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HIGHWAY COSTS

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FOREWORD

From the fact that

- vast sums of money have been expended for improving and maintaining highway facilities during the past third of a century,
- all of this money has been derived from some sort of impost on the general public through property taxes and bond issues or on motor vehicle owners and users through registration fees, gasoline taxes and other imposts,
- all of this money has been spent by some unit of government, such as Federal, State, county, road district or municipality,
- these improved highways and streets have become a roadway for a great transportation system, and
- they are used by a vast number of automobiles which furnish individual transportation for persons, whether on pleasure or business bent, and by a large number of trucks and buses engaged in commercial operations in competition with other transport agencies, including the railroads,

arise two important questions.

It is generally conceded that this competition should be fair. If it is to be fair, then, apart from the question of comparable regulation, highway transport should directly or indirectly pay fully for the costs of providing and maintaining its roadway facilities, just as railroads must provide and maintain their roadways.

We have asked three eminent highway engineers, of long experience and training in highway construction, design and cost to study this problem and report their conclusions to us. They have made an investigation and written a report. That report is submitted herewith.

ARE HIGHWAY USERS FULLY PAYING FOR THE FACILITIES PROVIDED FOR THEM AND WHICH THEY USE? They answer, No. In the twelve-year period 1921-1932 for which data are available, they have failed to pay fully for the facilities provided for them and which they use by \$9,756,000,000. For the year 1932 the deficiency amounted to \$682,000,000. This is subsidy. Subsequent figures show that the subsidy was not diminished for the succeeding years up to and including 1937.

HAVE DIFFERENT TYPES OR CLASSES OF MOTOR VEHICLES HAD IMPOSED UPON THEM COSTS COMMENSURATE WITH THE FACILITIES THEY REQUIRE AND WITH WHICH THEY HAVE BEEN PROVIDED? They again answer, No. The failure to pay by groups or classes of motor vehicles is shown in the study for the year 1932 and fair approximation for the year 1937. For the year 1932 the deficit or subsidy ranges per vehicle from \$876 for a three-ton truck to \$2,000 for the heaviest permissible truck, and for a seven-passenger bus, \$75 and a twenty-passenger bus, \$376.

This study demonstrates beyond any doubt that highway transport has been and is being substantially subsidized by government.

These are the facts. What is to be done about it?

J. J. PELLEY,

President, Association of American Railroads.

January 26, 1939.

MR. J. J. PELLEY,
President, Association of American Railroads,
Washington, D. C.

Dear Mr. Pelley:

In complying with your request, we submit herewith a report based upon extended investigation covering highway costs for the United States and a proper apportionment of these costs to motor vehicle owners.

We present immediately hereafter the findings that we have made with respect to highway costs and a proper allocation of these costs to motor vehicles.

Following these findings is a condensed statement of the principles and methods which we have employed in the study.

Then follows the complete and detailed study of the subject.

Very truly yours,

C. B. BREED,
CLIFFORD OLDER,
W. S. DOWNS.

FINDINGS

1. Total highway cost for twelve-year period 1921-1932:

(a) State highways _____	\$4,749,071,000
(b) County and local roads _____	8,996,345,000
(c) City streets _____	7,130,730,000
Total _____	\$20,876,146,000

2. Highway costs properly chargeable to motor vehicle owners for the twelve-year period:

		<i>Per cent of Total Cost</i>
(a) State highways _____	\$4,269,373,000	89.90%
(b) County and local roads _____	8,074,413,000	89.75%
(c) City streets _____	3,444,563,000	48.31%
Total _____	\$15,788,349,000	75.63% aver.

3. Subsidy to motor vehicles for twelve-year period was:

Total costs chargeable to motor vehicles _____	\$15,788,349,000
Total payments of motor vehicles _____	6,031,395,000
Total subsidy _____	\$9,756,954,000

4. Subsidy to motor vehicles for the year 1932:

Cost _____	\$1,495,218,000
Motor vehicle payment _____	812,685,000
Subsidy _____	\$682,533,000

5. In 1932 typical motor vehicles failed to pay their proportion of highway and street costs:

	<i>Amount Chargeable</i>	<i>Amount Paid</i>	<i>Deficit</i>
Passenger car _____	\$42.40	\$27.13	\$15.27
Truck, 1 1/2 tons and less (private) _____	96.40	51.43	44.97
Truck, 1 1/2 tons and less (for hire) _____	208.71	100.71	108.00
Truck, 3 tons and less than 5 tons (private) _____	809.90	196.02	613.88
Truck, 3 tons and less than 5 tons (for hire) _____	1,145.73	269.01	876.72
Trucks, 5 tons (private) _____	1,432.36	270.88	1,161.48
Trucks, 5 tons (for hire) _____	2,024.45	369.81	1,654.64
Truck, over 5 tons (private) _____	1,705.53	356.40	1,349.13
Truck, over 5 tons (for hire) _____	2,412.41	491.76	1,920.65
Bus, over 20 passengers (common carrier) _____	1,318.48	441.61	876.87

6. After 1932 and until 1938 partial figures only are available for highway expenditures, but an analysis of these figures shows that in the year 1937 there was no less subsidy than in 1932.

PRINCIPLES AND METHODS EMPLOYED

The problem involves a study of the expenditures on all highways and streets down to the latest year for which such data are available.

An analysis of these expenditures requires two important steps:

1. The determination of the total annual cost of highways and streets, the portion of these annual costs actually contributed by motor vehicles and by general taxation and the equitable amounts motor vehicles and the public should have paid. From the above the amount of subsidy to motor vehicles as a whole, if any, follows.

2. The determination of the equitable distribution of highway costs, chargeable to motor vehicles as a whole, among the different classes of vehicles. If a subsidy is found, the amount by which each class of motor vehicles has failed to pay its fair share should then be determined.

The period specifically reviewed was 1921-1932.

The year 1921 was chosen as the beginning of this period because the records for previous years were incomplete and in many respects unobtainable. The year 1932 was selected as the end of the period because that year was the last one for which comprehensive data were available.

The depreciated value of all highways and streets as of the end of 1920 was brought forward into the period 1921-1932 by estimating its original cost and assuming that one-half of its service life had been used up. Rights-of-way values were excluded and therefore left as a contribution by the public.

The data for subsequent years so far as available, have been compiled and analyzed and are included in the study separately.

A part of the expenditures for the period under review was provided by general taxation and a part by motor vehicle charges. The later charges were fixed by legislative action in the various States without the benefit of any economic analysis of highway costs.

To determine whether or not motor vehicles as a whole paid their fair share during the period under review there was required an analysis of highway costs on some equitable principles that would determine the fair share of the annual costs of highways which should be borne by the users. This led to the use of public utility principles as the proper basis of analysis of highway expenditures and financing.

These principles and the public utility concept as applied to highways have been approved by many authorities and have been sustained by the courts as applicable to highway finance and to charges to users for highway service.

On this basis all capital expenditures were then converted into annual costs by applying a proper service life to the various highway elements purchased through capital expenditures. To these were

added all other annual costs such as maintenance and operation interests and taxes on the unamortized portions. The sum of these cost items represented the annual costs year by year for the twelve-year period.

The total of annual costs for the twelve-year period amounted to about 21 billion dollars.

Just here arises the problem of determining the equitable amounts that motor vehicles on the one hand and the public on the other should have paid. The year 1904 was chosen as the year just preceding any substantial influence of the motor vehicle. For a long period before 1905 the public paid through general taxation for all highways and streets. The annual rate of such expenditures amounted to about \$1.00 per capita for rural roads and \$4.20 per capita (city population) for city streets. Even though it is well known that prior to 1905 a large part of highway expenditures was for commercial transportation, we have assumed that the amount the public would have been willing to continue to pay for highways during the period under review would have been the same per capita as it had actually paid for several years prior to the advent of the motor vehicle.

There was, therefore, charged against the general public each year \$1.00 per capita for rural road expenditures and \$4.20 per capita (city population) for city streets as equitably dividing the highway costs between motor vehicles and the general taxpayers.

We have determined on the basis set forth above that the motor vehicles should have paid during this period about 16 billion dollars. They did pay about 6 billions. We have determined that general taxpayers should have paid about 5 billions. They did pay about 15 billions.

Thus, there was a subsidy of about 10 billion dollars enjoyed by motor vehicles as a whole for the twelve-year period.

Motor vehicles actually paid about 30 per cent of the annual costs of highways and streets and the public paid about 70 per cent. Our study concludes that motor vehicles as a whole should have paid 75 per cent and the public 25 per cent of the total annual costs.

The next step required the distribution of the annual costs of highways and streets between the different classes of motor vehicles so that the subsidy as a whole might be appraised for each class of vehicle.

Some of the highway and street elements have been provided solely for heavier and wider vehicles, practically all used in commercial transport. The capital cost of these elements that has been especially provided for these larger and wider vehicles has been determined. For rigid and flexible pavements this amount was determined by application of the increment method proposed by the Joint Committee of Railroads and Highway Users according to which each class of vehicle should pay its fair share of the total annual cost and "the total additional cost of construction, improvements and maintenance to make a road suitable for a type of vehicle requiring such additional cost should be shared by each vehicle of that type and each vehicle

of greater size. Thus, each should share in the base cost plus all increments of cost up to and including cost required by it."

Twelve per cent of the capital costs for cuts and fills for pavements and structures on rural roads was determined as fairly chargeable solely to the wide vehicle. This 12 per cent was applied only to the amounts expended for the roads requiring improved surfaces.

It is then necessary to charge to each motor vehicle its fair share for the use it makes of the highway system as a whole. The motor vehicle owner who operates his car 20,000 miles in a year should obviously pay more than the owner who operates only 5,000 miles. Consequently, the individual motor vehicle is charged the costs allocated to its class on the basis of the number of times it uses the road, that is, on a vehicle mile basis.

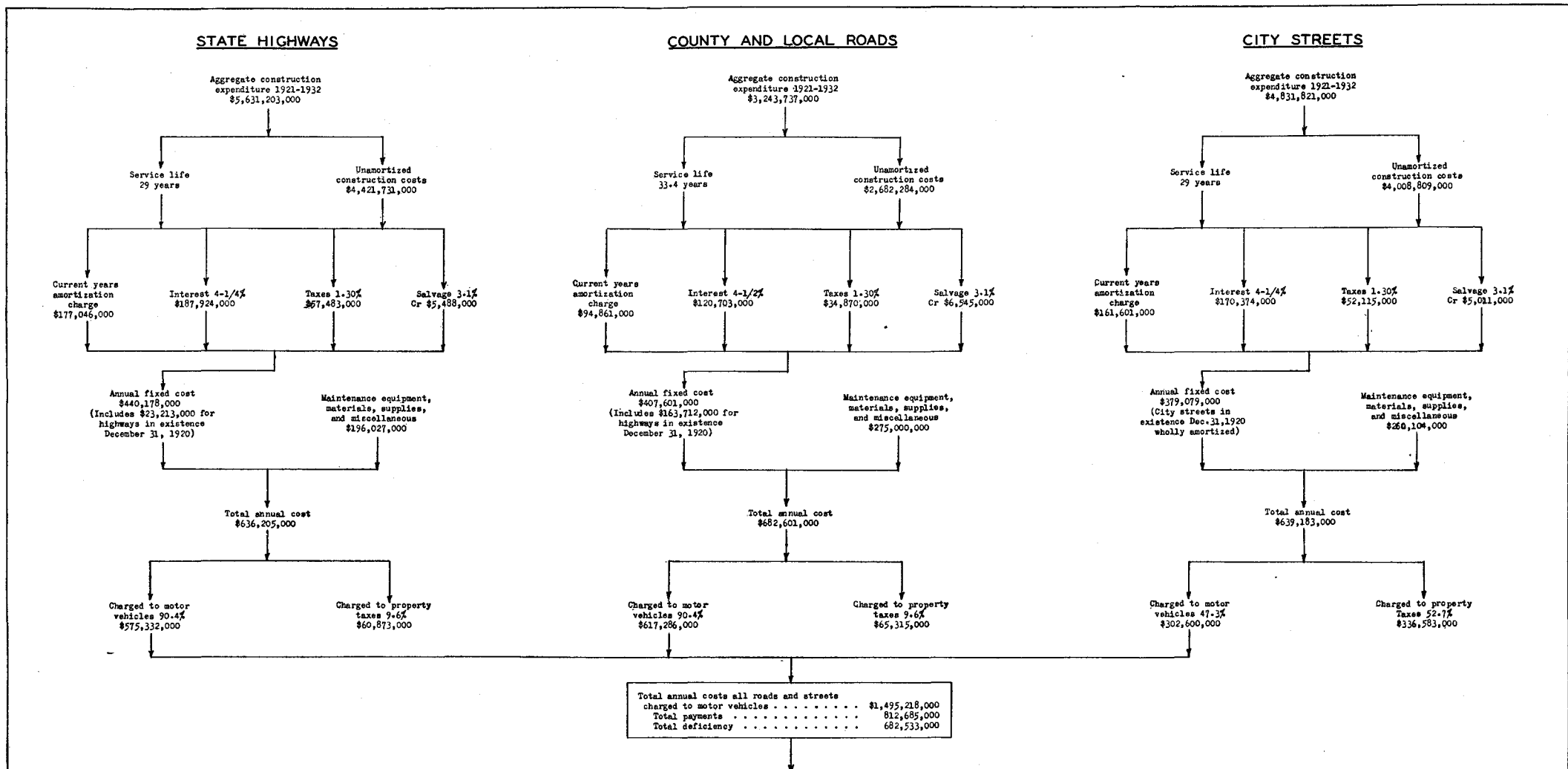
Because some maintenance costs vary with weight of vehicle and others do not, the maintenance costs are charged to each motor vehicle partly on a ton mile basis and partly on a vehicle mile basis, viz., three-fourths of maintenance costs on rural roads are chargeable on a ton mile basis and one-fourth on a vehicle mile basis; on city streets, one-half is charged on the ton mile basis and the other half is on a vehicle mile basis.

To illustrate the application of the adopted principles the year 1932 has been chosen because it was the latest year for which complete data were available. The analysis shows for the year 1932 that the passenger motor vehicles paid 64 per cent of the amount charged to them and the largest and heaviest trucks paid only 25 per cent of the amount charged to them. Intermediate types of vehicles in all instances paid less than their fair proportion. The type which came closest to paying its proper share was the farm truck, which contributed 83 per cent of the amount we have determined it should have paid.

These percentages are, of course, general and apply only to this national study. The application of the principles in this report to a study of any individual State may show different percentages of subsidy and may in some instances show that for certain types of vehicles there is no subsidy.

The study as a whole indicates clearly that there has been a very large subsidy to highway transport.

HIGHWAY COSTS AND THEIR ALLOCATION FOR YEAR 1932



Item	Contract Carrier Buses			Common Carrier Buses			Private Trucks										For Hire Trucks											
	Passenger cars	Taxicabs	School buses	7 pass-engers & less	8 to 20 pass-engers	Over 20 pass-engers	7 pass-engers & less	8 to 20 pass-engers	Over 20 pass-engers	Farm trucks	1 1/2 tons & less	Over 1 1/2 tons & less than 3 tons	Combin-ations	3 tons & less than 5 tons	Combin-ations	5 tons	Combin-ations	Over 5 tons	Combin-ations	1 1/2 tons & less	Over 1 1/2 tons & less than 3 tons	Combin-ations	3 tons & less than 5 tons	Combin-ations	5 tons	Combin-ations	Over 5 tons	Combin-ations
Annual charges per vehicle	\$42.40	\$169.61	\$124.69	\$87.47	\$263.99	\$373.74	\$220.92	\$789.19	\$1 118.48	\$33.00	\$96.40	\$187.53	\$250.40	\$809.90	\$581.41	\$1 432.36	\$1 433.13	\$1 705.53	\$1 946.57	\$208.71	\$361.93	\$354.41	\$1 145.73	\$823.16	\$2 024.45	\$2 026.29	\$2 412.41	\$2 754.94
Annual payments per vehicle	27.13	89.11	73.34	55.89	125.18	243.56	146.20	297.75	441.61	27.42	51.43	97.73	144.89	196.02	219.75	270.88	305.38	356.40	486.30	100.71	166.87	213.26	269.01	320.41	369.51	432.26	491.76	707.89
Deficiency per vehicle	15.27	80.50	51.35	31.58	138.81	130.18	74.72	491.44	876.87	5.58	44.97	89.80	105.51	613.88	361.66	1 161.48	1 127.73	1 349.13	1 460.27	108.00	195.06	141.15	876.72	502.75	1 654.64	1 594.03	1 920.65	2 047.05

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APPENDIX A

DISTRIBUTION, BY TYPE OF ROAD, OF COST OF STATE HIGHWAYS AND LOCAL ROADS, EXCEPT UNIMPROVED EARTH ROADS, IN EXISTENCE DECEMBER 31, 1921, ON BASIS OF 1917-1924 COST OF FEDERAL-AID ROADS

Type of road	Mileage 1921 <i>a</i>		Average cost of Federal-aid roads 1917-1924 <i>b</i>	Total cost				Total cost adjusted*				
	State highways	Local roads		State highways		Local roads		State highways		Local roads		
				Amount (2×4)	Per cent of total	Amount (3×4)	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	
	(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Improved Type:												
1 Improved earth (established to grade and drained).....	21,384	<i>c</i> 232,176	\$7,800	\$166,795,200	8.99	\$1,810,972,800	18.20	\$125,096,400	8.68	\$1,207,303,127	14.92	
2 Sand-clay and top-soil.....	8,709	54,467	7,400	64,446,600	3.47	403,055,800	4.05	48,334,950	3.35	268,701,180	3.32	
3 Gravel.....	36,279	163,351	9,900	359,162,100	19.35	1,617,174,900	16.25	269,371,575	18.70	1,078,105,819	13.32	
4 Water-bound macadam.....	16,976	60,333	17,500	297,080,000	16.00	1,055,827,500	10.61	222,810,000	15.47	703,877,961	8.70	
5 Bituminous macadam by penetration.....	6,708	3,556	29,100	195,202,800	10.52	103,479,600	1.04	146,402,100	10.16	68,985,710	0.85	
6 Bituminous concrete and sheet asphalt.....	2,844	3,735	<i>d</i> 33,500	95,274,000	5.13	125,122,500	1.26	71,455,500	4.96	83,414,166	1.03	
7 Portland cement concrete.....	9,860	5,905	38,300	377,638,000	20.34	226,161,500	2.27	283,228,500	19.66	150,772,826	1.86	
8 Brick and block.....	2,003	1,427	<i>d</i> 44,700	89,534,100	4.82	63,788,900	0.64	67,150,575	4.66	42,524,175	0.53	
9 Miscellaneous.....	993	10,311	<i>d</i> 16,900	16,781,700	0.91	174,255,900	1.75	12,586,275	0.87	116,169,438	1.44	
Unimproved Type:												
10 Earth and partly graded.....	97,159	<i>c</i> 2,186,329	<i>e</i> 2,000	194,318,000	10.47	4,372,658,000	43.93	194,318,000	13.49	4,372,658,000	54.03	
Total.....	202,915	2,721,590	f	\$1,856,232,500	100.00	\$9,952,495,400	100.00	\$1,440,753,875	100.00	\$8,092,512,402	100.00	
Average cost.....	.....	.....	.....	\$9,148	.....	\$3,057	.....	\$7,100	.....	\$2,973	.....

a State highways from Bureau of Public Roads report M-4 (1920); Local roads from M-5 (1921).
b Cost data from Bulletin No. 914, Bureau of Public Roads, Page 113.
c Total earth roads (2,418,506 miles) was here divided on basis of 1923 proportion.
d Sheet asphalt assigned same cost as bituminous concrete and block paving same as cost of brick.
e Estimated.
f Assigned average of all types.

* Improved road figures were adjusted by reducing costs shown in Columns 5 and 7 for improved types Nos. 1 to 9. State highways (Column 5) reduced 25 per cent and local roads (Column 7) 33.3+ per cent. No adjustments were made in figures for type No. 10—Unimproved earth, and partly graded.

APPENDIX B
PERCENTAGE DISTRIBUTION OF COST OF HIGHWAY ELEMENTS IN RURAL ROADS ON DECEMBER 31, 1921

Type of road	Percentage of average cost per mile represented by: a			Percentage of total cost		Percentage distribution of cost of State highways			Percentage distribution of cost of local roads		
	Grading	Surfacing	Structure	State highways d	Local roads d	Grading (5x2)	Surfacing (5x3)	Structures (5x4)	Grading (6x2)	Surfacing (6x3)	Structures (6x4)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Improved Type:											
1 Improved earth (established to grade and drained).....	72	..	28	8.68	14.92	6.25	.....	2.43	10.74	.....	4.18
2 Sand-clay and top-soil.....	46	25	29	3.35	3.32	1.54	0.84	0.97	1.53	0.83	0.96
3 Gravel.....	35	47	18	18.70	13.32	6.54	8.79	3.37	4.66	6.26	2.40
4 Waterbound macadam.....	20	69	11	15.47	8.70	3.09	10.67	1.70	1.74	6.00	0.96
5 Bituminous macadam by penetration.....	15	75	10	10.16	0.85	1.52	7.62	1.02	0.13	0.64	0.09
6 Bituminous concrete and sheet asphalt.....	12	82	6	4.96	1.03	0.60	4.07	0.30	0.12	0.84	0.06
7 Portland cement concrete.....	15	77	8	19.66	1.86	2.95	15.14	1.57	0.28	1.43	0.15
8 Brick and block.....	10	85	5	4.66	0.53	0.47	3.96	0.23	0.05	0.45	0.03
9 Miscellaneous.....	b 26	b 59	b 15	0.87	1.44	0.23	0.51	0.18	0.37	0.85	0.22
Unimproved Type:											
10 Earth and partly graded.....	e 72	..	e 28	13.49	54.03	9.71	.....	3.78	38.90	.....	15.13
Total.....	..	..	..	100.00	100.00	32.90	51.60	15.50	68.52	17.30	24.18

- a From Bureau of Public Roads, Bulletin No. 914, page 114. Ratios for grading include miscellaneous cost; ratios for surfacing include cost of shoulders.
b Assigned average of all types.
c Assumed to be the same as for graded and drained roads.
d See Appendix A, Columns 10 and 12.

APPENDIX C
CONSTRUCTION EXPENDITURES ON STATE HIGHWAY SYSTEMS, 1921-1932
ADJUSTED TO INCLUDE PRO-RATA SHARE OF ADMINISTRATION AND ENGINEERING EXPENSES FOR
YEARS 1921 TO 1927

Year	Construction expenses as originally reported ^a	Miscellaneous expenses as originally reported ^a	Per cent miscellaneous expenses of construction expenses	Miscellaneous expense incl. administration and engineering expenses as originally reported ^a	Estimated miscellaneous expenses	Estimated administration and engineering expenses	Total construction expenses incl. maintenance expenses as originally reported ^a	Per cent construction expenses of construction expenses including maintenance	Administration and engineering expenses pro-rata share to construction expenses	Construction expenses adjusted to include administration and engineering expenses
	1	2	3 = 2÷1	4	5 = 1×Av. of 3	6 = 4 - 5	7	8 = 1÷7	9 = 6×8	10 = 1+9
1921	\$284,802,460	.....	.....	\$16,417,808	\$1,884,925	\$14,532,983	\$349,135,619	81.430	\$11,838,719	\$296,136,179
1922	287,461,018	.....	.....	19,976,406	1,905,868	16,070,538	882,801,509	79.284	14,318,011	301,779,029
1923	279,992,788	.....	.....	26,407,129	1,856,852	24,550,777	855,821,946	78.800	19,846,012	299,388,800
1924	382,835,696	.....	.....	31,165,081	2,594,886	28,680,195	487,142,258	78.485	22,470,409	404,806,105
1925	359,827,894	.....	.....	38,618,053	2,581,241	36,036,812	508,680,944	76.544	27,580,218	416,907,597
1926	356,174,616	.....	.....	38,250,111	2,861,433	35,388,678	481,791,929	78.927	26,561,419	382,706,085
1927	404,217,317	.....	.....	48,828,297	2,679,951	46,148,346	548,000,675	74.441	34,949,551	435,586,873
1928	538,048,138	\$4,011,820	0.746	.....	.....	.....	.....	.....	.....	538,048,138
1929	557,400,625	5,524,858	0.991	.....	.....	.....	.....	.....	.....	557,400,625
1930	718,117,045	2,227,459	0.312	.....	.....	.....	.....	.....	.....	718,117,045
1931	730,954,832	4,312,553	0.590	.....	.....	.....	.....	.....	.....	730,954,832
1932	551,445,859	4,418,117	0.801	.....	.....	.....	.....	.....	.....	551,445,859
Total	\$5,474,772,778	.....	Average 0.638	.....	.....	.....	.....	.....	\$156,429,844	\$5,681,202,122

^a From annual Tables F-2, Bureau of Public Roads.

APPENDIX D
ANALYSIS OF MISCELLANEOUS REVENUES, STATE HIGHWAY DEPARTMENTS, 1921 TO 1932
(All amounts in thousands)

A—DISTRIBUTION IN YEARS FOR WHICH INFORMATION IS AVAILABLE IN REPORTS OF BUREAU OF PUBLIC ROADS

Item	1925	1926	1927	1928	1929	1930	1931 ^a	1932 ^a
1. Fines, fees, tolls, permits, etc.....	\$511	\$388	\$239	\$1,732	\$181	\$1,790	\$7,407	\$8,091
2. Amounts indicated as refunds for work performed and other amounts representing a reduction of cost of high-ways, such as railroad participation, sale of material, cash discounts, equipment and garage rentals, etc.....	7,514	5,460	2,550	2,951	3,728	4,004	7,193	7,721
3. Interest received on deposits.....	471	854	1,109	264	1,440	2,246	1,503	1,289
4. Miscellaneous receipt, transfers, etc., not identified with users or constr.....	835	2,743	5,808	2,500	1,380	4,533	1,886	4,581
Total.....	9,331	9,445	9,706	7,447	6,729	12,573	17,989	21,682
Per cent item 2 of total.....	80.52	57.80	26.27	39.63	55.40	31.84	59.80	52.12

B—DETERMINATION OF ITEM (2) BY YEARS ON BASIS OF AMOUNTS REPORTED PLUS A PORTION OF AMOUNTS NOT SEPARATELY REPORTED, ON BASIS OF PROPORTIONS FOUND IN (A)

Year	Reported	Total not detailed	Proportion allocable to Item 2		Total item
			Per cent	Amount	
1921	.....	\$7,237	b 45.64	\$3,303	\$3,303
1922	.....	8,236	b 45.64	3,759	3,759
1923	.....	15,498	b 45.64	7,074	7,074
1924	.....	13,850	b 45.64	6,093	6,093
1925	\$7,514	5,721	80.52	4,606	12,120
1926	5,460	3,779	57.80	2,185	7,645
1927	2,550	2,816	26.27	739	3,289
1928	2,951	5,165	39.63	2,047	4,998
1929	3,728	4,998	55.40	2,769	6,497
1930	4,004	4,511	31.84	1,436	5,440
1931	7,193	3,155	59.80	1,886	9,079
1932	7,721	4,240	52.12	2,210	9,931
Total	\$41,121	\$78,706	.....	\$38,107	\$79,228

^a Tolls received by the State of New Jersey in 1931 (\$5,961,348 and 1932 (\$6,868,140) from the Port of New York Authority and the Delaware River Joint Commission are disregarded in the apportionment of amounts not separately reported.

^b Item (2) as adjusted, 1925 to 1932..... \$58,999
Total miscellaneous income, 1925 to 1932..... 129,286
Per cent item (2) to total miscellaneous income 45.64

APPENDIX E
STATE MOTOR-FUEL TAX RECEIPTS, 1921-1932
 Source: Annual reports G-1, of Bureau of Public Roads

Year	Gross receipts less refunds (all states)	For states reporting complete data			For states not reporting collection and administration cost		Total collection and administration cost (all states)	Net receipts (gross receipts less refunds, and collection and administration costs)
		Gross receipts less refunds	Collection and administration costs		Gross receipts less refunds	Collection and administration cost estimated		
			Amount	Per cent of gross receipts				
1	2	3	4	5=4+3	6=2-3	7=6×5	8=4+7	9=2-8
1921	\$5,382,111	.....	.....	a .272248	\$5,382,111	\$14,653	\$14,653	\$5,367,458
1922	12,703,078	.....	.....	a .272248	12,703,078	34,584	34,584	12,668,494
1923	38,566,338	.....	.....	a .272248	38,566,338	104,996	104,996	38,461,342
1924	80,442,295	.....	.....	a .272248	80,442,295	219,003	219,003	80,223,292
1925	148,858,087	\$79,851,186	\$217,393	.272248	68,506,901	186,509	403,902	147,954,185
1926	187,603,231	104,323,120	294,066	.281880	83,280,111	234,750	528,816	187,074,415
1927	258,838,813	168,245,481	573,693	.340986	90,593,332	308,911	882,604	257,956,209
1928	304,871,766	212,245,600	744,134	.350600	92,626,166	324,747	1,068,881	303,802,885
1929	431,811,519	330,868,880	857,703	.259227	100,442,639	260,374	1,118,077	430,193,442
1930	493,865,117	396,102,731	1,316,199	.332287	97,762,386	324,852	1,641,051	492,224,066
1931	536,397,458	492,403,493	2,331,669	.473528	43,993,965	208,324	2,539,993	533,857,465
1932	513,047,239	460,802,294	3,028,153	.657148	52,244,945	343,327	3,371,480	509,675,759
Total	\$3,011,387,052	\$2,244,842,785	\$9,363,010	.....	\$766,544,267	\$2,565,030	\$11,928,040	\$2,999,459,012

a No collection and administration costs being reported for the years 1921 to 1924 inclusive, the average for 1925 was here used.

APPENDIX F
STATE MOTOR VEHICLE RECEIPTS, 1921-1932
 Source: Annual reports MV-2, of Bureau of Public Roads

Year	Gross receipts (all states) ¹	Refunds	Gross receipts less refunds (all states)	For states reporting complete data			For states not reporting collection and administration costs		Total collection and administration cost (all states)	Net receipts (gross receipts less refunds, and collection and administration costs)
				Gross receipts less refunds	Collection and administration costs		Gross receipts less refunds	Collection and administration cost estimated		
					Amount	Per cent of gross receipts				
1	2	3	4=2-3	5	6	7=5+6	8=4-5	9=8x7	10=6+9	11=4-10
1921	\$122,478,864	.....	\$122,478,864	.....	.....	a 6.827850	\$122,478,864	\$7,750,268	\$7,760,268	\$114,728,888
1922	152,047,824	.....	152,047,824	.....	.....	a 6.827850	152,047,824	9,621,358	9,621,358	142,426,466
1923	188,970,992	.....	188,970,992	.....	.....	a 6.827850	188,970,992	11,967,801	11,967,801	177,018,191
1924	225,492,252	.....	225,492,252	.....	.....	a 6.827850	225,492,252	14,268,811	14,268,811	211,223,441
1925	260,819,621	\$412,696	260,206,925	\$284,105,973	\$14,818,875	6.827850	26,100,952	1,651,629	16,465,504	248,741,421
1926	289,282,852	45,801	289,236,551	240,353,799	15,892,875	7.024678	47,902,752	3,865,014	20,247,689	267,988,862
1927	301,061,132	138,454	300,922,678	258,574,518	14,876,410	5.866682	47,848,160	2,777,768	17,654,176	289,268,502
1928	322,630,025	62,583	322,577,442	277,536,727	15,178,999	5.469186	46,040,715	2,463,360	17,642,359	304,935,083
1929	347,843,543	248,131	347,595,412	314,902,390	17,402,798	5.526410	32,698,022	1,806,750	19,209,548	328,385,864
1930	365,704,860	185,587	365,519,273	321,084,542	19,196,926	5.978776	34,434,731	2,058,775	21,255,701	384,263,572
1931	344,337,654	107,470	344,230,184	318,181,389	21,516,119	6.762218	26,048,795	1,761,478	28,277,595	320,952,589
1932	324,278,510	216,352	324,052,158	303,175,225	19,690,116	6.494632	20,879,933	1,356,075	21,046,191	308,006,967
Total	\$3,233,742,419	\$1,409,074	\$3,232,333,345	\$2,262,894,563	\$189,557,918	.....	\$969,438,782	\$60,839,081	\$200,896,999	\$3,031,936,346

¹ No collection and administration costs being reported for the years 1921 to 1924 inclusive, the average for 1925 was here used.

APPENDIX G

A DISCUSSION OF FORMULAS FOR DESIGN OF RIGID PAVEMENTS

In this report the corner formula is used to establish the relation between wheel load and thickness of concrete pavement required. This formula as given on p. 60 has the following form:

$$t = \sqrt{\frac{3W}{f}}$$

where t = thickness of pavement
 W = wheel load
 f = allowable fiber stress in tension.

This formula assumes (a) that the slab receives no support from the subgrade for some distance back from the corner and (b) that the wheel load is applied at the extreme corner of the pavement slab. The distance of non-support is of no significance under the above assumptions, because this distance does not appear in the formula. Under these conditions the load-supporting capacity of the slab may be obtained by assuming it to act as a simple cantilever, and then applying the accepted laws of mechanics. As, in any such formula, the accuracy of the results depends upon the accuracy of the assumptions made in its derivation, (a) and (b) will be further discussed.

Two conditions that apply in the case of actual pavements confirm the correctness of the first assumption which presumes that immediately under the load the slab may frequently receive no support from the subgrade. The first of these conditions is due to the fact that pavements warp or curl, due to unequal temperatures in the top and bottom surfaces. Thus when the top surface cools at night the edges and corners curl upward to such an extent as to be entirely out of contact with the subgrade.¹ Exactly the same effect occurs when the exposed top of the slab dries out more rapidly than the bottom, the bottom being more protected as regards the evaporation of contained moisture.

The second condition is due to the fact that while a subgrade may possess distinct elastic properties, the elastic limit may be so low as to be greatly exceeded by the pressures imposed upon it where the deflection of the slab under load is greatest. If the pressure at and surrounding this point exceeds the elastic limit of the subgrade a permanent depression of the subgrade is inevitable and there is a separation between slab and subgrade when the load is released or passes on. This condition obviously applied in the case of the Spangler tests described in the Proceedings of the 15th Annual Meeting of

¹ See Bulletin Numbers 18 and 21, State of Illinois, Department of Public Works and Buildings.

the Highway Research Board.³ When the separation due to warping is added to the permanent depression caused by load, even the maximum load may not produce contact between the slab and the subgrade at a point or area under the load.³ It then becomes obvious that assumption (a) of the corner formula actually applies for the pavement slabs in service.

Assumption (b) that the load is applied to the mathematical corner is not strictly true, since when wheels are equipped with pneumatic tires the center of the area of load application may be near but never exactly at the corner when the full load is on one slab. When a load is applied at a distance from the corner, the stress is less than that indicated by the corner formula by an amount depending upon the relative distances of the load and the actual line of support from the mathematical corner. For example, if the center of the load is 4" from the corner and the line of support is 24" from the same point, the error is about 17 per cent. If the load is in the same position and the line of support is 36" from the corner, the error is only about 11 per cent.

As corner breaks almost always appear at distances of from two to three and one-half feet from the corner, the error may normally be assumed to be substantially less than 17 per cent and, in any case, *it is always on the safe side*. In other words, it theoretically introduces a small factor of safety.

In the application of the Westergaard and Spangler formulas, the actual position of the load is used, but it is assumed that the subgrade support at any point is in proportion to the slab deflection at that point. Or, expressed differently, that at the mathematical corner (in the case of corner loading) the subgrade support is greater than anywhere else. It has been shown, that for the critical condition caused by frequent warping, this cannot possibly be true and the condition is made worse in any case where the elastic limit of the subgrade has at any time been exceeded. The error due to this cause *is always on the dangerous side*. This is confirmed by the Spangler tests in which the observed maximum stresses were about 42 per cent and 55 per cent in excess of the maximum computed in accordance with Westergaard.⁴ Similarly in a later study of a slab in which warping was prevented,⁵ Spangler found that the corner formula gave a stress 46

³ Spangler conducted tests on 10' x 12' slabs 6" thick on an artificial clay foundation. The experiments were conducted in the basement of a building under ideal conditions. Static loads were applied through circular loading blocks and stresses computed from strain measurements at different points near the corner of the slab. From his experimental data and using the Westergaard approach, Spangler developed formulas for maximum probable stress due to corner loadings.

⁴ See Figure 3 of Bulletin Number 18, State of Illinois, Department of Public Works and Buildings.

⁵ See figures 17 to 19 in Spangler's paper (Proc. 15th Annual Meeting Highway Research Board) from which relationships of the corner, Westergaard and Spangler formulas with respect to test results, may be derived.

⁶ Proceedings 17th Annual Meeting Highway Research Board, 1936, p. 222.

per cent higher than the highest stress found experimentally, and that Westergaard method gave a stress 10 per cent lower.

From the above, we conclude that the simple corner formula should be used in preference to the Westergaard formula because it is the one that has exerted the greatest influence upon actual design and it is also decidedly more representative of the conditions that apply in the actual road slab.

APPENDIX H

THE FACTOR OF IMPACT IN HIGHWAY DESIGN

If there is no source of impact inherent within the vehicle itself there can be no impact effect providing the road surface presents no irregularities. Some years ago the Illinois Highway Department started an elaborate experimental investigation, *not of impact forces* but of the *stress effect of impact forces* upon the pavement slab itself. The distinction is very important. This series of tests resulted in the conclusion "that no allowance for impact need be made in the design of a pavement, the nature of which makes practicable the construction and maintenance of a reasonably smooth surface."¹ During the years 1924 and 1925, another series of investigations of the same nature was undertaken by the Illinois Highway Department which were reported in 1931 in "Illinois Division of Highways," "Reports of Investigations" Volume I by V. L. Glover, Engineer of materials. The results of this later investigation may be summed up in the words of a paragraph heading on page 30 which reads as follows: "Impact on Illinois Pavements a Negligible Quantity." It is of particular interest to note that all of the Illinois tests were made with solid rubber tire equipment and it is well known that pneumatic tires cause less impact than solid tires under otherwise equal circumstances. If no impact allowance be required for solid tires surely none is needed for pneumatic tires.

James A. Buchanan, Associate Engineer of Tests, U. S. Bureau of Public Roads, in an article entitled "Impact Reactions Developed by a Modern Motor Bus"² states: "So far as these tests have indicated, the impact forces developed by balloon and high pressure tires do not reach dangerous proportions as long as the surface is reasonably smooth and designed for the wheel loads involved." The words "designed for the wheel loads involved" as used in this connection can only mean the static wheel loads. It is of particular interest to note that this statement includes high pressure tires.

In more recent tests³ Buchanan found that impacts of 1.1 to 1.2 times the static wheel load might be expected occasionally (from 0 to 140 times per mile) with balloon tires on smooth pavements of cement concrete or bituminous materials. In these tests, however, the impact was obtained indirectly from accelerations measured on the vehicle. The actual stresses induced in the pavements were not measured.

Due to the fleeting character of highway loads and the inertia of

¹ Highway Research in Illinois, by Clifford Older, Transactions American Society of Civil Engineers, Volume LXXXVII, page 1222.

² "Public Roads," April 1931.

³ Road Impact Produced by a Heavy Motor Bus, "Public Roads," November 1932.

the pavement and foundation, the stresses developed under moving loads are probably less than those induced by an equivalent static load. Westergaard recognized this possibility and included it among the limitations to his formulas for design.⁴

A clear distinction should be made between the term "impact" and the effect of a suddenly applied load. Impact may be described as the blow which is experienced when a moving body expends some of its energy by suddenly striking an object. A load may be suddenly applied without impact when a body moving in the same plane with its weight supported on a smooth surface passes quickly from one place to another, as from one pavement slab to another. It is a recognized principle of mechanics that a load suddenly applied may double the stresses set up within the supporting member; but here again in the case of pavements the fleeting character of the wheel load (like a person skating on ice) develops stresses which are probably less than those induced by an equivalent static load.

On flexible pavements the time of duration of the load will have an even greater effect on the stresses imposed than for rigid types. A static load of a given amount standing on a flexible pavement might cause deformation of the surface, whereas the same load, passing rapidly over the surface, would be gone before deformation had time to occur. In such a case the static load would be more severe than the moving load. The relative effect of dynamic and static loads on flexible pavements is now being studied by European and American engineers.⁵ Due to their flexible nature, these surfaces are able to absorb a considerable impact force due to irregularities without permanent injury.⁶

In actual practice some engineers have advocated a percentage allowance for impact (frequently 50 per cent) and others have made no allowance for impact in design. There are excellent reasons why a factor of 1.5 should be applied to the wheel load for design purposes. In concrete pavements, for example, there are always transverse joints or cracks over which wheel loads pass suddenly from one slab to the next. Loads suddenly applied and then left upon any elastic support momentarily cause twice the effect of the static load. Glover found by experience that this effect for rolling highway loads was about 1.5 instead of 2. The existence of this effect probably accounts for the fact that many concrete pavements have failed, although the Westergaard and even the Corner formula indicate that they should not have failed under the wheel loads permitted by them.

In establishing ratios of thickness for the allocation of costs, the result will be the same whether or not a percentage is added to the static wheel load for a suddenly applied load.

⁴Stresses in Concrete Pavements Computed by Theoretical Analysis, "Public Roads," April 1926, p. 35.

⁵Present Knowledge of the Design of Flexible Pavements, "Public Roads," January 1938.

⁶Effect of Pavement Type on Impact Reaction, "Public Roads," August 1928.

APPENDIX I

DISCUSSION OF FORMULA FOR DESIGN OF FLEXIBLE PAVEMENTS— EXTRACT FROM ASPHALT POCKET REFERENCE FOR HIGHWAY ENGINEERS

The formula $t = \sqrt{\frac{W}{\pi s}} - e$ for the design of the thickness of flexible type pavements is given in Fig. 2 of the body of this report together with a graphical representation of the assumptions upon which it is based. The terms have the following meaning:

- t = thickness of pavement in inches
- W = wheel load in pounds
- s = bearing power of the subgrade in pounds per square inch
- e = radius (in inches) of the circle over which the wheel load is assumed to be distributed.

This formula does not mathematically demonstrate that the thickness of a pavement varies directly as the square root of the wheel load, because there are two terms in the right-hand side of the equation; the first term obviously does vary as the square root of the wheel load (since π and s are constants for a given subgrade) but the second term ($-e$) is not under the square root sign. Actually, e which increases as the wheel load also varies approximately as the square root of the wheel load. For example, a wheel load of 2,000 pounds often has a tire with a contact area of about 34 sq. in., which is equivalent to a circle of radius 3.3 inches. A wheel load of 7,500 pounds often has an area of contact of about 79 sq. in. which is equivalent to a circle of radius 5.0 inches. In other words, when the wheel load is increased about four times the value of e does not quite double. The above discussion is based upon single tires for both 2,000 and 7,500 pound wheel loads, which is consistent with the assumption in the formula that the load is distributed over a circle. If dual tires are used the same relationship will apply.

Since s also varies substantially as the square root of the wheel load, then both terms on the right-hand side of the formula vary as the square root of the wheel load, and the application of the formula over the normal range of wheel loads will result in a thickness proportional to the square root of the wheel load.

This is demonstrated below where the formula is applied to bituminous types with appropriate values substituted for s in Fig. 23 reproduced from "Asphalt Pocket Reference for Highway Engineers." (See below.) This diagram shows that for any given subgrade support a wheel load of 8,000 pounds requires twice the thickness of pavement required for a 2,000-pound wheel load. For example, Fig. 23 shows

that if the subgrade support is 10 lbs. per square inch, the thickness required for a 2,000-lb. wheel load is about 5" and for a 8,000-lb. wheel load it is about 11"; similarly, for subgrade of 30 lbs. per square inch the relative thicknesses of pavement are about 2" and 4". This supports the square root relation, because when the load is quadrupled the thickness requirement is approximately doubled. The square root of the wheel load relation is therefore substantiated and recommended for design by one of the leading authorities in the bituminous pavement field.

The complete Chapter VII on "Design of Asphalt Pavements" from the Asphalt Institute's "Pocket Reference for Highway Engineers" is reproduced below.

"VII. DESIGN OF ASPHALT PAVEMENTS

"129. FLEXIBILITY AND RIGIDITY.—Bituminous pavements are classified generally as 'flexible surfaces.' Actually it is possible to build asphaltic concrete and similar types so as to behave like rigid pavements, but this is not desirable because a slight yielding to meet the changing conditions of temperature and traffic is a distinct advantage in providing for greater durability and lower maintenance.

"There are two approaches to the rational design of pavements. In the rigid type it has been assumed that by constructing a slab having high tensile strength, all weak areas in the subgrade would be bridged and the load thus transferred to stronger adjacent support. Cracking occurs when this support is not provided, and in a sense it is like designing a bridge without information as to location of the piers and abutments. In the flexible type it is assumed that the pavement will be always in continuous intimate contact with the subgrade and that the load will be transmitted to it in a substantially uniform manner without the concentration which occurs under bridging action.

"There has been some misunderstanding in regard to the manner in which loads are transmitted through flexible pavements to the subgrade. When a load is applied to such surfaces through a bearing area, there are two fundamental resistances developed; one, perimeter-shear which is a function of the length of perimeter of the bearing area, and second, internal compressive resistance which is a function of the area involved. As the load is applied and for surface deflections of minor character (.00 to .05 inches), resistance to perimeter-shear develops rapidly. This rate of increase in shear resistance with small deflections may be so great that there will be a negative moment under the center of the bearing area. As loading increases, resistance due to compression becomes a factor and further deflection is opposed by the combined effect of both perimeter-shear and the pressure resistance developed in the body of the pavement. In turn, lesser intensity loads are distributed to the base and subgrade; lesser because

applied over a greater area, and because of an irregular area of loading as contrasted with the area of tire contact.

“It is evident that the ability to transmit loads most efficiently (through high shear values) will thus depend:—upon the density of surface and base, upon a high degree of internal friction between

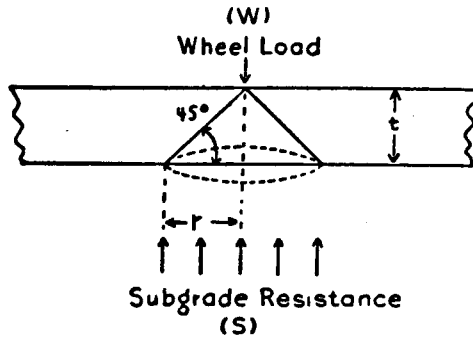


FIG. 21. DISTRIBUTION OF SURFACE LOADS THROUGH FLEXIBLE PAVEMENTS

particles or a combination of the two. The duration of load application is of great importance, as the shorter the period the more nearly does any surface behave like a completely elastic substance. This means that dynamic resistance usually outweighs any actual impact forces, and that a design which contemplates static load conditions will be entirely adequate for these same loads in motion. This has great bearing in highway and airport design where loads are fleeting in character.

“From these premises it is thus possible to proceed to a mathematical determination of thickness requirements.”

“130. DISTRIBUTION OF LOADS.—A static load applied to the surface of a stable, flexible pavement is distributed downward in a conoidal fashion. The boundary of this pressure cone is a surface which in cross-section is defined by the limiting angle of pressure distribution. This angle varies with the depth and with the applied load, but in regions of low stress (at bottom of pavement) approaches a slope of 2 to 1 (horizontal to vertical). For all practical purposes it is sufficient to assume this angle as 45° , and the area over which pressure is applied as a circle having a radius equal to the pavement depth. (See Fig. 21.) Pressure distribution over the base or subgrade while not absolutely uniform, may be so assumed for purposes of calculation and an adequate margin of safety to care for this variation will be provided by increasing the subgrade support 50% above that theoretically required.

“It is evident therefore that the pavement thickness must be sufficient to provide distribution of load over a large enough area of sub-

grade so that its total resistance shall not be exceeded. To have equilibrium the following equation is obvious.

$$W = \pi r^2 S$$

In the 45° triangle $r = t$

$$\therefore W = \pi t^2 S$$

$$\text{and } t = .564 \sqrt{\frac{W}{S}}$$

Where

t = thickness of pavement in inches.

W = wheel load in pounds.

r = radius of circle of load distribution (inches).

πr^2 = area of circle of load distribution.

S = subgrade resistance in pounds per sq. in.

“This equation assumes application of load at a point, whereas actually it is applied over an area, this area depending upon the number and kind of tires, and their contact area when under load. The effect is to develop a higher resistance to shear and to distribute the load over a greater area of subgrade. This increased shear value and greater distribution of load exists up to a certain critical area, which is approximately 100 square inches. However, as this is about the maximum area of the tire contact under the heaviest truck loads, it is to be noted that the usual highway traffic is of a kind most favorable for development of the maximum bearing value in soils. (See Fig. 22.)

“The minimum required thickness is thus reduced as shown in the following equation:

$$W = \pi r^2 S$$

In the large 45° triangle $r = t + e$

$$\therefore W = \pi (t + e)^2 S$$

$$\text{or } t = .564 \sqrt{\frac{W}{S}} - e$$

where e = radius of tire area contact

“Fig. 23 shows the required thickness of pavement with relation to subgrade support..

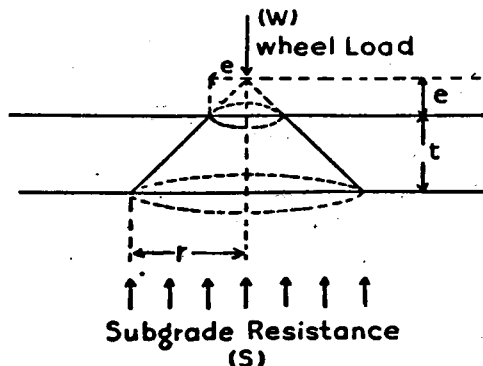


FIG. 22. EFFECT OF TIRE CONTACT ON LOAD DISTRIBUTION

“Subgrade resistance varies according to changes in moisture, and pavement thickness should be designed therefore for the most adverse condition, which is usually during early spring. Any soil at its optimum moisture content has a resistance sufficient to carry the highway load, and as reduced support comes usually from too much moisture, the first item in subgrade design is to provide adequate drainage. No matter what it costs to drain a roadbed properly, it is the cheapest method for insuring maximum subgrade support. Corrugated iron pipe or clay tile for culverts and seepage drains are both inexpensive, efficient and highly durable, while proper side ditches and an elevated roadbed should be obtained wherever possible, so as to lower the ground water level.”

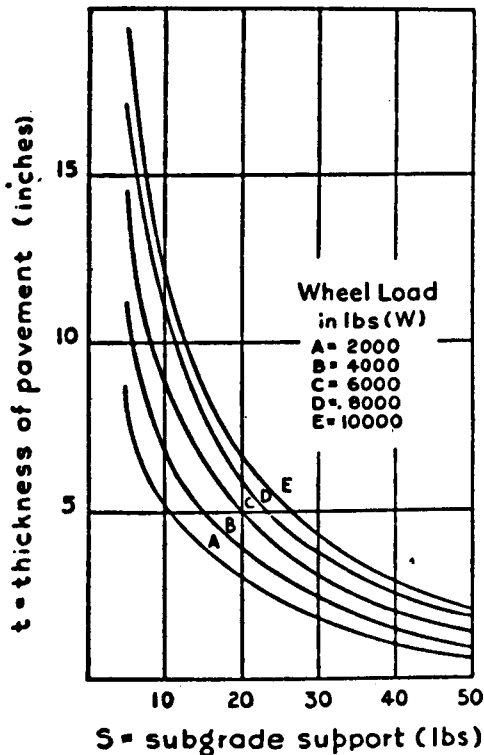


FIG. 23. THICKNESS OF PAVEMENT WITH RELATION TO SUBGRADE SUPPORT

“131. RELATION OF SUBGRADE TO DESIGN.—The design of flexible pavements thus includes two elements—the pavement itself and the subgrade upon which it rests. Economy in design can be obtained either by varying the pavement thickness according to the

natural subgrade support or by increasing the subgrade resistance through admixture of low cost aggregate, chemicals, bituminous products* or combination thereof. Selected cheap local materials may be used to construct a course between subgrade and base. Such materials as sand-clay, disintegrated granite, tuff and pit-run gravel are employed. As a practical matter it is best practice to bring the subgrade to a uniform condition over the entire road length, so that pavement thickness will be uniform throughout and construction procedure simplified. The admixture of as little as 2 inches of stone screenings or sand to a subgrade will often change its support value from 10 lbs. to 20 lbs. or more per sq. in. thereby markedly reducing the required pavement thickness. Such possibilities are all too frequently overlooked, largely because evaluation of subgrade often is made by guess instead of by measurement. For example, from Fig. 23 it will be noted that for a 25 lb. subgrade, and a 10,000 lb. wheel load, a pavement thickness of a little over 5 inches is required, while for a 10 lb. subgrade and a 50 lb. subgrade and the same load, 12 inches and 2 inches respectively are required.

“For various types of asphalt pavements, there is usually a given thickness which is most economical to construct, by reason of either the aggregate particle size available from commercial production, or the limitations of equipment manipulation. Thus in penetration macadam, 2½ inches to 3 inches depth is best because stone can be prepared most efficiently in these sizes and asphalt can be forced into the voids in a satisfactory manner. Asphaltic concrete can be thoroughly consolidated in layers up to 4 inches depth for coarse mixes and 3 and 2 respectively for finer mixtures. Road-mix surfaces can be mixed thoroughly and spread and rolled efficiently in depths up to 3 inches, while surface treatments can be handled in amounts up to one inch depth.

“An asphalt pavement is thus designed from the surface downward, first selecting the wearing course, next the base, and finally, bringing the subgrade up to the required support. The base thickness should be determined by balancing the cost of its increased depth against the cost of raising subgrade support. Usually the base thickness is determined by the minimum thickness to which it is practicable to build it, as it is almost invariably true that it is cheaper to increase the subgrade support. For example, 4½ inch waterbound macadam base is an economical depth to construct in one layer, and would be generally employed. It is deep enough to use commercially available stone to advantage, and to be closely keyed together so that no weak area can develop. In combination with a 2½ inch penetration wearing course, it then becomes a simple matter to determine the amount of subgrade stabilization required. As a factor of safety, this subgrade support should be made approximately 50% above that shown in the table. Thus for the 7 inch pavement depth, under a

* See Public Roads, May, 1936.

10,000 lb. wheel load, a subgrade support of 20 lbs. is indicated. It should be brought up to 30 lbs.

“The design of cross section for flexible pavements is also different from rigid pavements and, while a thickened edge is desirable for certain types of cold-laid mixtures and surface treatments, this is to prevent the entry of water between base and wearing course, rather than to give added support. The pavement thickness should be uniform and, if there is more danger of loss of subgrade support at the outside of a pavement, the remedy is to increase it at such points, rather than to thicken the pavement. It is necessary, however, that the base be of sufficient width so that a load applied at the edge of the surface course may be transmitted to the subgrade. This increased base width on each side should be at least equal to its depth, and as a matter of practice seldom should be less than 12 inches. The shoulder material should be brought over this widened base, so that traffic will be confined to the surface only.”

“132. BASES AND SURFACE COURSES.—The pavement proper is usually constructed in two layers, the lower layer called the base and the upper layer the surface course. This is done largely for the purpose of economy as, while the surface of a road must resist abrasion and the entry of water, the lower portion only needs to supply stability under distribution of traffic load. The relative thickness of base and surface course should be determined according to available aggregate, climate and traffic condition. As a rule the principal differences are the use in the base of larger size aggregate, a lesser volume of asphalt or both. For example, sand-asphalt uses the same aggregate but a leaner mixture for the base course, while asphaltic concrete bases contain both larger aggregate and less asphalt.

“Sometimes the base course is composed entirely of non-bituminous materials, such as waterbound macadam, portland cement concrete or sand-clay mixtures. (See Chapter X.) Macadam bases are employed under all types of surface but particularly penetration macadam and cold-laid mixtures. Sand-clay, limerock and similar bases are usually covered with heavy surface treatments.”

“133. TYPICAL CROSS SECTIONS.—A base thickness greater than 6 inches is rarely required, as it is usually possible to increase the subgrade resistance even under most adverse conditions to at least 25 lbs., for which value a total pavement thickness of 5 inches is sufficient. The surface course thickness is controlled largely by construction requirements, which include size of aggregate employed, and character of spreading and finishing operations. Mixed surface courses are usually $1\frac{1}{2}$ to 2 inches thick when using sand and 2 to $2\frac{1}{2}$ inches when using coarser aggregates, while for penetration macadam $2\frac{1}{2}$ to 3 inches is required. As a general rule the base should be thicker than the surface course as more complete balance is thereby obtained. Some typical cross sections for different types, as shown in Fig. 24, will indicate these relationships.”

“134. RELATION OF TRAFFIC TO TYPE AND DESIGN.—
 The several sections in Fig. 24 are not interchangeable for all conditions of traffic and climate, and there is thus brought in the selection of type for a given situation as the final item in design. In such selection, probable traffic changes within the expected pavement life should be appraised, after careful traffic surveys, and plans provided for additional pavement thickness as required. This latter procedure is termed stage construction, and often makes for great economy because of the very large difference in the traffic load upon the several classes of highways. The 10,000 lb. wheel loads are confined largely to city streets and trunk lines, and pavements thereon should be designed accordingly. Secondary and third class roads seldom have wheel loads exceeding 4,000 lbs. (a five ton truck) and, whereas for a 25 lb. subgrade a pavement thickness of 6 inches or more is required for the heaviest loading, one-half that amount is sufficient on the secondary roads.



1" hot surface treatment on
 8" limerock base



2" macadam road-mix top on
 6" gravel base



2½" penetration macadam top
 4½" waterbound macadam base



2" asphaltic concrete top on
 3" asphaltic concrete base



1½" sheet asphalt top
 1½" asphalt binder course
 6" p.c. concrete base



1½" sheet asphalt top
 3½" asphaltic concrete base

FIG. 24. TYPICAL SECTIONS

“Thus surface treatments and road-mixes would be used for the lighter traffic situations, with asphaltic concrete, sheet asphalt and penetration macadam for heavy traffic. The selection of type within each group is largely a matter of aggregate availability rather than difference in durability. In the south where sand-clay and limerock are available, very strong bases may be constructed cheaply, and the hot asphalt surface treatment is all that is required to take abrasion and distribute the traffic load. Where excellent trap rock abounds, penetration macadam is the logical choice and similarly for coastal areas and sand mixes would be most economical, with stone or gravel types in more inland locations.

“In some cases purely local aggregates are not strong enough in themselves for a given type but are the only ones available. It has been learned that often a very small amount of imported aggregate will correct the deficiency and permit the use of local aggregates in mixtures, after first determining proportions as a result of a series of tests with the stability machine. (See 86.) Often soft stone or gravel will be substantially toughened after coating with asphalt and make satisfactory bases, while in an untreated condition they would not be suitable. Such potentialities may be developed through proper laboratory studies, which are all too often overlooked.”

“135. SURFACE TEXTURE.—In recent years much attention has been given to the non-skid character of pavement surfaces, with a marked tendency toward the construction of quite open coarse textures. This trend was emphasized until many wearing courses were being laid which were extremely porous. Recent exhaustive studies at Iowa State College have conclusively shown that the sand-paper finish usually present on sheet asphalt or asphaltic concrete has the highest coefficient of friction of all pavements. The action of balloon tires now produces a tearing action in place of the kneading action of the old hard tires, and there is now little tendency to close a pavement surface for which allowance need be made. In view of the fact that a dense surface is the most waterproof and durable, all open or porous texture surface courses should be finished with a thin but rich seal coat covered with fine aggregate. One-tenth to one-quarter gallon asphalt per square yard covered with a slight surplus of sand cover will usually be sufficient. Hot-mix surfaces and penetration macadam are exceptions as they carry such a heavy asphalt content as to be completely waterproof without sand asphalt seal coats. (See Chapter VIII.)

“One current practice in finishing sheet asphalt is definitely harmful; that of applying a dust cover to the finished surface. This cover serves no useful purpose, fills the voids between the sand grains of the surface and often covers defective construction procedure. Its requirement in specifications is a carry-over from the past when plant control was less efficient and, under no circumstances, should it be now permitted.”

“136. EDGE PROTECTION.—The practice of building portland cement concrete edging for rural asphalt pavements is not only a wasteful extravagance but also is detrimental to the pavement itself. This does not apply to urban and suburban curb and gutter construction which is an entirely different matter—where the curb is required for drainage control and sidewalk support. Except for curb and gutter construction portland cement concrete edging should be omitted. It adds nothing to the strength of the pavement and is certain to separate from it, thus permitting entry of surface water as well as retaining ground water which would otherwise drain off at the sides. Its cost is so high that either the asphalt pavement proper may be widened several feet or the entire shoulders may be of low cost asphalt construction such as surface treatment, road-mix or plant-mix for less than the cost of the edging.”

APPENDIX J

THEORETICAL ANALYSIS OF RELATION BETWEEN WHEEL LOADS AND THICKNESS OF FLEXIBLE PAVEMENT REQUIRED¹

In approaching the problem of the relation between wheel loads and the required thickness of flexible pavements, from a purely theoretical view point, one naturally turns to the classical theory of load transmission developed by Boussinesq in 1885. According to this theory, if a load P is applied at a point on the surface of a supporting material, it will produce stresses within the material according to the following equation:

$$q = \frac{3}{2\pi} \frac{P}{z^2} \cos^3 \theta$$

wherein q is the vertical stress at any point within the material whose position is determined by its depth z , and the angle, θ , between the vertical and a line connecting the given point with the point of load application. See Fig. 1.

The ideal material which Boussinesq had in mind when developing this theory would be best represented by a large block of steel. However, its application to other solids and to soils has given results which in general show at least a rough check with actual measurements; frequent use is made of the above formula for approximate determinations of pressures in soils.

Application of this equation is extremely simple. Assume a load of 1,000 lbs. on the surface of a pavement 8" thick. The stress on the subgrade directly under the load would be

$$\frac{3}{2\pi} \times \frac{1000}{82} \times 1 = 7.46 \text{ lbs. per sq. in.}$$

The stress 6" out from this point would be $\frac{3}{2\pi} \times \frac{1000}{82} \times \left(\frac{4}{5}\right)^3 = 2.44$ lbs. per sq. in.

Proceeding in this fashion to other points, a complete picture of the stress on the subgrade can be obtained, as shown in Fig. 2. Now suppose that the load is increased to 4000 lbs. A glance at the equation shows that the stress at every point on the subgrade would be quadrupled, the maximum becoming 29.84 lbs. per square inch. Or, in general, the intensity of stress increases directly with load.

Next assume that the character of the subgrade is such that the stresses produced by the thousand-pound load are about as much as the subgrade can stand. The quadrupled stresses under the

¹Prepared with the advice of Dr. Glennon Gilboy, Associate Professor, and Mr. D. W. Taylor, Assistant Professor of Soil Mechanics, Massachusetts Institute of Technology.

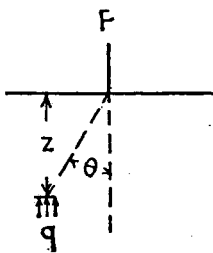


Fig. 1

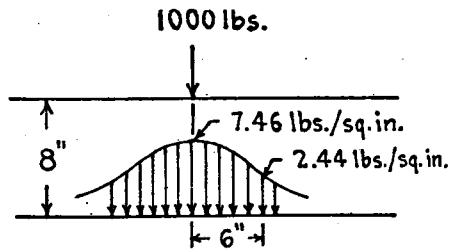


Fig. 2

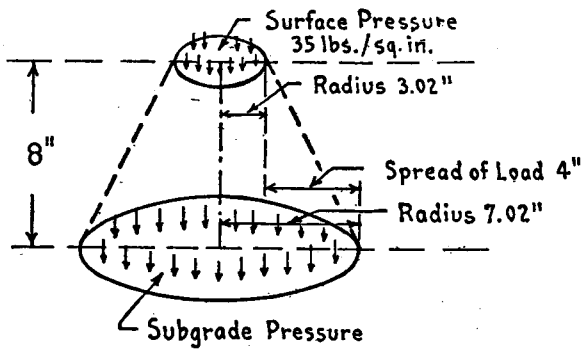


Fig. 3

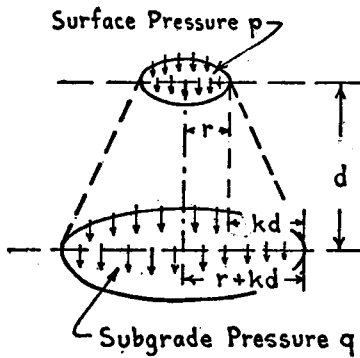


Fig. 4

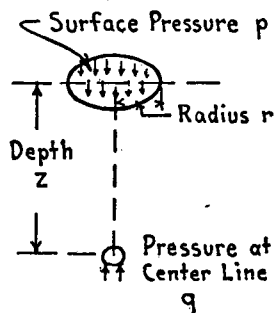


Fig. 5

4000-lb. load would, therefore, be expected to produce failure. The next question is: How much thicker should the pavement be to support the 4000-lb. load? The equation shows that if P is quadrupled, z must be doubled to obtain the same stresses. The pavement, therefore, should be 16 inches thick. Or, in general, the required thickness increases with the square root of the load.

The foregoing analysis has been based on a load applied at a mathematical point, which is, of course, a practical impossibility. A wheel load applied to a pavement is distributed over an area dependent on the characteristics of the tire. The next step is to investigate the effect of this distribution upon subgrade stresses. In particular, if tires were so designed and inflated that the 1000-lb. and the 4000-lb. loads of the previous example produced equal pressures per unit of area on the pavement, would not this equalization of surface pressure automatically produce equal stresses in the subgrade?

The answer to this question is not as easy to obtain as was the case with the point loads. However, a useful approximate solution can be developed by a method widely employed in the design of building foundations. This method consists of assuming the load to spread at a certain angle outward from the area of application, thus obtaining an average load intensity on any lower level. An illustration will make the method clearer than a mere detailed explanation.

Consider that the 1000-lb. load of the previous example is spread over a circular area such that the average pressure is 35 lb. per square inch. The area would then have a radius of about 3.02 inches. Assume a spread coefficient of $\frac{1}{2}$. Then at the bottom of an 8" pavement the radius would be 4" greater, or a total of 7.02 inches. The area of a circle of this radius is 154.8 sq. in. Dividing the load, 1000 lbs., by this area gives an average intensity on the subgrade of 6.46 lbs. per sq. in. as indicated in Fig. 3.

Now assume that this stress is about all the subgrade can stand, and work backward to find the thickness of pavement required for the 4000-lb. load. This load, at a pressure of 35 lbs. per sq. in., would be spread over an area of radius 6.04 inches. The radius of the subgrade area required to maintain an intensity of 6.46 lbs. per sq. inch would be 14.04 inches. Subtracting the two, the increment of radius produced by the spread would have to be 8 inches, corresponding to a pavement thickness of 16". Here again, quadrupling the total load requires doubling the thickness of pavement.

This result can be generalized by developing a simple formula. Let the average surface pressure be p , spread over a circle of radius r , and let the average subgrade pressure be q , over an area of radius $r + kd$, where d is the pavement thickness and k is the

co-efficient of spread. See Fig. 4. Since the total load is the same, the following relation must hold.

$$p \pi r^2 = q \pi (r + kd)^2$$

This can readily be transformed into

$$\sqrt{\frac{p}{q}} - 1 = \frac{kd}{r}$$

In this form, the equation is most instructive. If the surface pressure, p , is to be kept constant, an increase of total load merely means an increase in r ; quadrupling the load doubles r . Furthermore, if the subgrade pressure q , is to be held constant, the whole left-hand side of the equation is constant. Hence an increase in r must be exactly matched by an increase in d , *irrespective of any assumption made as to the value of k* . Thus the conclusion is again reached that, for equal surface and subgrade pressures, the thickness of pavement increases with the square root of the load.

It might be argued that the simple spread assumption just outlined gives results so far from the real distribution that no valid conclusions can be drawn. In fact, however, solutions more nearly correct mathematically lead to the same general relation. For example, S. D. Carothers in "Elastic Equivalence of Statistically Equipollent Loads," Proceedings of the International Mathematical Congress in Toronto (1924), Vol. II, p. 518, gives for the maximum stress intensity beneath a circular loaded area the expression:

$$q = -\frac{p}{2\pi} \left(\omega - z \frac{\partial \omega}{\partial z} \right)$$

where ω is the solid angle subtended by the loaded circle at the point and is equal to $2\pi \left(1 - \frac{z}{\sqrt{z^2 + r^2}} \right)$, and where r is the radius of the loaded circle, which, differentiated, becomes

$$\frac{\partial \omega}{\partial z} = -\frac{2\pi}{\sqrt{z^2 + r^2}} \left(1 - \frac{z^2}{z^2 + r^2} \right)$$

Calling compression positive and substituting the above values in the original formula, the expression becomes:

$$q = p \left[1 - \left(\frac{1}{1 + \left(\frac{r}{z} \right)^2} \right)^{\frac{3}{2}} \right]$$

the notation being as shown in Fig. 5.

Since the relation between r and z is a simple ratio, it is evident that for equal surface and subgrade pressures—i. e., p and q constants—any change in r produced by a change in total load must

be matched by an equal change in z ; and, since r increases with the square root of the load, z , or the depth of pavement, must also increase with the square root of the load.

As a measure of the degree to which the strength of the subsoil is taxed, a more fundamental quantity than the direct stress q which has been used above is the maximum shearing stress, s . The formula from the theory of Elasticity for this stress caused by a point load P when Poisson's ratio is 0.5 is

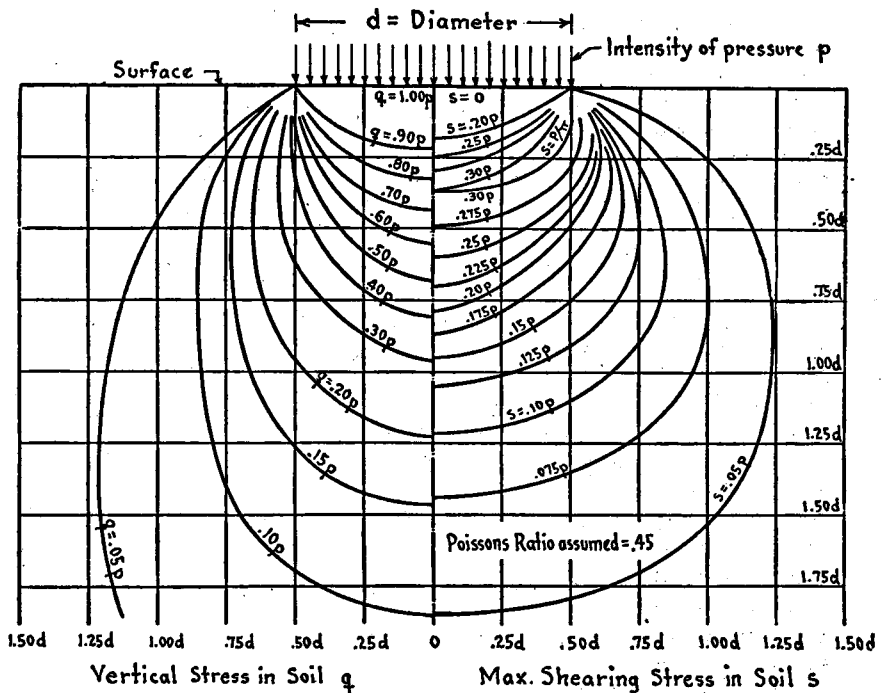
$$s = \frac{3}{4\pi} \frac{P}{z^2} \cos^2 \theta.$$

A comparison of this formula with that given for q (page 129) will show that the conclusion based on that formula also holds for s . Thus, if P is quadrupled, the depth at which a given value of maximum shearing stress occurs is doubled, or, z varies as \sqrt{P} . It can also be demonstrated that this same relationship holds under loads which are distributed over finite areas, also for any given value of Poisson's ratio and in addition, when the soil is not isotropic. However, the formulas for these more complex conditions are too involved to be presented here.

The distribution of direct stress q and maximum shearing stress s below a circular area has been investigated by Dr. Leo Jürgenson² and is shown graphically in Fig. 6. Curves connecting points having equal maximum shear s are shown in the right-hand side of the diagram. Similar curves connecting points of equal direct stress q are shown in the left-hand side of the diagram. Note that values of s and q are expressed as fractions of p , the pressure intensity on the loaded area, and the depth to any given stress is expressed in terms of d , the diameter of the loaded area. That is, the depth to any given induced stress is proportional to the diameter of the loaded area. For a constant intensity of pressure p , the total load $P = \frac{\pi d^2}{4} p$, from which it will be seen that for different total loadings, P is proportional to d^2 or conversely d is proportional to \sqrt{P} . Then since the depth to a given stress intensity is proportional to the diameter, it must likewise be proportional to the square root of the total applied load.

For example, if a load of 1000 lbs. is applied over a circle of diameter 8 inches, a direct stress of, say $q = .20 p$ will be induced at a depth of $1.22 d = 9.76''$ (See Fig. 6). If the load is increased to 4000 lbs. and p remains the same, the area of distribution will have to be increased 4 times. This is accomplished by doubling the diameter. For the same value of $q = .20 p$ the depth now becomes $1.22 \times 16 = 19.52''$, i. e., twice what it was before. That

²"The Application of Theories of Elasticity and Plasticity to Foundation Problems," Journal, Boston Society of Civil Engineers, Vol. XXI, No. 3, July, 1934.



DISTRIBUTION OF STRESS UNDER A CIRCULAR FOOTING

Fig. 6

is, the depth to a point of equal stress has increased in proportion to the square root of the applied load.

A few words on the subject of bearing capacity are now in order. It has been assumed in this discussion that the subgrade could withstand a certain amount of stress, and that an excess beyond this amount would produce failure, irrespective of the area over which the stress might be applied. In other words, the subgrade stress q of Fig. 4, which has been described as the stress just causing failure, has been assumed to be a constant for any given soil and not dependent on the radius ($r + kd$) of the loaded area. This assumption is reasonable for subgrades deriving the major portion of their strength from cohesion. However, it will not hold for cohesionless soils such as sand and gravel. The criterion is whether the soil is of approximately constant strength within the zone of stress, or whether it becomes stronger with depth. In isolated building foundations the zone below any footing within which appreciable stresses are caused extends down one or two times the footing diameter. Within this depth the strength of a highly cohesive soil is essentially constant. For a cohesionless soil, the

strength at any point is roughly proportional to the depth of the point. The average strength below footings on cohesionless soils therefore varies approximately as the size of loaded area. Thus, if a load of 3 tons on an area 1 foot square applied to a bed of gravel produces failure, an intensity of 9 tons per square foot, or a total of 81 tons, would be required to produce failure of an area 3 feet square. The reason is that under the larger area the stresses go correspondingly deeper, where the material is stronger.

This is of much importance in the design of building foundations, however, there are two reasons why this increase of strength of cohesionless soil does not sensibly vitiate the conclusions previously reached for highway subgrades. First, the weight of a pavement produces considerable surface strength in a sand or gravel subgrade, hence the increase in strength within the stressed zone is not as important as might at first be assumed. Second, experience proves that pavements laid on good sand or gravel subgrades seldom give trouble; the poorer clay subgrade types, which are by far the more numerous, are the ones requiring careful design; and these are the types of material to which the preceding analysis is most likely to be applied.

Up to this point of the discussion the limiting stresses considered have been stresses corresponding to complete failure. As a practical matter no road should be so designed. Rather than allow on the subgrade, the stress q which just causes failure, the allowable stress should be q divided by a reasonable factor of safety, which may be denoted by q' . Using q' as the permissible direct stress in the soil, the reasoning in the above derivations is in no way invalidated. Similarly s' may be used to denote an allowable value of maximum shearing stress and it may be concluded that with a given factor of safety, the required depth is proportional to the square root of the wheel load.

A thorough investigation into the problem should include a study of relative settlements which would occur in subgrades under various loads. To illustrate this, consider two pavements, the first carrying a load which is four times as large as that on the second, while the thickness is twice as much for the first as for the second, the two pavements being on similar subgrades. Since the square root of load is proportional to the thickness for the two cases the two are equally safe on the basis of the above discussion. However, under the larger load there is a deeper zone within which stresses, compressions and distortions occur and thus there will be greater settlement. From this viewpoint, if a given value of allowable settlement is adopted as a criterion, the law of thickness proportional to square root of load is unsafe and in the above example the second pavement would have to be more than twice as thick as the first.

Thus it appears that the best theoretical analyses now available support the conclusion derived from engineering experience that heavier vehicles require thicker pavements, even though the intensity of load on the pavement may be the same. For this case, increasing

the pavement thickness in proportion to the square root of the load seems to be a reasonable criterion. For the case of heavy trucks using inflation pressures twice to three times those of passenger vehicles, the situation is correspondingly aggravated, and pavements definitely thicker than those indicated by the square root relation appear necessary.

APPENDIX K

HIGHWAY USE AS AFFECTING ALLOCATION OF CAPITAL COSTS

VIEWS OF CLIFFORD OLDER

The principle adopted by the Joint Committee of Railroads and Highway Users, quoted on page 57, and adopted as basic in this report, states an equitable method of cost allocation, because—

1. It is obvious that all vehicles, without exception, require and use every facility necessary for the accommodation of the basic vehicle (ordinary automobile).

2. Each and every one should, therefore, share in the cost of providing the basic facility (basic road) *in proportion to its use of the facility.*

It is further obvious that if the cost assigned to the basic facility is fully adequate to provide the facilities necessary to serve every need of the basic vehicle, as we believe it to be, such vehicle should not be charged with any part of the costs of the added facilities made necessary wholly by the other classes of vehicles.

Likewise the added facilities made necessary by the second class of vehicles are required and used by all the succeeding classes as well and their costs should, therefore, be borne by the succeeding classes in proportion to their use of them. In turn, the second class should not be charged with any of the costs peculiar to the succeeding classes. This principle, of course, extends in the same way, step by step, up through all the succeeding classes.

Having determined as fairly as possible the cost of the facilities required by the various vehicles, the determination of the fair proportion of the annual capital costs that should be borne by each class of vehicle and each individual vehicle may easily be found, as in the report, by simple calculations, providing the *use* by classes of vehicles and by individual vehicles can be determined and expressed in terms of a fair common unit.

In the report the unit of use adopted is the vehicle mile. The adequacy of this unit may well be questioned. To illustrate the significance of a proper choice of the unit of use, a short section of highway will be chosen and the effect of use be analyzed. A toll bridge is selected because the relation between use and the revenue necessary to meet costs is readily visualized in such case.

In the case of the McKinley Bridge constructed over the Mississippi River at St. Louis about 25 years ago, the space between the trusses was designed and reserved for the sole use of interurban trains. On brackets outside of the trusses was built a narrow roadway on each side of the spans, thus providing for a single lane of highway

traffic in each direction which taken together correspond to a two-lane highway. There could be no passing of vehicles traveling in the same direction, which is also true in the case of a two-lane highway when the traffic in both lanes reaches a certain density. Toll was charged to compensate for the cost of adding these roadway lanes.

It is obvious that the bridge company might have designed the floor beam brackets and floor system for basic vehicles only and added only enough steel to the trusses to support the added weight of a continuous line of basic vehicles. In this case, use would be restricted to the basic vehicles. This would have involved a very definite and easily determinable annual capital cost chargeable through tolls to the basic vehicles that used the roadways. Regardless of all the intricacies of the six million dollar bridge structure, all the inducement that was offered to vehicle owners in return for the toll charge was the use of two roadway channels, strips or lanes of usable space, each of a definite width and height, and about one mile long.

The details of providing for such roadways suitable for any design and weight of vehicle follow the pattern well understood by all structural engineers. It is roughly as follows: If planned for automobiles only, the design (and cost) of the structural support immediately under the wheels would be a function of the wheel load of the basic vehicle while that of the trusses would depend upon the gross load of one basic vehicle multiplied by the number that could come upon each roadway at one time. Likewise for heavier vehicles the added cost of providing for them might easily be determined.

If the roadways were designed merely for the basic vehicle, to come out even the bridge company would then have to make the toll charge against each automobile such that the collections during the year from the users would equal the annual cost of the facilities provided for them. Suppose the traffic in each of the two roadway channels was 10,000 ordinary automobiles per day and that this included all the cars of normal length that could pass over the bridge in one day when traveling at the normal speed of such vehicles. In other words, the capacity of the roadways was equivalent to 10,000 round trips of an automobile per day and this amount of traffic used them. Then to gain the daily cost (annual cost divided by 365) the toll per car (each way) would have to be the daily cost divided by 20,000.

Numbers. It will be recognized at once that if in this case a certain 1,000 automobiles should each make ten round trips per day (20,000 total passages over the river) instead of 10,000 cars one round trip each per day, the 1,000 cars would consume the whole bridge capacity and the bridge company would be in the red 90 per cent of the cost unless each car was charged for each trip. This clearly illustrates the fact that the number of different vehicles alone is no reasonable measure of use.

Vehicle Miles. Clearly in the above case the proper charge against each vehicle of the same length that travels at the normal speed for vehicles of its class would have to be based upon the number of trips

and not upon the number of different cars registered or licensed. The same toll per car and per day would obtain if the charge for vehicles of the same class is based on a vehicle mile as the unit of use. This illustrates the vehicle mile basis of use adopted in the report. It is perhaps not altogether a satisfactory measure of use because all vehicles are not of the same length and they do not travel at the same speed. This introduces the element of road occupancy.

Length-Number of Axles. The length of the vehicle has an important influence upon fair charges. A commercial vehicle may have the same width and wheel load as the basic automobile and, while its gross weight might be much greater, its load per foot of length might be made the same by merely increasing length and adding axles in proportion. Such vehicle would then add nothing at all to the cost of providing the roadways for the basic vehicle and unless restricted by law (or by company regulation in the case of the bridge illustration) the vehicle in the form of a tractor-trailer combination might be of *any* length depending only upon the power plant that could be provided within the axle load limit. Now, suppose half of the vehicles using the bridge are of this type and although they might travel at the same speed as the normal vehicle, they are of such length that each uses up three times as much of the length of the roadway lane as the basic passenger automobile. In this case the total capacity of the bridge would again be cut to a gross of 5,000 vehicle round trips per day. Of these there would be 2,500 normal passenger automobiles and the same number of long vehicles. To compensate for loss of revenue, the bridge company would again either have to double the toll for all vehicles, which would obviously be unfair to the passenger automobile, or *triple* the charge for the long vehicle, which would obviously be the fair thing to do. This illustrates the fairness of multiplying vehicle miles by the number of axles supporting the vehicle.

Length-Time Relation. Speed determines the time of occupancy and is, therefore, an exceedingly important factor. Suppose that half of the vehicles (all of the same length and wheel load) should be so under-powered that they could maintain only 50 per cent the normal speed of the other half and that they were moving as mixed traffic. Then, in the case of the bridge illustration, only 5,000 round trips per day would consume the total capacity and the bridge company would again be in the red, this time to the tune of 50 per cent, unless it either doubled the toll on all vehicles, which would obviously be unfair, or tripled the toll charged the slow vehicles, which caused the loss of capacity, which would seem fair. Furthermore, if normally only 10 per cent of the half-speed vehicles should be on the bridge at the same time, a mixture of this 10 per cent would reduce the capacity and revenue by 50 per cent and the proper charge against the slow 10 per cent should then be 11 times that of the normal vehicle in order to place the burden squarely where it belongs and provide the necessary revenue.

It thus appears that the inverse effect of speed might properly be chargeable at a much greater rate than in direct proportion to speed reduction.

The highway utility has nothing whatever to sell except space channels or lanes and both time and space are the essence of their value to the user. Therefore, it might be argued that fair charges (stated mathematically) should increase directly with length and inversely with some power of the normal speeds of different vehicles or classes of vehicles. In other words, if a commercial or other vehicle should be both longer and slower than the normal passenger automobile, it is obvious that, in the case of the bridge illustration, the bridge company would of necessity apply a factor of speed and a factor of length in order to be fair to all users and at the same time recover the necessary costs.

The principle is believed to be rigidly correct for the conditions assumed, that is, whenever and wherever the traffic flow on a two-lane road is great enough to prevent or seriously hinder the passing of vehicles moving in the same direction. It may also be argued that it is correct, although the traffic volume on the greater part of the highway system is relatively small. For example, it is universally recognized that in the case of an office building, warehouse or rental factory it is fair to charge rent on a basis of the time and space reserved, although often they may not be enough to absorb the space available. There is no reason why the same principle should be different for highway time and space.

It then seems worth while to consider whether or not it is possible to determine a fair measure of the unit of use when both time and length (number of axles) are taken into consideration.

The length of a vehicle bears a somewhat definite relationship to its gross weight when the axle load is fixed. For example, to double the weight, the number of axles must be doubled and hence the length increased. To double the number of axles does not necessarily double the length, but practically it must very nearly be doubled if the axle load is constant. Furthermore, as the gross load is increased, the normal speed is usually decreased. Certainly this is true on hills. The double factor (speed and length), in terms of consumption of the usable space channel, varies directly with length and inversely with speed.

The ton mile suggests itself as possibly being approximately in proportion to this double factor and it is a common conception that ton miles measure use. As a test of this measure, assume that the gross weight of a passenger automobile is two tons and that of the maximum truck combination 20 tons. On the basis of ton miles as a measure of "units of use" the ratio would be as 1 is to 10, which should then be applied to the mileage as a measure of lengthtime occupancy. Comparison might be made as follows: The passenger automobile occupation of lanes as compared with that of the truck would be about as 13 feet is to 40 feet or as 1 is to 3. Now, assume that the inverse

relation of speed is as 1 to 2 (25 and 50 miles per hour). This would apparently make the total factor 6, but we have shown that an inverse speed factor of 1 to 2 should triple the fair charges for speed, even if there were as many of these trucks as automobiles. This would result in a proper unit of use as measured by length-speed responsibility in the proportion of 1 to 9, which is reasonably close to the 1 to 10 ratio found on the basis of ton miles. As a matter of fact, however, truck traffic is only about 13 per cent of the total, and this would greatly increase the ratio.

The sponsor of this Appendix believes that the ton mile as a measure of use is conservative and that it should be used instead of vehicle miles.

Buses usually operate at speeds comparable to those of passenger automobiles; hence, the speed factor does not apply. They are, however, usually from one to three times longer; hence, a factor for width should be applied.

In this Appendix, width is not considered as a factor of occupancy because, in the body of the report, the added costs due to width are allocated separately.

Grading and Structures. It is clear that the physical elements of grading and structures make available nothing more or less than the same usable space channels or lanes provided by the pavement. In fact, these elements are nothing more or less than a part of the basic road. When the available lanes in which the pavement on roadway surface is divided are occupied or partly occupied by traffic, the earthwork or grading and structures is correspondingly occupied. Hence, it is clear that the use made of the grading and structures by traffic is in exactly the same proportion as the use made of the pavement. The annual cost, therefore, of these items should be charged to the various vehicles on the same basis as the pavement—in other words, in proportion to whatever "unit of use" basis is selected for the pavement.

APPENDIX L

STUDY OF MOTOR VEHICLE SPEED IN MASSACHUSETTS

In 1934 the Massachusetts Accident Survey made an extensive study of motor vehicle speeds, distinguishing between passenger cars, light trucks, heavy trucks, and buses. Figure 7 shows typical results of this investigation for three different road conditions; straight-a-ways, hillcrests, and sharp curves. On straight roads light trucks travel on the average 2.4 miles per hour slower than passenger cars and heavy trucks 6.3 miles per hour slower. Buses, on the other hand, travel about 1 mile per hour faster than passenger cars. At hillcrests the light trucks run 2.5 miles per hour slower and the heavy trucks 7.9 miles per hour slower than passenger cars.

The speed distribution curve for hillcrests shows that about 12 per cent of the heavy trucks travel at from 10-15 miles per hour which is slower than the slowest passenger car recorded. Buses are also slowed down by hills and average 5.4 miles per hour slower than passenger cars. The retarding effect of hills on the different types of vehicles was as follows: passenger cars slowed down 14%, light trucks 15%, heavy trucks 22%, and buses 30%. On curves the different types of vehicles have about the same speed difference between them as on straight-a-ways, but the general speed of all traffic is slowed down about 8 miles per hour. The buses show a lesser tendency to slacken speed on curves than do the other types.

Necessity for Multiple Lane Roads. Because of the difference in speed of vehicles and particularly because of the slow speed of heavily loaded trucks extra lanes are required to prevent repeated delays and congestion resulting from the difficulty which the faster more mobile passenger cars have in readily passing the slower vehicles. Dean A. N. Johnson of the University of Maryland determined the working or free moving capacity of a 2-lane road as 1,000 vehicles per hour. His investigations were carried on largely during peaks in passenger car traffic and do not reflect the influence of trucks. Highways with a high percentage of trucks are now commonly built with 4 lanes even when the hourly flow seldom reaches 1,000 vehicles per hour.

A study of truck delays made by Professor C. B. Breed, showed considerable inconvenience and delay caused by trucks on a 2-lane road when the hourly flow was only about 250 vehicles. The effect of the slower trucks is to collect a line of cars waiting for opportunity to pass. This occurs especially where the alignment is crooked and the profile hilly. There may be long stretches of unoccupied road between these groups of vehicles, so that an observer standing by the road side would not get the impression that the road was congested, but the actual effect on vehicles trailing behind the trucks on this

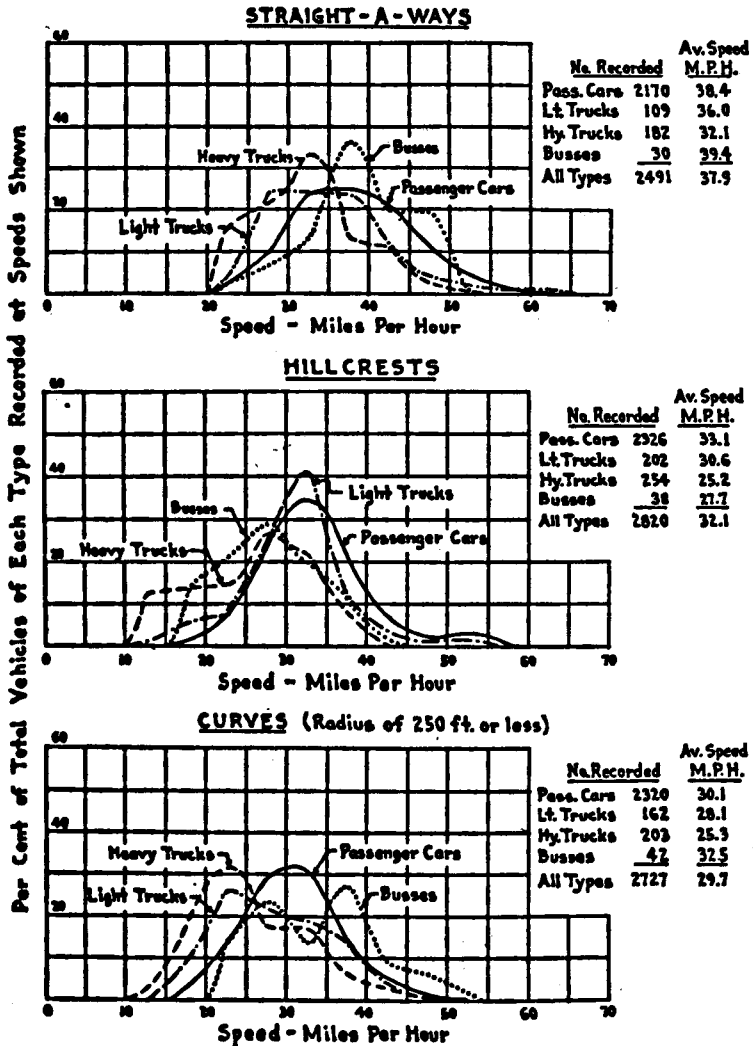


FIGURE 7

SPEED RANGE DIAGRAMS — COMPILED FROM RECORDINGS AT SIX TYPICAL LOCATIONS ON MASSACHUSETTS STATE HIGHWAYS FOR EACH ROAD CONDITION

road is the same as though general congestion was present. This congested condition often lasts several minutes and covers a number of miles until conditions favorable to passing are encountered.

This condition is particularly acute on grades where over-loaded trucks often cannot travel more than 5 to 10 miles per hour. These locations are usually marked with restricting center lines so that it is a violation of the traffic law to pass even if no opposing traffic is present. For safety 3-lane roads are commonly restricted to 2-lanes at summits by painting a white line along the middle of the middle lane so that the center lane which is usually available for passing slower vehicles cannot be used.

To relieve this situation, Massachusetts has in certain instances widened some of its 3-lane roads to 4 lanes at summits. The policy of widening 2- and 3-lane roads to 4 lanes at summits is being seriously considered by many States on roads where 2 or 3 lanes are ample for passenger car traffic alone. Obviously, the motor truck and the bus have a special responsibility for widening at hill tops and for the early adoption of multiple lane roads in general on commercial highways. These widenings are often very expensive.

Delays and Inconveniences Caused by Motor Trucks. In the foregoing discussion the delays and inconveniences caused by trucks on grades and curves have been pointed out. In order to obtain some quantitative data on this subject, a series of tests was run on 2-lane roads in Massachusetts. These tests were run on 18- and 20-foot roads typical of the period 1921-1932 with frequent curves and grades but not excessively hilly or crooked. The tests were made by attempting to drive at the normal speed for passenger cars on these roads and noting the delays caused by speed reduction on account of overtaking trucks or passenger cars or any other condition causing delay. The runs were made on a Monday in December, 1935, when traffic was light, amounting to only about 200 vehicles per hour. (Figure 6.)

These tests showed the following results:

1. Motor trucks were frequently trailed by one to three vehicles waiting for a chance to pass even when the density of traffic was not over 200 vehicles per hour including both directions of traffic.
2. Difficulty in passing motor trucks was the largest source of delay. On the average, these delays amounted to about twice those caused by overtaking and passing passenger cars.
3. Delays on account of railroad crossings, villages or intersection were less than those incurred in overtaking and passing either passenger cars or trucks.
4. On account of the difference in speed, a minute spent in trailing a truck on the average resulted in three times as much delay as a minute spent following a passenger car.
5. Passenger cars were frequently forced to travel on the unpaved shoulder in passing trucks on an 18-foot surface. When two trucks

passed each other they had to use both shoulders to get their desired clearance. The 18-foot surface was definitely inadequate for motor truck traffic.

6. Passenger car drivers were observed to take chances rather than wait behind trucks for a safe opportunity to pass.

7. Motor trucks were observed to obstruct the view of hazardous conditions along the road, such as railroad crossings, curves and intersections, thereby cutting off warning of these conditions from the trailing vehicles.

APPENDIX M
FEDERAL APPROPRIATIONS FOR HIGHWAY PURPOSES—
YEARS 1917 TO 1937

(Source: United States Government Reports)

Fiscal year in which appropriation became available	Federal-aid highway			
	Regular Federal-aid funds	Emergency and relief funds	Value of surplus war materials distributed	Total
1917	\$5,000,000	.....	.....	\$5,000,000
1918	10,000,000	.....	.....	10,000,000
1919	65,000,000	.....	.....	65,000,000
1920	95,000,000	.....	.....	95,000,000
1921	100,000,000	.....	\$100,000,000	200,000,000
1922	75,000,000	.....	17,110,751	92,110,751
1923	50,000,000	.....	22,663,235	72,663,235
1924	65,000,000	.....	58,111,836	123,111,836
1925	75,000,000	.....	8,978,412	83,978,412
1926	75,000,000	.....	8,160,801	83,160,801
1927	75,000,000	.....	9,574,965	159,574,965
1928	75,000,000	.....	.....	75,000,000
1929	75,000,000	b \$5,197,294	.....	80,197,294
1930	75,000,000	b 3,654,000	.....	78,654,000
1931	125,000,000	c 83,051,936	.....	208,051,936
1932	125,000,000	.....	.....	125,000,000
1933	125,000,000	c 120,000,000	.....	245,000,000
1934	a	d 400,000,000	.....	400,000,000
1935	a	e 143,143,175	.....	143,143,175
1936	125,000,000	f 500,000,000	.....	625,000,000
1937	125,000,000	.....	.....	125,000,000
Total, 1917-37	\$1,540,000,000	\$1,255,046,405	\$224,600,000	\$3,019,646,405
Amount deducted from regular Federal-aid fund in 1933, account of emergency loan of \$80,000,000 in 1933.....				16,000,000
Total appropriations—Federal-aid highways.....				\$3,003,646,405
Federal appropriations for highways other than Federal-aid:				
Highways in National parks, forests, public lands and Federal reservations				244,038,800
Mt. Vernon Memorial Highway.....				7,200,000
Arlington Memorial Bridge.....				12,000,000
Inter-American Highway.....				1,125,000
International Highway Congress.....				55,000
Total.....				\$264,418,800
Total Federal appropriations for all highways.....				\$3,268,065,205

a No regular Federal-aid appropriations made for 1934 and 1935.

b For emergency flood relief damages to highways.

c Includes \$3,051,936 appropriated for flood relief. It also includes an emergency appropriation of \$80,000,000 approved December 20, 1930, allocated as a loan to the States for matching Federal-aid and to be repaid over a period of five years beginning in 1933 by deductions from future Federal-aid allotments. The \$120,000,000 in 1933 was also allotted as a loan to match Federal-aid funds and was to be repaid over a period of ten years beginning in 1938 by deductions from future Federal-aid allotments. In 1933, about \$16,000,000 was deducted from the regular Federal-aid allotments as the first repayment on the \$80,000,000 loan, but under the Hayden-Cartwright Act, 1934, repayments of the remaining \$64,000,000 and of the entire \$120,000,000 were rescinded.

d Authorized by the National Industrial Recovery Act, 1933.

e Includes \$10,000,000 for emergency flood-relief for highways, and \$100,000,000 appropriated (\$200,000,000 authorized) for highway construction under the terms of the Hayden-Cartwright Act, 1934, and \$33,143,175 Loan-and-Grant funds made by the Public Works Administration in 1934 and 1935.

f Amount actually allocated according to provisions of Emergency Relief Appropriation Act of 1935. Of this amount \$200,000,000 was allocated for highway purposes, \$200,000,000 for grade crossing work and \$100,000,000 was provided as unappropriated balance of the \$200,000,000 authorized by the Hayden-Cartwright Act, 1934 (see note e). The Emergency Relief Appropriation Act authorized the allocation of an amount not to exceed \$800,000,000 for highways, roads, streets, and grade crossing elimination.

Notes: Table 3 does not include the sum of \$500,000 appropriated by Congress in 1912, prior to the enactment of the Good Roads Act of 1916, for the purpose of aiding the states in improving rural post roads. The appropriation of 1912 provided "That the State or local subdivision thereof in which such improvement is made under this provision shall furnish double the amount of money for the improvement of the road or roads so selected." (Public—No. 336—62d Congress, Post Office Appropriation Act—Approved August, 24 1912).

APPENDIX N
HIGHWAY BONDS OUTSTANDING—YEARS 1904 TO 1932

Year	State highway and bridge bonds <i>a</i>	County highway and bridge bonds <i>b</i>	City street bonds <i>c</i>
1904	\$4,525,000	.....	\$256,267,042
1905	4,825,000	.....	266,493,219
1906	5,701,000	.....	308,204,813
1907	7,073,000	.....	334,823,179
1908	18,036,000	.....	370,975,948
1909	20,007,500	.....	424,612,232
1910	26,467,500	.....	462,175,265
1911	38,747,000	.....	479,616,523
1912	53,319,000	\$202,007,776	495,974,447
1913	82,544,000	229,403,355	.....
1914	93,264,000	229,438,582	.....
1915	111,958,500	.....	562,823,268
1916	123,578,000	.....	618,279,057
1917	139,915,000	.....	657,008,598
1918	147,101,500	.....	711,993,298
1919	176,645,000	.....	706,962,058
1920	212,147,900	.....	.....
1921	272,205,100	876,738,200	.....
1922	410,702,600	.....	.....
1923	472,868,300	.....	747,031,699
1924	549,684,750	.....	874,068,767
1925	700,575,850	.....	1,055,048,135
1926	765,677,950	.....	1,186,587,201
1927	857,314,950	.....	1,318,003,889
1928	892,539,150	.....	1,389,964,174
1929	1,008,856,150	1,826,924,000	1,538,215,258
1930	1,151,571,820	1,809,032,034	1,711,350,325
1931	1,226,934,601	1,764,985,210	1,736,093,708
1932	1,277,204,775	.....	1,599,258,151

a State highway and bridge bonds from records of U. S. Dept. of Agriculture, Bureau of Public Roads.

b County highway and bridge bonds from following sources: Years 1912 and 1913 from Bulletin No. 136, U. S. Dept. of Agriculture; years 1914 and 1921 from Bulletin No. 1279, U. S. Dept. of Agriculture; year 1929 from statement by Bureau of Public Roads entitled "Local Road Bonds Outstanding—1929 and Interest Rates"; years 1930 and 1931 were developed from data published by Bureau of Public Roads showing bond receipts and bond payments.

c City street bonds from reports of U. S. Dept. of Commerce, Bureau of the Census, covering cities having population of over 30,000. Bonds for cities having between 2,500 and 30,000 population estimated by Bureau of Railway Economics. (For method of estimating, see "An Economic Survey of Motor Vehicle Transportation in the United States," Appendix N, Table IV, p. 206—Bureau of Railway Economics, Special Series No. 60).

APPENDIX O
STATE MOTOR-VEHICLE RECEIPTS AND MOTOR-FUEL TAXES—
YEARS 1901 TO 1935

Source: United States Department of Agriculture, Bureau of Public Roads)

Year	Registration fees (Registration and other fees combined)	Motor-fuel tax receipts (Gross receipts less refunds)
1901	\$954*	.....
1902	1,082	.....
1903	26,865	.....
1904	33,411	.....
1905	62,509	.....
1906	192,706	.....
1907	335,624	.....
1908	486,380	.....
1909	942,675	.....
1910	2,234,913	.....
1911	3,967,475	.....
1912	5,661,043	.....
1913	8,192,253	.....
1914	12,382,031	.....
1915	18,245,711	.....
1916	25,865,369	.....
1917	37,501,233	.....
1918	51,477,419	.....
1919	64,697,255	\$1,022,514
1920	102,546,212	1,363,902
1921	122,478,654	5,382,111
1922	152,047,824	12,703,088
1923	188,970,992	38,566,338
1924	225,492,252	80,442,295
1925	260,619,621	148,358,087
1926	288,282,352	187,603,231
1927	301,061,132	258,838,813
1928	322,630,025	304,871,766
1929	347,843,543	431,311,519
1930	355,704,860	493,865,117
1931	344,337,654	536,397,458
1932	324,273,510	513,047,239
1933	302,694,065	518,195,712
1934	304,923,000	565,027,000
1935	322,776,536	616,851,671
1936	359,783,000	686,631,000
1937	399,613,000	756,930,000
Total to end of 1937	\$5,258,390,140	\$6,157,408,861

* New York State, only.

NOTE: Latest revised figures used throughout this table.

APPENDIX P
STATE OF INDIANA
AMOUNTS LEVIED FOR RURAL HIGHWAYS IN THE AGGREGATE
AND ON A PER CAPITA BASIS, 1900 TO 1920

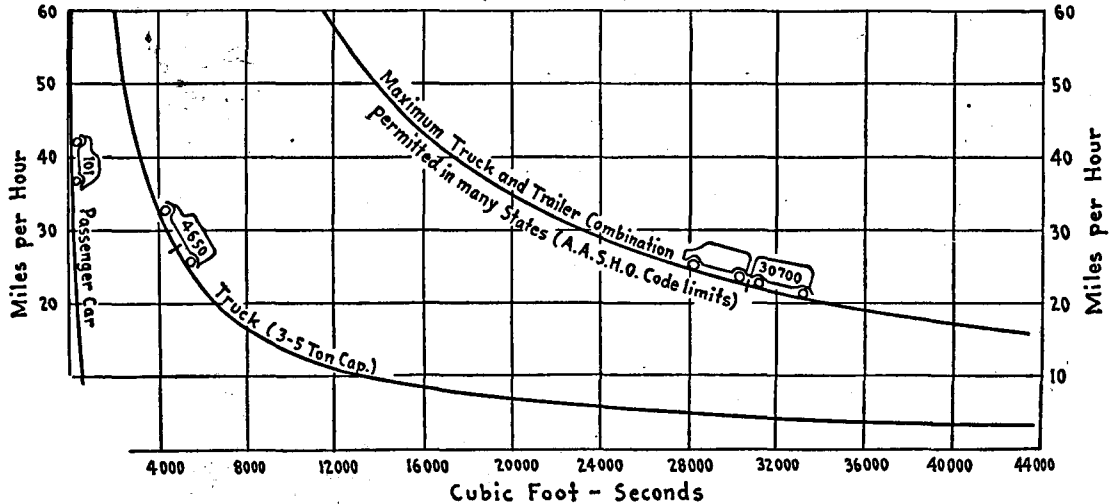
Year	Population	Amount levied for rural highways	Amount per capita
1900	2,516,463	\$3,662,657.82	\$1.46
1901	2,534,903	3,885,075.85	1.53
1902	2,553,345	2,182,748.76	.85
1903	2,571,786	3,742,683.64	1.46
1904	2,590,227	2,318,127.22	.89
1905	2,608,669	3,666,551.89	1.41
1906	2,627,110	4,741,299.41	1.80
1907	2,645,551	5,131,793.53	1.94
1908	2,663,993	5,655,107.54	2.12
1909	2,682,434	6,157,992.00	2.30
1910	2,700,876	7,239,111.28	2.68
1911	2,723,827	7,700,248.04	2.83
1912	2,746,779	8,419,759.74	3.07
1913	2,769,730	9,508,546.80	3.43
1914	2,792,681	11,236,416.28	4.02
1915	2,815,633	9,621,379.25	3.42
1916	2,838,584	12,157,680.46	4.28
1917	2,861,535	12,170,493.66	4.25
1918	2,884,487	13,798,739.33	4.78
1919	2,907,438	14,270,777.71	4.91
1920	2,930,390	16,476,721.42	5.62

APPENDIX Q

Road Occupancy with Mileage Factor

equals Width x Height x Length x Time to travel Length x Mileage Factor

For Passenger Car $5.7 \times 5.7 \times 13.5 \times \frac{13.5 \times 3600}{5280 M} \times 1.00 = \frac{4030}{M}$; Annual Mileage = 7,000, Factor = 1.00
 For Truck (3-5 Tons Cap.) $8.0 \times 10.5 \times 25.0 \times \frac{25 \times 3600}{5280 M} \times 3.58 = \frac{128000}{M}$; " " = 25,000, " = 3.58
 For Maximum Combination permitted in many States (A.A.S.H.O. Code limits) $8.0 \times 12.5 \times 45.0 \times \frac{45 \times 3600}{5280 M} \times 5.00 = \frac{690000}{M}$; " " = 35,000, " = 5.00
 M = Speed in Miles per Hour



ROAD OCCUPANCY WITH MILEAGE FACTOR