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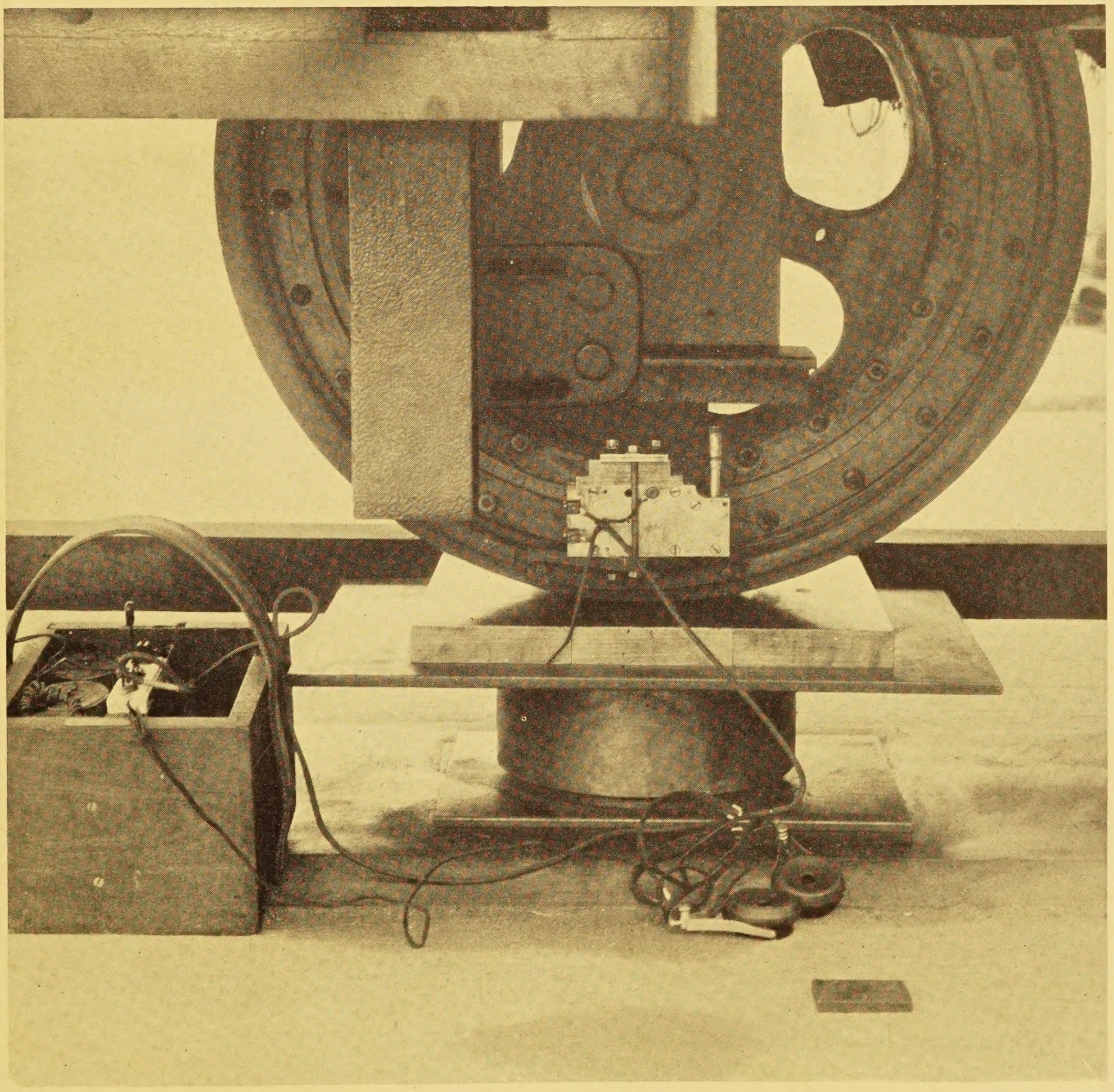

Apparatus for Impact Tests on Types of Wheels

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EFFECT OF WHEEL TYPE ON IMPACT REACTION

By **JAMES A. BUCHANAN**, Associate Engineer of Tests, and **E. G. LAPHAM**, Junior Highway Engineer, Division of Tests, United States Bureau of Public Roads

A RESEARCH investigation with the object of obtaining information regarding the relative protective or cushioning quality inherent in different types of wheel was carried on by the Bureau of Public Roads in 1927 and 1928. This project was a part of the study being made by the bureau concerning the general subject of motor-truck impact.

As it was necessary to limit the scope of the investigation, normal equipment for a 2-ton truck was selected as being a fair basis for comparison. Accordingly, all known manufacturers of "cushion" wheels [1] of this capacity were invited to submit wheels for test, but for various reasons many declined, and only two wheels of the cushion type were made available. These and a conventional wood-spoke artillery wheel were used in the program, and each was successively equipped with dual new cushion, dual new solid, and dual worn solid tires. For purposes of comparison, tests were also made on a pneumatic tire mounted on a rigid wheel.

It is believed that the method of test outlined, in addition to giving definite information regarding particular wheel types, will be of value to wheel manufacturers and others interested in the development of cushioning devices for automotive equipment.

PROCEDURE AND EQUIPMENT DESCRIBED

There appeared to be two general methods by which the desired information might be obtained—first, by comparing the magnitude of the impact forces produced by each type of wheel under definite and identical test conditions, and, second, by determining the variations in the test conditions which were necessary to cause the different wheels to produce impact reactions of equal magnitudes.

Data for these comparisons have been taken and will be discussed in detail later. In addition, there has been developed other information of interest in connection with the general subject of motor-truck impact.

Wheels.—As previously stated, the program included two wheels of the cushion type and one of the conventional rigid type as a standard of comparison.

The two cushion wheels differed from each other fundamentally in that one (designated as wheel RS in this report) utilized rubber in shear as the cushioning medium, while the other (designated as wheel RC) utilized rubber in compression.

The rigid wheel (referred to as wheel WM) was of the wood-spoke, metal-felloe type of construction.

The three types of wheel are shown diagrammatically in Figure 1.

Tires.—The tire equipment used on the wheels included one set of each of the following types, selected to represent the range in tire conditions (exclusive of pneumatic) which are found on the highways.

Tire NC represents dual 36-inch by 5-inch new, hollow-center cushion tires.

Tire NS represents dual 36-inch by 4-inch new, regular solid tires. Such tires are sometimes referred to as being of the low-profile, solid type.

Tire WS represents dual 36-inch by 4-inch solid tires having a tread thickness of about five-eighths inch visible beyond the steel tire flange. These tires were obtained by cutting down new tires to the required thickness to simulate tires worn down in service. As they were cut down in a machine they differed from traffic-worn tires in that they were true and round. They also differed in that they had not deteriorated by aging.

The sets of tires were placed on the wheels in turn, care being taken to insure that they were pressed on the wheels in a uniform manner. The three sets of wheels and three sets of tires provided a total of nine combinations for use in the tests.

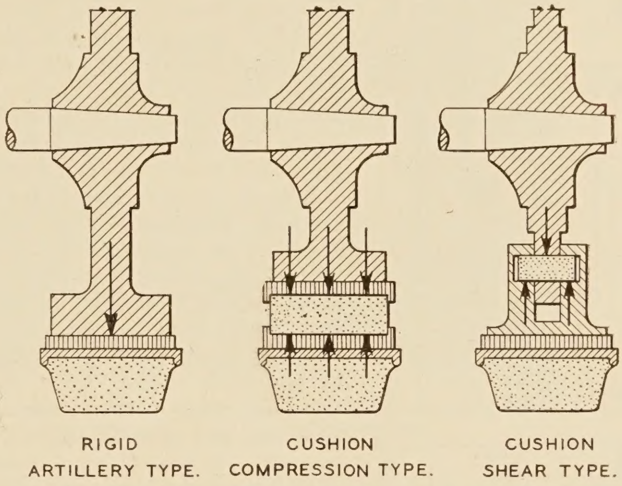

FIGURE 1.—DIAGRAMMATIC REPRESENTATION OF WHEEL TYPES TESTED

STATIC TESTS MADE ON EACH WHEEL AND PAIR OF TIRES

Each wheel and pair of tires was subjected to a static load test up to 28,000 pounds (about three and one-half times the normal capacity load) in a universal testing machine. The displacements of the hub and of the tire rim were measured with dial micrometers, load increments of about 1,000 pounds being used. Figure 2 shows how micrometers were placed on both sides of the wheel, and a knife edge under the plate on which the wheel rested which distributed the load evenly to both tires. The average of the deflections indicated at the rim was taken as the tire deformation, the average of the deflections at the hub was taken as the combined deformation of wheel and tire, and the difference between the two was taken as the wheel deformation.

PRELIMINARY TESTS INDICATE NECESSITY FOR USE OF IMPACT MACHINE

In earlier impact tests of trucks and tires [2] a procedure was developed whereby the impact reaction between the pavement and the tires of a moving truck was obtained by computing its sprung and unsprung components and combining the two. The sprung component was obtained from a record of the deflection of

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[1] A cushion wheel, as distinguished from a rigid wheel, is one which has cushioning material incorporated in the supporting structure of the wheel.

[2] Public Roads, vol. 7, No. 4, June, 1926, Motor Truck Impact as Affected by Tires, Other Truck Factors, and Road Roughness, by James A. Buchanan and J. W. Reid.

the truck spring at the instant of impact. The unsprung component was obtained from the known unsprung mass and the acceleration or deceleration imparted to that mass, as measured by an accelerometer attached to the hub of the wheel.

It was recognized that the construction of a cushion wheel necessarily subdivided the unsprung mass of the truck into two or more portions. Since the major portion was still rigidly connected to the hub, it was thought that reactions based on hub accelerations, as outlined above, might give data sufficiently accurate for the purpose of this investigation. A series of tests was carried out operating the 2-ton test truck equipped successively with the various wheels over the artificially roughened test road described in the report of the previous test. A study of the data obtained indicated the necessity of determining the importance of the difference in acceleration of the component parts of the unsprung mass. Accordingly, a few preliminary tests were made on the impact testing machine[3] used in former tests. These preliminary tests showed definitely that the component masses of cushion wheels are subject to different accelerations during impact and that the divergence of the rim acceleration from that of the hub varied with the type of wheel, the type of tire, and the specific test conditions. It was then decided that a complete series of tests on the impact machine would furnish data which would satisfy the objects of the investigation and, further, that tests with a truck on the road could not be depended upon to accomplish these objects.

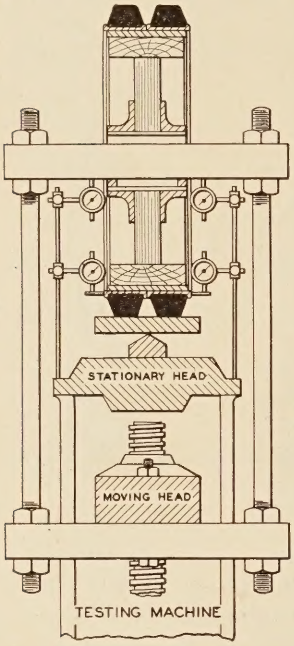

Figure 2.—Diagram of Set-up for Static Load-Deflection Tests

INSTRUMENTS USED IN FINAL IMPACT TESTS DESCRIBED

The impact testing machine, in addition to permitting the various changes of wheel-tire combinations, also allowed wide ranges in truck-spring pressure and height of drop. For these tests the truck spring attached to the unsprung weight of the impact machine was adjusted to a deformation of 1½ inches (corresponding to a load of 2,000 pounds) at the instant the tires made contact with the surface on which they were dropped. The height of fall was defined as the vertical distance the wheel dropped, under the combined influences of gravity and the truck spring, from its position when released by the cam to its position at contact of the tires with the surface on which they were dropped. This height of fall was recorded graphically, together with the displacements of the hub and rim after contact, by means of styli attached to the various parts and bearing on plates holding silicated paper, as shown in Figure 3. The height of "free" fall was varied between 0.2 inch and 2 inches.

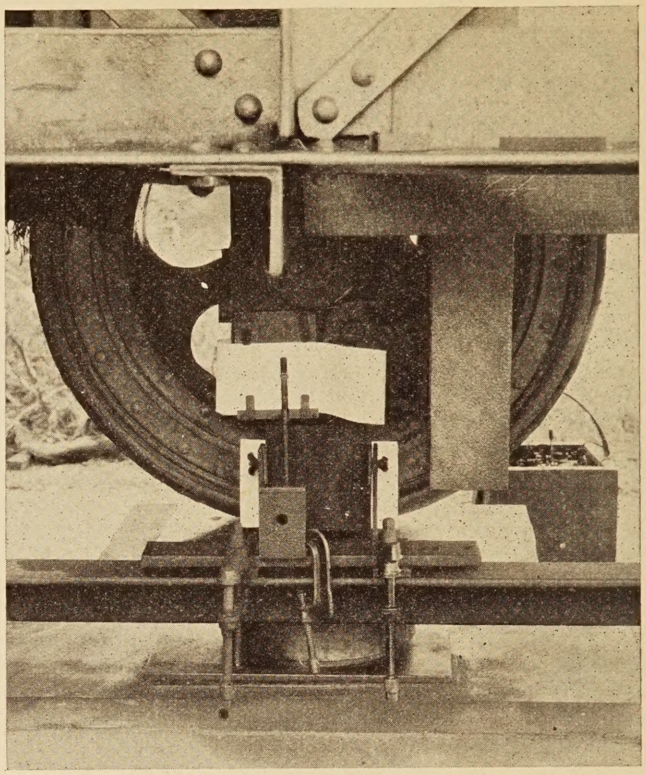

Figure 3.—The Displacement Recording Device. The Horizontal Angle Near the Bottom Extends Beyond the Concrete Slab and is Independently Supported

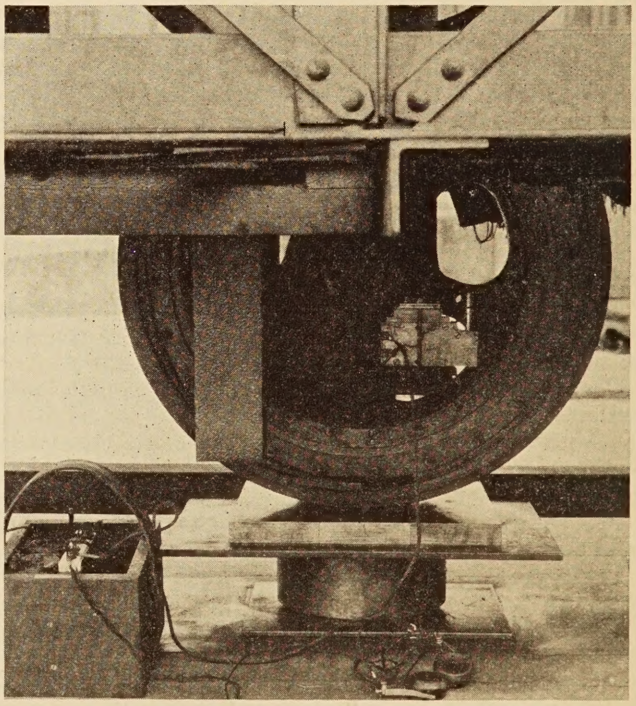

Figure 4.—The Accelerometer Mounted to Measure Acceleration of the "Hub" Portion of the Unsprung Mass

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[3] Public Roads, vol. 5, No. 2, April, 1924, Impact Tests on Concrete Pavement Slabs, by L. W. Teller.

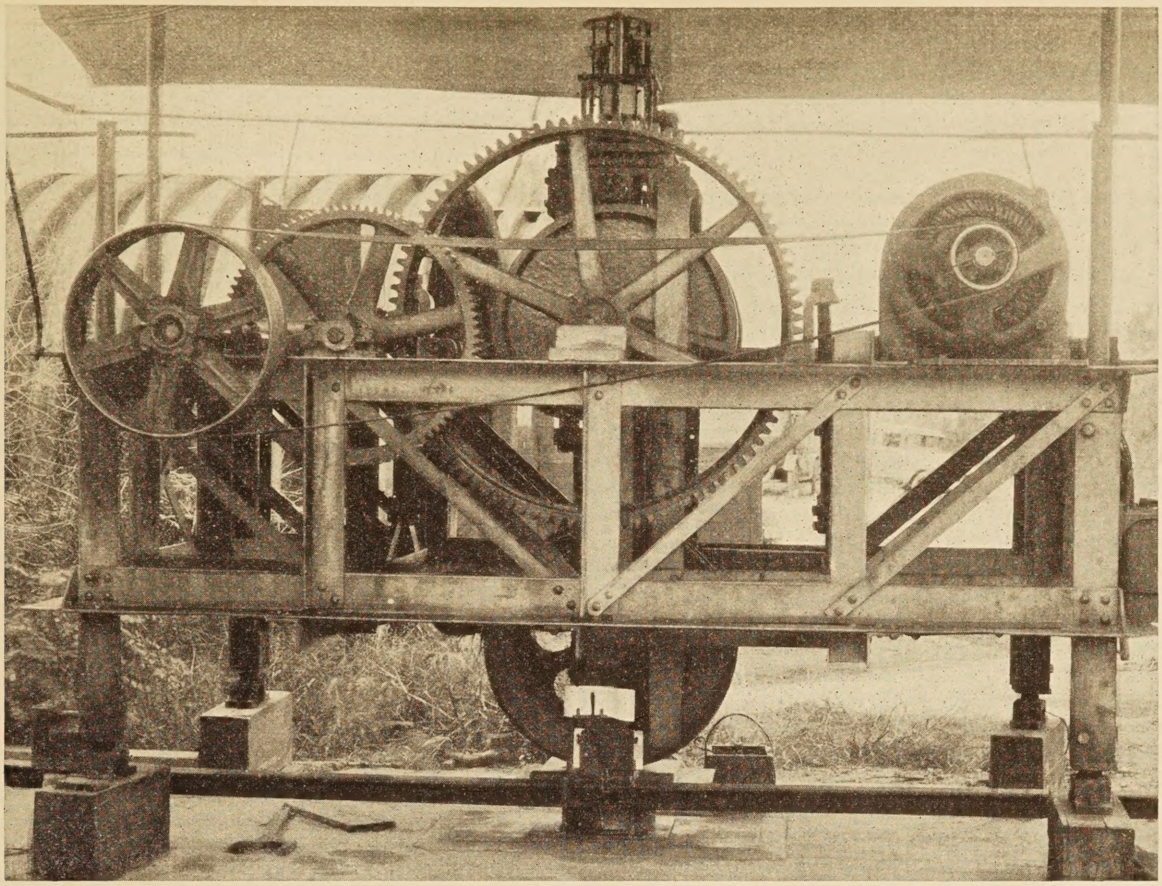

FIGURE 5.—GENERAL VIEW OF THE TESTING MACHINE SHOWING THE INSTALLATION OF A MULTIPLE-ELEMENT COIL SPRING ACCELEROMETER AT THE TOP OF THE PLUNGER CARRYING THE WHEEL

A Kreuger cell,[4] as shown in Figures 3 to 5, was placed directly under the wheel on the pavement slab, upon which the wheel-tire combination was dropped. By this means a direct determination of the magnitude of the impact force was obtained. As demonstrated by Professor Kreuger and corroborated by other tests by the Bureau of Public Roads, such cells deform under normal static calibration conditions in the same manner that they do under motor-truck impact conditions, and the results obtained in these tests justify confidence in their use.

The tests were made on a concrete slab, heavily reinforced and about 12 feet square. Its minimum thickness is 8 inches and the subgrade is firm. A machined steel plate was cemented on the surface to provided a uniform bearing for the base of the Kreuger cell.

The accelerometer used to measure the decelerations of the hub of the wheel and of the rim of the tire is of the contact type. It is a single-cell instrument,[5] designed by Dr. Benjamin Liebowitz for the use of a special accelerometer subcommittee of a cooperative committee on motor-truck impact tests.[6] It consists of a cantilever flat steel spring pivoted at the point of maximum bending moment and extended beyond the pivot to carry a suitable weight or inertia element. The weighted end is restrained from oscillating, except through a very small arc, by means of upper and lower stop screws, which are also insulated electric contacts. For any given initial deflection of the spring, applied by means of and measured by a screw micrometer, it is necessary for a definite acceleration to act upon the weighted end in order to produce sufficient force to separate the upper contacts or engage the lower contacts. Radio head phones are used to determine the proper setting of the micrometer to "balance" the acceleration impressed on the instrument.

This accelerometer was alternately secured to the unsprung mass to which the hub of the wheel was attached and to the unsprung mass of the felloe portion of the wheel which carried the dual tires. A shelf riveted to the main unsprung portion of the impact machine afforded a convenient means of attaching the instrument when measuring "hub" accelerations. A similar shelf for the attachment of the instrument when measuring "rim" accelerations was provided for by machining a vertical plane surface on the steel flange of the tire and tapping holes into the flange in order to bolt the instrument shelf securely to it. The instrument in the two positions is shown in Figure 4 and on the cover page.

Data concerning the action of coil spring accelerometers under cushion-wheel conditions were obtained with

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[4] Public Roads, vol. 5, No. 10, December, 1924. Accurate Accelerometers Developed by the Bureau of Public Roads, by L. W. Teller. See also, for a mathematical discussion, Transactions No. 2 of the Engineering Science Academy, Stockholm, 1921; Method for Measuring and Calculating the Magnitude of Forces with Particular Regard to Impact Forces, by Prof. H. Kreuger.

[5] See Journal of the Society of Automotive Engineers, vol. 18, No. 3, March, 1926, pp. 249–251, Micrometer Type of Contact Accelerometer.

[6] This cooperative committee represents the Rubber Association of America, the Society of Automotive Engineers, and the United States Bureau of Public Roads. The wheel tests herein described were not a part of the activities of the cooperative committee.

a four-element instrument attached to the top of the "plunger" or unsprung mass of the impact machine. The data obtained with this instrument were not intended for use in this investigation and are not included in the report. This installation is shown in Figure 5.

IMPACT FORCES MEASURED BY DIRECT AND INDIRECT METHODS

Each wheel and tire combination to be tested was installed in the proper position in the impact-testing machine and the machine was leveled so that the guides for the plunger carrying the wheel were vertical. The Kreuger cell was placed between the tires and the pavement and the machine was adjusted until the distance between the point of maximum elevation of the wheel and that of contact of the tires with the surface of the Kreuger cell gave a desired height of fall. The truck spring in the testing machine was then adjusted to give the desired pressure when the tires made contact with the Kreuger cell.

The contact accelerometer was installed to measure hub accelerations and the impact testing machine was set in motion, the cam raising and dropping the unsprung weight about seven times per minute. The micrometer setting on the accelerometer was varied until three out of six consecutive drops of the wheel registered in the phones, and the setting was noted. This process was repeated with the accelerometer installed to record rim accelerations. The Kreuger cell was then removed and its plane surface was smoked lightly, after which the cell was replaced and a single drop made upon it. The diameter of the resulting record on the smoked surface was read by two observers using a Brinell microscope. The average reading of the diameter was recorded. If, as occasionally happened, there was an appreciable difference between the readings of the two observers the test was repeated. Six individual drop tests on the Kreuger cell were taken in the above manner. The average of the six recorded diameters was referred to a calibration curve for the cell and the magnitude of the impact force determined for the given test condition.[7]

RESULTS OF STATIC AND IMPACT TESTS PRESENTED

Table 1 gives the load-deflection data for the static tests on the three tires and on the three wheels. These data are represented graphically in Figures 6 and 7, respectively. Figure 8 shows the same relation for each wheel-tire combination, and was obtained from the data in Table 1.

Table 2 gives the weights of the various tires, the elements of the various wheels, the unsprung portions of the testing machine, and the total hub and rim components for each wheel-tire combination.

Tables 3, 4, and 5 contain the data for the impact tests on the three wheels equipped with cushion, new solid, and worn solid tires. The height of fall shown in the first column was measured upward from the position of the wheel at contact with the surface on which it struck to the position from which it was dropped. The displacements shown in the second to fifth columns, inclusive, were measured downward from this same datum (position of the wheel at contact) and are either tire deflections (rim displacements) or a combination of the tire and wheel deflections (hub displace-

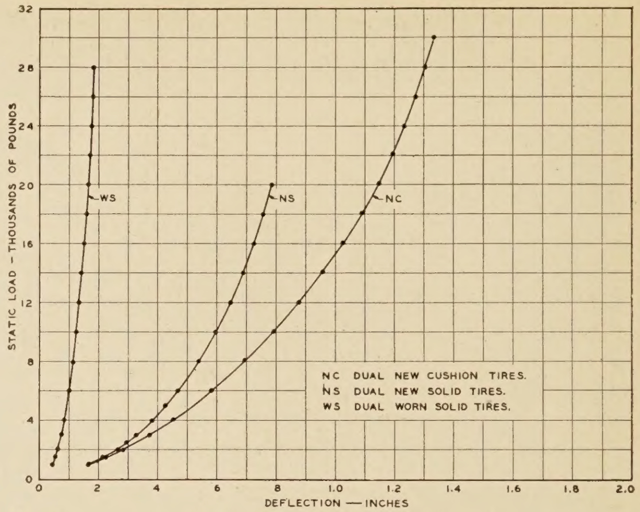

Figure 6.—Static Load-Deflection Curves for Tires

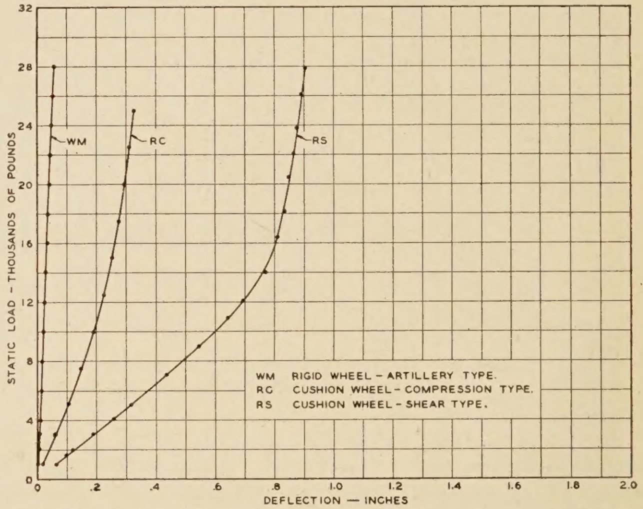

Figure 7.—Static Load-Deflection Curves for Wheels

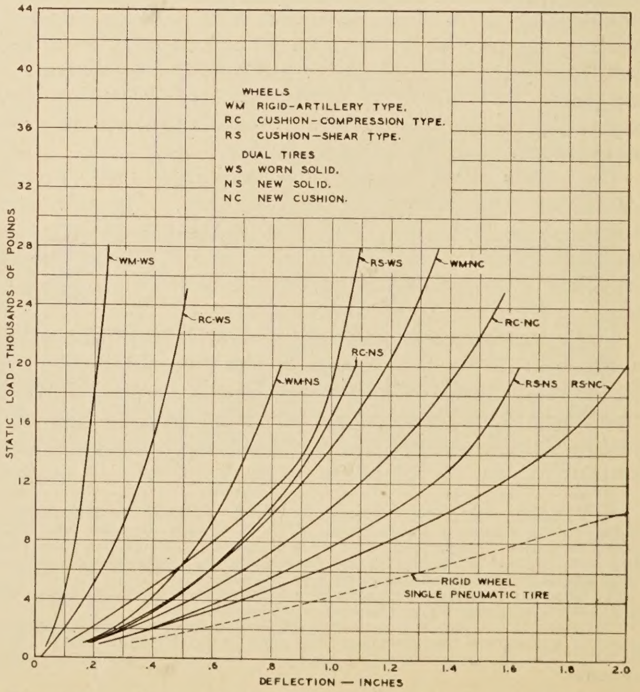

Figure 8.—Static Load-Deflection Curves for Wheel-Tire Combinations

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[7] The same two observers read the diameters of the Kreuger cell records during these tests and the static tests upon which the calibration curve for the cell was based.

ments). The displacements under static load were tabulated simply as a matter of information, and the values do not appear in any of the diagrams.

The total reaction was measured directly by the Kreuger cell and was also computed using the following equation:

$$F = M_h A_h + M_r A_r + (M_h + M_r)g + P$$

in which

F is the computed total reaction between the tire and the slab or road surface.

M_h and M_r are the respective masses of hub and rim portions of the wheel.

A_h and A_r are the respective accelerations of the hub and rim portions of the wheel.

g is the acceleration of gravity.

P is the pressure of the vehicle spring at the instant of maximum acceleration.

TABLE 1.—*Deflections of tires and wheels under static load*

Tire NC		TIRE NS		Tire WS		Wheel RS		Wheel RC		Wheel WM	
Load	Deflection	Load	Deflection	Load	Deflection	Load	Deflection	Load	Deflection	Load	Deflection
Lbs.	*Ins.*	*Lbs.*	*In.*	*Lbs.*	*In.*	*Lbs.*	*In.*	*Lbs.*	*In.*	*Lbs.*	*In.*
0	0	0	0	0	0	0	0	0	0	0	0
380	.038	200	.045	370	.015	100	.022	500	.006	370	.000
780	.132	500	.103	830	.038	680	.042	1,000	.018	830	.001
1,040	.170	1,000	.168	1,000	.043	1,000	.063	3,010	.060	1,000	.001
1,500	.227	1,500	.217	1,570	.055	1,620	.097	5,130	.106	1,570	.003
2,000	.282	2,000	.266	2,030	.062	2,000	.119	7,500	.148	2,080	.005
3,000	.372	2,500	.294	3,070	.075	3,050	.188	10,000	.190	3,070	.008
4,060	.452	3,000	.326	4,030	.085	4,090	.258	12,500	.224	4,080	.009
6,060	.582	4,000	.381	6,070	.101	5,050	.318	15,000	.252	6,070	.011
8,030	.692	5,000	.426	7,950	.114	7,030	.437	17,500	.274	7,950	.015
10,020	.792	6,000	.468	10,030	.125	9,000	.545	20,000	.292	10,030	.020
12,020	.878	8,000	.539	11,990	.135	10,970	.642	22,500	.310	11,990	.023
14,050	.958	10,000	.596	14,030	.145	12,070	.692	25,000	.326	14,060	.027
16,050	1.027	12,000	.647	16,020	.152	14,020	.770	------	------	16,020	.032
18,100	1.090	14,000	.690	17,930	.159	16,410	.810	------	------	17,930	.035
20,110	1.148	16,000	.727	20,000	.165	18,150	.833	------	------	20,000	.039
22,120	1.195	18,000	.758	22,000	.171	20,470	.849	------	------	22,000	.043
24,000	1.232	20,000	.787	24,020	.176	22,030	.863	------	------	24,020	.048
26,000	1.272	------	------	26,000	.181	23,800	.876	------	------	26,000	.052
28,000	1.303	------	------	28,000	.185	26,060	.890	------	------	28,000	.057
30,000	1.332	------	------	------	------	27,900	.904	------	------	------	------

TABLE 2.—*Weights of tires, elements of wheels, the unsprung portion of testing machine, and the total hub and rim components for each wheel-tire combination*

Tire:	Pounds
NC	282½
NS	202½
WS	146

Wheel	Hub portion	Rim portion	Total
	Pounds	*Pounds*	*Pounds*
RS	106	135	241
RC	193	137	330
WM	85	110	195

	Pounds
Unsprung weight of impact machine	1,157
Extension rings used with tire NC	76½

COMPOSITE UNSPRUNG WEIGHTS

Wheel	Hub component	Rim component		
		Tire NC	Tire NS	Tire WS
	Pounds	*Pounds*	*Pounds*	*Pounds*
RS	1,263	494	338	281
RC	1,350	496	340	283
WM	1,242	469	313	256

This formula is based on the assumption that the measured values of acceleration of the hub and of the rim and that of the spring pressure are simultaneous. No experimental evidence was obtained that this assumption is correct. Had more test apparatus been available it is possible that some information on this point could have been obtained.

WHEEL-TIRE COMBINATIONS CLASSIFIED ACCORDING TO RESULTS OF STATIC TESTS

The static load-deflection curves of the respective wheels, tires, and wheel-tire combinations are shown in Figures 6 to 8. The relative facility with which such

TABLE 3.—*Impact data for tire* NC

Height of fall	Displacement				Maximum acceleration		Computed force				Measured force
	Static		Dynamic								
	Rim	Hub	Rim	Hub	Rim	Hub	Rim	Hub	Spring	Total	Total
In.	*In.*	*In.*	*In.*	*In.*	*Ft./sec.²*	*Ft./sec.²*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*
Wheel WM: Rim weight ...... 469 pounds. Hub weight ...... 1,242 pounds.							Total static load ..... 3,536 pounds. Unsprung weight .... 1,711 pounds. Sprung weight .... 1,825 pounds.				
0.523	0.436	0.444	0.824	0.845	154.5	164.2	2,250	6,330	1,130	11,421	10,900
.691	.440	.440	.890	.912	189.2	194.3	2,757	7,490	1,000	12,958	12,700
1.196	.444	.449	1.053	1.085	259.1	280.5	3,775	10,820	730	17,036	17,000
Wheel RC: Rim weight ...... 496 pounds. Hub weight ...... 1,350 pounds.							Total static load ..... 3,596 pounds. Unsprung weight .... 1,846 pounds. Sprung weight .... 1,750 pounds.				
.470	.445	.480	.795	.887	135.7	151.5	2,091	6,350	1,050	11,337	10,860
.685	.438	.473	.869	.976	159.6	189.7	2,459	7,950	900	13,155	12,700
1.047	.445	.483	.979	1.114	192.8	244.8	2,970	10,260	700	15,776	15,550
1.510	.445	.485	1.054	1.253	254.5	313.1	3,920	13,130	470	19,366	19,600
Wheel RS: Rim weight ...... 494 pounds. Hub weight ...... 1,263 pounds.							Total static load ..... 3,387 pounds. Unsprung weight .... 1,757 pounds. Sprung weight .... 1,630 pounds.				
.539	.421	.556	.768	1.094	148.4	155.0	2,278	6,076	730	10,841	9,550
.690	.434	.560	.805	1.173	170.3	177.5	2,613	6,960	600	11,930	10,600
1.176	.441	.575	.947	1.416	250.9	265.2	3,850	10,400	200	16,207	13,600
1.940	.431	.569	1.103	1.706	378.4	382.5	5,805	15,000	−425	22,137	18,300

TABLE 4.—*Impact data for tire* NS

Height of fall	Displacement				Maximum acceleration		Computed force				Measured force
	Static		Dynamic								
	Rim	Hub	Rim	Hub	Rim	Hub	Rim	Hub	Spring	Total	Total
In.	*In.*	*In.*	*In.*	*In.*	*Ft./sec.²*	*Ft./sec.²*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*
Wheel WM: Rim weight ...... 313 pounds. Hub weight ...... 1,242 pounds.							Total static load ..... 3,555 pounds. Unsprung weight .... 1,555 pounds. Sprung weight .... 2,000 pounds.				
0.442	0.342	0.342	0.610	0.623	171.9	185.6	1,672	7,160	1,500	11,887	11,100
.708	.335	.335	.670	.685	228.0	252.5	2,217	9,740	1,400	14,912	14,400
1.183	.343	.344	.788	.818	343.2	384.5	3,336	14,830	1,175	20,896	21,400
Wheel RC: Rim weight ...... 340 pounds. Hub weight ...... 1,350 pounds.							Total static load ..... 3,610 pounds. Unsprung weight .... 1,690 pounds. Sprung weight .... 1,920 pounds.				
.425	.343	.385	.580	.674	132.6	161.7	1,400	6,780	1,425	11,295	11,050
.696	.338	.377	.652	.768	159.6	224.4	1,685	9,410	1,250	14,035	14,000
1.188	.336	.375	.762	.918	236.6	344.3	2,498	14,430	1,000	19,618	19,600
Wheel RS: Rim weight ...... 338 pounds. Hub weight ...... 1,263 pounds.							Total static load ..... 3,351 pounds. Unsprung weight .... 1,601 pounds. Sprung weight .... 1,750 pounds.				
.521	.332	.471	.545	.896	167.3	153.5	1,756	6,020	1,040	10,417	9,630
.708	.315	.456	.580	.973	211.1	179.5	2,216	7,040	920	11,777	11,150
1.077	.323	.460	.650	1.132	315.7	254.5	3,312	9,980	670	15,563	14,300
1.562	.334	.476	.735	1.328	481.4	342.2	5,052	13,425	350	20,428	18,600

Table 5.—*Impact data for tire* WS

Height of fall	Displacement				Maximum acceleration		Computed force				Measured force
	Static		Dynamic								
	Rim	Hub	Rim	Hub	Rim	Hub	Rim	Hub	Spring	Total	Total
In.	*In.*	*In.*	*In.*	*In.*	*Ft./sec.^{2}*	*Ft./sec.^{2}*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*
Wheel WM: Rim weight...... 256 pounds. Hub weight...... 1,242 pounds.							Total static load..... 3,888 pounds. Unsprung weight.... 1,498 pounds. Sprung weight....... 2,390 pounds.				
0.134	0.115	0.122	0.138	0.142	115.3	123.9	916	4,780	2,370	9,564	7,670
.224	.112	.114	.159	.172	159.6	195.8	1,269	7,550	2,275	12,592	12,300
.334	.119	.121	.183	.211	207.1	263.7	1,646	10,170	2,230	15,544	16,490
.493	.105	.110	.192	.230	298.9	349.4	2,376	13,480	2,200	19,554	20,440
Wheel RC: Rim weight...... 283 pounds. Hub weight...... 1,350 pounds.							Total static load..... 3,908 pounds. Unsprung weight.... 1,633 pounds. Sprung weight....... 2,275 pounds.				
.188	.139	.175	.165	.255	68.9	126.0	605	5,280	2,150	9,668	8,750
.429	.124	.174	.196	.335	205.5	225.4	1,806	9,450	2,025	14,914	15,450
.700	.138	.180	.220	.397	377.9	329.0	3,320	13,800	1,900	20,653	21,100
Wheel RS: Rim weight...... 281 pounds. Hub weight...... 1,263 pounds.							Total static load..... 3,694 pounds. Unsprung weight.... 1,544 pounds. Sprung weight....... 2,150 pounds.				
.482	.112	.260	.160	.555	552.3	181.6	4,820	7,120	1,625	15,109	11,800
.718	.124	.265	.183	.650	741.0	243.3	6,465	9,540	1,475	19,024	15,300
1.183	.140	.280	.222	.816	1,243.4	362.1	10,850	14,200	1,200	27,794	21,800

curves may be obtained would make them a convenient means of determining relative cushioning, provided the conclusions reached as a result of static and impact tests were compatible. The following discussion is primarily concerned with those cases which do not involve intersecting curves or curves closely adjacent to one another.

The critical factor affecting the magnitude of impact forces is the acceleration (or deceleration) of the vertical motion. This rate of change in vertical velocity will depend upon the magnitude of the initial velocity and the character of the resistance of the cushioning medium. A less stiff medium deflects further and therefore requires a longer time interval to reduce the vertical velocity to zero. For such media as are of interest in this problem, the longer the time interval consumed in changing velocity the lower the rate of change, or acceleration, will be.

In either static or impact tests, the work done on a given cushioning medium is the same (neglecting hysteresis effects) where a given maximum resisting force has been reached, regardless of the time involved, and is therefore a valid basis for comparisons. The area between the load-deflection curve and the deflection axis, between the limits of zero and the specified maximum load, is a direct measure of the work done. If the load-deflection curves were rectilinear, the work done would, of course, be proportional to the deflection. Where the curves are obviously analagous or similar, as in the respective groups in these tests, the areas representing the amounts of work done will bear approximately the same relations as the deflections produced. Thus, an order of stiffness based upon the relative deflections under a given static load is readily obtainable and is reasonably sound physically, particularly where the respective curves do not intersect.

On the above basis the static load-deflection curves indicate that the arrangement of the wheels in the order of increasing stiffness is:

(1) Wheel RS, cushion—shear type;
(2) Wheel RC, cushion—compression type;
(3) Wheel WM, rigid—artillery type;

and of the tires:

(1) Tire NC, new cushion;
(2) Tires NS, new solid;
(3) Tire WS, worm solid.

The arrangement of the wheel-tire combinations, in the order of decreasing stiffness, is given in Table 6. This arrangement is based on the static tests, but it should be kept in mind that the possible differential action of the component parts of the cushion wheels under impact conditions might result in local changes in an order of stiffness based upon impact tests. It should also be noted that very small differences in the deflections at a given load do not indicate appreciable differences in stiffness and should not be accepted as a rigid criterion.

Table 6.—*Deflections of wheel-tire combinations under static loads*

Wheel-tire combination	Load or resisting force		
	10,000 pounds	15,000 pounds	20,000 pounds
	Inches	*Inches*	*Inches*
WM-WS	0.15	0.18	0.21
RC-WS	.31	.40	.46
WM-NS	.62	.74	.82
RS-WS	.72	.93	1.01
RC-NS	.79	.96	1.08
WM-NC	.81	1.02	1.18
RC-NC	.98	1.24	1.44
RS-NS	1.20	1.49	1.63
RS-NC	1.38	1.78	1.99

As will be seen later, the load-deflection relations for the tires under static and impact conditions appear to be compatible, and the stiffness series established by the static tests agree in general with those of the impact tests.

IMPACT TEST RESULTS SHOW SAME ORDER OF CUSHIONING QUALITY AS INDICATED BY STATIC TESTS

In the preceding discussion of the static tests it was assumed that the relative stiffness of a wheel-tire combination should be based upon the work done or energy absorbed in developing a given resisting force. The system being conservative, it follows, disregarding incidental losses, that, when the maximum resisting force or impact pressure is attained, the work done on the cushioning elements is equal to the kinetic energy at the instant of impact. This kinetic energy is equal to the potential energy put into the system by raising its mass above the contact position against the influences gravity and of the truck spring. The gravity component is, of course, dependent upon the height of fall or distance the mass is raised above contact. Since the truck-spring pressure at contact, or initial deflection, was maintained constant throughout all test conditions, the spring component is also dependent upon the height of fall or added deflection beyond the contact position. Under these conditions the height of fall is an approximate measure of the energy available at that instant. It therefore follows that the height of fall required to develop a given maximum resisting force or reaction between the tires and the Kreuger cell is a useful measure of the relative stiffness of the wheel-tire combinations under the particular impact test conditions.

The impact forces developed by the three wheels (as measured by the Kreuger cell) are plotted against the corresponding heights of drop in Figures 9, 10, and 11, each figure representing one tire condition. The relative stiffness of the wheels may be found for each tire condition by comparing the heights of fall required to develop a given impact pressure. A comparison of all of the wheel-tire combinations may be made from Figure 12. The heights of fall required to develop given impact pressures are given in Table 7 in the order of decreasing stiffness derived from the static tests (Table 6). A greater height of fall indicates a greater amount of energy absorbed, and therefore a less stiff or better cushioning combination. Table 7 shows that the heights of drop generally increase with the previously established order of decreasing stiffness.

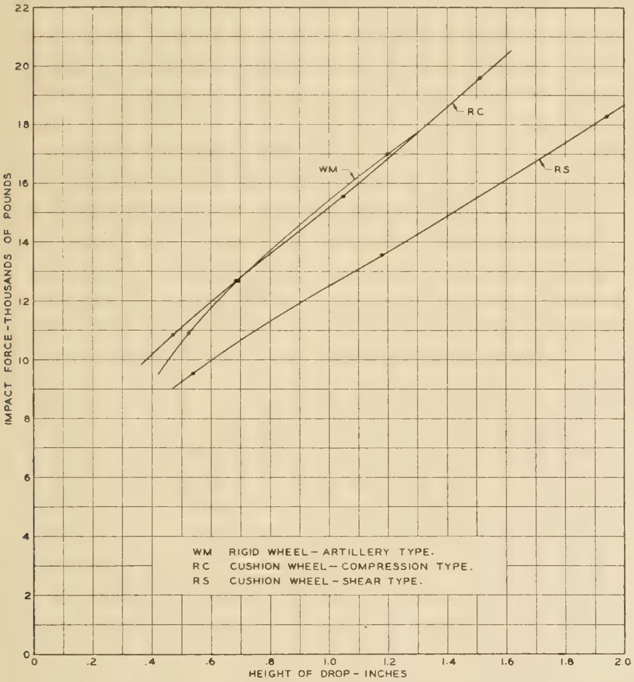

Figure 9.—Impact Force Developed by Each Type of Wheel as Measured by Kreuger Cell. Wheels Equipped with Dual New Cushion Tires

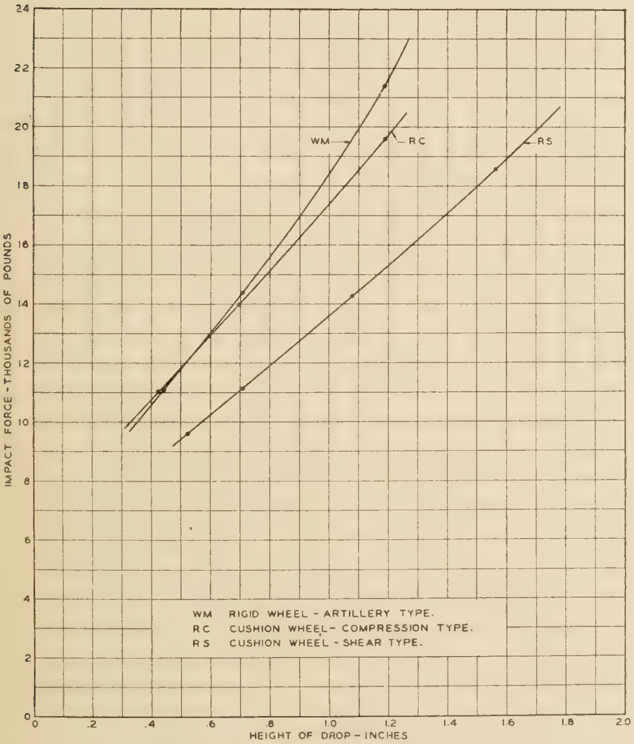

Figure 10.—Impact Force Developed by Each Type of Wheel as Measured by Kreuger Cell. Wheels Equipped with Dual New Solid Tires

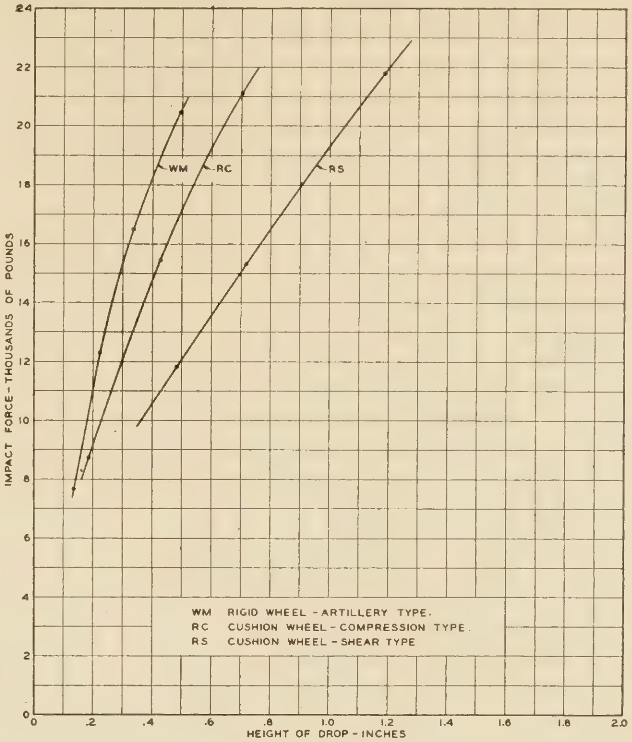

Figure 11.—Impact Force Developed by Each Type of Wheel as Measured by Kreuger Cell. Wheels Equipped with Dual Worn Solid Tires

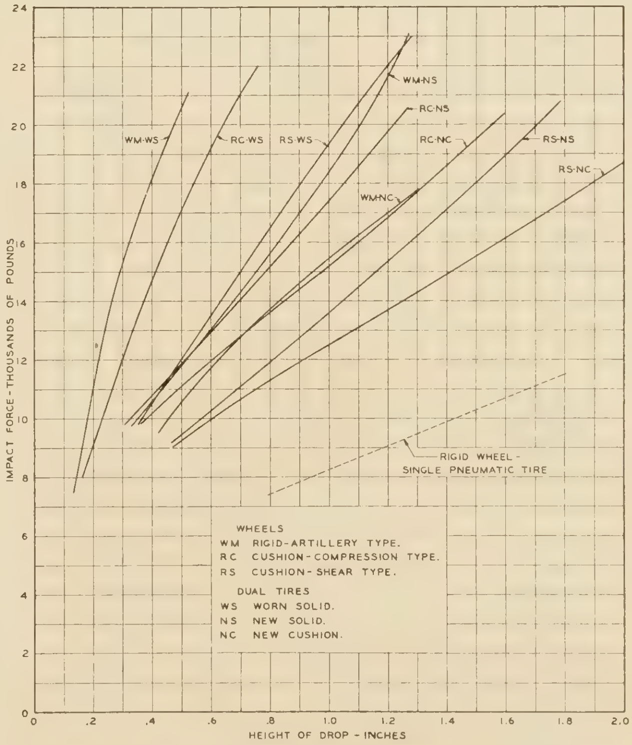

Figure 12.—Impact Force Developed by Each Wheel-Tire Combination as Measured by Kreuger Cell

TABLE 7.—*Heights of drop for given impact forces*

Wheel-tire combination	Impact pressure measured by Kreuger cell		
	10,000 pounds	15,000 pounds	20,000 pounds
	Inches	*Inches*	*Inches*
WM-WS	0. 18	0. 29	0. 47
RC-WS	. 23	. 41	. 64
WM-NS	. 35	. 75	1. 10
RS-WS	. 36	. 70	1. 05
RC-NS	. 33	. 79	1. 22
WM-NC	. 45	. 95	
RC-NC	. 38	. 98	1. 55
RS-NS	. 57	1. 16	1. 71
RS-NC	. 60	1. 41	[1] 2. 20

[1] Extrapolated result.

The data presented in Table 7 show the variations in test conditions which were necessary to cause the different wheel-tire combinations to produce impact reactions of equal magnitudes. In Table 8 the data are presented to show the variations in the magnitude of the impact forces produced by the wheel-tire combinations under identical test conditions. Here the order of listing is the same as before, and, with the exception of two combinations which indicate a relatively unimportant reversal at heights of drop of 1 inch or less, the arrangement indicates increasing cushioning qualities from top to bottom, as in Table 6. It should be emphasized that where there are only slight differences in cushioning qualities another test condition should be sought as a criterion, and preferably the criteria should be based on many tests under a wide variation in test conditions.

TABLE 8.—*Magnitude of impact forces for given heights of drop*

Wheel-tire combination	Height of drop in inches							
	0. 25	0. 50	0. 75	1. 00	1. 25	1. 50	1. 75	2. 00
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
WM-WS	13, 500	20, 600						
RC-WS	10, 700	17, 100	21, 900					
WM-NS		11, 800	15, 000	18, 400	22, 700			
RS-WS		12, 000	15, 800	19, 300	22, 600			
RC-NS		11, 900	14, 600	17, 400	20, 400			
WM-NC		10, 600	13, 300	15, 400	17, 400			
RC-NC		11, 100	13, 200	15, 200	17, 300	19, 500		
RS-NS		9, 400	11, 500	13, 600	15, 800	18, 000	20, 400	
RS-NC		9, 300	11, 000	12, 500	14, 000	15, 500	17, 100	18, 700

CHARACTER OF TIRES AFFECTS CUSHIONING QUALITY OF WHEEL

In determining the relative cushioning qualities of various wheels, the tire equipment used in testing is an important factor. If the tires in themselves are capable of a considerable cushioning action, then the cushioning quality of the wheel is relatively of less importance. On the other hand, the cushioning qualities of wheels may become very pronounced when inferior tire equipment is used. This is evident in comparing the curves (figs. 9 to 11) for the wheels when equipped with different tires. Table 9 shows that there is little difference between wheel RC and wheel WM when cushion tires NC are used and a small, though appreciable, difference between wheel RS and wheel WM with the same tires. There is a marked difference, however, between wheel WM and either of the cushion wheels when worn solid tires WS are used. In Table 9 the values for the cushion wheels have also been expressed as a percentage of the value for the rigid wheel for the same test conditions. A study of Table 9 and Figures 9 to 11 leads to the conclusion that the less effective the cushioning quality of the tire equipment the more effective will be the cushioning quality of the wheel.

TABLE 9.—*Influence of tire equipment on impact force*

Tire	Wheel	Height of drop to produce 15,000-pound impact force		Impact force for 0.5 inch height of drop	
		Inches	*Per cent*	*Pounds*	*Per cent*
WS	WM	0. 29	100	20, 600	100
	RC	. 41	141	17, 100	83
	RS	. 70	241	12, 000	58
NC	WM	. 95	100	10, 600	100
	RC	. 98	103	11, 100	105
	RS	1. 41	148	9, 300	88

STATIC VERSUS IMPACT TESTS

In making a direct comparison of the static and dynamic behavior of the wheels, it is necessary to compare load-deflection curves for the two conditions. The static and impact load-deflection data have been plotted for the three wheels, equipped with cushion tires (fig. 13), solid tires (fig. 14), and worn tires (fig. 15). In Figure 16 the impact load-deflection curves are given for all wheel-tire combinations.

Figures 13 to 15 show that rigid wheel WM deflects approximately equal amounts under static and impact loads of equal magnitudes regardless of the tire equipment. It is also evident that cushion wheels RC and RS deflect noticeably less (from 10 to 30 per cent) under impact pressures than under static pressures of the same magnitude. This difference between the deflections under static and dynamic conditions may be due to the tire, the wheel, or the particular combinations involved. By plotting the tire deflection (rim displacement after contact) against impact pressure as measured by the Kreuger cell (fig. 17) and comparing with the static load-deflection curves, it is seen that the tires deflect approximately the same amounts under impact loads as they do under equivalent static loads. A like comparison can not be made of the deflections of the wheels alone under static and impact conditions, because a direct measurement of the impact pressures at the wheels—i. e., between the wheel and tires—can not readily be made. We are led to believe, however, that, since the cushioning media of the tires acted in substantially the same manner under static and impact conditions, the cushioning media of the wheels, being of the same material, would do likewise. The differences mentioned above are probably due to some inherent characteristics of the particular wheel-tire combination, such as those caused by variations in the rim mass and the relative stiffness of the two cushioning media.

A reasonable explanation of the differences in the deflection of the wheel-tire combinations under static and dynamic conditions may be made if the wheel and tire do not develop their maximum pressures simultaneously. The tires must develop a greater resisting force than the wheel, because the kinetic energy of the rim (M_rA_r in the formula) must be absorbed by the tires or pavement and does not react on the wheel. On the other hand, the energy stored up in the hub (M_hA_h) is absorbed by the cushioning medium, if any, of the wheel, as well as by the tires and pavement. The unsprung masses and the ratios of the unsprung masses to their respective cushioning elements can so modify the development of resisting forces by the

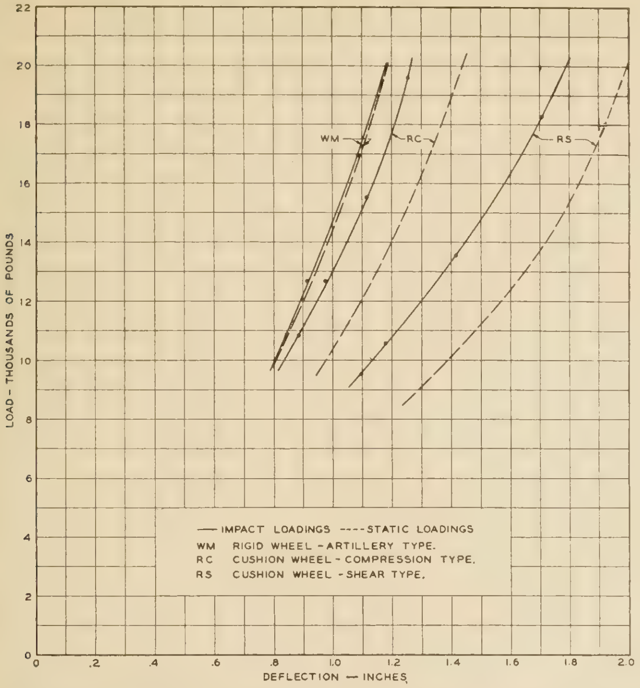

Figure 13.—Comparison of Total Deflections of Different Wheels Equipped with New Cushion Tires under Impact and Static Loads

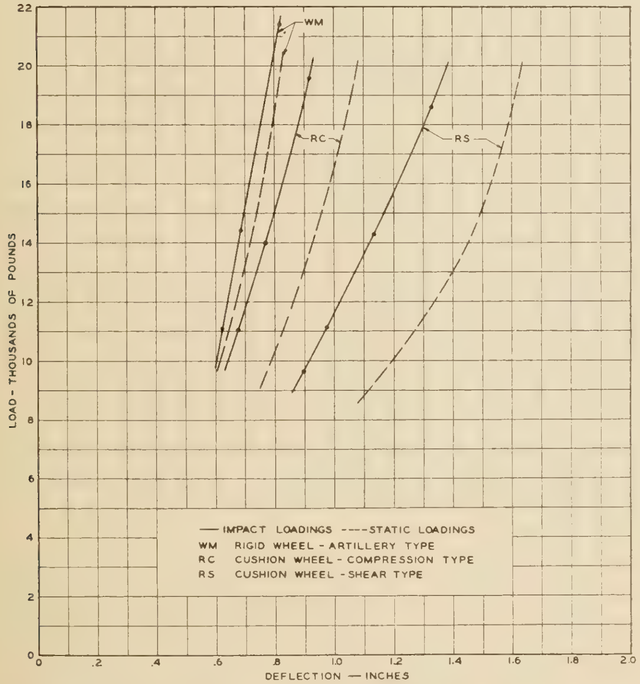

Figure 14.—Comparison of Total Deflections of Different Wheels Equipped with New Solid Tires under Impact and Static Loads

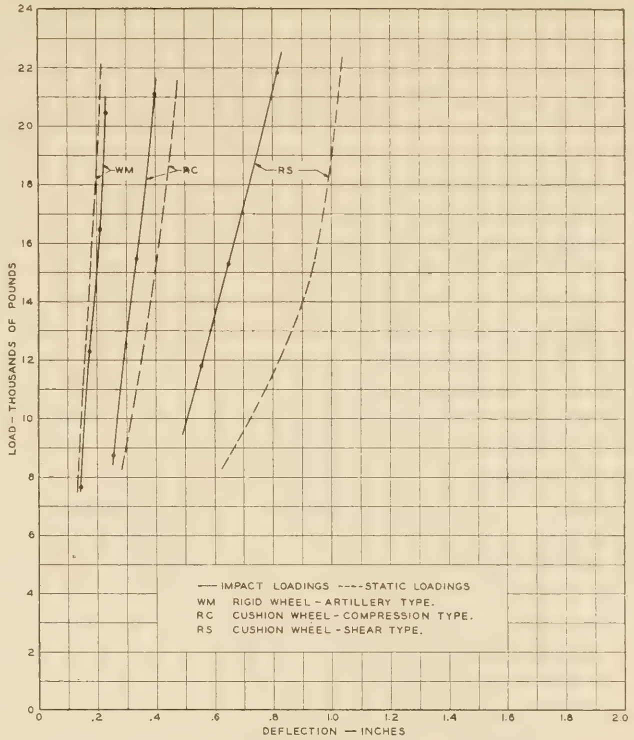

Figure 15.—Comparison of Total Deflections of Different Wheels Equipped with Worn Solid Tires under Impact and Static Loads

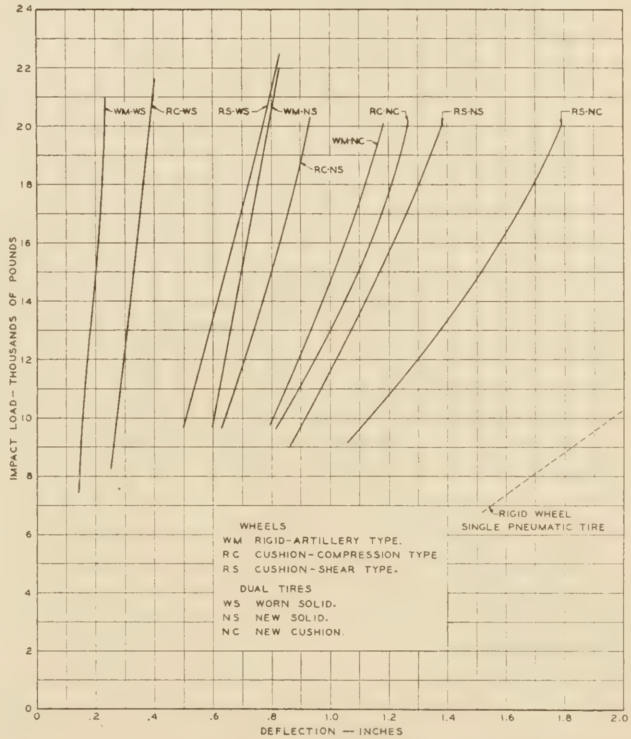

Figure 16.—Comparison of Deflections of All Wheel-Tire Combinations under Impact Loads

various cushioning media in the system that the magnitude of the reaction at the pavement is considerably affected.

The combined deflections of the wheel-tire combinations are given for several impact force magnitudes in Table 10. The deflection values, which are the displacements of the hub after the tire makes contact with the Kreuger cell, are taken from Figure 16. The arrangement of the series is the same as in Tables 6 to 8, and it is evident that the combined deflections of the wheel-tire combinations under impact conditions (Table 10) show the same general tendencies that they did under static conditions (Table 6). The fact that rigid wheel WM and cushion wheel RC show a difference appreciably less under impact conditions than they do under static conditions is attributed to the material increase in the mass of wheel RC (see Table 2) without a sufficient compensating decrease in stiffness (see fig. 6).

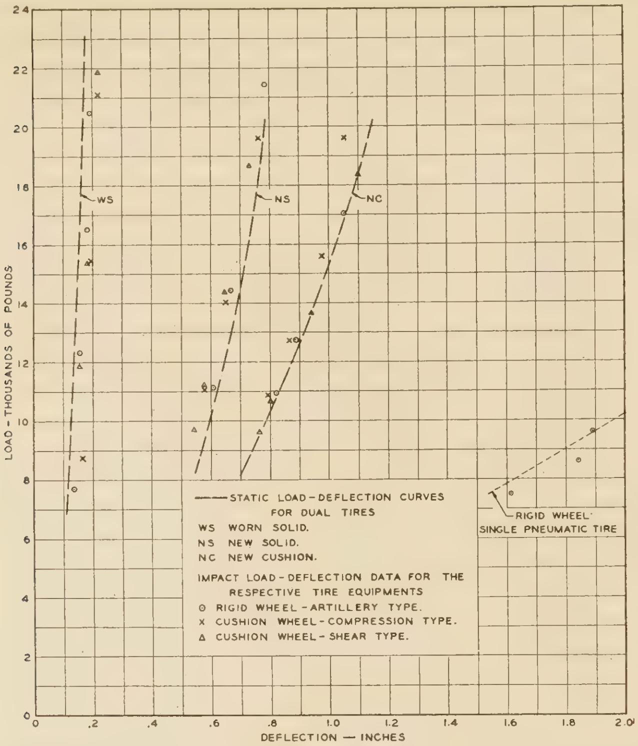

FIGURE 17.—LOAD VS. DEFORMATION OF TIRE EQUIPMENTS

TABLE 10.—*Combined deflections of wheel and tire for given impact forces*

Wheel-tire combination	Impact pressure on Kreuger cell		
	10,000 pounds	15,000 pounds	20,000 pounds
	Inches	*Inches*	*Inches*
WM-WS	0. 16	0. 20	0. 23
RC-WS	. 27	. 33	. 39
WM-NS	. 60	. 70	. 79
RS-WS	. 50	. 64	. 77
RC-NS	. 64	. 80	. 92
WM-NC	. 80	1. 01	1. 18
RC-NC	. 84	1. 09	1. 26
RS-NS	. 91	1. 17	1. 38
RS-NC	1. 13	1. 51	1. 79

COMPUTED VERSUS DIRECTLY MEASURED IMPACT FORCES

Throughout this report the directly measured forces (by the Kreuger cell) have been used as a basis for comparison. In the case of the computed forces; there is no certainty that the maximum acceleration values used in the computations are simultaneous in their occurrence. If they are not simultaneous, greater maximum forces would be indicated as reacting between the tire and the pavement than actually existed. Referring to Tables 3 to 5, it is noted that the computed force exceeded the Kreuger force for about 80 per cent of the test conditions. Although the theory concerning the nonsimultaneous attainment of maximum acceleration values is mathematically tenable, it is not conclusively proved by the above-mentioned results. Everything considered, however, it is thought that the forces indicated by the Kreuger cell afford a more uniform or standardized basis for comparing impact reactions in these tests.

TEST CONDITIONS AFFECT RELATION BETWEEN RIM AND HUB ACCELERATIONS

A detailed discussion concerning the time relation of the hub and rim accelerations of the various wheel-tire combinations is probably intimately related to a discussion of the magnitudes of these accelerations. Such a discussion is, however, more properly in a field of study for automotive engineers and will not be attempted here other than to note that rim acceleration may be greater than, equal to, or less than hub acceleration according to the variations in test conditions.

PNEUMATIC TIRES ON RIGID WHEELS COMPARED WITH CUSHION WHEELS

Since cushion wheels in themselves may contribute some cushioning in addition to that afforded by the tires, the question naturally arises as to how such wheels equipped with solid or cushion tires compare with pneumatic equipment on rigid wheels. The desirability of having information on this point was recognized, and the original program was amplified somewhat to provide the data.

There are two types of pneumatic equipment which are considered standard for the wheel loads used in these tests. These are 40-inch by 8-inch single and 36-inch by 6-inch dual tires. Although for purposes of direct comparison with the other tire equipments used in the program it would have been preferable to test the dual pneumatic tires, this was not possible, because of certain space limitations in the impact-testing machine. The data for the combination of rigid wheel and penumatic tire given in Table 11 were obtained with a 40-inch by 8-inch tire inflated to a pressure of 105 pounds per square inch. The data are also shown as dotted curves in Figures 8, 12, 16, and 17. The effect of using the single instead of the replacement size dual tires is to increase somewhat the cushioning shown by the pneumatic equipment. The magnitude of this effect may be judged by data obtained in previous tests [8] where it was shown that, on the average, the impact reaction of dual pneumatic 36-inch by 6-inch tires was about 120 per cent of that of a single 40-inch by 8-inch tire, all other test conditions being the same.

It is evident from the data obtained that, after making ample allowance for the added stiffness of replacement size dual tires, the pneumatic tire and rigid wheel equipment provides somewhat greater cushioning (as indicated by lower impact reactions for the same test condition) than does even a new cushion tire on either of the cushion wheels tested.

TABLE 11.—*Impact test data for a single pneumatic tire on a rigid wheel*

Unsprung weight, 1,395 pounds; sprung weight, 1,200 pounds; total weight, 2,595 pounds]

Height of fall	Displacement		Acceleration	Computed force			Measured force
	Static	Dynamic		Hub	Spring	Total	
Inches	*Inches*	*Inches*	*Ft./sec.*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
0. 812	0. 688	1. 613	155. 5	6, 740	−250	7, 885	7, 500
1. 270	. 682	1. 841	199. 7	8, 650	−700	9, 345	8, 600
1. 274	. 692	1. 890	210. 1	9, 100	−800	9, 695	9, 600
1. 793	. 693	2. 168	243. 9	10, 570	−1, 300	10, 665	11, 500

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[8] See references in footnotes 2, 3, and 4.

(Continued on page 97)

A TEST FOR INDICATING THE SURFACE HARDNESS OF CONCRETE PAVEMENTS

Reported by L. W. TELLER, Senior Engineer of Tests, Division of Tests, United States Bureau of Public Roads

THERE has long been a need for a test which would indicate the surface hardness of concrete pavements. While normally the wear produced by rubber-tired vehicles is not serious, there are cases where the surfaces of concrete pavements have not possessed the necessary resistance and appreciable wear has occurred. The engineer has had no way of measuring the effect on surface hardness of factors such as sand-cement ratio, type of sand, admixtures or methods of curing, and for this reason there is a noticeable lack of data on the subject of wear resistance. A number of methods of test have been proposed at different times but none of these has come into general use. This paper describes a device which has been developed by the Bureau of Public Roads for indicating, by tests in place, the surface hardness of concrete pavements. It was designed primarily to secure data on the relative surface hardness of concrete cured by different processes and has been in use sufficiently to demonstrate its usefulness.

THE WEAR MACHINE DESCRIBED

The principle of the machine, which is shown in Figure 1, is very simple. Three narrow steel wheels, placed tangentially to a single circular path (fig. 2), are caused to roll along this path at a constant speed and under a constant load. The depth of wear produced in the circular path by any given number of wheel passages is used as a measure of the hardness of the surface being tested.

Mechanically the machine is not complex. It consists primarily of a wear unit and a power unit. The wear unit which is shown in Figure 2 consists of a roughly circular steel plate carrying three 100-pound segmental lead weights and supported by the three tangential wheels mentioned above. This plate revolves around a vertical spindle at its center. The wheels are 8 inches in diameter, have a ¼-inch half-round face or edge and are made of hardened steel. The path followed by the wheels is 21 inches in diameter. The total weight of the unit is 463.5 pounds or 618 pounds per inch of width of the supporting wheels. The speed of rotation of the plate is about 35 revolutions per minute. Thus, any given point in the wear path is subjected to 105 wheel applications per minute

The spindle in the center of the plate is connected through a knuckle to a vertical shaft set in a long vertical bearing in the center of the frame or power unit shown in Figure 3. This shaft is turned by a 1½-horsepower electric motor operating through a worm and worm gear. The shaft carries a spline which permits it to move up or down through the worm gear. As the wheels wear into the concrete the vertical shaft moves downward through the gear, since the shaft is connected firmly, although not rigidly, to the rotating plate and the gear housing is fixed in the supporting frame. This arrangement permits a determination of the depth of wear at any time by a measurement of the position of the end of the vertical shaft with respect to any fixed point, such as the gear housing.

This method of measurement is shown in Figure 4. When readings are being made, a steel U-frame is placed on two ground steel surfaces set in the top of the gear housing. This frame carries a micrometer

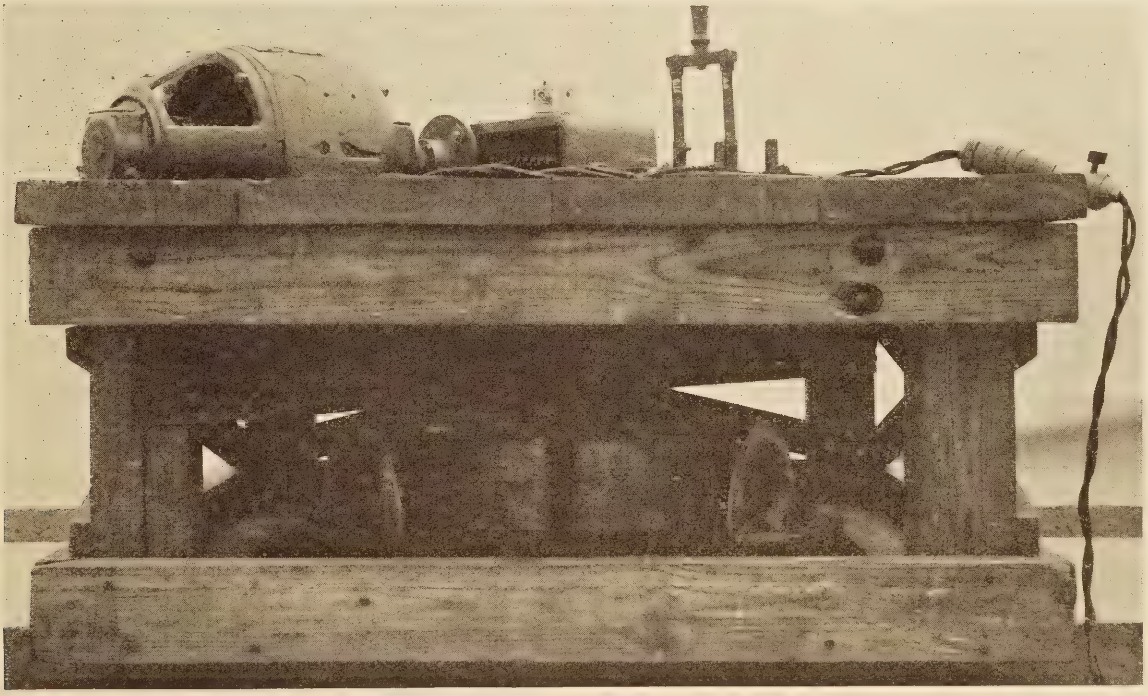

FIGURE 1.—GENERAL VIEW OF COMPLETE MACHINE

dial reading to thousandths of an inch and the stem of the dial bears against the end of the vertical driving shaft. A revolution counter is actuated by a cam on the vertical shaft and may be seen back of the left leg of the U-frame shown in Figure 4. This counter registers the number of revolutions of the main plate.

Power may be supplied from any source, such, for instance, as a drill spindle, but the electric drive shown in the photographs has been found to be very convenient and has the added advantage that the device may be taken anywhere in the field, provided that a small gasoline engine-driven generator is available.

It should be mentioned that wear wheels of soft steel were tried at first. Although not entirely unsatisfactory, they are not nearly so well suited to the purpose as the high-grade steel which has been hardened (and ground if necessary).

TEST PROCEDURE SUITED TO FIELD USE

When the machine is being transported the frame is lifted off from the wear unit and is reassembled just before a test is made. This adds greatly to the portability of the machine.

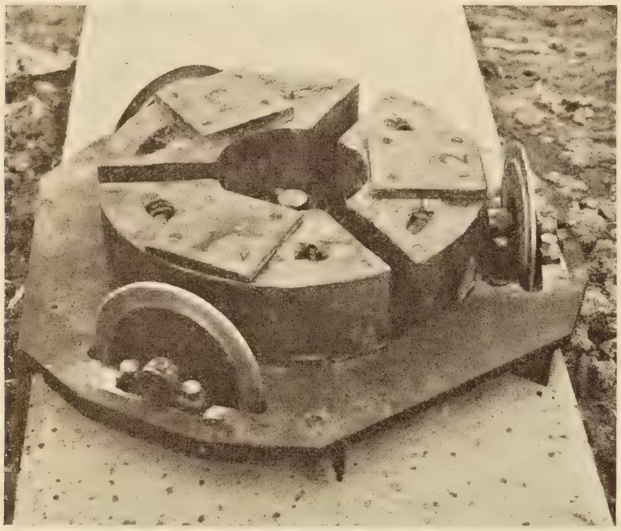

Figure 2.—The Wear Unit, Consisting of Three Tangential Steel Wheels, Supporting a Constant Load of 618 Pounds per Inch of Wheel Width

The spot chosen for a test should be as smooth as possible, since data which are obtained from a rough surface are likely to be erratic during the early part of the test. The wear unit is placed in position over the spot to be tested and the frame is lowered over it. The knuckle, which couples the vertical shaft to the wear unit, is connected, and the three locking springs, which hold this knuckle in firm contact at all times, are fastened. The motor is connected to the power supply and the machine is set in motion. After the plate has revolved four or five times a set of initial readings is taken.

The procedure in taking readings is as follows: The position of No. 1 wheel is marked on the pavement and a reading is made with the micrometer dial The plate is then revolved through 30° and another dial reading taken, the position of No. 1 wheel being again marked on the pavement. The plate is revolved through another 30°, a third dial reading is taken and the position again marked. These three dial readings are averaged for the initial or zero wear reading. The machine is now set in motion and the plate is revolved any desired number of times, say 25 or 50, after which another series of readings is taken, care being exercised that the position of the plate is the same each time as it was when the zero readings were made. It has been found that at least three readings are necessary to obtain a good average value for the depth of wear. Actually, this average is that of nine points on the wear track.

After reading the depth of wear the plate is again rotated the specified number of times and another series of readings is made. Experience will show the total number of revolutions which will constitute a satisfactory test. In the tests so far conducted between 1,000 and 1,500 revolutions per test have been used and it is believed that this number is ample. The results are purely comparative, however, no attempt having been made to standardize the test.

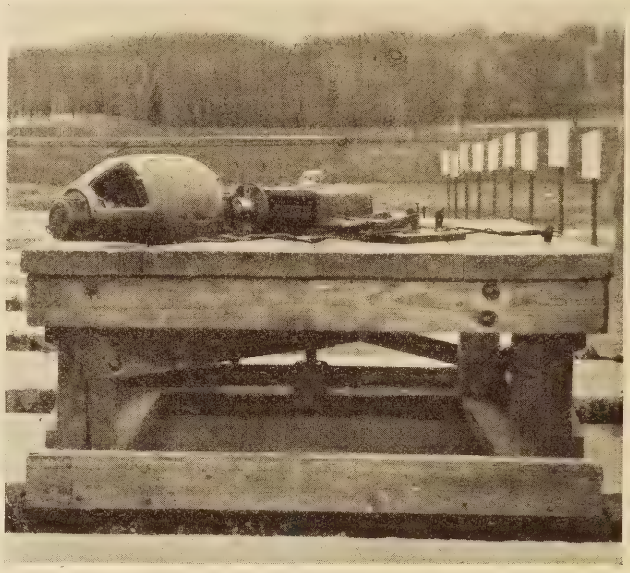

Figure 3.—The Driving Unit with the Wear Unit Removed

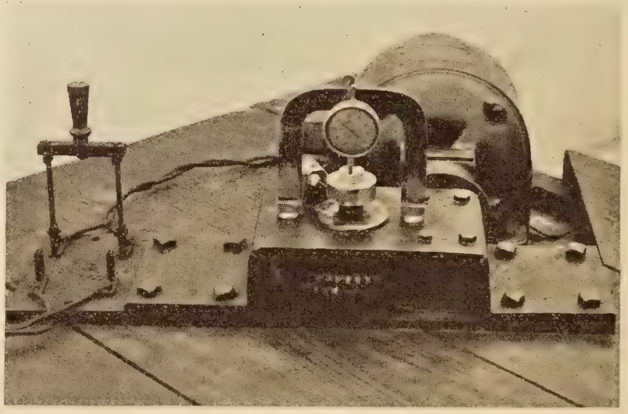

Figure 4.—Steel U-frame Used in Making Measurements of the Depth of Wear. Operating Switch, Driving Motor and Revolution Counter Are Also Shown

It was thought that the consistency of the data might be affected by the accumulation of dust in the path of wear. This possibility was investigated by running a number of duplicate tests, in one-half of which the dust was blown from the track at frequent intervals with an air blast. The data obtained indicated that neither the amount of wear nor the consistency of the results was affected to any measurable degree by the presence of the dry powder.

It has been noticed, however, that tests made when the pavement is moist show abnormally low wear, probably due to the fact that the worn particles, when damp, pack in the wear path and thus protect the bottom of the groove.

TYPICAL DATA PRESENTED

Figure 5 shows typical data obtained with this machine. The two curves represent the wear produced on two slabs of presumably identical concrete which had been cured by two different methods. Each curve was determined by averaging the data for five tests. The individual points have been left off the curve for slab A to avoid confusion. The dispersion of points in the data shown for slab B is typical, however. It is usually found that there is quite a little difference in hardness between different points on the same pavement and this is reflected in the apparent inconsistency of several tests on the same pavement. There is also difficulty in reading depth of wear to a thousandth of an inch on a surface as irregular as a concrete slab. This is shown by the failure of the observed points to follow a smooth curve. For both of these reasons it is most desirable to average a considerable number of readings when drawing general conclusions regarding the surface hardness of a pavement as a whole.

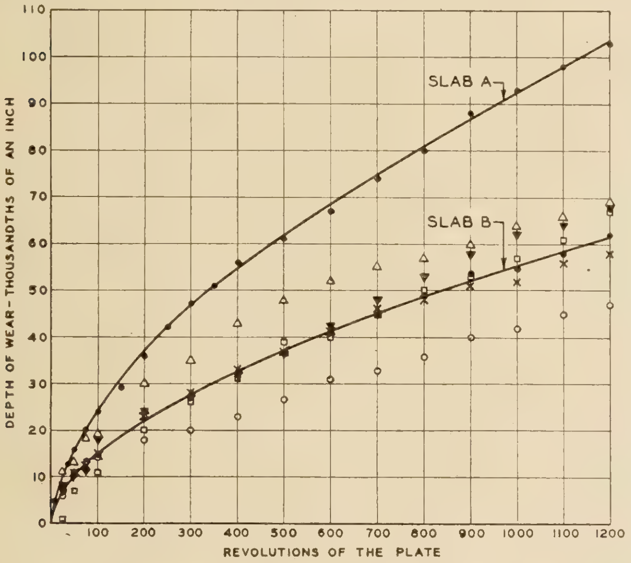

Figure 5.—Results of Tests on Two Slabs of the Same Concrete but Cured by Different Methods. Each Curve Represents the Average of Five Tests

Figure 6 shows other data typical of that which has been obtained. In this figure are wear resistance curves for concretes made from radically different aggregates (although in each concrete both the fine and coarse aggregate came from the same basic material). Since the portion of the curves shown represents wear of the mortar, it is quite evident that considerable differences in the surface hardness of concrete pavements may be due to the character of the fine aggregates used.

These two figures are included to give a general idea of the data which may be obtained and to illustrate two of the many possible uses which may be made of such a machine.

It is realized that the mechanical design of the machine is susceptible to improvement. However, the design as it stands is simple, reliable and portable, the test is fairly rapid to make and it is believed that the data obtained are a measure of surface hardness.

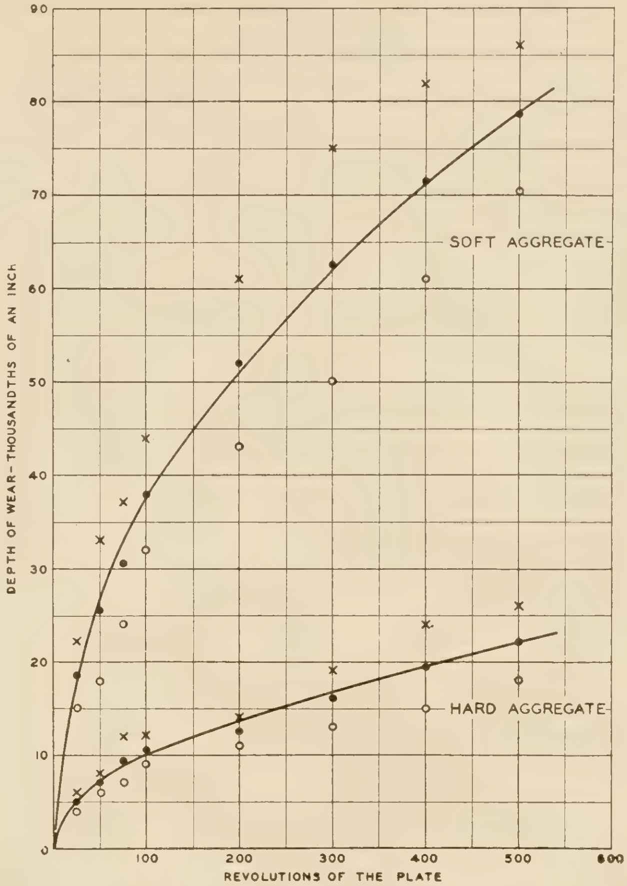

Figure 6.—Results of Tests on Concrete Made With Different Aggregates

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(Continued from page 94)

GENERAL INDICATIONS SUMMARIZED

The major indications from this series of tests are as follows:

1. Other conditions being equal, cushioning material incorporated in the supporting structure of a truck wheel reduced its impact reactions. This reduction may be negligible or important, depending upon the construction of the wheel and the tire equipment used on it.

2. The cushioning properties of cushion wheels become more pronounced as the cushioning properties of the tire equipment used on them decrease.

3. The additional weight sometimes necessitated by cushion-wheel design may partially or even entirely offset the advantage gained by the cushioning action of the wheel structure in so far as the impact reaction on the pavement is concerned.

4. For the conditions of these tests, observed tire deflections for impact pressures are practically the same as those observed for static pressures of the same magnitudes.

GENERAL FEATURES OF DESIGN OF CROSS SECTION OF CONCRETE PAVEMENTS ON FEDERAL-AID PROJECTS SUBMITTED IN 1928

State	Width	Thickness			Thickened edge width	Crown	Mix proportions	Steel used in reinforced type			Steel used in plain type
		Edge	Center	Edge				Bars, pounds per 100 square feet	Mesh, pounds per 100 square feet	Location	
	Feet	*Inches*	*Inches*	*Inches*							
Alabama	18	9	6	9	3 feet	2 inches	1:2:3				2 ¾-inch round smooth oiled edge bars.
Arizona	18	6	6	6		1⅛ inches	1:2:3½				None.
Arkansas	18	9	6	9	2 feet	1½ inches parabolic	1:2:3½				4 ½-inch round smooth edge bars.
California	20	9	[2] 9	9	3 feet	1 inch	1:2:4				4 ½-inch square edge bars.
Colorado	18	9	6½	9	3 feet	1½ inches parabolic	1:2:3				Dowels only.
Connecticut	20	8	8	8		1½ inches, circular	1:1¾:3½ 1:2:3½	105	99	Top and bottom	
Delaware	15	7	6	7	Curved	do	1:2:4 [3]				Do.
Florida	18	9	6	9	3 feet	2¼ inches	1:2:3 to 1:2:4				Do.
Georgia	18	9	6	9	3 feet	1½ inches	1:2:3½				Do.
Idaho	20	9	6	9	2 feet	1 inch	1:2:3				None.
Illinois	18 20	9 9	6 7	9 9	2 feet 3 feet	1 inch, circular	1:2:3½				2 ¾-inch round smooth edge bars.
Indiana	18	9	7	9	2½ feet	2 inches	1:2:3				Do.
Iowa	18	10	7	10	4 feet	2 inches	(4)				4 ⅝-inch round smooth edge bars.
Kansas	18	9	6	9	do	2 inches, parabolic	1:1¾:2¾ 1:1¾:3½				2 ¾-inch round smooth edge bars.
Kentucky	18	9	6	9	2 feet	1½ inches	1:2:3½				Do.
Louisiana	18, 20	8	6	8	Curved	2½ inches	1:2:3½		47.5	2 inches from top	
Maine	20	9	7	9	4 feet	1½ inches	1:2:3½	116		Top and bottom	
Maryland	16	9	6.3	9	do	2 inches	1:2:4				None.
Michigan	20	9	7	9	3 feet	1½ inches, parabolic	1:2:3½	60	59	2 inches from top	Dowels only.
Minnesota	20	9	7	9	4 feet	1 inch	1:2:3½				6 ⅝-inch round edge bars.
Mississippi	18	7 9	6 6	7 9	Curved 2 feet	2 inches, circular	1:2:3		86	2 inches from top	2 ¾-inch round edge bars.
Missouri	18	9	6	9	do	1½ inches	1:2:3½				Do.
Montana	18, 20	9	6	9	do	2 inches, circular	1:2:3				2 1-inch round edge bars.
New Hampshire	18	9	6	9	do	1 inch	1:2:3		67–75	2 inches from top	
New Jersey	20	8 9	8 9	8 9		1½ inches	1:2:3½	85	76	do	
New Mexico	18	9	6	9	2 feet	1 inch, parabolic	1:2:3				Dowels only.
New York	18, 20	8 8	8 7	8 8	9–10 feet	1⅛ to 1¼ inches	1:2:3½	53.9	53.4	2 inches from top	
North Carolina	16, 18, 20	6 8 8	6 6 7	6 8 8	Curved	1½ to 2 inches, parabolic.	1:1.8:4 to 1:2:5¼				Dowels only.
Ohio	18, 20	9	7	9	2 feet	1 inch, curved	1:2:3				2 ¾-inch round smooth edge bars.
Oklahoma	18	9	6	9	do	2 inches, parabolic	1:2:3½				6 ½-inch round deformed edge bars.
Pennsylvania	18	8 9	6 7	8 9	Curved	1 inch, parabolic	1:2:3¼ 1:2:3½	56	95	2 inches from top	6 ⅝-inch round edge bars.
Rhode Island	20, 30, 40	8	8	8		1½ inches, circular	1:2:3		42	do	
South Carolina	18	7½ 8	6 6½	7½ 8	Curved	2 inches, parabolic	1:2:4				Dowels only.
Tennessee	18	8	6	8	do	1½ inches, parabolic	1:2:3½				Do.
Texas	18	9	6	9	2 feet	2 inches, parabolic	1:2:3½				4 to 6 ½-inch round edge bars.
Utah	18	9	6	9	do	1 inch, plane	1:2:3				None.
Vermont	18	7	7	7		2 inches, plane	1:2:4	79.5		2 inches from top and bottom.	
Virginia	18	8	6	8	Curved	2¼ inches	1:2:4				None.
Washington	18, 20	9	6½	9	2 feet	2 inches	1:2:3				Dowels only
West Virginia	16, 18	7 8	7 8	7 8		2¼ inches	1:1¾:3¼ 1:2:3		56	2 inches from top	
Wisconsin	20	9	6½	9	4 feet	1 inch, parabolic	1:2:4				Do.

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[2] Double thickened edge section used with 6-inch thickness at center of half width.

[3] Admixture ⅒ cubic foot hydrated lime per bag of cement.

[4] Proportioned by weight; 1 pound cement to 3.78 pounds aggregate, or 1 pound cement to 5.18 pounds aggregate.

GENERAL FEATURES OF DESIGN OF CROSS SECTION OF CONCRETE PAVEMENTS ON FEDERAL-AID PROJECTS SUBMITTED IN 1928—Continued

State	Longitudinal joint		Transverse joints				Dowels	
	Type	Gage No. or width	Type	Spacing	Width	Filler	Longitudinal joints	Transverse joints
					Inches			
Alabama	Deformed metal plate	16	Expansion	50 to 200 feet	½–1	Premolded or poured	2 feet by ½ inch round, 5 feet C. to C.	None.
Arizona	None		Contraction	50 feet				Do.
Arkansas	Deformed metal plate	16	Expansion	do	¾	Premolded or poured	4 feet by ½ inch round, 5 feet C. to C.	6 ½ inch round.[1]
California	Weakned plane		Expansion	60 feet	½	Premolded	None	10 ¾ inch by 2 feet.[1]
			Contraction	20 feet		None	do	None.
Colorado	Deformed metal plate	18	Expansion	60 feet	½	Premolded	4 feet by ½ inch round, 5 feet C. to C.	Do.
Connecticut	Bituminous, poured or premolded.	½, ¼ inch	do	do	½	Premolded or poured	None	Do.
Delaware	Deformed metal plate	16	Construction	As necessary		None	4 feet by ½ inch round, 5 feet C. to C.	7 ¾ inch round.[1]
	Weakened plane		do	do		do	None	Do.
Florida	None		Expansion	40 feet	½–¾	Premolded or poured	do	8 ½ inch round.[1]
Georgia	Deformed metal plate	16	do	End of run	½–¾	Poured	4 feet by ½ inch round, 4 feet C. to C.	None.
Idaho	Weakened plane		do	60 feet	½–⅝	Premolded	None	Do.
			Contraction	20 feet	½			
Illinois	Deformed metal plate	18	Construction	As necessary			4 feet by ½ inch round, 5 feet C. to C.	Do.
Indiana	Deformed metal plate or weakened plane.	16	do	do			4 feet by ⅝ inch round, 5 feet C. to C.	6 4 feet by ¾ inch round.[1]
Iowa	Deformed metal plate	18	do	do			5 feet by ⅝ inch round, 4 feet C. to C.	10 2 feet by ⅝ inch round.[1]
Kansas	do	18	Expansion	100 feet	¾	Poured	4 feet by ½ inch round, 5 feet C. to C.	None.
			Contraction	50 feet				
Kentucky	do	16	Construction	As necessary			do	Do.
Louisiana	do	16	Expansion	100 feet	½	Premolded or poured	do	8 ½ inch by 4 feet round.[1]
Maine	Construction (plain)		do	40 feet	½	Premolded	None	10 ⅜ inch by 2 feet round.[1]
Maryland	Weakened plane		Construction	As necessary			do	None.
Michigan	Deformed metal plate	16	Expansion	100 feet	1	Premolded	4 feet by ½ inch round, 1 foot 8 inches C. to C.	Do.
Minnesota	do	16	do	201 feet	2	do	4 feet by ½ inch round; 5 feet C. to C.	6 ¾ inch by 2½ inches round.[1]
			Deformed metal plate.	40 feet				None.
Mississippi	None		Expansion	30 feet	½	Premolded	None	8 ¾ inch by 4 feet round.[1]
	Deformed metal plate	18		50 feet			4 feet by ½ inch round, 5 feet C. to C.	
Missouri	do	16	Construction	As necessary			do	None.
Montana	Weakened plane		Expansion	30 feet	⅜	Premolded	None	Do.
New Hampshire	Construction (plain)		do	50 feet	¼–¾	Premolded or poured	do	8 ⅝ inch by 2 feet round.
New Jersey	Expansion	½ inch	do	34 to 45 feet		do	do	6 ¾ inch by 20 inches round.[1]
New Mexico	Deformed metal plate		do	60 feet	¾	Premolded	4 feet by ½ inch round, 5 feet C. to C.	None.
New York	Construction (plain)		do	78 feet	¾	Premolded or poured	None	8 ¾ inch by 18 inches round.[1]
North Carolina	None		Construction	As necessary				9¾ inches by 2 feet, round (oiled).
Ohio	Weakened plane or deformed metal plate.		do	do			4 feet by ½ inch round, 5 feet C. to C.	None.
Oklahoma	Deformed metal plate	18	Expansion	50 feet	1	Poured	do	Do.
Pennsylvania	do	14	do	Designed	½	Premolded	do	Do.
Rhode Island	Expansion	¾ inch	do	100 feet	¾	do	None	8 ½ inch by 2 feet round.
South Carolina	Only on doubtful subgrade.	16–18	do	40 feet	⅜–¾	do	4 feet by ½ inch round, 5 feet C. to C.	None. None.
Tennessee	Deformed metal plate	16	do	do	¾	Premolded or poured	do	6 ¾ inch by 4 feet round.[1]
Texas	do	18	do	40 to 100 feet	1	Premolded	do	8 ⅝ inch by 3 feet round.[1]
Utah	Weakened plane		do	25 feet	⅜	do	None	None.
Vermont	Construction		do	End of run	½	do	2 feet by ¾ inch round, 3 feet 4 inches C. to C.	8 ¾ inch round.[1]
Virginia	None		Construction	As necessary				None.
Washington	Weakened plane		Expansion	40 feet	½	Premolded	2 feet by ½ inch round, 8 feet C. to C.	Do.
			Contraction	20 feet	⅝			
West Virginia	Deformed metai plane	14	Construction	As necessary			None	Do.
Wisconsin	do	18	Expansion	50 feet	¼–½	Premolded	4 feet by ½ inch round, 3 feet 11 inches C. to C.	4 ⅝ inch round.[1]

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[1] One end free.

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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.

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387D. Public Road Mileage and Revenues in the Southern States, 1914.
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390D. Public Road Mileage and Revenues in the United States, 1914. A Summary.
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*532D. The Expansion and Contraction of Concrete and Concrete Roads. 10c.
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*670D. The Results of Physical Tests of Road-Building Rock in 1916 and 1917. 5c.
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1486D. Highway Bridge Location.

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Report of a Survey of Transportation on the State Highways of Vermont.
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.

REPRINTS FROM THE JOURNAL OF AGRICULTURAL RESEARCH

Vol. 5, No. 17, D- 2. Effect of Controllable Variables upon the Penetration Test for Asphalts and Asphalt Cements.
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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UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

CURRENT STATUS OF FEDERAL AID ROAD CONSTRUCTION

AS OF

JUNE 30, 1929

STATE	COMPLETED MILEAGE	UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FEDERAL-AID FUNDS AVAILABLE FOR NEW PROJECTS	STATE
		Estimated total cost	Federal aid allotted	MILEAGE			Estimated total cost	Federal aid allotted	MILEAGE				
				Initial	Stage[1]	Total			Initial	Stage[1]	Total		
Alabama	1,960.7	$ 3,258,926.95	$ 1,627,437.04	224.7	21.0	245.7	$ 430,398.21	$ 215,199.10	6.4	14.3	20.7	$ 2,243,381.25	Alabama
Arizona	887.8	2,199,816.28	1,859,989.34	100.5	30.1	130.6	226,598.57	170,606.04		29.4	29.4	2,653,890.02	Arizona
Arkansas	1,745.1	3,656,725.36	1,799,403.14	102.9	6.5	109.4	529,229.73	262,782.41	25.3	6.0	31.3	2,104,522.21	Arkansas
California	1,625.5	9,612,659.34	4,324,210.30	265.4	9.9	275.3	2,536,332.71	1,117,206.50	31.6	19.5	51.1	821,207.18	California
Colorado	1,137.4	3,993,909.55	2,068,568.40	128.8	26.6	155.4	770,144.32	412,855.91	25.8	12.4	38.2	1,673,794.83	Colorado
Connecticut	229.3	792,275.72	217,937.99	12.5		12.5	1,372,239.99	559,118.95	8.0		8.0	558,722.80	Connecticut
Delaware	212.9	753,366.80	298,843.42	15.7		15.7	535,184.40	262,260.69	30.8		30.8	47,336.16	Delaware
Florida	449.0	2,734,529.08	1,135,234.01	90.9	5.7	96.6						1,965,926.62	Florida
Georgia	2,564.7	3,757,836.66	1,673,267.89	163.9	36.9	200.8	37,129.17	18,192.86	2.9		2.9	2,018,492.49	Georgia
Idaho	1,144.5	905,547.56	542,064.66	77.5		77.5	202,122.35	121,880.16	16.3		16.3	856,815.71	Idaho
Illinois	1,888.6	19,245,292.23	8,620,190.39	572.8		572.8	648,000.00	324,000.00	22.5		22.5	2,642,000.00	Illinois
Indiana	1,266.7	8,958,464.70	4,278,868.78	275.9		275.9	1,058,051.61	504,631.00	35.3		35.3	134,519.81	Indiana
Iowa	3,009.1	3,527,407.02	1,582,809.17	53.4	82.3	135.7	2,464,679.61	998,305.35	25.7	63.9	89.6		Iowa
Kansas	2,539.5	3,432,075.07	1,346,245.56	243.8		243.8	2,067,844.93	981,277.15	135.9	11.5	147.4	1,144,315.96	Kansas
Kentucky	1,314.5	4,598,602.22	2,194,672.33	243.8	3.4	247.2	463,762.16	231,833.31	40.3		40.3	757,788.11	Kentucky
Louisiana	1,321.4	3,623,495.55	1,803,969.15	151.9		151.9	287,899.05	105,752.71	.2	8.2	8.4	1,150,105.07	Louisiana
Maine	480.5	1,883,862.41	646,104.12	44.3		44.3	941,331.71	381,984.35	29.7		29.7	1,111,122.42	Maine
Maryland	627.9	167,810.00	62,360.00	3.6		3.6	980,260.95	456,710.00	39.3	16.8	56.1	213,725.37	Maryland
Massachusetts	570.7	5,097,641.63	1,538,226.50	91.1		91.1	258,186.27	75,125.87	1.9	3.4	5.3	1,787,319.03	Massachusetts
Michigan	1,470.2	10,224,762.17	4,374,874.40	251.3		251.3	2,155,000.00	933,716.86	51.6	9.5	61.1	1,424,179.67	Michigan
Minnesota	3,872.6	4,888,903.63	1,671,618.27	197.6	93.4	291.0	1,498,509.36	416,297.96	74.7	16.6	91.3	410,000.00	Minnesota
Mississippi	1,656.5	4,736,296.26	2,130,632.99	196.4	17.4	213.8	188,293.15	94,146.56	12.9		12.9	1,361,970.25	Mississippi
Missouri	2,278.1	9,068,176.63	3,483,757.97	211.8	56.2	268.0	3,342,376.38	1,279,693.85	16.5	91.4	107.9	136,556.02	Missouri
Montana	1,538.9	5,089,960.81	3,187,267.45	354.2	8.1	362.3	1,758,524.56	967,070.97	166.0		166.0	3,613,761.84	Montana
Nebraska	3,628.2	2,892,184.38	1,438,788.31	240.5	60.2	300.7	1,558,312.11	711,443.12	54.0	134.7	188.7	2,539,681.66	Nebraska
Nevada	1,081.6	1,144,050.62	1,002,938.37	114.5	112.4	226.9	334,482.30	297,187.45	.6	92.4	93.0	204,689.18	Nevada
New Hampshire	332.7	561,177.02	198,553.31	12.5	1.0	13.5	252,935.68	97,410.00	6.5		6.5	188,125.54	New Hampshire
New Jersey	462.6	4,565,550.60	815,205.00	54.3		54.3	521,240.38	130,335.00	8.7		8.7	625,470.08	New Jersey
New Mexico	1,868.1	2,261,247.93	1,429,503.15	137.6		137.6	241,716.29	154,094.12	9.0		9.0	1,153,455.48	New Mexico
New York	2,182.7	23,451,671.43	5,137,430.55	343.6		343.6	9,105,046.33	2,054,505.00	137.5		137.5	4,295,740.58	New York
North Carolina	1,712.0	1,375,152.61	687,576.28	80.4	7.2	87.6	272,103.36	131,967.67	14.2		14.2	1,721,786.21	North Carolina
North Dakota	3,675.8	3,234,518.96	1,329,006.06	482.5	138.2	620.7	1,143,646.71	429,101.68	124.7	231.9	356.6	982,621.03	North Dakota
Ohio	2,013.1	11,976,628.49	4,206,990.80	257.2		257.2	4,310,036.60	997,860.29	59.7	19.3	79.0	2,755,365.68	Ohio
Oklahoma	1,823.7	1,499,899.94	668,725.70	78.8	5.8	84.6	1,392,362.75	617,562.37	38.4	17.1	55.5	913,425.83	Oklahoma
Oregon	1,147.9	793,251.14	391,848.56	48.2		48.2	1,137,687.38	708,004.14	72.9	44.8	117.7	1,430,698.62	Oregon
Pennsylvania	2,072.9	12,854,654.57	3,395,873.25	202.5	14.1	216.6	3,619,350.36	1,267,978.20	81.9		81.9	1,855,478.52	Pennsylvania
Rhode Island	165.2	1,562,040.98	403,211.55	23.9		23.9	70,170.40	22,755.00	1.5		1.5	548,347.68	Rhode Island
South Carolina	1,813.8	4,080,278.30	823,426.61	128.9	37.4	166.3	368,829.54	85,000.00	14.2		14.2	886,629.83	South Carolina
South Dakota	3,310.8	3,727,628.20	2,010,354.66	488.6	47.7	536.3	440,580.75	232,278.85	49.0	28.6	77.6	371,595.94	South Dakota
Tennessee	1,148.4	3,605,466.41	1,672,582.01	119.8		119.8	342,937.22	171,468.59	15.9		15.9	1,096,306.59	Tennessee
Texas	6,064.2	17,723,807.68	7,610,655.50	657.9	253.2	911.1	7,000,086.00	2,998,213.00	173.2	139.1	312.3	36,517.80	Texas
Utah	918.3	1,727,297.51	1,165,860.46	68.0		68.0	246,869.73	182,643.58	18.4		18.4	361,621.97	Utah
Vermont	229.0	1,889,278.37	632,504.02	38.1		38.1	20,051.36	10,025.68	.1		.1	62,786.68	Vermont
Virginia	1,345.6	2,754,082.68	1,196,688.51	95.3	18.9	114.2	476,187.94	201,193.99	22.1	3.1	25.2	758,318.82	Virginia
Washington	854.4	3,721,579.95	1,238,875.25	73.1	18.1	91.2	1,039,326.93	480,000.00	21.9	11.7	33.6	917,100.03	Washington
West Virginia	683.3	2,842,654.78	1,149,762.08	68.9	17.8	86.7	1,323,627.44	515,302.72	24.8	12.3	37.1	77,371.86	West Virginia
Wisconsin	2,056.1	9,777,590.68	4,308,468.14	307.1	29.3	336.4	754,725.77	363,097.16	38.9		38.9	338,759.36	Wisconsin
Wyoming	1,674.6	1,526,197.61	979,518.74	155.1	8.9	164.0	213,573.07	140,210.67	28.7	27.4	56.1	313,862.69	Wyoming
Hawaii	39.5	402,261.10	137,426.82	6.6		6.6	562,688.38	247,259.61	16.6		16.6	1,072,664.16	Hawaii
TOTALS	78,096.6	238,158,495.57	96,500,346.96	8,358.6	1,167.7	9,526.3	61,500,673.97	24,137,546.45	1,833.0	1,065.3	2,898.3	56,339,874.64	TOTALS

[1] The term stage construction refers to additional work done on projects previously improved with Federal aid. In general, such additional work consists of the construction of a surface of higher type than was provided in the initial improvement.

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