MICHIGAN
STATE HIGHWAY DEPARTMENT
Charles M. Ziegler
State Highway Commissioner

MODERN HIGHWAY LOADINGS IN RELATION TO PAVEMENTS AND BRIDGES

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

MODERN VEHICLE LOADINGS IN RELATION TO PAVEMENTS AND BRIDGES

INTRODUCTION

In order to facilitate the movement of war traffic in Michigan, the Administration in cooperation with those of other States, agreed to accept for the duration of the war emergency loading standards prepared by the Public Roads Administration.(1) The change in wartime load restrictions effected in Michigan an increase in the gross load on tandem axles of 4,000 pounds. Surveys show that in actual practice, weight restrictions on both single and tandem axles have been quite widely exceeded under the plea that overloads were necessary to speed the war effort.

Wartime conditions were also responsible for the construction of many new motor transport units designed especially to handle heavier loads. These transport units are now engaged in hauling peacetime commodities under the war emergency load restrictions. Such conditions as these have naturally created a desire on the part of truck operators for higher load limits after the war emergency. Consequently, legislation to that effect is now being proposed by the American Trucking Association.

With these facts in mind, an investigation has been made at the suggestion of Commissioner Charles M. Ziegler to determine what effect the increased axle loadings will have on concrete pavements. It follows that increased axle loads will result in greater gross vehicle weights; consequently, the effect of greater gross vehicle loads on existing bridge structures was also given due consideration in the investigation.

This report has for its purpose the presentation of important factual information concerning modern motor transport loadings in Michigan, the destructive effect of these loadings on highway structures in the light of present knowledge, and methods for their control. This material is intended to serve as a reference and guide in legislative matters pertaining to future motor vehicle load restrictions.

The material presented in the report is based on Loadometer Surveys conducted by the Planning and Traffic Division and from special studies performed by the Bridge Division on highway loadings in relation to the posting and protection of bridge structures. Also included in the source of information are such agencies as the American Association of State Highway Officials, the Public Roads Administration and the Illinois Department of Highways. Considerable valuable information was derived from the current studies on concrete pavement design now in progress by the Testing and Research Division of the Highway Department.

The investigation reveals a definite upward trend in axle loads and gross vehicle weights. Also there is indicated a general practice of overloading axles encouraged no doubt by wartime conditions. This current practice of overloading must be reduced to a minimum as a safeguard against accelerated pavement destruction.

Repeated tests as well as theoretical analysis indicate that the maximum stresses induced in concrete pavement slabs under static conditions are a function of the wheel load and are not greatly affected by axle spacing provided the distance between separate wheel loads is not less than 3-1/2 to 4 feet. This holds true for other types of pavements as well. From this it might be inferred that 18,000 pound loads could be permitted on all axles irrespective of how they may be grouped without causing more injury to the pavement than that of a single 18,000 pound axle load provided the axles are spaced not less than 5 feet 6 inches apart. At the present time any recommendation for future legal weight restrictions based on this conclusion may lead to serious difficulties because of the present lack of basic information on the dynamic effects of multiple or group axle loadings on pavement stresses and the breakdown of pavements, and also because of the many uncertainties in the ultimate structural adequacy of the pavement resulting from current construction practices. All of these factors must be taken into consideration when establishing load limitations.

In the case of bridge structures the gross weight of the vehicle is the governing factor in design and, consequently, definite design standards have been established based on the relation between gross load and corresponding moment and shear values for different span lengths. As a protection to bridge structures these design loadings should not be exceeded.

In view of these facts no increase in axle loads should be permitted at this time. Furthermore, it is extremely important that rational load laws be enacted and adequate means provided to enforce them in order that the public investment may be satisfactorily protected. It would seem that the incorporation of some version of the load formula law into Michigan's current motor vehicle law is advisable at this time.

The report consists of four parts; the first contains a review of Michigan's motor vehicle regulations and data showing present load conditions on the highways; the trend in State regulations covering the size and weights of vehicles is presented in part two; included in part three are results of investigations covering the effect of multiple axle loadings on concrete pavement slabs; the fourth, and last, part discusses modern highway loadings in relation to bridges.

PART I

THE MOTOR TRANSPORT SITUATION IN MICHIGAN

The increase in maximum gross weights of individual motor transport vehicles in Michigan during the past 30 years is very interesting. The first motor vehicle law passed in 1917 permitted no trucks over 30,000 pounds gross weight to travel the highways. In 1925 the law was amended whereby the maximum weight was reduced to 28,000 pounds with additional stipulations that the maximum load on any single axle should not exceed 18,000 pounds, or 13,000 pounds per axle when the axles were spaced less than 10 feet apart. In 1929 the legal restriction on gross weight was abolished and in its place special restrictions on axle loading were substituted. The maximum load per single axle remained at 18,000 pounds for spacings greater than 9 feet. However, for axle spacings less than 8 feet, 6 inches the following values were stipulated:

9 feet and over 18,000 pounds

8' 6" to 9'	13,500 pounds	5' 6" to 6' 6"	11,000 pounds
7' 6" to 8' 6"	13,000 pounds	4' 6" to 5' 6"	10,300 pounds
6' 6" to 7' 6"	12,000 pounds	3' 6" to 4' 6"	9,500 pounds

The last major change in the motor vehicle law relative to maximum axle loads occurred in 1933. At that time legal restrictions on axle loads were changed to the following values:

Axle Spacing	Axle Load, in Pounds Solid Tires	Pneumatic Tires
9 feet and over	16,000	18,000
3' 6" to 9'	11,600	13,000
Less than 3' 6"	8,000	9,000

A maximum wheel load of 700 pounds per inch width of tire was also specified.

Under the present law the maximum gross weight permitted on a motor transport unit is restricted only by the spacing of the axles permitted by the dimensions of the unit.

Digest of Present Michigan Load Law

In the 1945 issue of Michigan Laws[2] related to Motor Vehicles and their operation on the streets and highways, the following regulations are stipulated:

1. Size of Vehicles and Loads
   a. No vehicle, unladen or with load, shall exceed a total outside width of 96 inches.
   b. No vehicle, unladen or with load, shall exceed a height of 12 feet 6 inches.
   c. No single vehicle including load shall exceed a total length of 35 feet.
   d. No combination of unladen or loaded vehicles coupled together shall exceed a total length of 50 feet.
2. Wheel and Axle Loads
   a. The total load on any single wheel shall not exceed 700 pounds per inch of width of tire.

b. The total load on any single axle shall not exceed 18,000 pounds when equipped with pneumatic tires, or 16,000 pounds with solid rubber tires.

c. When the distance between any pair of axles is less than 9 feet, or more than 3 feet 6 inches, the total load on either of the two axles shall not exceed 13,000 pounds for pneumatic tires and 11,600 pounds for solid rubber tires.

d. When the distance between any pair of axles is less than 3 feet 6 inches, the total load on the two axles shall not exceed that of a single axle with similar tires.

3. Gross Weights

No ceiling on gross weight of vehicles is stipulated. The gross weight is subject to limitations imposed on wheel and axle loads, as well as dimensional restrictions imposed by law on the manufacture of motor transport units.

4. Seasonal Regulations

The maximum axle and wheel loads mentioned above are subject to a fixed reduction by State authorities for a definite period during the spring of the year. The regulations are:

a. The maximum axle loads on concrete pavements, or pavements with concrete bases, shall be reduced 25 percent and the wheel load shall not exceed 525 pounds per inch width of tire.

b. The maximum axle loads on all other types of roads shall be reduced 50 percent and the wheel load shall not exceed 450 pounds per inch width of tire.

c. The regulation shall be in effect during the months of March, April, and May, and may be suspended at the discretion of the State Highway Commissioner when and where conditions of the highways warrant it.

5. Special Vehicles

Any special vehicle of any kind for which the interpretations of the above provisions do not apply shall not be permitted on the highways without a signed permit by the State Highway Commissioner. The permit restricts the use of such vehicles to one trip within a period of 10 days.

The Michigan Law provides no definite regulation as to the total gross weight of any vehicle. The number of axles is limited only by the legal maximum length restrictions for single and combination units which in time will govern the total gross load. Thus, the law would permit the operation of a vehicle combination 80 feet long having 11 axles at 18,000 pounds spaced 8'-0" centers with a total possible gross load of 198,000 pounds or having 6 axles at 18,000 pounds spaced 9 feet apart with a possible gross load of 108,000 pounds. According to loadometer surveys by the Planning and Traffic Division, tractor-trailer combinations are now operating on the highways of Michigan with total gross loads in excess of 100,000 pounds.

Existing Load Conditions on Michigan Highways

In order to facilitate an understanding of load conditions imposed by motor transport units now using the highways in Michigan, several charts have been prepared which represent graphically data obtained from yearly loadometer studies conducted by the Planning and Traffic Division.(5)

Presented in Figure 1, are nineteen possible combinations of motor transport units together with their permissible maximum gross weight limits under conditions designated A, B and C.

Condition A represents Michigan's prewar legal restrictions of 18,000 pounds on a single axle and 13,000 pounds on tandem axles while the gross weights under condition B are in accordance with war emergency restrictions permitting 18,000 pounds on a single axle and 16,000 pounds on tandem axles.

In the case of Condition C the gross weights were determined in accordance with an understanding between the Department and the Trucking Association whereas the load on tandem axles shall be 16,000 pounds when the transportation unit contains only 1 tandem axle group and 13,000 pounds per axle when the unit contains more than one group of tandem axles. Under these arrangements it may be observed from Figure 1 that legal maximum gross loads of 113,000 pounds are possible under condition C and 128,000 pounds under B.

In the event that the over-all length of motor transport units should be increased in the future, even greater gross weights may be expected under the present Michigan Law.

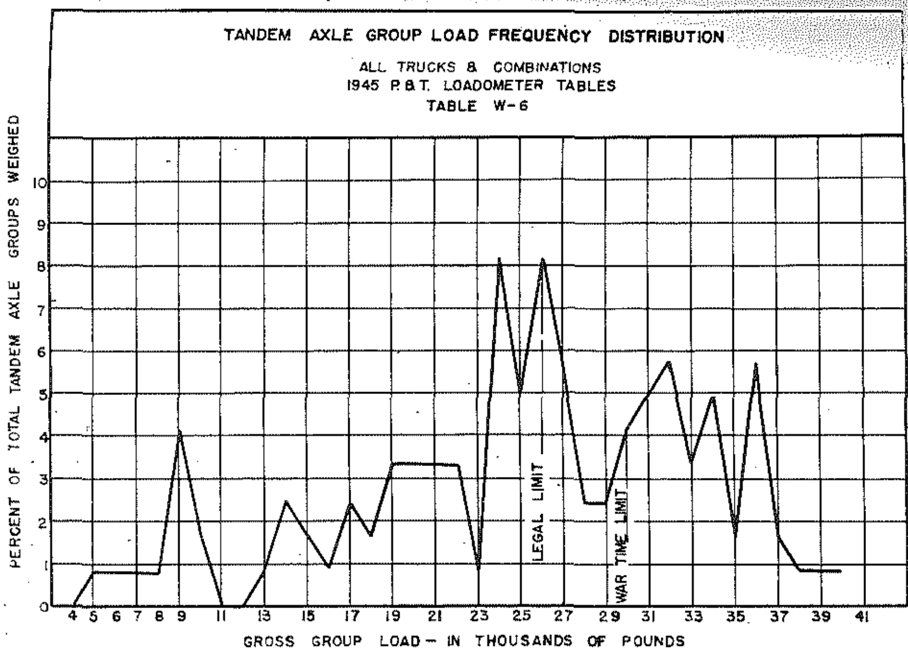
The graphs presented in Figure 2 disclose the frequency distribution of single axle loads, group-axle loadings and total vehicle weights for the prewar year of 1938 and for the wartime period during 1943, 1944 and 1945. The graphs bring out two significant points; first, they show the upward

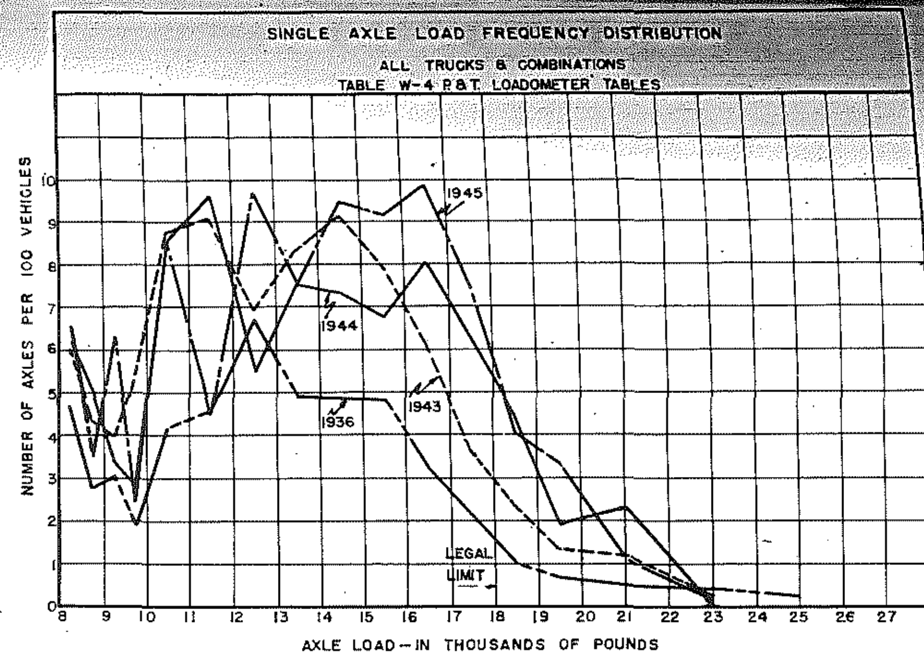
Class	TYPE	VEHICLE DESIGNATION	MAXIMUM LEGAL GROSS WEIGHT, LBS. A	B	C
TRUCK CLASS I		2 ★	27,000	27,000	27,000
		3 ★	35,000	39,000	39,000
TRACTOR & SEMI-TRAILER CLASS II		2S1 ★	45,000	45,000	45,000
		2S2 ★	53,000	57,000	57,000
		3S1	53,000	57,000	57,000
		3S2	61,000	69,000	61,000
TRUCK & TRAILER CLASS III		2-2 ★	63,000	63,000	63,000
		3-2 ★	71,000	75,000	75,000
		2-3	71,000	75,000	75,000
		3-3	79,000	87,000	79,000
TRACTOR, SEMI-TRAILER & TRAILER CLASS IV		2S1-2 ★	81,000	81,000	81,000
		2S1-3	89,000	93,000	93,000
		2S2-2 ★	89,000	93,000	93,000
		2S2-3 ★	97,000	105,000	97,000
		3S1-2	89,000	93,000	93,000
		3S1-3	97,000	105,000	97,000
		3S2-2	97,000	105,000	97,000
		3S2-3	105,000	117,000	105,000
		3S2-4	113,000	129,000	113,000

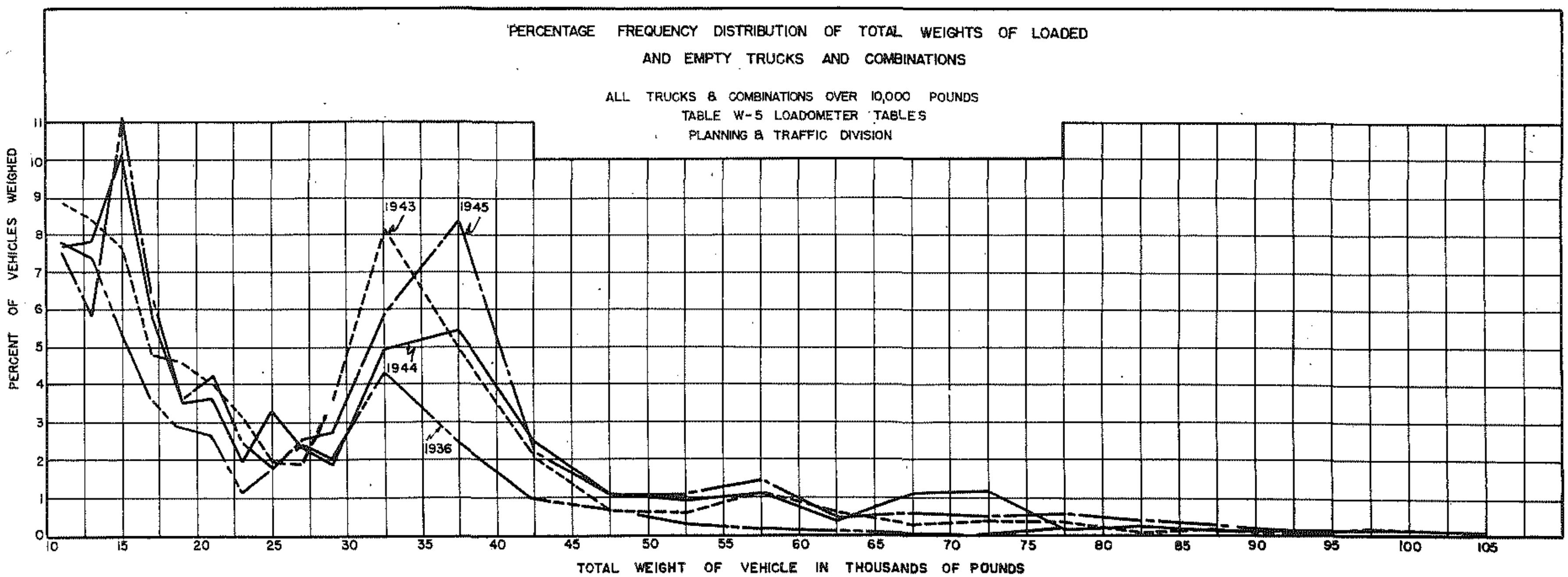
CLASSES I-II-III-IV DESIGNATED BY BRIDGE DIVISION
DESIGNATION NUMBERS BY PLANNING AND TRAFFIC DIVISION
A - 18,000 LBS. ON SINGLE AXLES - 13,000 LBS. ON TANDEM AXLES - 9,000 LBS. ON FRONT AXLES.
B - 18,000 LBS. ON SINGLE AXLES - 15,000 LBS. ON TANDEM AXLES - 9,000 LBS. ON FRONT AXLES.
C - 18,000 LBS. ON SINGLE AXLES - 15,000 LBS. ON TANDEM AXLES WHEN TRAIN CONTAINS ONE TANDEM AXLE GROUP - 13,000 LBS. ON TANDEM AXLES WHEN TRAIN CONTAINS MORE THAN ONE TANDEM AXLE GROUP - 9,000 LBS. ON FRONT AXLE.
★ ENCOUNTERED IN 1945 SURVEY

CLASSIFICATION *and* GROSS WEIGHTS *of* MOTOR TRANSPORT UNITS

Figure 1







L O A D   F R E Q U E N C Y   D I S T R I B U T I O N   C H A R T S

Figure 2

trend in gross vehicle loads brought about by the wartime load standards and second, they reveal the extent to which overloading of single axles and tandem axle groups prevails in Michigan at the present time. Data supporting the graphs are given in Tables I, II and III.

A study of loadometer values taken from the 1945 loadometer tables reveals that out of a total of 647 single axles weighed, 78 axles or approximately 12 percent exceed the legal limit of 18,000 pounds. A similar study of total loads on tandem axle groups weighed at the same time indicates that out of a total of 121 such axle groups weighed, a total of 55 groups or 45 percent of the units exceeded 26,000 pounds, and a total of 24 or 20 percent exceeded a total load of 32,000 pounds which is 2,000 pounds over the wartime restrictions.

Group-Axle Loadings

Researches by C. B. McCullough and Glenn S. Paxson of the Oregon State Highway Department(4), led them to conclude that in case of modern heavy transport units and combinations the concentration of axle loads in a compact group near the midsection of the transport combination or train is more likely to affect controlling stresses in certain bridge members than is either the gross weight or the extreme axle spacing.

With this in mind a study has been made of 1945 loadometer survey data to determine the relation of actual to permissible gross weights of critical axle groups on vehicles operating in Michigan. The data are presented in Table IV and analyzed graphically in Figure 3. The axle groups have been divided into three classes designated as groups 1, 2 and 3. Group 1 pertains

TABLE I - NUMBER OF AXLE LOADS OF VARIOUS MAGNITUDES PER 100 LOADED AND EMPTY CIVILIAN TRUCKS AND COMBINATIONS OF EACH TYPE AT 10 LOADOMETER STATIONS

Loadometer Tables by Planning and Traffic Division

Axle Load in Pounds	All Trucks and Combinations				
	1936	1942	1943	1944	1945
Under 8,000	187.69	187.78	176.11	175.42	170.41
8,000 - 8,499	4.62	3.55	6.02	6.23	6.59
8,500 - 8,999	2.79	4.70	4.31	5.03	3.47
9,000 - 9,499	3.04	3.97	3.96	3.38	6.37
9,500 - 9,999	1.93	3.09	5.40	2.81	2.40
10,000 - 10,999	4.17	5.20	8.80	8.61	8.54
11,000 - 11,999	4.66	6.00	9.10	9.63	4.49
12,000 - 12,999	6.78	5.33	6.98	5.48	9.70
13,000 - 13,999	4.92	6.08	8.32	7.55	7.58
14,000 - 14,999	4.84	7.32	9.13	7.36	9.44
15,000 - 15,999	4.81	6.84	7.93	6.79	9.17
16,000 - 16,999	3.26	6.02	6.09	8.04	9.89
17,000 - 17,999	2.14	3.59	3.64	6.37	7.42
18,000 - 18,999	1.02	1.61	2.40	4.47	4.06
19,000 - 19,999	0.77	1.16	1.40	1.92	3.39
20,000 - 21,999	0.54	1.04	1.20	2.31	1.10
22,000 - 23,999	0.48	0.09	0.26	0.06	0.13
24,000 - 25,999	0.24			0.06	
26,000 - 27,999					
28,000 - 29,999					
30,000 - 34,999					
35,000 - 39,999					

TABLE II - PERCENTAGE FREQUENCY DISTRIBUTION OF TOTAL WEIGHTS OF LOADED AND EMPTY CIVILIAN TRUCKS AND COMBINATIONS OF EACH TYPE AT 10 LOADOMETER STATIONS

Loadometer Tables by Planning and Traffic Division

	All Trucks and Combinations				
Total Weight in Pounds	1936	1942	1943	1944	1945
Under 10,000	53.47	41.57	31.25	32.55	28.58
10,000 - 11,999	7.88	7.53	8.88	7.71	7.54
12,000 - 13,999	7.45	6.77	8.45	7.86	5.78
14,000 - 15,999	5.37	8.00	7.70	10.20	11.21
16,000 - 17,999	3.66	6.27	4.82	5.76	6.42
18,000 - 19,999	2.94	3.70	4.60	3.51	3.60
20,000 - 21,999	2.67	2.80	4.02	3.61	4.42
22,000 - 23,999	1.17	1.44	3.18	1.96	2.49
24,000 - 25,999	1.86	1.51	1.99	3.32	1.80
26,000 - 27,999	2.42	1.49	1.91	2.33	2.57
28,000 - 29,999	2.05	2.01	3.58	1.89	2.75
30,000 - 34,999	4.39	6.88	8.14	4.94	5.87
35,000 - 39,999	2.50	5.53	4.96	5.49	8.42
40,000 - 44,999	0.94	2.16	2.04	2.50	2.18
45,000 - 49,999	0.67	0.68	0.66	1.09	1.06
50,000 - 54,999	0.28	0.45	0.56	0.90	1.07
55,000 - 59,999	0.11	0.05	1.09	1.09	1.41
60,000 - 64,999	0.06	0.19	0.58	0.31	0.90
65,000 - 69,999		0.24	0.24	1.07	0.54
70,000 - 74,999		0.43	0.36	1.14	0.47
75,000 - 79,999	0.11	0.10	0.36	0.13	0.55
80,000 - 84,999			0.09	0.25	0.39
85,000 - 89,999		0.05	0.18	0.13	
90,000 - 94,999		0.05	0.09	0.13	
95,000 - 99,999		0.10	0.18		0.08
100,000 - 109,999			0.09	0.13	0.08

TABLE III - PERCENTAGE FREQUENCY DISTRIBUTION OF TANDEM AXLE LOADS FOR LOADED AND EMPTY CIVILIAN TRUCKS AND COMBINATIONS OF EACH TYPE AT 10 LOADOMETER STATIONS

Loadometer Tables by Planning and Traffic Division

Weight on Tandem Axles Pounds	1945
4,500 - 5,499	.83%
5,500 - 6,499	.83%
6,500 - 7,499	.83%
7,500 - 8,499	.83%
8,500 - 9,499	4.13%
9,500 - 10,499	1.65%
10,500 - 11,499	0
11,500 - 12,499	0
12,500 - 13,499	.83%
13,500 - 14,499	2.48%
14,500 - 15,499	1.65%
15,500 - 16,499	.83%
16,500 - 17,499	2.48%
17,500 - 18,499	1.65%
18,500 - 19,499	3.31%
19,500 - 20,499	3.31%
20,500 - 21,499	3.31%
21,500 - 22,499	3.31%
22,500 - 23,499	.83%
23,500 - 24,499	8.26%
24,500 - 25,499	4.96%
25,500 - 26,499	8.26%
26,500 - 27,499	5.79%
27,500 - 28,499	2.48%
28,500 - 29,499	2.48%
29,500 - 30,499	4.13%
30,500 - 31,499	4.96%
31,500 - 32,499	5.79%
32,500 - 33,499	3.31%
33,500 - 34,499	4.96%
34,500 - 35,499	1.65%
35,500 - 36,499	5.79%
36,500 - 37,499	1.65%
37,500 - 38,499	.83%
38,500 - 39,499	.83%
39,500 - 40,499	.83%

TABLE IV - SUMMARY OF GROUP-AXLE GROSS WEIGHTS
1945 PLANNING AND TRAFFIC LOADOMETER SURVEY

TANDEM AXLE, GROUP TYPE I		SINGLE AXLES, GROUP TYPE II		MULTIPLE AXLES, GROUP TYPE III	
Extreme Axle Spacing	Gross Weight	Extreme Axle Spacing	Gross Weight	Extreme Axle Spacing	Gross Weight
4.0	19,400	18.5	27,000	21.2	34,000
4.6	19,500	14.2	27,500	15.8	34,600
4.0	19,500	13.3	28,300	18.5	35,200
4.4	20,100	21.3	29,900	15.2	36,700
4.2	20,700	19.8	30,000	21.7	37,100
4.5	21,200	15.3	30,000	17.6	37,300
4.4	21,800	13.0	30,400	20.7	37,500
4.6	23,000	17.7	30,600	18.4	37,800
4.2	23,500	13.4	30,600	22.8	38,500
4.0	23,600	15.6	30,700	13.2	38,700
4.5	23,800	18.8	30,800	14.0	40,200
4.1	23,900	14.3	30,800	14.4	40,200
4.0	24,000	13.4	30,900	18.4	40,200
4.5	24,000	17.0	31,000	22.1	40,800
4.6	24,200	17.5	31,100	20.0	41,900
4.4	24,700	15.2	31,100	21.5	42,000
4.2	24,900	14.0	31,100	14.0	42,100
4.2	25,100	15.6	31,200	16.7	42,300
4.0	25,200	17.7	31,200	20.7	42,500
4.0	25,300	15.8	31,200	18.5	42,500
4.6	25,500	17.3	31,400	18.0	42,700
4.8	25,600	15.8	31,500	18.4	42,800
4.0	26,000	15.7	31,600	17.6	43,000
4.6	26,000	21.8	31,600	18.0	43,600
4.0	26,100	17.5	31,600	13.8	43,600
4.0	26,400	19.4	31,600	22.4	44,100
4.5	26,400	19.8	31,800	13.4	44,100
3.7	26,400	17.5	31,900	14.6	45,100
4.0	26,500	18.0	32,100	16.5	45,400
4.0	26,700	20.0	32,300	13.6	45,500
4.0	27,200	15.7	32,500	18.8	46,700
4.0	27,300	17.5	32,500	17.9	47,100
4.0	27,300	17.5	32,500	21.6	47,400
4.5	27,400	17.5	32,700	19.5	47,600
4.5	27,600	17.5	32,800	19.7	47,600
4.0	28,400	21.3	32,900	17.4	47,900
4.0	28,500	12.5	33,100	18.0	48,000
4.4	28,600	17.5	33,300	18.0	48,100
4.0	28,800	18.8	33,400	17.6	48,200
4.0	30,300	18.9	33,400	19.4	48,300
4.4	30,300	16.0	33,400	15.5	48,600
4.8	30,400	19.2	33,400	18.4	48.900
4.5	30,500	15.6	33,600	20.7	49,500
4.4	31,000	16.0	33,600	18.9	49,600
4.0	31,200	22.0	33,600	18.8	49,900
4.6	31,200	20.2	33,700	19.9	50,000
4.0	31,300	18.0	33,800	20.4	50,200
4.2	31,300	15.0	33,900	13.2	50,500
5.5	31,700	19.0	33,900	22.0	50,700
4.5	31,900	13.8	34,100	18.7	50,800
4.6	32,000	20.0	34,200	18.5	50,900
4.4	32,200	20.0	34,300	20.7	51,800
4.0	32,400	15.8	34,300	22.6	52,600
4.6	32,400	21.8	34,400	16.5	52,600
4.0	33,000	17.6	34,400	17.0	52,600
4.4	33,000	22.2	34,400	19.4	53,100
4.0	33,200	19.5	34,400	20.9	53,500
4.6	33,600	15.2	34,500	21.7	55,000
4.4	33,800	16.0	34,500	20.2	55,200
4.4	33,800	19.8	34,500	17.6	55,600
3.8	33,900	20.4	34,600	16.7	56,800
4.0	34,000	18.0	34,600	21.8	56,900
4.0	34,000	16.0	34,700	17.7	59,900
4.0	34,200	13.7	34,800		
4.2	34,600	16.0	35,200		
4.6	35,000	20.5	35,500		
4.4	36,000	15.9	35,800		
4.0	36,000	17.0	36,000		
4.0	36,200	15.8	36,200		
4.4	36,400	20.0	36,200		
4.0	37,000	16.6	36,500		
3.9	37,600	20.2	36,700		
4.2	39,400	17.7	36,800		
4.0	39,900	17.8	37,400		
		17.4	37,900		
		17.0	39,600		
		16.0	39,800		
		20.0	41,500		

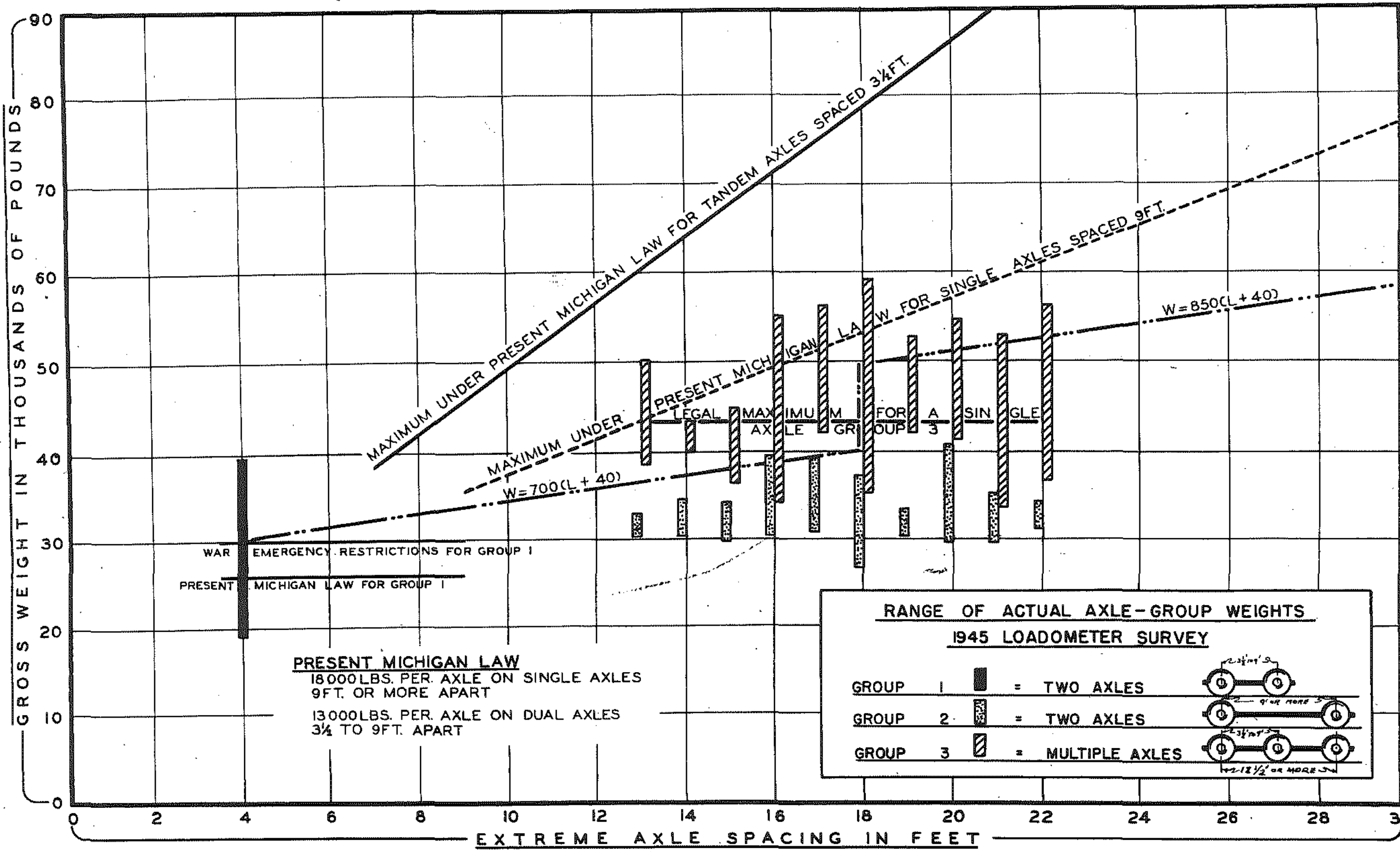


Figure 3

ACTUAL *and* PERMISSIBLE GROSS WEIGHT *of* AXLE GROUPS *in relation to* EXTREME GROUP AXLE SPACING to tandem axle groups at four foot average extreme spacing of the axles. The data in Table III shows that the gross weight of such tandem groups varied from approximately 10,000 to 33,000 pounds or 3,000 pounds over the permissible wartime restrictions. Approximately 47 percent of tandem axle groups weighed exceeded 30,000 pounds, the wartime limit in Michigan.

In the case of Group 2, which considers the spacing of two single axles between 13 and 22 feet as a group, very little overloading was encountered—about 12 percent. But for Group 3, consisting of a tandem axle group at a maximum axle spacing of 4 feet and a single axle together making a 3 axle group with over-all axle spacing up to 22 feet, considerable overloading was quite in evidence. Whereas the maximum gross weight for Group 3 under wartime conditions is 48,000 pounds, it was found that out of a total of 68 axle groups counted, 28 or 41 percent of these exceeded a gross total weight of 48,300 pounds; the maximum weight encountered was 59,900 pounds.

The factual data presented in the preceding paragraphs would indicate the need for corrective measures to mitigate the present practice of overloading axles, especially certain critical axle groups, and to limit the gross weight of modern motor transport units to values consistent with present design requirements.

PART II

TRENDS IN STATE REGULATIONS OF SIZE AND WEIGHTS OF MOTOR TRANSPORT VEHICLES

Uniformity in minimum standards governing sizes and weights of motor transport vehicles should be one of the most desirable objectives of highway administration in order to establish a basis for the design of pavements and structures included in the post war highway construction program. Although a study of the problem indicates considerable confusion among the States in regard to load laws, there is, however, a definite trend toward the adoption of uniform standards which will eventually facilitate highway transportation throughout the country.

Regulation of Gross Weight of Vehicles

A study of the legal restrictions imposed by the various States indicates that the weight limits in general take the following pattern:

1. Limitation placed upon individual axles
2. Limitation placed upon total weight of vehicle
3. A limiting load relationship between total weight of axle groups and overall axle spacing of the group

In Michigan limitations only on individual axle loads and axle spacing govern, with an additional requirement of maximum load per inch of width of tire.

At the present time over half of the States impose a gross weight limitation in conjunction with individual axle load restrictions which is based on the Gemeny formula. In 1931, A. L. Gemeny (5) of the Public Roads Administration presented the results of an investigation of this problem which pointed to the adoption of a formula wherein the gross load on any two or more consecutive axles of a vehicle or combination of vehicles would vary with the distance L in feet between the first and last axles of the group of axles under consideration.

The formula, with few exceptions is expressed as

$$W = C\,(L+40)$$

Where: W = gross load in pounds
L = the wheel base of any axle group, in feet
C = an empirical constant to be established for loading desired

Maximum limitations are also placed by the various States on heights, widths and lengths. Table V contains a summary of the limitations imposed by each state as of May, 1945 compiled by the National Highway Users Conference.(6)

Limits Proposed by the National Interregional Highway Committee

In their report to the President in 1944 on a proposed system of interregional highways, the National Interregional Highway Committee recommended that the roadways and structures on the interregional highway system should be of such design as to support vehicles of the weights and dimensions shown in Table VI in such frequency and distribution thereof to be expected 20 years from date of construction.(1)

They also recommend the formula law to control the gross weight of vehicles with values of the coefficient C equal to 650 when values of L are less than 18 feet and a value of C equal to 750 when the distance L is greater than 18 feet, the load on a single axle remaining at the normal value of 18,000 pounds.

Limits Proposed by the American Trucking Association, Inc.

A committee of the American Trucking Association, after a study of the report on the proposed interregional highway system by the National Interregional

TABLE V - STATE SIZE AND WEIGHT LIMITS

Compiled from Data by National Highway Users Conference
Effective May, 1945

State	Maximum Width (inches)	Maximum Height (feet)	Maximum Length Single Unit	Maximum Length Tractor-Semi-Trailer	Maximum Length Other Combinations	Maximum Weight Single Axle (pounds)	Maximum Weight per inch width of tire	Maximum Gross Weight by Formula
Alabama	96	12½	35	45	N.P.	18,000 (ballon)	600	700 (L + 40) any unit or combination
Arizona	96	14½	35	65	65	18,000	700	
Arkansas	96	12½	35	45	45	18,000	Table	650-700 (L + 40) 2 or more consecutive axles and any unit or combination
California	96	13½	35	60	60	18,000	P - N.S. 600 - S	800 (L + 40) over 18' 700 (L + 40) 18' or less 850 (L + 40) (or 68,000 lbs. max.) 25' - 45' inclusive; 800 (L + 40) 2 or more axles is between 14' - 18' inclusive
Colorado	96 102 - Rear P	12½	35	45	50	18,000 (ballon) 16,000 (others)	P - N.S. 500 - S	750 (L + 40)
Connecticut	96 - 102	12½	40	40	N.P.	N.S. (not more than 80% of gross load on any one axle)	P - N.S. 800 - S	
Delaware	96	12½	35	45	45	18,000 - P 16,000 - S	700	
Washington, D.C.	96	12½	35	50	50	18,000	N.S.	
Florida	84	12½	35	45	45	16,000	600	
Georgia	96	13½	35	45	45	18,000 (ballon) 16,000 (others)	N.S.	700 (L + 40) any unit or combination
Idaho	96	14	35	45	65	18,000	800 (graduated according to tire width)	
Illinois	96	N.S.	35	35	40	16,000	800	
Indiana	96	12½	36	45	45	18,000	800	750 (L + 40) 2 or more consecutive axles, and any unit or combination
Iowa	96	12½	35	45	N.P.	18,000	N.S.	28,000+(L x 800)
Kansas	96	12½	35	45	45	18,000 (ballon) 16,000 (others)	N.S.	700 (L + 40) only applies to combinations
Kentucky	96	12½	26½	33	N.P.	16,000	600	28,000 maximum gross weight
Louisiana	96	12½	35	45	45	18,000 (ballon) 16,000 (others)	Table	
Maine	96	12½	45	45	45	22,000 16,000 (axles less than 10')	600	
Maryland	96	N.R.	55	55	55	22,400 18,000 (if less than 50" apart)	600	750 (L + 40) any unit or combination
Massachusetts	96 [1] 102 Rear P	N.R.	33 35 (buses)	40	N.S.	N.R.	800	
Michigan	96	12½	35	50	50	18,000 - P 16,000 - S	700	
Minnesota	96	12½	40	45	45	18,000 - P 12,000 - P axles under 8' 10,800 - S	N.R.	750 (L + 40)
Mississippi	96	12½	40	40	55	18,000 (ballon) 16,000 (others)	N.S.	
Missouri	96	12½	35	45	45	18,000	600	
Montana	96	13½	35	60	60	18,000 - P 16,000 - S	N.S.	650 (L + 40) up to 20' 750 (L + 40) above 20'
Nebraska	96	12½	35	42	45	18,000 16,000	N.S.	750 (L + 40) any unit or combination
Nevada	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	600	
New Hampshire	96	N.R.	35	45	45	18,000	800	
New Jersey	96	12½	35	45	50	Table	Table	
New Mexico	96 100 Rear P	12½	35	60	60	18,000	700 - P 500 - S	750 (L + 40) 2 or more consecutive axles, any unit or combination
New York	96 106 Rear P	13	35	50	50	22,400 - P 17,900 - S	800 - P 640 - S	750 (L + 40) 3 or more consecutive axles, any unit or combination
North Carolina	96	12½	35	48-1	48-1	18,000 (ballon) 16,000 (others)	600	
North Dakota	96	12½	35	40	40	18,000 14,000 (less than 8' apart)	550	750 (L + 40) any unit or combination
Ohio	96	12½	35	45	60	18,000 - P 16,000 - S	650	750 (L + 40) 3 or more axles
Oklahoma	96	12½	45	45	45	N.S.	600	
Oregon	96	12½	35	50	60 50	18,000 (on paved highways 16,000 (unpaved)	600 (500 lbs. under 30" wide when total tires)	700 (L + 40) any unit or combination
Pennsylvania	96	12½	33	45	50	20,000	800	
Rhode Island	102	12½	35	45	45	22,400	800	
South Carolina	96	12½	40	50	50	18,000 (ballon) 16,000 (others)	N.R.	700 (L + 40)
South Dakota	96	13	35	45	45	18,000 (ballon) 16,000 (others)	600	600 (L + 40) any unit or combination
Tennessee	96	12½	35	45	45	18,000	N.S.	700 (L + 40) any unit or combination
Texas	96	12½	35	45	45	18,000 (ballon) 16,000 (others)	650 (ballon) 600 (others)	700 (L + 40) any unit or combination
Utah	96	14½	45	60	60	18,000 - P 13,500 - S	800 (according to tire width)	700 (L + 40) any unit or combination
Vermont	96	12½	50	50	50	N.R.	600	
Virginia	96	12½	33 (buses 35')	45	45	18,000 16,000	650	
Washington	96	12½	35	60	60	18,000	500	750 (L + 40) over 18'; 650 (L + 40) 18' or less
W. Virginia	96	12½	35	45	45	18,000 (Pneumatic in industrial areas) 14,000 (Solid in industrial areas)	N.S.	1330-1000-670 (L + 40) (applies to highways dependent on type of bridges thereon)
Wisconsin	96 104 (urban buses)	12½	33 35 (buses)	45	45	19,000 (on Class A highways) 12,000 (Class B highways)	800	
Wyoming	96	12½	40	50	60	18,000 (ballon 16,000 (others)	800	850 (L + 30) over 18' 650 (L + 40) 18' or less

N.P. - Not permitted   N.R. - No Restriction   N.S. - Not Specified   1 - Exclusive of bumpers   P - Pneumatic   S - Solid

TABLE VI

HIGHWAY LOADINGS RECOMMENDED FOR THE PROPOSED INTERREGIONAL HIGHWAY SYSTEM (1)

(National Interregional Highway Committee)

Width	96 in.
Height	12 1/2 ft.
Length (over-all, including bumpers and load)	
(1) Single vehicles	35 ft.
(2) Tractor-semitrailer combinations	50 ft.
(3) Other combinations	60 ft.
Axle Load* on pneumatic tires	18,000 lb.

Gross weight

On any vehicle or combination of vehicles according to the formula $W = C (L + 40)$

In which:

W = gross weight of vehicle in pounds

L = Length in feet between the forward and rear axles of the vehicle or combination of vehicles or any group of axles thereof.

C = A coefficient with the following values:

For values of L less than 18 ft.	650
For values of L equal to or greater than 18 ft.	750

* Defined as the total load on all wheels whose centers may be included between two parallel transverse vertical planes 40 in. apart.

Highway Committee, recommended that minimum standards of design should be set up for the proposed system of interregional highways, but it is believed that the standards of design and load limitations recommended for the interregional system were too low and that they should be liberalized in order that a check should not be placed on the development of highway transport in America.(1)

The vehicle sizes and weights and construction standards recommended by the American Trucking Association are presented in Table VII. The table gives two recommended limitations designated A and B. The limitations imposed under item A are the same as those proposed by the National Interregional Highway Committee, whereas the recommendations under item B are more liberal and are intended for future primary highway construction.

In addition to vehicle size changes, the formula law is approved for controlling the gross weight of vehicles, but in this case the values of C are increased from 650 to 750 for lengths less than 18 feet and from 750 to 850 when L is greater than 18 feet.

<u>Policy of the American Association of State Highway Officials</u>

Over a period of years the A.A.S.H.O. Committee on Highway Transport has been actively engaged in studying the highway transport problem with the objective of formulating a policy concerning the maximum dimensions, weights and speeds of motor vehicles to be operated on the highways of the United States. In April, 1946 the Highway Transport Committee prepared a draft of recommended restrictions which has been submitted to the several States for consideration and adoption. (7)

TABLE VII

VEHICLE SIZES AND WEIGHTS AND CONSTRUCTION STANDARDS

RECOMMENDED BY THE AMERICAN TRUCKING ASSOCIATION, INC. (1)

A - Recommended minimum allowable vehicle sizes and weights:

Width	96 in.
Height	12 1/2 ft.
Length, (1) single vehicle	35 ft.
(2) tractor, semi-trailer	50 ft.
(3) other combinations	60 ft.
Axle load on pneumatic tires	18,000 lbs.

Gross weight according to the formula W = C (L + 40)
in which:
C = 650 where L is less than 18 ft.
C = 750 where L is equal to or greater than 18 ft.

B - As minimum for future primary highway construction

Width, over-all	102 in.
Width, body	96 in.
Height	13 1/2 ft.
Length, (1) single vehicle	40 ft.
(2) tractor semi-trailer	60 ft.
(3) other combinations	65 ft.
Axle loads, (1) On high-pressure tires	18,000 lb.
(2) On balloon tires	20,000 lb.

Gross weight according to the formula W = C (L + 40)
in which:
C = 750 where L is less than 18 ft.
C = 850 where L is equal to or greater than 18 ft.

It is the opinion of the American Association of State Highway Officials that the adoption by all States of uniform standards governing the maximum dimensions, weights, and speeds of motor vehicles operating over the highways is necessary for the following reasons:

1. To establish one of the fundamental prerequisites of highway design.
2. To promote efficiency in the interstate operation of motor vehicles.
3. To promote the safety of highway transportation.
4. To establish a present basis for regulation of the many relationships between the dimensions and weights of motor vehicles and the strengths and capacities of existing highways.

The weight standards recommended by the Highway Transport Committee are as follows:

a. No axle shall carry a load in excess of 18,000 pounds. An axle load shall be defined as the total load transmitted to the road by all wheels whose centers may be included between two parallel transverse vertical planes 40 inches apart, extending across the full width of the vehicle.

b. No group of axles shall carry a load in pounds in excess of the value given in Table VIII corresponding to the distance in feet between the extreme axles of the group, measured longitudinally to the nearest foot.

TABLE VIII

Permissible Loads Recommended by the A.A.S.H.O.
Highway Transport Committee
Based on Formula $W = 1,025\ (L + 24) - 3\ L^2$

Distance in feet between the extremes of any group of axles	Maximum load in pounds carried on any group of axles
4	32,000
5	32,000
6	32,000
7	32,000
8	32,610
9	33,580
10	34,550
11	35,510
12	36,470
13	37,420
14	38,360
15	39,300
16	40,230
17	41,160
18	42,080
19	42,990
20	43,900
21	44,800
22	45,700
23	46,590
24	47,470
25	48,350
26	49,220
27	50,090
28	50,950
29	51,800
30	52,650
31	53,490
32	54,330
33	55,160
34	55,980
35	56,800
36	57,610
37	58,420
38	59,220
39	60,010
40	60,800
41	61,580
42	62,360
43	63,130
44	63,890
45	64,650
46	65,400
47	66,150
48	66,890
49	67,620
50	68,350
51	69,070
52	69,790
53	70,500
54	71,200
55	71,900
56	72,590
57	73,280

c. The maximum axle and axle-group loads recommended in paragraphs (a) and (b) above are subject to reasonable reduction in the discretion of the appropriate highway authorities during periods when road subgrades have been weakened by water saturation or other cause.

d. The operation of vehicles or combinations of vehicles having dimensions or weights in excess of the maximum limits herein recommended shall be permitted only if authorized by special certificate issued by an appropriate State authority.

It has been publicly (8) announced that the standards governing the maximum dimensions, weights and speeds of motor vehicles proposed by the Highway Transport Committee of the American Association of State Highway Officials have been adopted by a letter ballot of the member State Highway Departments, with a recommendation that they be incorporated in the motor vehicle laws of all States. These standards also have the endorsement of the Public Roads Administration, which participated in the study.

To facilitate comparison, the standards of the three committees discussed in the preceding paragraphs have been summarized in Table IX together with the limitations imposed by the present Michigan vehicle law. In comparing the various proposed standards it is of interest to note that the Committees are in general agreement on two significant points concerning load restrictions; first, that the load on a single axle should not exceed 18,000 pounds and second, that the gross weight of vehicles should be controlled by the Conway formula or a modification thereof. Furthermore, it is significant to note that the axle loads proposed by the Committees are not as high as

TABLE IX

COMPARISON OF HIGHWAY LOADINGS RECOMMENDED BY CERTAIN AGENCIES (1)

	Michigan	A.A.S.H.O. 1946	National Interregional Highway Committee	American Trucking Ass'n. Inc.	American * Trucking Ass'n.
Width	96 in.	96 in.	96 in.	96 in.	102 in.
Height	12 1/2 ft.	12 1/2 ft.	12 1/2 ft.	12 1/2 ft.	13 1/2 ft.
Length (Over-all, including bumpers and load)					
(1) Single vehicles	35 ft.	35 ft.	35 ft.	35 ft.	40 ft.
(2) Tractor-semitrailer combinations	50	50	50	50	60
(3) Other combinations	50	60	60	60	65
Axle load on pneumatic tires	18,000 lbs.	18,000 lbs.	18,000 lbs.	18,000 lbs.	18,000 (H.P.) 20,000 (Balloon)
Gross weight	No Restrictions	Formula (A)	Formula (B)	Formula (B)	Formula (C)

Formula A: $W = 1,025 (L + 24) - 3 L^2$

Formula B: ($W = 650 (L + 40)$ when L is less than 18 ft.
($W = 750 (L + 40)$ when L is equal to or greater than 18 ft.

Formula C: ($W = 750 (L + 40)$ when L is less than 18 ft.
($W = 850 (L + 40)$ when L is equal to or greater than 18 ft.

L = length in feet between the forward and rear axles of a vehicle or combination of vehicles or any group of axles thereof.

* Minimum requirements for future primary highway construction.

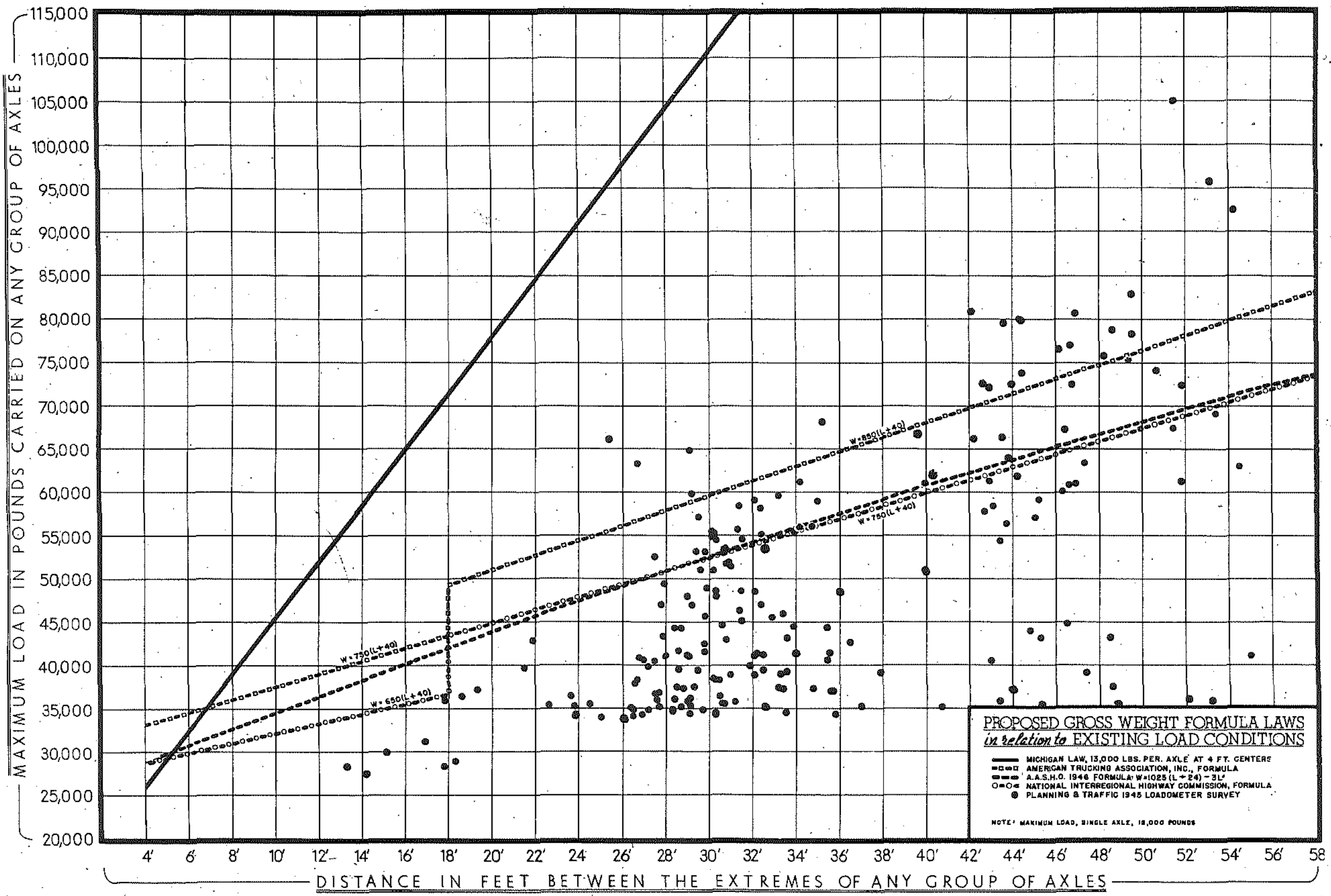
those now considered by several states, while on the other hand the gross load computed by the formulas are higher than those permitted in many States. See Table V. In the case of Michigan, the formula law would result in a substantial reduction in gross weight loads on the highways.

The Effect of the Formula Law on Load Limitations

It is of interest to compare permissible axle groups and gross vehicle loads under the various proposed formula laws with axle groupings and gross-load practices actually found in motor transport vehicles comprising the heaviest loads on the highways. Attention is called to Figure 4 which illustrates graphically the formulas proposed by the American Association of State Highway Officials, the National Interregional Highway Commission and the American Trucking Association and their relative effect in controlling gross weights in relation to axle spacings. A curve showing permissible gross loads under the present Michigan law is also included for comparative purposes.

Furthermore, there have been superimposed on the graph in Figure 4, as illustrated by the black dots, actual gross vehicle and axle group weights in relation to the respective extreme axle spacings of the groups which were encountered during the 1945 loadometer survey.

It is obvious from Figure 4 that Michigan is quite generous in the matter of restricting the gross weight of vehicles. Further the graph shows how the imposition of a similar formula law in Michigan would affect the gross weights of motor transport units now in service.



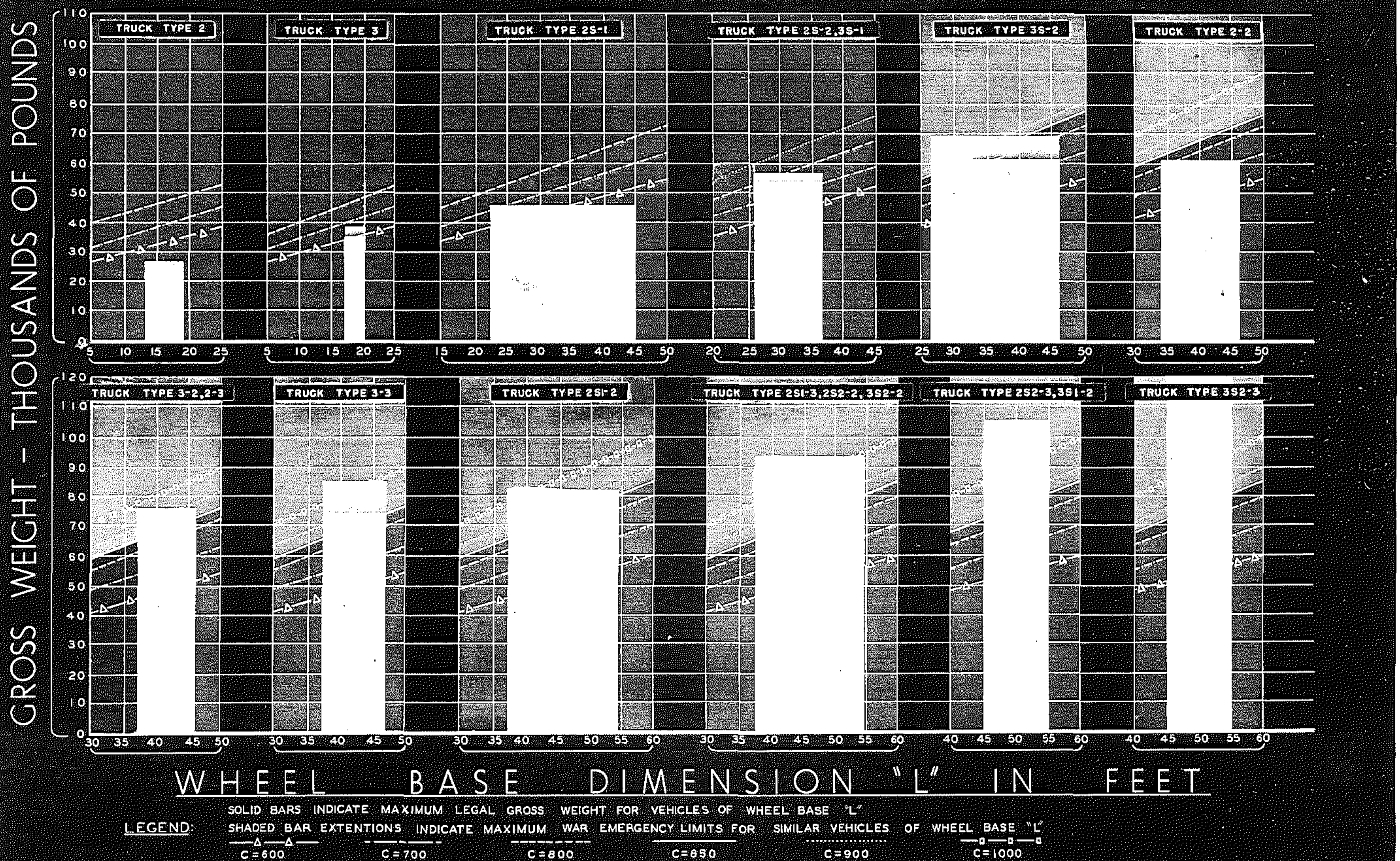
PROPOSED GROSS WEIGHT FORMULA LAWS
in relation to EXISTING LOAD CONDITIONS
MICHIGAN LAW, 13,000 LBS. PER. AXLE AT 4 FT. CENTERS
AMERICAN TRUCKING ASSOCIATION, INC., FORMULA
A.A.S.H.O. 1946 FORMULA: W=1025 (L + 24) − 3L²
NATIONAL INTERREGIONAL HIGHWAY COMMISSION, FORMULA
PLANNING & TRAFFIC 1945 LOADOMETER SURVEY
NOTE: MAXIMUM LOAD, SINGLE AXLE, 18,000 POUNDS
W = 850(L + 40)
W = 750(L + 40)
W = 650(L + 40)
MAXIMUM LOAD IN POUNDS CARRIED ON ANY GROUP OF AXLES
115,000
110,000
105,000
100,000
95,000
90,000
85,000
80,000
75,000
70,000
65,000
60,000
55,000
50,000
45,000
40,000
35,000
30,000
25,000
20,000
4' 6' 8' 10' 12' 14' 16' 18' 20' 22' 24' 26' 28' 30' 32' 34' 36' 38' 40' 42' 44' 46' 48' 50' 52' 54' 56' 58
DISTANCE IN FEET BETWEEN THE EXTREMES OF ANY GROUP OF AXLES

Figure 4

The Effect of C in the Gemeny Formula

From axle spacings derived from the loadometer surveys and weight data based on Michigan's vehicle law, twelve vehicle combination types, as illustrated in Figure 1, have been set up in Figure 5 to show the relation between weight conditions now imposed by law and the limiting factors of vehicle loads under the Gemeny formula for a given range of C values. It can be seen in Figure 5 that the imposition of the formula law in Michigan with a value of C in keeping with current thinking would result in a substantial reduction in axle loads on motor transports in the tractor, semi-trailer and trailer class.

It has been brought out in the previous discussion that the value of C in the Gemeny formula most commonly used by the States using the formula law, varies from 600 to 1,000, the most common value used being 750. In order to compare these values for C with those actually found in practice, maximum values of C were obtained from the 1945 Planning and Traffic Loadometer tables and plotted in Figure 6 in relation to distance between the extreme axles of the group for which the value of C was computed. The dots appearing above a horizontal line through a selected value of C represent overloaded axle groups for that particular set of conditions.



EFFECTS AT VARIOUS VALUES OF "C" IN GEMENY FORMULA ON GROSS LOAD LIMITS FOR DIFFERENT VALUES OF "L" (W=C(L+40)

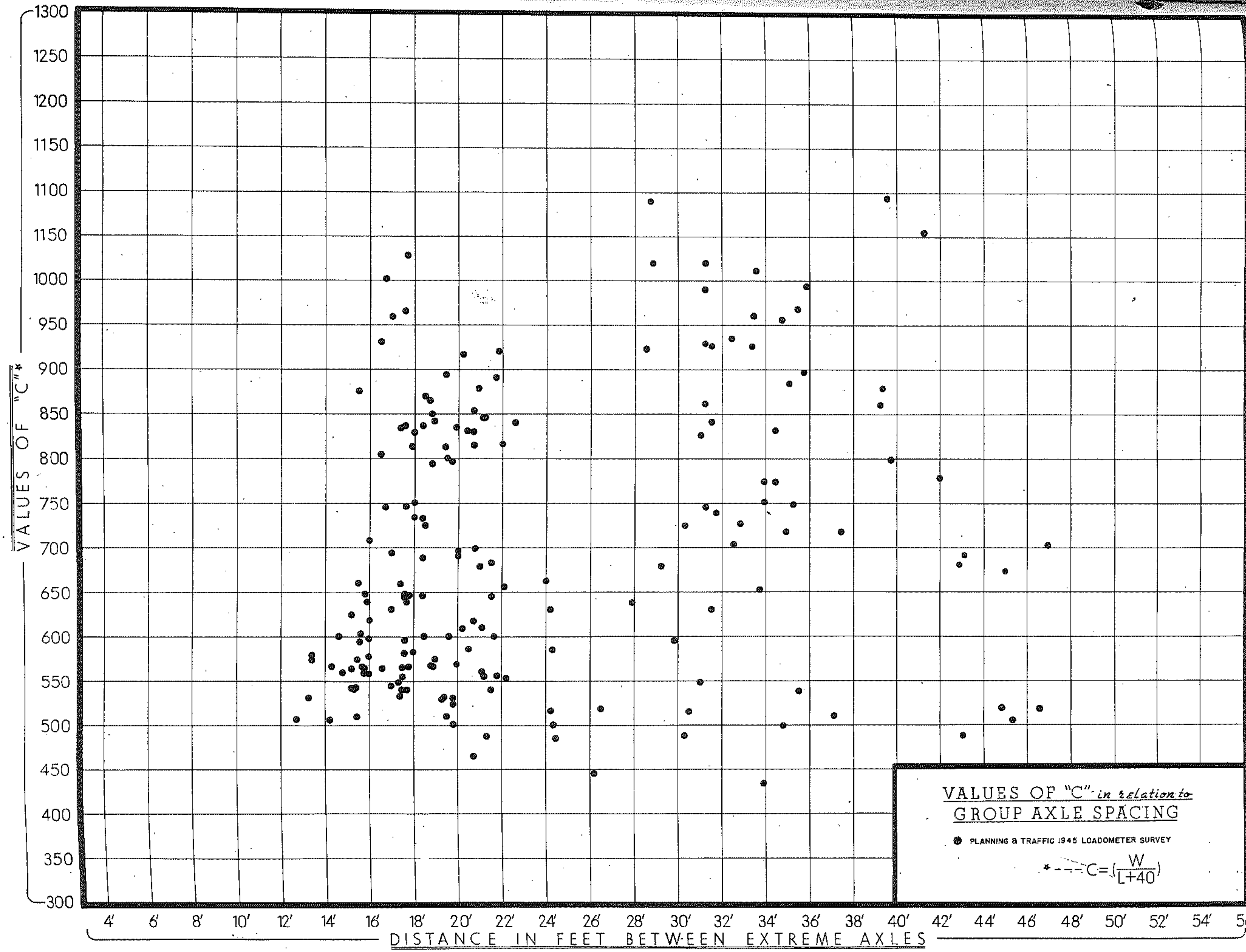

VALUES OF "C"*
DISTANCE IN FEET BETWEEN EXTREME AXLES
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
4'
6'
8'
10'
12'
14'
16'
18'
20'
22'
24'
26'
28'
30'
32'
34'
36'
38'
40'
42'
44'
46'
48'
50'
52'
54'
56'
VALUES OF "C" in relation to
GROUP AXLE SPACING
PLANNING & TRAFFIC 1945 LOADOMETER SURVEY
* --- $C = (\frac{W}{L+40})$

Figure 6

PART III

EFFECT OF MULTIPLE AXLE LOADINGS ON CONCRETE PAVEMENT SLABS

Limitations imposed on individual axles are primarily for the purpose of protecting pavements while limitations on gross weight (in relation to wheel base and axle groupings) are necessary to prevent overstressing of highway bridge structures. Therefore, the imposition of limitations on highway loadings necessitates an analysis of both pavements and bridge structures in relation to the same loading conditions. The effect of loads on highway bridges can be readily ascertained by means of well established mathematical relationships, whereas in the case of pavement surfaces theoretical analysis must be supplemented by field and laboratory experimentations. With these facts in mind investigations have been conducted in the part by the Public Roads Administration, Illinois Division of Highways and the Michigan State Highway Department to determine stresses induced in concrete pavements by single and multiple axle loadings located at critical points in the slab. A discussion of the studies will be covered in the following text.

<u>Investigation by the Public Roads Administration</u>

In 1925 the U. S. Bureau of Public Roads conducted static loading tests upon a 6 inch pavement slab using actual truck loads and a special trailer. The investigation was conducted for the purpose of comparing the relative stresses in the pavement produced by 4 and 6 wheel vehicles. The effect of axle spacing was also studied.(8)

Their work in connection with the effect of axle spacings and single axles versus dual axles indicates, as shown in Figure 7, that under equivalent axle loadings the stresses produced by dual axles are not greater than

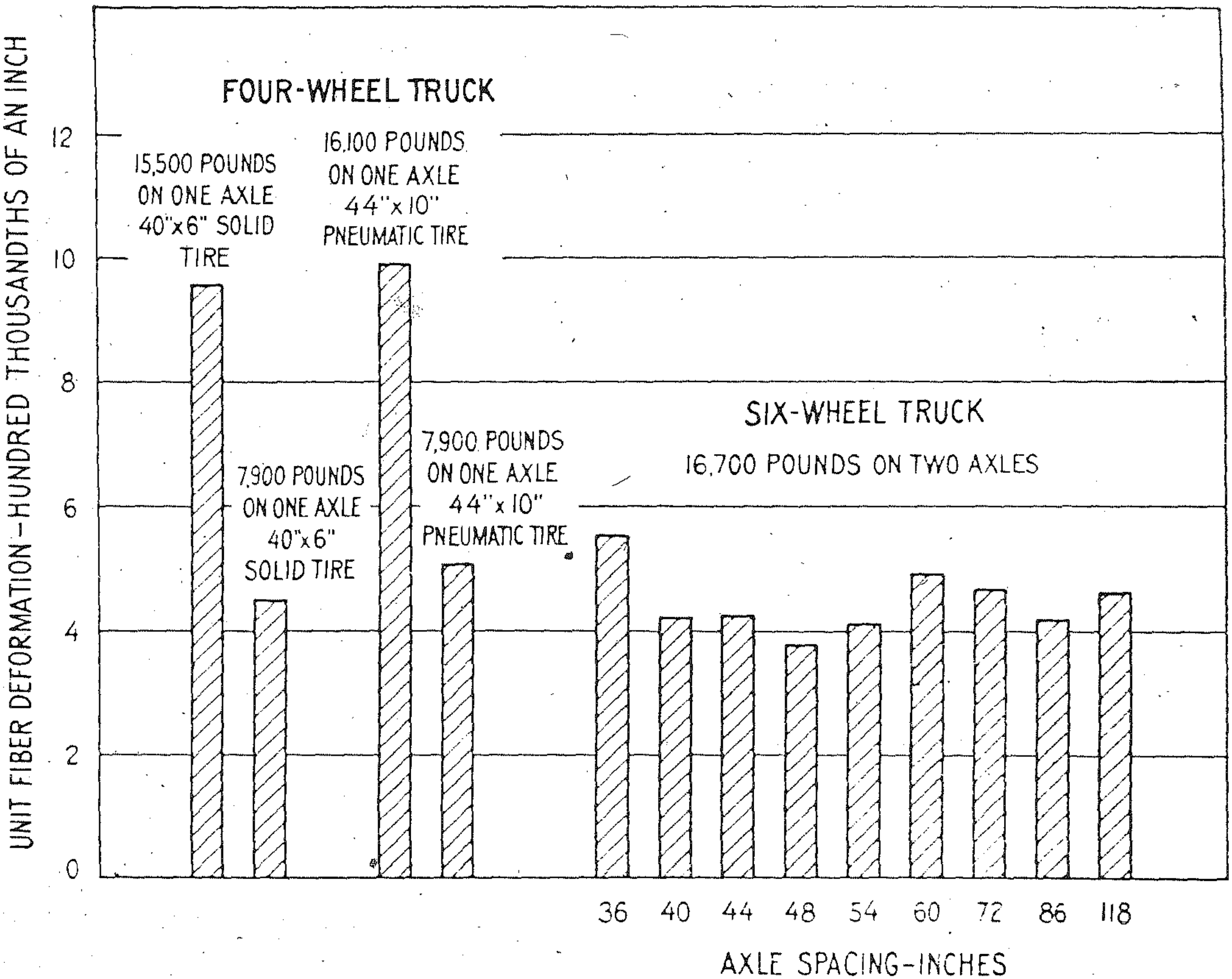


Figure 7 -Unit fiber deformations of 6-inch concrete slab by 4-wheel and 6-wheel trucks

those produced by a single axle when the spacing of the dual axles exceeds 40 inches.

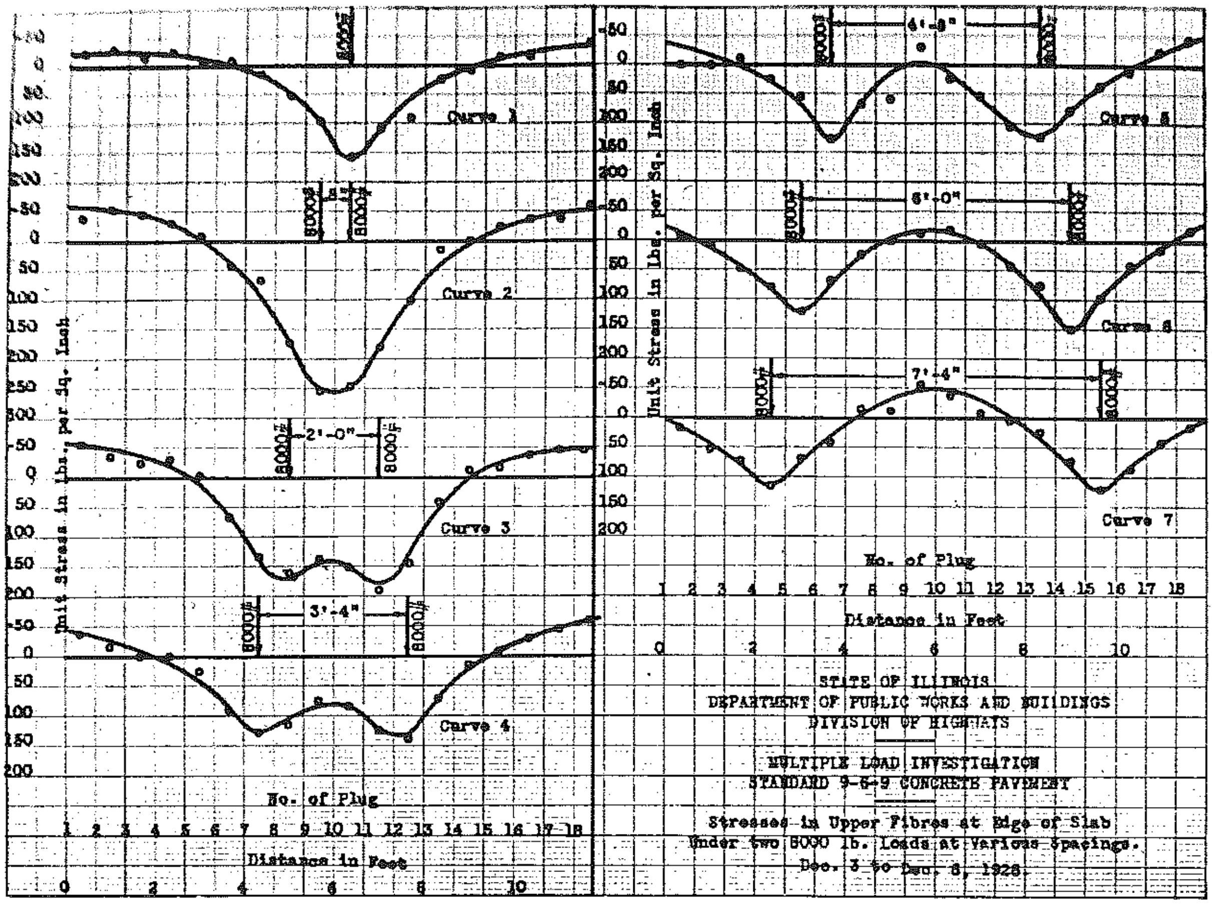
Investigation by Illinois Division of Highway

In 1931 the Illinois Division of Highways undertook an investigation to obtain data upon which to base legislation to amend provisions in their motor vehicle law. The investigation included first, a record of strains and deflections at the longitudinal edge of a 9-6-9 inch pavement to compare the effect of a single load of 8,000 pounds with that of two 8,000 pound loads spaced at different intervals (subsequently repeated using 10,000 pounds as a check test) and second, a similar study wherein a four wheel truck and a six wheel truck with equivalent axle loadings were employed.[10]

As shown in Figure 8 these tests demonstrate that two equal static loads, each on tandem wheels at the pavement edge spaced at least three feet four inches apart, do not produce a maximum unit stress exceeding that under a single wheel with the same load. From their studies they concluded that the pavement would support any number of 16,000 pound axle loads at 3' 4" spacings without subjecting the slab to stresses greater than those produced by a single 16,000 pound axle load.

Investigations by the Michigan State Highway Department

In 1944 the Department established an investigation to study the destructive effect of loads upon concrete slabs including single and multiple axles at various spacings. Load-deflection-strain relationships under static load conditions were studied at critical positions in a full scale concrete slab 11 feet wide 28 feet long and 9 inches thick. Standard dual wheel truck axles were loaded with forces of 18,000, 16,000 and 13,000 pounds. A progress


Unit Stress in Lbs. per Sq. Inch
Curve 1
Curve 2
Curve 3
Curve 4
Curve 5
Curve 6
Curve 7
8000#
2'-0"
3'-4"
4'-8"
6'-0"
7'-4"
No. of Plug
Distance in Feet
STATE OF ILLINOIS
DEPARTMENT OF PUBLIC WORKS AND BUILDINGS
DIVISION OF HIGHWAYS
MULTIPLE LOAD INVESTIGATION
STANDARD 9-6-9 CONCRETE PAVEMENT
Stresses in Upper Fibres at Edge of Slab
Under two 8000 lb. Loads at Various Spacings.
Dec. 3 to Dec. 8, 1928.

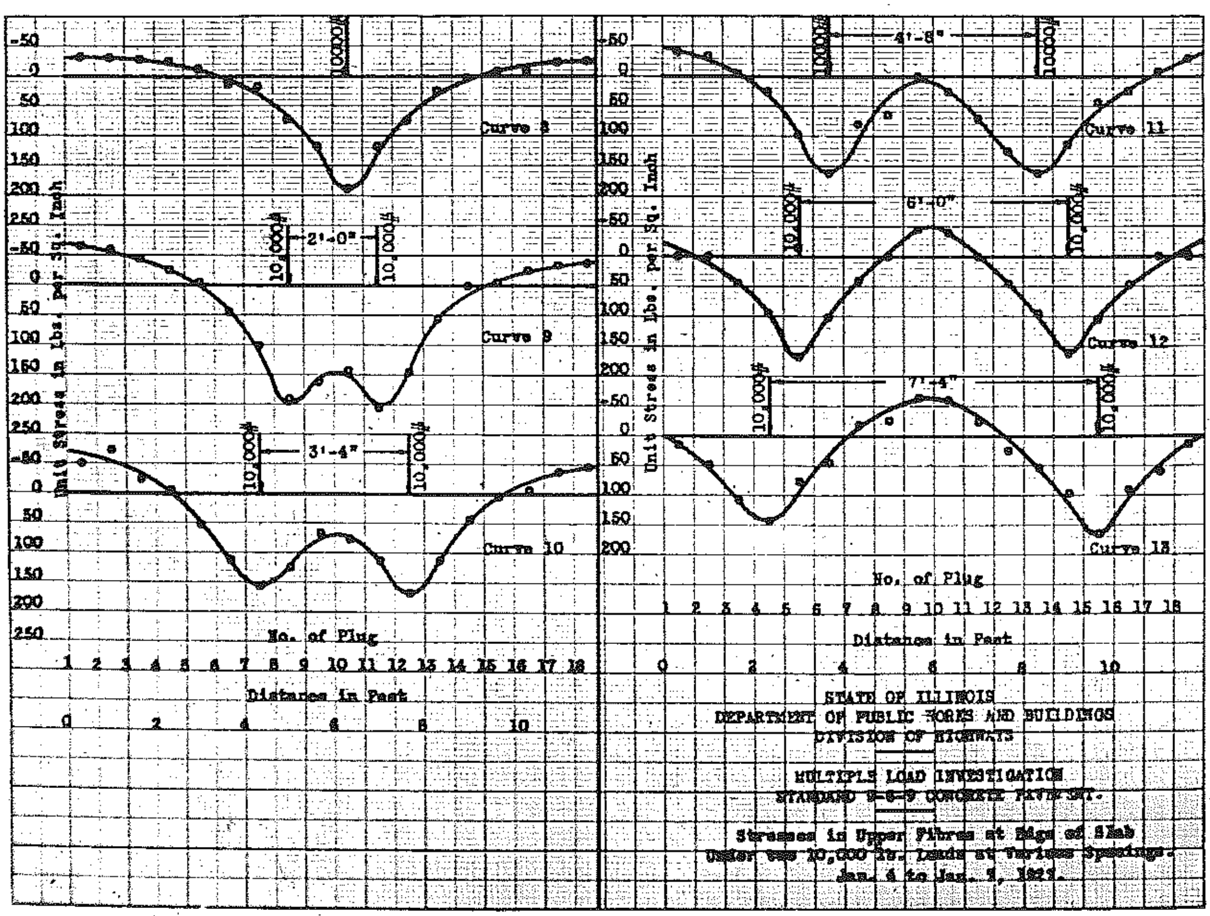

Unit Stress in Lbs. per Sq. Inch
Curve 8
Curve 9
Curve 10
Curve 11
Curve 12
Curve 13
10,000#
2'-0"
3'-4"
4'-8"
6'-0"
7'-4"
No. of Plug
Distance in Feet
STATE OF ILLINOIS
DEPARTMENT OF PUBLIC WORKS AND BUILDINGS
DIVISION OF HIGHWAYS
MULTIPLE LOAD INVESTIGATION
STANDARD 9-6-9 CONCRETE PAVEMENT.
Stresses in Upper Fibres at Edge of Slab

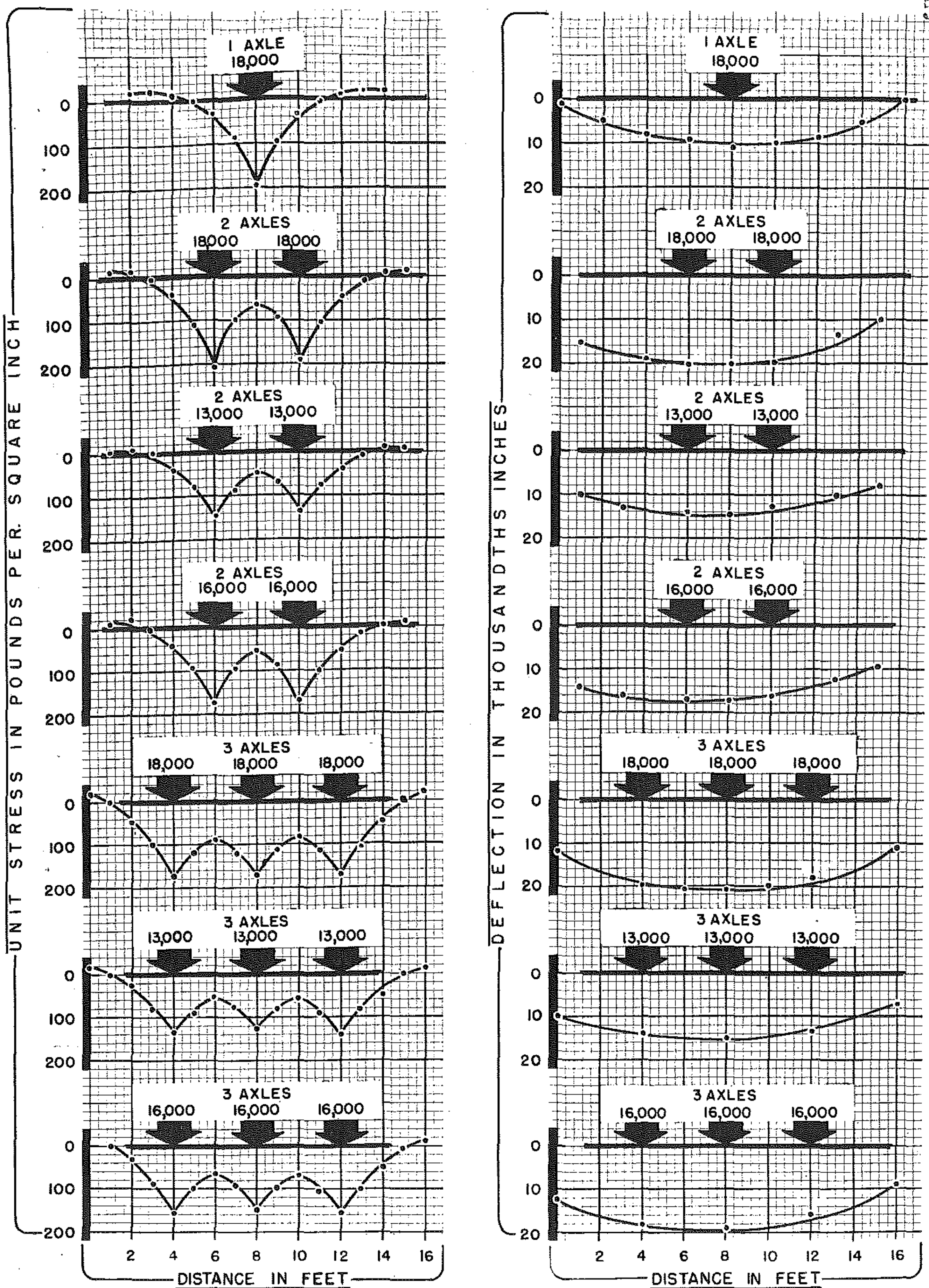
Figure 8

report on this work was submitted to the Department in November, 1946.(11)

For the purpose of this report only pertinent data from the investigation will be presented. Maximum unit stresses determined from the load tests are presented in Table X. Strain-deflection curves for single and multiple axles located at the longitudinal edge and at the free corner of the slab are shown in Figures 9 and 10.

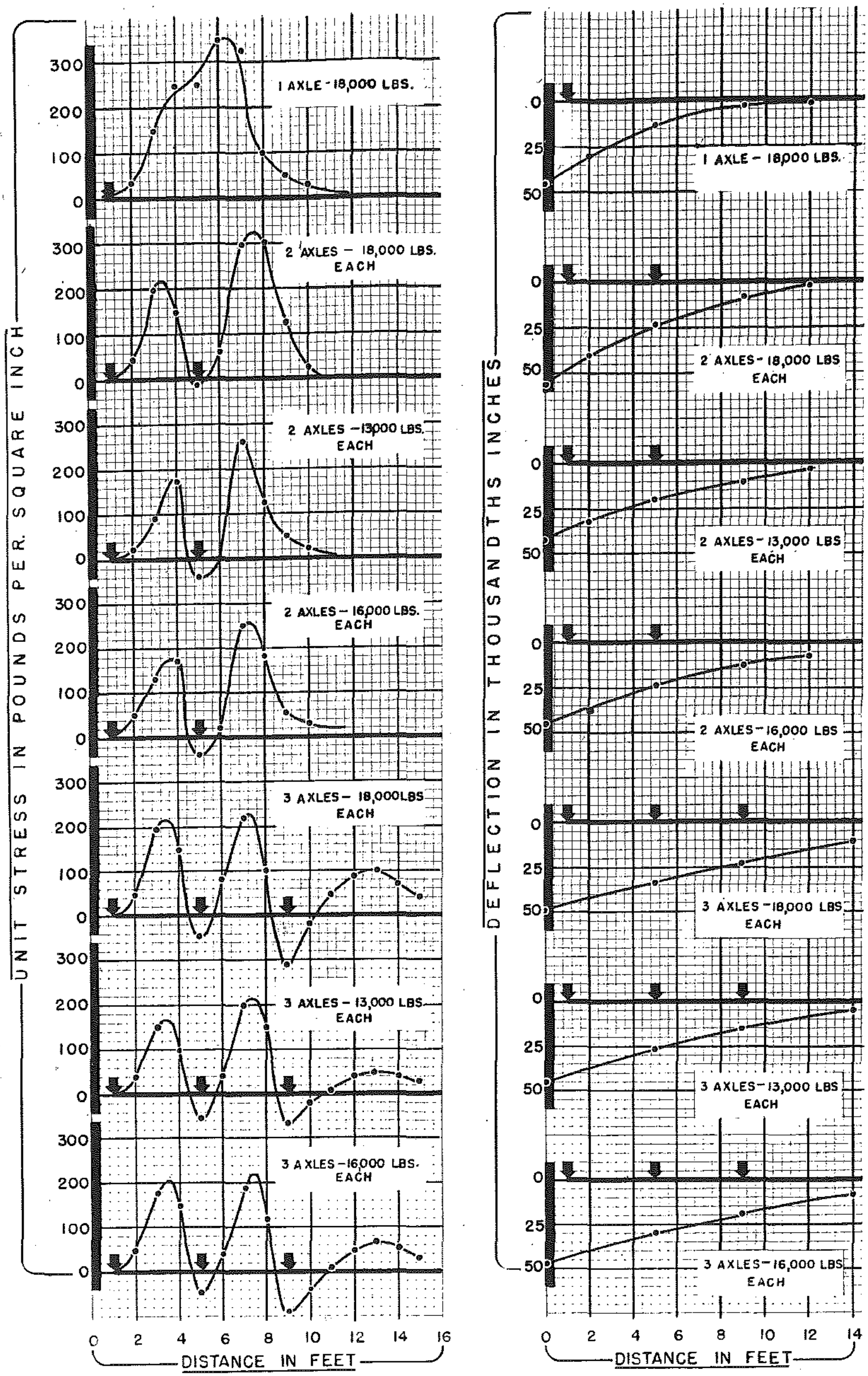
The findings of the investigation substantiate those of other researches in that the stresses induced by tandem axles spaced not less than 4 feet apart are not, within the tolerance of the test, greater than those produced by a single axle of equivalent loading. The deflection of the longitudinal free edge of the slab under tandem axles is considerably greater than that caused by a single axle, whereas at the corner the deflection caused by the single axle is not materially less than that caused by either tandem or multiple axle groups of corresponding loadings. Three axle groups do not produce maximum strains or deflections materially in excess of tandem axles of equivalent loading.

From the foregoing discussion of stresses induced in concrete pavement slabs by single and multiple axle loadings, it might be inferred that the same load could be permitted on all axles irrespective of how they may be grouped without causing more injury to the pavement than that of a single axle load, provided the minimum axle spacing is not less than 42 inches. Any consideration as to the damaging effect of moving heavy vehicles on pavements is neglected. At the present time any recommendations for future legal gross vehicle weights based on this conclusion may lead to serious



STRESS *and* DEFLECTION *at the* EDGE

Figure 9



STRESS *and* DEFLECTION *at the* CORNER

Figure 10

TABLE X

MAXIMUM UNIT STRESSES AND DEFLECTIONS FOUND BY TESTS
ON 9 INCH UNIFORM PLAIN CONCRETE SLAB

Subgrade Modulus k in p.c.i.	Load per axle in pounds	Stress in p.s.i. when axles are at slab edge			Stress in p.s.i. when axles are at slab corner		
		1 axle	2 axles	3 axles	1 axle	2 axles	3 axles
60	13000	145	145	140	250	230	215
60	16000	180	175	160	270	280	220
60	18000	200	210	175	350	325	280
110	13000	140	135	125	200	200	180
110	16000	180	170	160	260	250	170
110	18000	200	190	175	300	280	200

Subgrade Modulus k in p.c.i.	Load per axle in pounds	Maximum Deflection-inches x 10^{-3} at slab edge			Maximum Deflection-inches x 10^{-3} at slab corner		
		1 axle	2 axles	3 axles	1 axle	2 axles	3 axles
60	13000	.008	.015	.015	.029	.042	.045
60	16000	.010	.017	.019	.036	.045	.047
60	18000	.011	.020	.021	.043	.055	.050
110	13000	.008	.014	.016	.020	.036	.040
110	16000	.009	.016	.018	.033	.041	.045
110	18000	.009	.018	.020	.045	.050	.050

difficulties. First, because of the present lack of basic information on the effect of dynamic loads on stresses and breakdown effect on pavements and second, because of the many uncertainties affecting structural adequacy due to current construction practices.

Construction Uncertainties Contributing to Structual Inadequacy

In the first place concrete as applied to a pavement slab is at best a heterogeneous conglomerate composed of pebbles, sand, portland cement and water. Due to present methods of mixing, placing and finishing, the concrete product varies in density and physical properties from one area to another in the slab and from top to bottom. Such conditions no doubt influence to a great degree the uniformity in physical properties and the magnitude of secondary stresses set up in the hardened concrete augmented by such factors as hydration shrinkage, differential moisture and temperature gradient between top and bottom of the slab, horizontal movement of the pavement under temperature changes and by the drag of load transfer devices and the unevenness of the subbase surface. Another factor intimately associated with pavement failure is the unpredictable characteristics of subgrade support brought about by inadequate and non-uniform compaction effort in conjunction with questionable subbase materials.

In addition to these factors practically nothing is known concerning the effect of dynamic loads including single and multiple axle groups as well as gross loads on the ultimate destruction of pavements through stress induction and slab deflections. Included in these considerations should be mentioned the influence of impact under moving loads in relation to pavement roughness which in turn is associated with age and wear and the combination of these load stresses with secondary stresses. Another major factor is the effect of axle loads and axle frequencies in relation to fatigue of concrete and in this same category the influence on induced stresses of unequal axle loads and overloading of axles.

Finally very little is known on the rate of breakdown of concrete slabs under fatigue and vibration especially in relation to type of concrete, age of concrete and stresses in concrete when exterior loads are applied.

It is a well known fact that the minor increase in gross loads permitted during the war emergency greatly accelerated the breakdown of certain pavements. Thus it would be disastrous to permit greater loads on pavements at this time until more basic information on the subject has been made available.

Influence of Tire Size and Inflation Pressure on Stresses.

Although the stresses in a concrete slab and the resistance to failure in a flexible surface are both somewhat dependent upon tire size and inflation pressure, these factors are of minor importance.

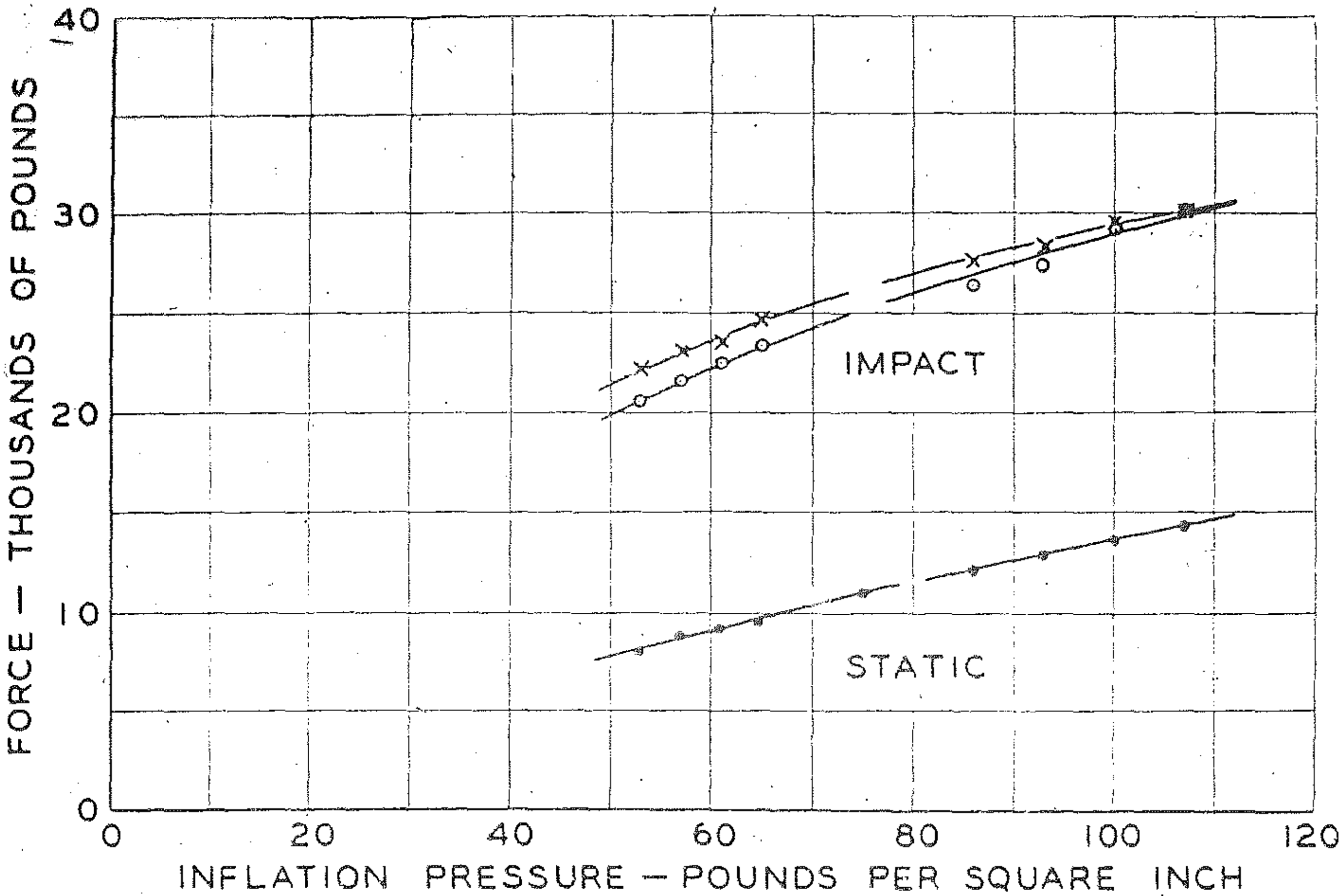
Static tests by G. S. Paxson [12] on 10.00-20 and 11.00-20 12 ply truck tires showed that the pavement stresses increased 5.8% as the inflation pressure increased from 60 to 90 p.s.i. He attributed this increase in stress to the slight reduction in tire contact area resulting from the increase in tire rigidity due to the higher air pressure.

Dynamic tests conducted by the Public Roads Administration [13] in which were included two types of pneumatic tires at different inflation pressures disclosed the fact that impact reactions vary almost in direct proportion to inflation pressures. Also severe roughness conditions of the pavement may cause load reactions as great as 3 times the static load with high pressure tire equipment. See Figure No. 11.

The data presented in Figure 11 shows an increase of 20% in impact force when the inflation pressure was increased from 70 to 110 p.s.i. For the same change in inflation pressure the reaction force under static conditions increased approximately 3.6 percent, which is in agreement with Paxson's results.

Additional dynamic tests were conducted upon a flexible pavement by the Public Roads Administration in 1935.[14] The results of this experiment showed little effect of tire contact area. However, the dynamic stresses recorded when solid rubber tires were driven over an obstruction were found to be 250 percent of the value obtained under high pressure pneumatic tires. With no obstruction the impact forces for solid rubber tires ranged from 230 to 250 percent of the corresponding values for the pneumatic tires.

The effect of contact area under dual wheels on flexible pavements was investigated by Boyd[15] in 1942. He suggested that tire loads be decreased 10 percent below the single wheel value when dual wheels were used. His studies revealed that the overlapping of the influence area from each tire when fully loaded caused total deflections which exceeded those caused by a single fully loaded wheel.



DROP IMPACT REACTIONS:—

× MAXIMUM AFTER PASSING 1½ BY 12 INCH OBSTRUCTION

o MAXIMUM AFTER PASSING 1½ BY 30 INCH INCLINED PLANE

STATIC REACTION:—

• LOAD WHEN TIRES ARE DEFLECTED 1½ INCHES

INFLUENCE OF INFLATION PRESSURE ON TIRE REACTIONS

PART IV

MODERN HIGHWAY LOADING IN RELATION TO BRIDGES

Although the investigation has been devoted primarily to studying the effect of multiple axle loads of different magnitudes on pavement slabs, the work cannot be successfully concluded without discussing the subject of axle loadings on bridge structures in the light of present design standards.

In order to keep pace with the trends in motor transport development, it obviously has been necessary to revise upward the standard of live loadings adopted in highway bridge design specifications. Because of the gradual increase in gross weights and variety of types of motor transport units using the highways in Michigan, the need was evident for a modern bridge posting system and satisfactory legislation for restricting maximum gross weights on the Highway system.

<u>Investigations by Bridge Division</u>

In 1941, after an extensive study of actual vehicle loading on the Michigan highway system, the Bridge Division developed a method for analyzing and posting structurally inadequate bridges.(16) Again in February, 1948 they proposed new legislation for the restriction of highway loads in order to protect even the more modern bridge structures on the trunkline system, especially those designed for H-15 loadings.(17) The Department has now adopted the A.A.S.H.O. H-20-S-16 loading as a standard for future bridge design on the state trunk line system.

After a careful study the Bridge Division concluded that the formula type law as used by many states would be satisfactory for Michigan as a method of controlling maximum loads in addition to the restrictions imposed by the present load law. The formulas proposed are as follows:

W = 700 (L + 40) when L is less than 18 feet.

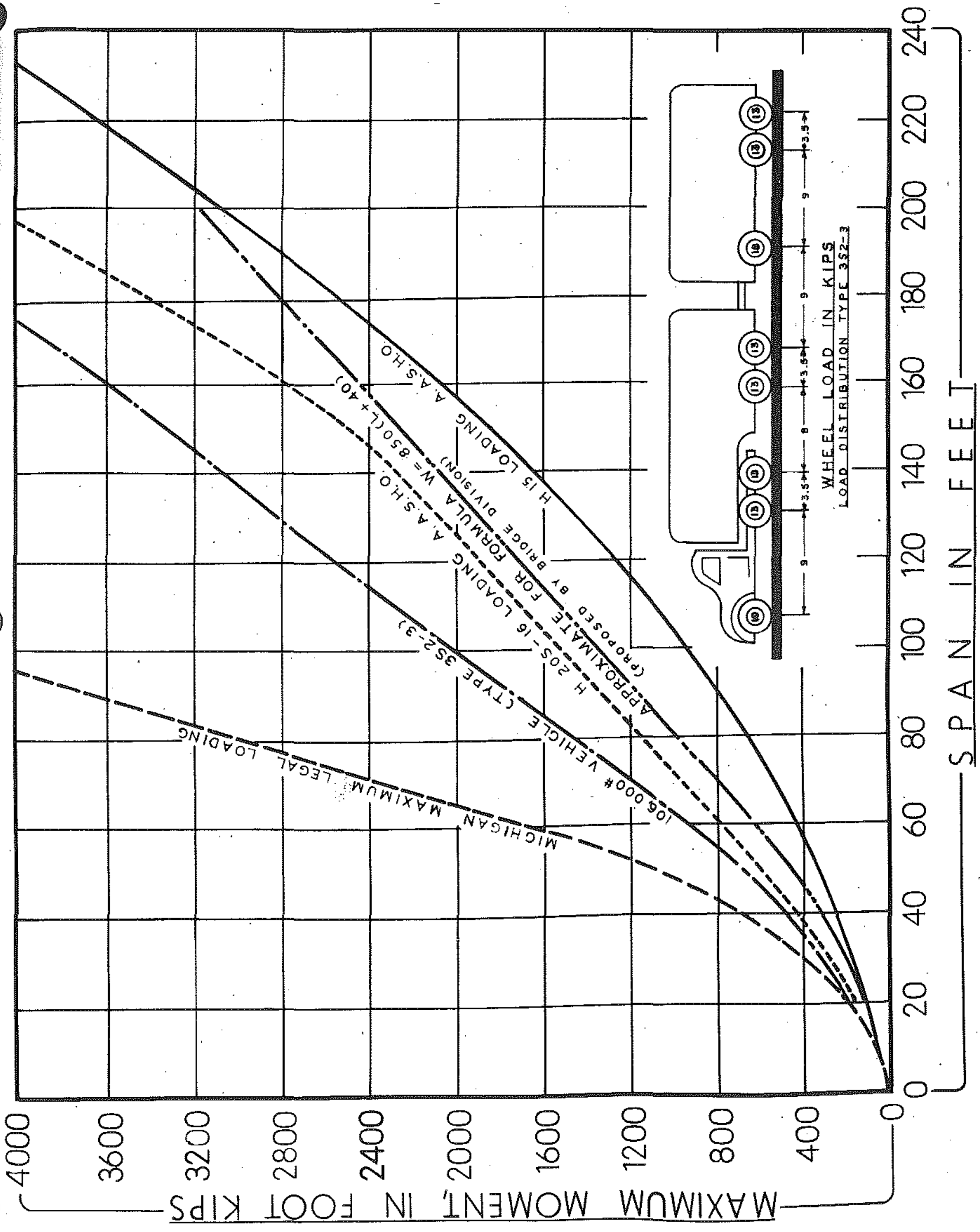
W = 850 (L + 40) when L is equal to or greater than 18 feet.

Where: L is the length in feet between extreme axles of a vehicle or combination of units or any axle group.

W is maximum gross weight in pounds.

The formula proposed by the Bridge Division is a compromise between the American Association of State Highway Officials and the American Trucking Association formulas. For example, when L is less than 18 feet, the C value of 700 in the Bridge Division formula will give gross weight values very close to those of the A.A.S.H.O. formula, whereas for values of L greater than 18 feet the Bridge Division formula coincides with the A.T.A. formula. This may be noted by studying the formula curves illustrated in Figure 4.

Furthermore, the gross weights permitted under the Bridge Division formula will cause moment values lying approximately midway between those induced by the A.A.S.H.O., - H 15 loadings and H 20, S-16 loading for equivalent length of span. This fact is clearly illustrated in Figure 12. Also in Figure 12 it may be seen that vehicles with gross weights exceeding 80,000 pounds will induce moments equal to and even greater than those recommended by the H 20, S-16 loading. As illustrated, a motor vehicle unit weighing 108,000 pounds will cause moments considerably in excess of those permitted under the H 20, S-16 loading. Impact has not been considered in plotting curves.



MAXIMUM MOMENT CURVES

Figure 12

CONCLUSIONS

The most important conclusions emanating from the investigation are reviewed as follows:

1. There is a definite upward trend in the gross weight of motor transport vehicles which no doubt has been brought about by wartime conditions.

2. Overloading of axles and axle groups has increased beyond reasonable limits and this practice should be discouraged as much as possible by educational methods and weight control.

3. Many gross weight loads and axle loads found on the highways are far in excess of the typical standard loadings utilized in the design of pavements and bridges.

4. The Gemeny formula or a modification thereof is now generally accepted as being the most logical method of controlling the gross weight of motor transport units. Its use is being gradually adopted by the several States.

5. Although research has shown that loads on multiple axles in tandem do not induce stresses in excess of those caused by a single axle of equivalent axle load, it is not considered wise to permit the maximum individual axle loadings on multiple axles because of the uncertainties in subgrade support and structural defects in the concrete and because of the larger deflections caused by the greater group loadings. The extent to which such deflections may affect the life of the pavement is not understood.

6. The basic criterion for concrete pavement design is the 9,000 pound wheel load with a reasonable allowance for impact. Therefore no load

conditions should be allowed which would cause stresses or deflections in excess of those induced by such a load acting at the most critical points in the slab under static or dynamic conditions.

7. There is little data available on the effect of dynamic loads, impact and axle frequencies which produce failure of pavements by fatigue. It is a well known fact that any increase in wheel loads or wheel load frequencies is accompanied by an accelerated breakdown of pavements. Thus it would seem unwise to permit greater loads on the highways until more basic information on the subject has become available.

8. The formulas recommended by the Bridge Division for restricting the gross weight of vehicles are consistent with modern highway bridge design standards and concur with similar formulas adopted by other States as well as with the policy of the A.A.S.H.O.

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