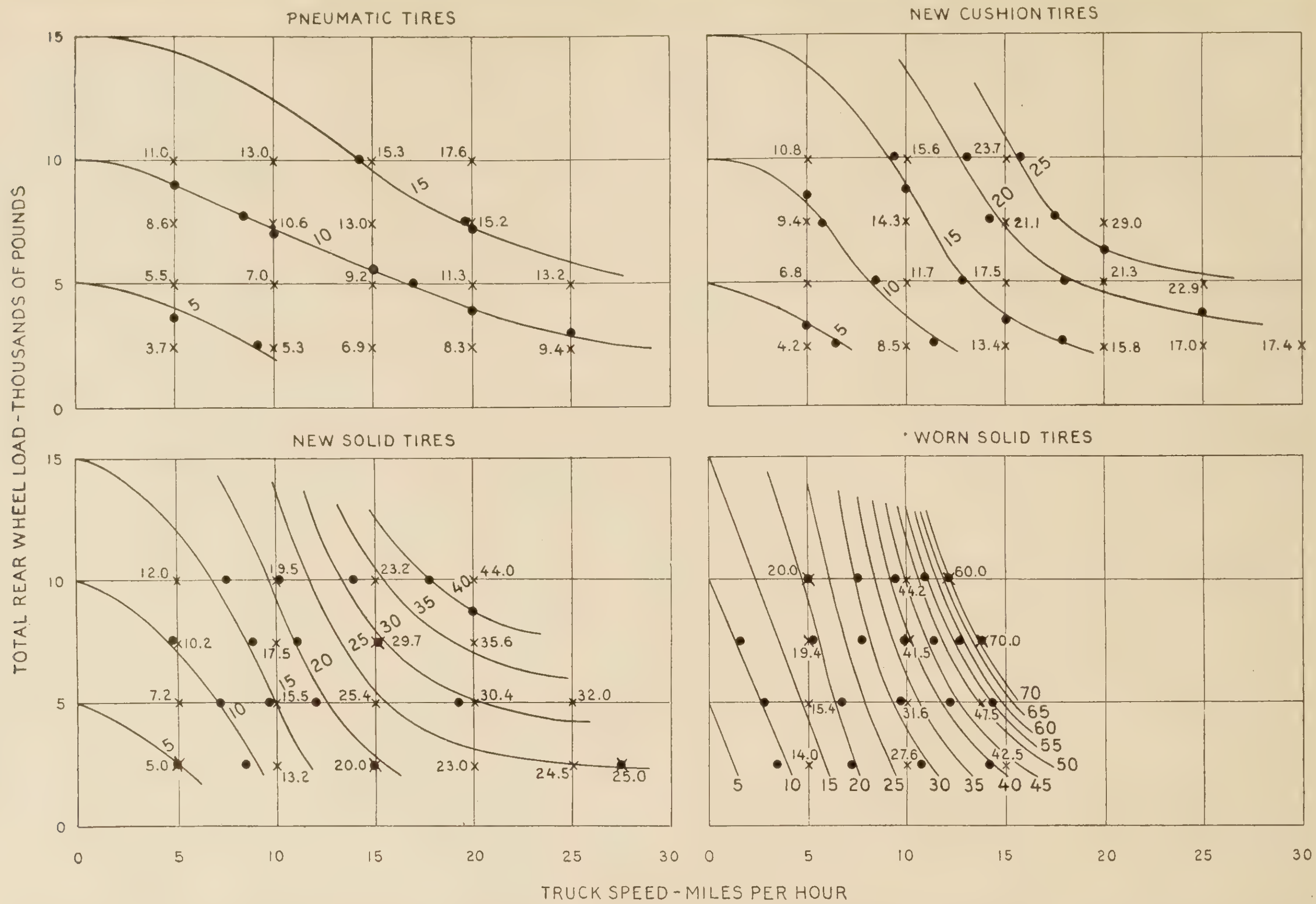

FIGURE 12.—ISODYNAMIC CURVES FOR STONE HIGHWAY (ROAD E) FOR DETERMINATION OF AVERAGE TOTAL VERTICAL REACTIONS IN THOUSANDS OF POUNDS OCCURRING AT THE RATE OF 100 PER MILE

percentages in Table 9 are not in every case the actual ratios of the computed averages because allowances have been made in order to approach more nearly average conditions of tires in service.

TABLE 9.—*Speeds at which approximately equal impact reactions would be produced by various types of tire equipment, as indicated by these tests*

Tire equipment	Relative speed						
	Per cent	*m.p.h.*	*m.p.h.*	*m.p.h.*	*m.p.h.*	*m.p.h.*	*m.p.h.*
Pneumatic	100	40	35	30	25	20	15
New cushion	55	22	19	16	14	11	8
New solid	40	16	14	12	10	8	6
Worn solid	20	8	7	6	5	4	3

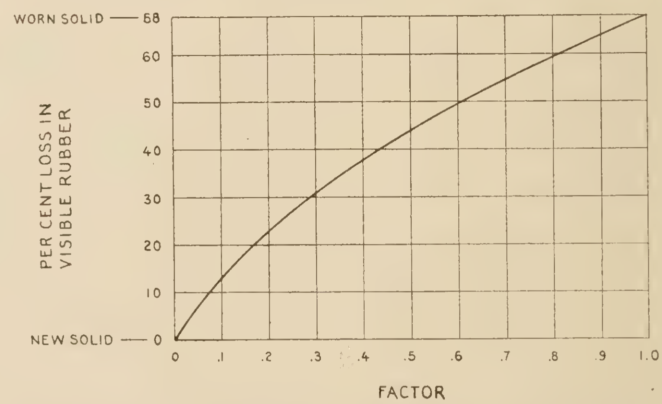

FIGURE 13.—DIAGRAM SHOWING FACTOR FOR USE IN EVALUATING PARTIALLY WORN SOLID TIRES INTERMEDIATE BETWEEN THE NEW SOLID AND WORN SOLID ISOGRAM TYPES

It will be noted that it is suggested that cushion tires be permitted to operate at 55 per cent of the speed allowed for pneumatic tires, and this is the actual average value found in the analysis of the test data. The tests reported in the article on pages 133 to 138 have indicated two conditions which were considered in arriving at this figure in which no allowance is made for slight wear found on nearly all tires in service. First, the effect of the loss of a unit height of visible rubber on the impact reaction increases as the amount of rubber worn off increases. The loss of the first inch in visible rubber height is not nearly so serious as are subsequent losses of 1 inch in height. Second, cushion tires and solid tires have practically the same cushioning properties when the load carrying capacities and the height of visible rubber are approximately equal. In this connection it has been suggested earlier in this report that the cushion tire designation be discontinued after such tires have been reduced to the height of the replacement sizes of regular solid tires. If these two indications are accepted as sound, they lead to the conclusion that cushion tires, so long as they are so classified, should be allowed a speed differential substantially the same as that indicated by the data from these tests, which were conducted with new cushion tires.

The tests indicate that new solid tires should be allowed to operate at a speed 45 per cent as great as that for pneumatic tires. As the average solid tire in service has undergone some wear, it is suggested that

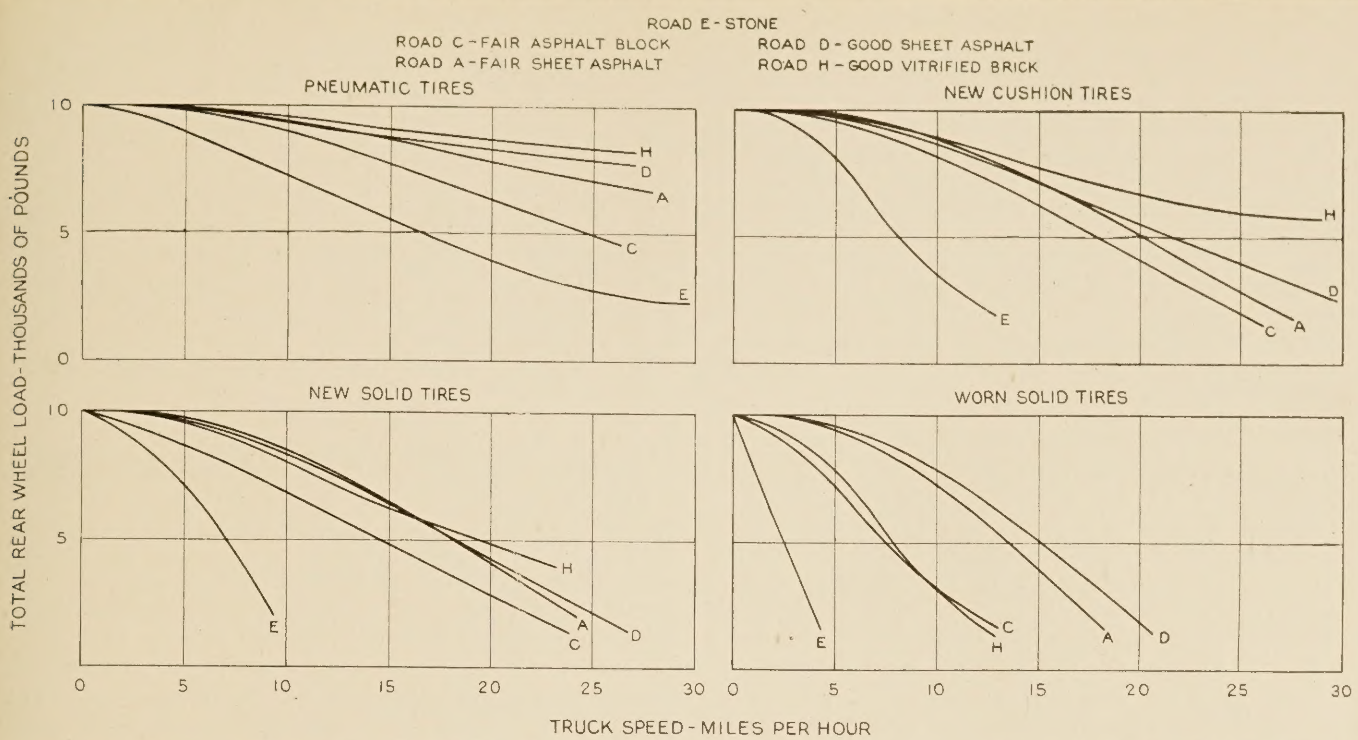

FIGURE 14.—ISODYNAMIC CURVES OF VARIOUS HIGHWAYS BASED ON 10,000-POUND TOTAL VERTICAL REACTION OCCURRING AT THE RATE OF 100 PER MILE

the speed for this class be lowered to 40 per cent of that permitted with pneumatic tires. This should give a differential better suited to the average condition of this class of tire.

Tires which have been worn down in service to the degree represented by the worn tires in the tests, in addition to having been subjected to aging and hardening influences are, as a rule, unevenly worn and are neither true nor round. Without question such service tires would cause appreciably greater reactions than those obtained with the test tires. As it would be practically impossible to select service-worn tires as being average or representative specimens, it was decided to cut down new tires to the height of rubber desired for the tests. It was realized that such test tires represented the best possible condition for worn tires and because of this the data are believed to be very conservative, and further, that any speed differential selected on the basis of these data should be considerably modified before it could properly be applied to the worn-tire class as a whole. For this reason the suggested value for this type is four-fifths of the actual value obtained from the isogram data.

OTHER ISOGRAM ARRANGEMENTS ILLUSTRATED

The isograms for the five road surfaces may be rearranged or regrouped in a number of ways in order to bring out various relations between the variable factors involved. An illustration of this is given in Figure 14, which shows the influence of the several surfaces on the combinations of wheel load and truck speed which result in a certain (10,000 pounds) impact reaction, the panels being for the several tire equipments. Similar graphs might be made for a series of impact reactions, such as 20,000 pounds, 30,000 pounds, etc.

The curves may be regrouped to show the influence of tire equipment on static wheel load and truck speed combinations which result in given impact reactions on given road surfaces. Other comparisons may be found desirable for application of the data to individual problems.

CHECK TESTS

Referring to Figure 5 it is noted that Road H is apparently smoother than Road D. A comparison of Figure 8 with Figure 9 and an inspection of Figure 14 shows that the impact data corroborate this for pneumatic, new cushion, and new solid tire equipments. The impact data for worn solid tire equipment, however, indicate that Road H is distinctly rougher than Road D. The reason for this apparent discrepancy is probably in the length of the contact between the tire and the road. Road D, being sheet asphalt, presents a continuous surface to the tire. On the other hand, Road H, being vitrified brick, presents joints approximately 3⅝ inches apart. The average lengths of contact of the four types of tire used in these tests are shown for the four wheel loads in Table 10, and these values show that the length of contact of worn solid tires is too short to overlap more than two joints of the vitrified brick (spaced 3⅝ inches) with the result that as each joint is passed it is the only joint in contact with the wheel. On the other hand, the other types of truck tire and the balloon tires on the passenger automobile which carried the relative roughness indicator had sufficient length of contact so that at least two joints were always within the contact length with a consequent decrease in the influence of the individual joints.

TABLE 10.—*Average length of tire contact with road surface in inches for various static wheel loads*

Type of tire	2,500 pounds	5,000 pounds	7,500 pounds	10,000 pounds
Dual pneumatic	7¼	9	10½	11¾
Dual new cushion	7¼	9	10	11
Dual new solid	6½	7½	8¼	8¾
Dual worn solid	3½	4¼	5	5¼

Although this theory appeared to be reasonable, it was thought advisable to rerun the tests with worn tires on the vitrified brick section, first, to check the findings for this particular test condition, and, second, to see if the isograms could be reproduced with reasonable accuracy. The original field tests on this surface were made in the latter part of November, 1926. Reruns were made during the latter part of January, 1927. The isogram drawn from the data of this check test with worn tires agrees very closely with the corresponding original isogram at the heavier loads, although the curves are somewhat steeper at the lighter loads. The discrepancy is not great, however, and is attributed mainly to weather differences; possibly there was a slight change in road roughness or in the condition of the tires which had not been used for a considerable period prior to the rerun tests. The check isogram is shown as Figure 15.

POSSIBLE MATHEMATICAL TREATMENT DISCUSSED

Further studies have indicated that the data may be condensed by the use of generalized coordinates. If the generalizations be properly made and not too broad the accuracy will not be seriously affected. Further development of the data at the present time necessitates greater dependence on the indications of the roughness indicator than its status now warrants.

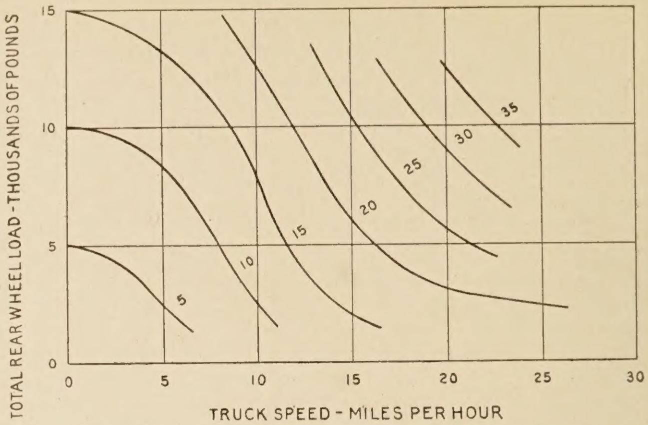

Figure 15.—Isodynamic Curves Resulting from Rerun Tests with Worn Solid Tires on Good Vitrified Brick Highway

Should this instrument eventually become standardized, it is not impossible that a formula may be developed for the computation of impact force for any combination of the four major variables, with an accuracy sufficient for most practical purposes.

(Continued from p. 138)

tire. This, again, should lead one to expect the difference between solid and cushion tires indicated in Figure 8.

As an example, consider the following cases for a 2-ton truck:

If the average height of visible rubber for a new solid tire were 2.1 inches, the corresponding average impact reaction would be about 340 per cent of the static load. If this tire were worn down to a height of visible rubber of 1 inch, it would have lost 1.1 inches of visible rubber, or about 52.5 per cent of what it originally had, and the average impact reaction would be about 220 per cent of that of the new tire. The reaction of the worn tire would thus amount to 2.20×340, or 748 per cent of the static load.

If the average height of visible rubber for a new cushion tire were 3.1 inches, the corresponding average impact reaction would be about 215 per cent of the static load. If this tire were worn down to the same height of visible rubber (1 inch) as the solid tire above mentioned, it would have lost 2.1 inches, or nearly 68 per cent, and the average impact reaction would be about 350 per cent of that of the new cushion tire. The reaction of this worn tire would thus amount to 3.50×215, or 753 per cent of the static load.

If the static load on the two types of tire were equal, the impact reactions for the tires worn to 1 inch of visible rubber would be approximately the same in pounds. If the tires were carrying their rated capacity loads, then the average reaction of the 4-inch solid tire worn to 1 inch of visible rubber would be approximately 7.48×2,000, or 14,960 pounds, and the average reaction of the 5-inch cushion tire worn to the same height of visible rubber would be approximately 7.53×1,700, or 12,800 pounds.

CORROBORATIVE TESTS

In a series of tests conducted in 1925 by Prof. J. T. Thompson at Johns Hopkins University[3] some relevant data were taken during the course of the investigations. Segments of a 3½-inch high-profile solid tire, each segment being cut to a different thickness, were fastened on the striking face of a trip hammer arranged to drop against a suitable anvil. It was found that the ratio of the impact force of the worn tire with respect to that of the new 3½-inch high-profile tire was 150 per cent when the visible rubber had been reduced by about 43 per cent and 240 per cent when the visible rubber had been reduced by about 71 per cent. The effect of the tire thickness on the impact force under these conditions was found to be generally comparable to the results found in the truck-impact tests.

TIRE-CUTTING MACHINE DESCRIBED

The tires were cut to the required thicknesses by a machine built for the purpose. The development of this machine was a by-product of the impact tests but it proved to be so satisfactory that a somewhat detailed description is included for the benefit of those who may desire to construct a similar device for truing tires which have become eccentrically worn. It consisted of the rear end of 2-ton truck securely mounted on a concrete platform, the left axle being locked and the differential driven by an electric motor through a belt and pulley reduction. The right wheel when mounted turned backward at the rate of about 90 revolutions per minute. A small lathe bed was arranged behind the right wheel so that the lathe carriage could carry cutting tools on the level of and parallel with the axle. Tires mounted on the wheel could be made to travel against cutting tools at the rate of about 15 feet per second. Figure 1 shows a general view of this apparatus with a tire with a completed cut mounted on the machine and a similar uncut tire shown at the right.

The technique in the use of this machine was developed as follows: A number of vertical cuts were made about one-half inch apart and to a depth within about one-sixteenth inch of the desired thickness. A horizontal cut was then made at the proper depth, carried beyond the first vertical cut, and the tool backed off. The first vertical cut was then completed with a manually held knife and the cut-off portion came off as a continuous band. The horizontal cut was then carried beyond the next vertical cut and the process continued until all the rubber to be removed had been taken off in a series of bands. The tire was kept wet to facilitate the cutting. By following this procedure, it was found that satisfactory finished surfaces which were quite true and smooth could be obtained.

[3] See Public Roads, vol. 7, No. 5, July, 1926

U. S. GOVERNMENT PRINTING OFFICE: 1930

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Report of the Chief of the Bureau of Public Roads, 1924.
Report of the Chief of the Bureau of Public Roads, 1925.
Report of the Chief of the Bureau of Public Roads, 1927.
Report of the Chief of the Bureau of Public Roads, 1928.
Report of the Chief of the Bureau of Public Roads, 1929.

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Report of a Survey of Transportation on the State Highways of New Hampshire.
Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio.
Report of a Survey of Transportation on the State Highways of Pennsylvania.

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Vol. 5, No. 19, D- 3. Relation Between Properties of Hardness and Toughness of Road-Building Rock.
Vol. 5, No. 24, D- 6. A New Penetration Needle for Use in Testing Bituminous Materials.
Vol. 6, No. 6, D- 8. Tests of Three Large-Sized Reinforced-Concrete Slabs Under Concentrated Loading.
Vol. 11, No. 10, D-15. Tests of a Large-Sized Reinforced-Concrete Slab Subjected to Eccentric Concentrated Loads.

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