WHY 18,000 POUNDS?
Axle Load Effect on Highway Design and Operation

By Herbert S. Fairbank, Deputy Commissioner
Bureau of Public Roads, U. S. Department of Commerce

Presented at the National Transportation Meeting of the
Society of Automotive Engineers

New York City, October 16, 1950

In the question which serves as the principal title of this paper, an attentive ear may detect overtones of skepticism. The instinctive response of one firmly convinced of the reasonableness of 18,000 pounds as a limit of the weight to be carried by a single axle of a motor vehicle might conceivably be a somewhat bickering, "Well, why <u>not</u> 18,000 pounds?"

The speaker will eschew the bickering response. Instead, he will attempt a reasoned answer to what he will assume to be a sincere question.

Some part of the heat that is generated in many discussions of the question doubtless arises out of misunderstanding between the disputants as to the precise nature and purpose of the limitation in dispute.

The 18,000-pound axle load limit <u>is</u> a limit prescribed by law in 34 States as a regulation binding upon the operation of present vehicles over present roads, its purpose the protection of the existing road system against undue wear and tear. It may also be regarded, and is so regarded by many who have no other than the public interest in view, as a limit of the weight which roads should now be designed to support, and hence a continuing limit upon the design and loading of vehicles.

Primarily a Regulatory Limit

It will be of advantage in our discussion clearly to distinguish these two concepts of the nature and purpose of the limitation. Accordingly, let us first consider the necessity, or may we preferably say, the advisability of 18,000 pounds as a limit regulatory of present vehicle operation for the prevention of undue wear and tear of existing roads.

What are the roads which the 18,000-pound axle load limit is intended to protect? What are their character and their condition?

In some of the comment of opponents of the limit the assumption seems implicit that all, or the only considerable part of all heavy vehicle movement is confined to the primary highways. It is apparently assumed also that the primary highways are preponderantly of such design as to withstand, without undue distress, the application of axle loads exceeding 18,000 pounds in such numbers and frequency as they are likely to occur. There is some vagueness as to just where the limit above 18,000 pounds is to be placed, and observation indicates that there are operators of vehicles who may suppose that the only limit to be respected should be one of their individual choice, be it 20,000 or upwards of 40,000 pounds.

But, for the moment let us confine our attention to the particularity and the character and the condition of the roads which the 18,000-pound axle load limit is intended to protect.

Roads in Need of Protection

Certainly they consist of the upwards of 350,000 miles of primary State highways. But they do not consist of these only. They include a substantially greater mileage of secondary and even tertiary roads, over which the heavier vehicles are regularly operated in significant numbers. There are, for example, some 500,000 miles of secondary and lesser roads over which milk collection trucks operate daily. These trucks are definitely not light vehicles. There axle loads may, and do reach and surpass the limit of 18,000 pounds. There are also the tank trucks that regularly deliver gasoline and heating oil to farms and communities on local roads. The mileage of such roads affected by these operations cannot be closely dimensioned, but it is considerable; and these vehicles also have the potential and the actuality of axle loading up to and beyond 18,000 pounds.

Coal is moved regularly by motor truck from mines to consumers in heavy loads over secondary and lesser roads, as well as primary highways. Sand and gravel pits and stone quarries are very often located on local roads, and the loads of these construction materials--among the heaviest observed on our highways--must perforce be moved over the local, as well as the primary roads. In parts of the country logging operations, likewise generative of heavy axle loading, utilize secondary and lesser roads to perhaps a greater extent than primary highways.

Nor can it presently be assumed, as once it could with some assurance, that the movement of farm produce, arising largely from origins on local roads, is a movement accomplished in light vehicles. Many of the vehicles operated by farmers' cooperative organizations and by the middleman buyers of farm produce, are heavy vehicles, and vehicles of heavy axle loading as, also, is the modern mechanized equipment of agriculture itself, which is by no means confined to the fields and farm lanes.

And, then, there are times when, with seasonal load restrictions enforced on primary highways in recognition of their temporarily frost-weakened condition, drivers of vehicles that would be rated as too heavy in their axle loads for the primary roads, find other and less diligently patrolled routes to their destinations via the lesser roads.

So, it is definitely not correct to assume that a limit of axle loading is required solely for the protection of primary highways upon which the heavier vehicle loading may be presumed to be confined. The need of protection extends also to a large mileage of local secondary and lesser roads.

Character and Condition of Roads Vary

Turning now to the character of the roads that require protection--roads which, as we have observed, are of secondary and lesser, as well as primary classification, it is perhaps unnecessary to labor the point that a great part of the secondary and lesser mileage is of relatively frail construction. That is a matter of common knowledge.

However, there appears to be an impression abroad that the primary highway system of the United States is rather uniformly improved in such manner as to enable it to serve, without undue distress, a heavy vehicle traffic of considerable proportions. More particularly, there appears to be the impression that axle loads exceeding 18,000 pounds in such numbers as they may and do occur, do not actually constitute a threat of undue wear and tear of the primary highway system. Again, it may be observed in passing, the magnitude of the excess over 18,000 pounds and the frequency of such excessive loading presumed to be feasible, are apparently not particularized in the minds of those who believe that the primary roads will withstand such applications, whatever they may be.

This impression is markedly erroneous. The primary highway system of the country is not all of one kind. It is not all of one condition. It is not all of one age. Its character and its qualities are the antithesis of these. It is a system of wide diversity in type of construction, in the dimensions of its design, in the condition of its surfaces and foundations, and (particularly relevant to the present discussion) in its load supporting capacity. The variation is not a condition of regional occurrence. The roads of one State are not all of strong design, those of another of lesser strength. The age, the type, the condition, the strength of the highway system in every State, the primary, as well as the secondary and lesser roads, vary from short section to relatively short section of every individual route composing the system.

Some of these widely variant sections of road doubtless have strength sufficient to enable them to withstand without appreciable effect applications of axle loads exceeding 18,000 pounds in high frequency. Among these the magnitude of load they will so withstand varies. Large parts of the highway system, more particularly the primary highway system, are believed to be able to withstand, without undue wear and tear, the operation of vehicles with axle loads of 18,000 pounds in practically unlimited frequency. Still larger parts suffer definite damage when subjected to axle loads of 18,000 pounds and less, the extent of the damage varying with the season and the frequency of the heavier load applications.

If, then, the highway system that requires for its protection a regulation of the axle loads of vehicles is of such diversity of strength and condition, how does it occur that a particular limit of axle loading--18,000 pounds--is chosen to afford the desired protection? The question appears to be reasonable. Obviously, considering the qualities of the situation as described, it can receive no wholly indisputable answer. It can, and does find a reasonable answer.

18,000 Pounds Not an Arbitrary Limit

Eighteen thousand pounds, as a limit of vehicle axle loading, is not, as some have said, just a figure materialized out of thin air. As a measure of road protection, it has a greater validity than another limit for which some preference is expressed. I refer to the limit of 22,400 pounds, which is established by law in 6 States. That limit has its origin in nothing other than the fact that long years ago the desirable limit of loading of a solid rubber tire was considered to be 800 pounds per inch of width. The width of the widest tire then manufactured being 14 inches, the maximum desirable weight per tire turned out to be 11,200 pounds, and the desirable combined loading of two tires on one axle, 22,400 pounds. This limit, which had some relevance to a type of tire no longer extensively used, has not now, and never has had, any rationally predetermined relation to the supporting capacity of existing roads.

In contrast, the 18,000-pound axle load limit has definite basis in the estimated safe supporting capacity of a particular type of road of a particular dimension. The type is a widely prevalent type--concrete. The dimension is a preponderant dimension of roads of that type--an edge thickness of 9 inches.

The estimate of the safe axle load capacity of concrete pavements of 9-inch edge thickness is based upon the mathematical theory of the behavior of slabs supported on elastic foundations, as developed particularly by the late Dr. H. M. Westergaard, confirmed and supplemented by numerous tests and experiments made both before and after Westergaard's demonstrations.

The Bates Road Test, conducted by the Division of Highways of the Department of Public Works and Buildings of Illinois in 1922 and 1923, was one of the earliest, and is perhaps the most widely known of the many experiments that have been made. It is only one of many experiments that have been made, all with the same purpose and similar results, including an extended series of tests by the Bureau of Public Roads at Arlington, Virginia.

To attempt a recital of the findings of these tests in detail would unpardonably extend the length of this paper; and for an audience of engineers such a recital is assumed to be unnecessary. Reports of the more significant tests have been published. They can be studied and understood by engineers.

It will suffice here to describe the nature of the evidence developed by the tests and the mathematical theory.

The Bates Road Test

The pioneer Bates Road Test was a traffic test of a road constructed for the experiment. Included in the road were 68 experimental pavement sections of varying material composition and design. Twenty-nine of the sections were paved with concrete of various thickness, design and composition, some with, and some without reinforcement.

These varying sections were subjected to a controlled test traffic consisting of Liberty trucks equipped with solid rubber tires. Starting with a loading of the vehicles which resulted in an application of 2,500 pounds by each rear wheel, a number of trips over the several sections was made with that loading. Subsequently, the loading was increased to apply successively by a substantial number of trips at each load, various wheel loads, ranging up to 13,000 pounds, corresponding to an axle load of 26,000 pounds.

Some of the pavement types represented were severely damaged and virtually destroyed under the lighter increments of load. In the case of some of the types it was difficult to discern a relation between the pavement behavior and the magnitude of the axle load. In the case of the sections involving concrete either as a base or a surface, however, such a relation could be observed, and it was most clearly discernable in the case of the concrete pavement sections. These sections could be observed to crack under the loading, and the increments of loading at which cracks formed in sections of the several thicknesses and designs represented, could be taken as an approximate measure of their strength or load supporting capacity.

Analyzing the results of the tests at their conclusion, Clifford Older, Chief Engineer of the Division of Highways, drew a relation (figure 1) between the edge thickness of the slab-type pavement sections and the magnitude of the respective wheel loads at which significant cracking occurred in the slabs of each thickness. This relation he found to conform closely with the equation:

$d = \sqrt{\frac{3W}{s}}$, in which

d = the depth of the pavement in inches
W = the wheel load in pounds
s = the modulus of rupture of the material of the slab in cross bending.

The determined modulus of rupture of the concrete of which the slabs were formed averaged at 700 pounds per square inch or better. This, according to the relation expressed, would indicate that a slab of 6-inch edge thickness should be cracked by a wheel load of 9,000 pounds; and the 6-inch slabs cracked under wheel loads of that magnitude or a little less.

The Effect of Fatigue

It was recognized that the cracking or failures observed in the tests were the result of a comparatively infrequent application of load. Most of the increments of load were applied only 3,000 times. In the whole test, with wheel loads increasing from 2,500 to 13,000 pounds, a total of 50,000 load applications, was the maximum experienced by any test section.

It was known that concrete, in common with other materials, is subject to fatigue, and will eventually fail under some repetition of stress which it will withstand once or a few times repeated.

To test the ability of concrete to withstand repeated stress, a machine was devised to apply repeated loads to concrete beams. From the tests made with this device, Older drew the following conclusions, which he reported in a paper presented before the American Society of Civil Engineers in 1924:

> "Plain concrete beams or slabs will sustain without failure from bending an indefinite number of repetitions of a load if the tensile fiber stress induced is less than 50% of the modulus of rupture. At the present time (December 1, 1923) there are in the fatigue machine test beams that have withstood without failure about 5,000,000 repetitions of a load sufficient to produce a fiber stress of approximately 50% of the modulus of rupture.
>
> "For loads causing fiber stress in excess of 50% of the modulus of rupture, the tendency to failure increases rapidly with the increase of this excess of stress. For instance, loads causing fiber stresses of about 60% of the modulus of rupture, repeated a few thousand times (rarely more than 30,000) will cause failure; for stresses in excess of 70% of the modulus of rupture, only a few hundred repetitions (rarely more than 5,000) are required."

In view of these findings Older suggested that the value of s that should be used in the equation $d = \sqrt{\frac{3W}{s}}$, in the design of concrete pavements expected to withstand numerous applications of specific maximum loads, should be a value no greater than 50% of the modulus of rupture of the concrete. If, then, the modulus of rupture be assumed at the common value of 700 pounds per square inch, the indicated slab thickness required for the safe support of 9,000-wheel loads (18,000-axle loads) would be 8.8 or, practically, 9 inches.

In disparagement of the Bates Road Test, it has often been remarked that the test pavement sections were laid directly on a typical Illinois black soil, imperfectly drained. Let it here be observed that a large part of the existing Illinois highway system and similar parts of the systems of other States have foundations of approximately the same character.

It is also remarked that the Bates Road Test vehicles were equipped with solid rubber tires, not with low-pressure pneumatic tires such as we use today. The Bates Road vehicles were equipped with solid rubber tires; and the vehicles were driven at a speed between 12 and 15 miles per hour. It is one of the findings of later tests, particularly the impact tests conducted at Arlington, Virginia, by the Bureau of Public Roads, that the impact force delivered to a road surface by a wheel passing over an obstruction on the road, is approximately the same for a solid-tired vehicle driven at 12 to 15 miles per hour and for a high-pressure pneumatic-tired vehicle driven at 40 miles per hour (figure 2). The impact delivered by a balloon-tired vehicle is of a slightly lower order.

Bates Road Conclusions Confirmed by Later Study

The Bates Road Test was a pioneer test. In many respects it did not measure up to the requirements of a thoroughly scientific test. But, let me add at once, that the principal pavement design conclusions drawn from this pioneer test have been remarkably confirmed by all later tests much more scientifically conducted, and by the mathematical theories of slab design of later development.

Load and Warping Stresses Combine to Produce Failure

We now know that the critical stresses developed in concrete pavement slabs are not those engendered by load alone, but the conjunction of load stresses with temperature warping stresses. We know this from many measurements of the actual strains produced in pavements by loads and by warping. And we know that the combined stresses in various parts of a pavement slab reach fatiguing magnitudes for pavements of various thickness under approximately the same loads that Older concluded to be critical. This statement is made with reference to pavements as they are now built, laid on foundations of the better sort now existing, and subjected to balloon-tired traffic. It is instanced by tables 1 to 4, inclusive, which give stress values calculated by the Westergaard formulae, empirically modified to accord with actual strain measurements, to be expected in slabs of various thickness when subjected to various static loads and corresponding impact forces.

Table 1.--Combined stresses for load at slab corner and partial subgrade support (corner warped upward).

Slab thickness	Dual wheel load		Tire size-dual	Stress		
	Static	Impact		Load	Warping	Combined
Inches	Pounds	Pounds	Inches	Pounds per square inch		
	8,000	10,000	10.00-20	373	29	402
7	9,000	11,250	11.00-20	404	29	433
	10,000	12,500	12.00-20	436	29	465
	11,000	13,750	12.00-22	456	29	485
8	8,000	10,000	10.00-20	304	32	336
	9,000	11,250	11.00-20	330	32	362
	10,000	12,500	12.00-20	357	32	389
	11,000	13,750	12.00-22	381	32	413
	8,000	10,000	10.00-20	255	34	289
9	9,000	11,250	11.00-20	278	34	312
	10,000	12,500	12.00-20	300	34	334
	11,000	13,750	12.00-22	319	34	353
	8,000	10,000	10.00-20	217	37	254
10	9,000	11,250	11.00-20	237	37	274
	10,000	12,500	12.00-20	257	37	294
	11,000	13,750	12.00-22	278	37	315

Westergaard corner formula (empirically modified)

$k = 200$
$E = 4,500,000$
$\mu = 0.15$

Table 2.--Combined stresses for load at interior of 12-foot by 20-foot slab with full temperature warping (afternoon of hot day).

Slab thickness	Dual wheel load		Tire size-dual	Stress		
	Static	Impact		Load	Warping	Combined
Inches	Pounds	Pounds	Inches	Pounds per square inch		
7	8,000	10,000	10.00-20	150	232	382
	9,000	11,250	11.00-20	165	232	397
	10,000	12,500	12.00-20	178	232	410
	11,000	13,750	12.00-22	192	232	424
8	8,000	10,000	10.00-20	117	254	371
	9,000	11,250	11.00-20	128	254	382
	10,000	12,500	12.00-20	139	254	393
	11,000	13,750	12.00-22	150	254	404
9	8,000	10,000	10.00-20	94	274	368
	9,000	11,250	11.00-20	104	274	378
	10,000	12,500	12.00-20	113	274	387
	11,000	13,750	12.00-22	122	274	396
10	8,000	10,000	10.00-20	79	284	363
	9,000	11,250	11.00-20	87	284	371
	10,000	12,500	12.00-20	94	284	378
	11,000	13,750	12.00-22	102	284	386

Westergaard formula for interior loading

$k = 200$
$E = 4,500,000$
$\mu = 0.15$
$Z = 0.05$
$L = 1.75$

Table 3.--Combined stresses for load at transverse edge of 12-foot by 20-foot slab with full temperature warping (afternoon of hot day). No load transfer across joint.

Slab thickness	Dual wheel load		Tire size-dual	Stress		
	Static	Impact		Load	Warping	Combined
Inches	Pounds	Pounds	Inches	Pounds per square inch		
	8,000	10,000	10.00-20	304	41	345
	9,000	11,250	11.00-20	333	41	374
7	10,000	12,500	12.00-20	358	41	399
	11,000	13,750	12.00-22	389	41	430
	8,000	10,000	10.00-20	237	38	275
	9,000	11,250	11.00-20	260	38	298
8	10,000	12,500	12.00-20	280	38	318
	11,000	13,750	12.00-22	307	38	345
	8,000	10,000	10.00-20	191	36	227
	9,000	11,250	11.00-20	211	36	247
9	10,000	12,500	12.00-20	227	36	263
	11,000	13,750	12.00-22	246	36	282
	8,000	10,000	10.00-20	158	31	189
	9,000	11,250	11.00-20	173	31	204
10	10,000	12,500	12.00-20	187	31	218
	11,000	13,750	12.00-22	203	31	234

Westergaard formula for edge loading (modified to provide full tire area on slab)

$k = 200$
$E = 4,500,000$
$\mu = 0.15$

Table 4.--Combined stresses in a 12-foot by 20-foot slab of thickened-edge design (9-inch edge, 7-inch center).

Slab thickness	Dual wheel load		Tire size-dual	Stress		
	Static	Impact		Load	Warping	Combined
Inches	Pounds	Pounds	Inches	Pounds per square inch		
			Corner			
9-7-9	8,000	10,000	10.00-20	311	31	342
	9,000	11,250	11.00-20	339	31	370
	10,000	12,500	12.00-20	381	31	412
	11,000	13,750	12.00-22	388	31	419
			Interior			
9-7-9	8,000	10,000	10.00-20	150	232	382
	9,000	11,250	11.00-20	165	232	397
	10,000	12,500	12.00-20	178	232	410
	11,000	13,750	12.00-22	192	232	424
			Transverse edge			
9-7-9	8,000	10,000	10.00-20	304	41	345
	9,000	11,250	11.00-20	333	41	374
	10,000	12,500	12.00-20	358	41	399
	11,000	13,750	12.00-22	389	41	430

Westergaard formulae adapted to thickened-edge cross section

$k = 200$
$E = 4{,}500{,}000$
$\mu = 0.15$
$Z = 0.05$
$L = 1.75$

The great majority of the concrete pavements now existing are of a quality no better, and rest upon support no more firm than is assumed in these tables. The preponderant cross-sectional design is of the 9-7-9-inch dimensions. Many existing pavements are of lesser supporting strength; few will support a heavier load.

Concrete Roads Overtaxed by Loads Exceeding 18,000 Pounds

It seems clear to a highway engineer that the great majority of the country's existing concrete pavements are overtaxed by axle loads exceeding 18,000 pounds. Accordingly, highway engineers are not surprised when their observation and daily experience indicate that as the numbers of such excessive loads have multiplied in recent years, the occurrence of concrete pavement failure has alarmingly increased, and the cost of maintenance of the existing pavements has increased in like disturbing progression.

Without detail of description reference is made here to three charts, figures 3, 4, and 5, which compare the maintenance cost experience on pairs of New Jersey concrete highways of closely similar physical characteristics but differing in each pair in the magnitudes of traffic loads applied to them. A fuller description of these charts may be found in Appendix III, entitled Road Damage by Trucks in New Jersey, of a statement made by Commissioner MacDonald of the Bureau of Public Roads in Hearings before the subcommittee of the Senate Committee on Interstate and Foreign Commerce pursuant to S. Res. 50, June 27, 1950.

The generation of increased maintenance cost of concrete pavements by the operation of increasingly heavy vehicles as indicated in these New Jersey cases is the result commonly experienced in various degrees in all States. The increased costs tell the same tale as the scientific tests and mathematical analyses, and as many observations of the difference of behavior of roads and parts of roads subjected to moderately and excessively heavy vehicles in all parts of the country. The tale is that our concrete roads--most of them--are overloaded, their lives shortened and their maintenance costs largely increased by the multiplication of axle loading over 18,000 pounds.

The Maryland Road Test

At this moment the attention of motor manufacturers (and I presume their automotive engineers), of motor truck operators, and highway engineers the country over, is focused on an accelerated traffic test of a road in Southern Maryland. The road is a typical mesh-reinforced concrete road with 12-foot lanes of 9-7-9-inch cross section, laid on a subgrade of about average character. It is being subjected in four of its parts to a controlled traffic of vehicles which motor manufacturers have donated and petroleum producers are fueling. The vehicles operating over the four separate parts are respectively two-axle vehicles with

18,000- and 22,400-pound maximum axle weights and three-axle vehicles with 32,000- and 44,800-pound tandem-axle weights. I trust it will not be deemed a prejudgment of the results of this test, which has still some two months to run, if I restate here the expectation I held before the test was begun, that it will simply confirm the conclusions that have been drawn from the previous tests and observations.

Tests of Flexible Pavements Projected

It has not escaped the notice of the speaker that all that has been offered as reason for the 18,000-pound axle load limit as a measure of protection for existing highways has been based on an accumulated knowledge of the behavior of one type of highway. This has been necessary if the reasons were to be stated in quantitative terms. The effects of load on other types of pavement have not been quantitatively determined as they have for the concrete type. Although a general knowledge of the behavior of flexible-type surfaces suggests no likelihood that they react to differences in loading in a manner markedly different from concrete pavements, the obvious fact that comparative tests of a satisfactory nature have not been made is not calculated to discourage the free assertion that all would be different were all our roads of the flexible-surface type.

Belatedly to seek the facts in this regard it is the intention of State highway officials to arrange for at least one, and perhaps two controlled traffic tests of flexible-type pavement at an early date. The divising of appropriate methods of measurement of the effect of load in this case present some problems which probably can be satisfactorily solved. When suitable measures are applied, it is, in the speaker's opinion, to be expected that they will reveal relations not essentially different from those demonstrated to exist in the behavior of rigid pavements.

In the meantime, there is the evidence that our pavements of an extensively used type--pavements that rate among all of the existing pavements certainly in the class of the stronger--that these pavements in the greater part of their existing mileage are overtaxed, are shortened in their useful lives, and are maintainable only at materially increased expense when the axle loads of vehicles rise in substantial frequency above the 18,000 pounds for which most of them have actually been designed. This, as it appears to a highway engineer--I may add, to nearly all highway engineers, to a substantial segment of the American public, its lawmakers and its governors--this it appears is a sufficient answer from one point of view to the question, "Why 18,000 pounds?" It seems to supply sufficient reason to justify the 18,000-pound axle load limit as a measure for the protection of existing highways from undue wear and tear.

18,000 Pounds as a Design Limit

If, now, we may briefly consider the 18,000-pound limit in its other aspect--as an assumed axle weight to be used by engineers as a basis of future road design--we will speak in less positive accents.

New roads can be built for heavier loads more cheaply than old roads can be operated under them. The building of the new roads will be extended over a somewhat prolonged period. The greater capital outlay will probably make possible a reduction of the current expense of the highway system which climbs higher and higher by the propulsion of excessive loads on highways built for lighter loads.

This other aspect of the question presents a complex economic problem which should receive careful attention.

At present, about 5 percent of all motor trucks and combinations as they are operated have axle loads exceeding 18,000 pounds. To a certain extent this percentage is affected by the presence of the legal limits, though only recently has there been much evidence that these limits are widely noticed.

It may be that if the legal constraint were removed more vehicles would be operated with axle loads of greater magnitude. The number in any case would be but a minute percentage of all the vehicles operating over the highway system, including passenger cars--for all of which the highways are provided.

The root incentive to heavier axle loading would remain, as it is, the desire to move more payload in one vehicle.

The first question to be answered--and it is a question that automotive engineers are most competent to answer--is whether it is necessary to increase axle loading in order efficiently to increase payload. On two-axle vehicles the answer is obvious; but what is the economic future of the two-axle vehicle?

Vehicle Operating Savings Offset by Higher Road Costs

If the answer to this first question indicates that some increase of axle loads is desirable in relation to the economy of vehicle operation, then how much increase is desirable? We will remember, of course, that with increase of axle load, in closer relation than with increased payload achieved without axle load increase, the cost of road building will increase. The increased highway cost must be accepted on many thousands of miles of highway. It will be necessitated solely by the heavier vehicles--relatively few in number at most--that utilize the increased axle loading. Who, but the owners of these few vehicles, are to pay this increase of road cost? Will the realizable vehicle-operating economies be sufficient to compensate the heavier charge for road use? These are the economic questions, extremely complex in their manifold implications, that must be puzzled out before we can come to satisfactory conclusions regarding the second aspect of our topical question.

If, in closing, I need give earnest of my interest in the finding of a satisfactory answer to this larger question, I need only mention, I hope, the research that has been undertaken with precisely that object, under the guidance of a committee of the Highway Research Board of which I am chairman, a committee on which distinguished members of your Society are serving in cooperation with representative truck and bus operators and highway engineers. Results of a first phase of this research, conducted in Pennsylvania, have, I believe, been presented before one of your meetings by Mr. Carl Saal. A second and more difficult phase is just beginning. It is of the utmost importance, in my opinion, that we find means to accelerate our somewhat lagging steps; and I pledge you my earnest best to do so.

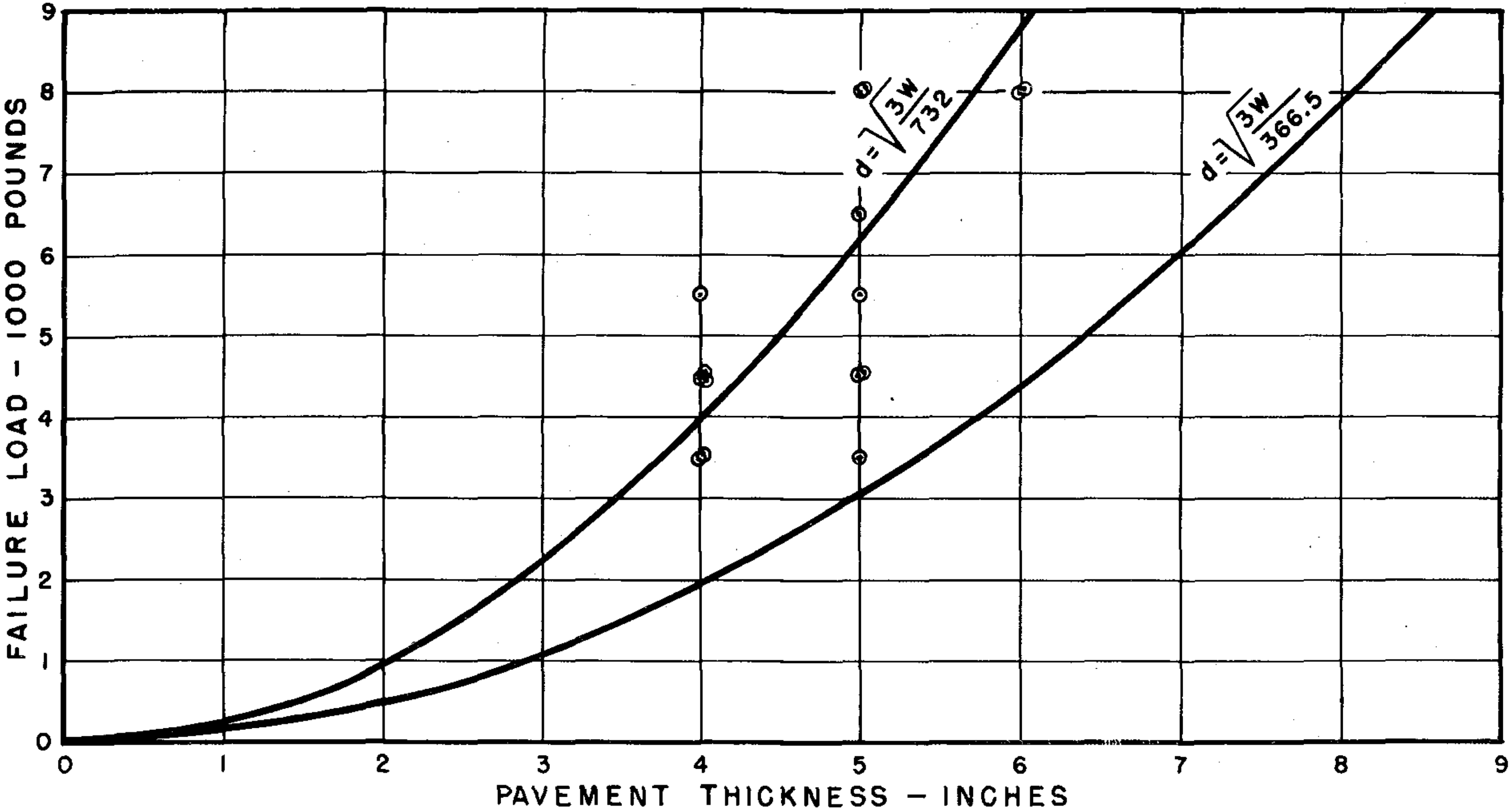
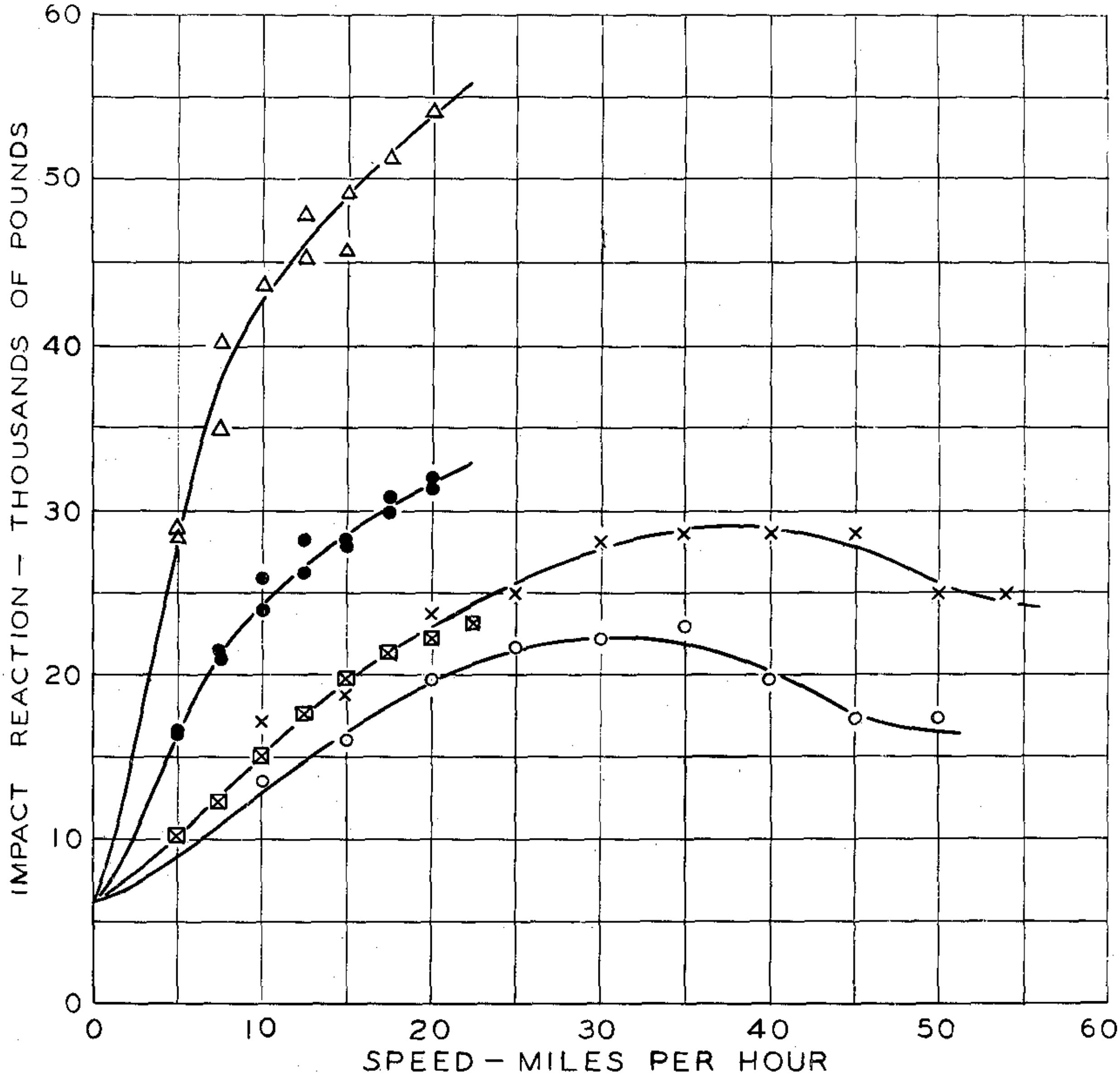


FIGURE 1. — RELATION OF CONCRETE PAVEMENT THICKNESS TO LOAD CAUSING CORNER BREAK IN BATES ROAD TEST



Δ — WORN SOLID TIRES ON TRUCK.
● — NEW SOLID TIRES ON TRUCK.
⊠ — HIGH PRESSURE TIRES ON TRUCK. (100 POUNDS PER SQUARE INCH.)
× — HIGH PRESSURE TIRES ON BUS. (100 POUNDS PER SQUARE INCH.)
o — BALLOON TIRES ON BUS. (61 POUNDS PER SQUARE INCH.)

FIGURE 2.- COMPARISON OF DATA FROM SEPARATELY CONDUCTED TRUCK AND BUS IMPACT TESTS, SHOWING REACTIONS PRODUCED BY VARIOUS TYPES OF TIRE EQUIPMENT. PLOTTED POINTS DENOTE IMPACT REACTIONS CAUSED BY DROP AFTER 1½ BY 30 INCH INCLINED PLANE

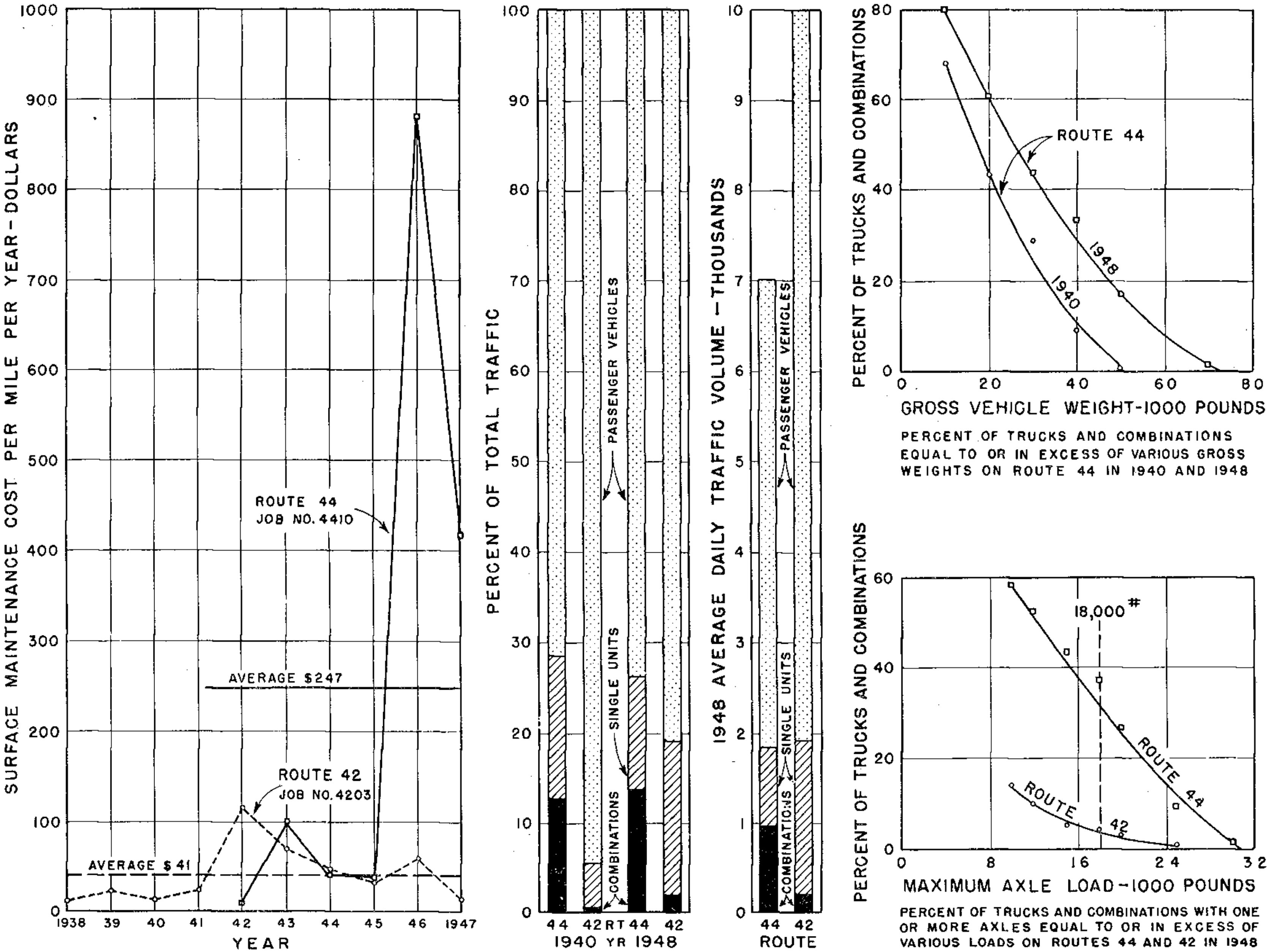


FIGURE 3.-PAIR "A"-COMPARISON OF NEW JERSEY STATE ROUTES 44 AND 42

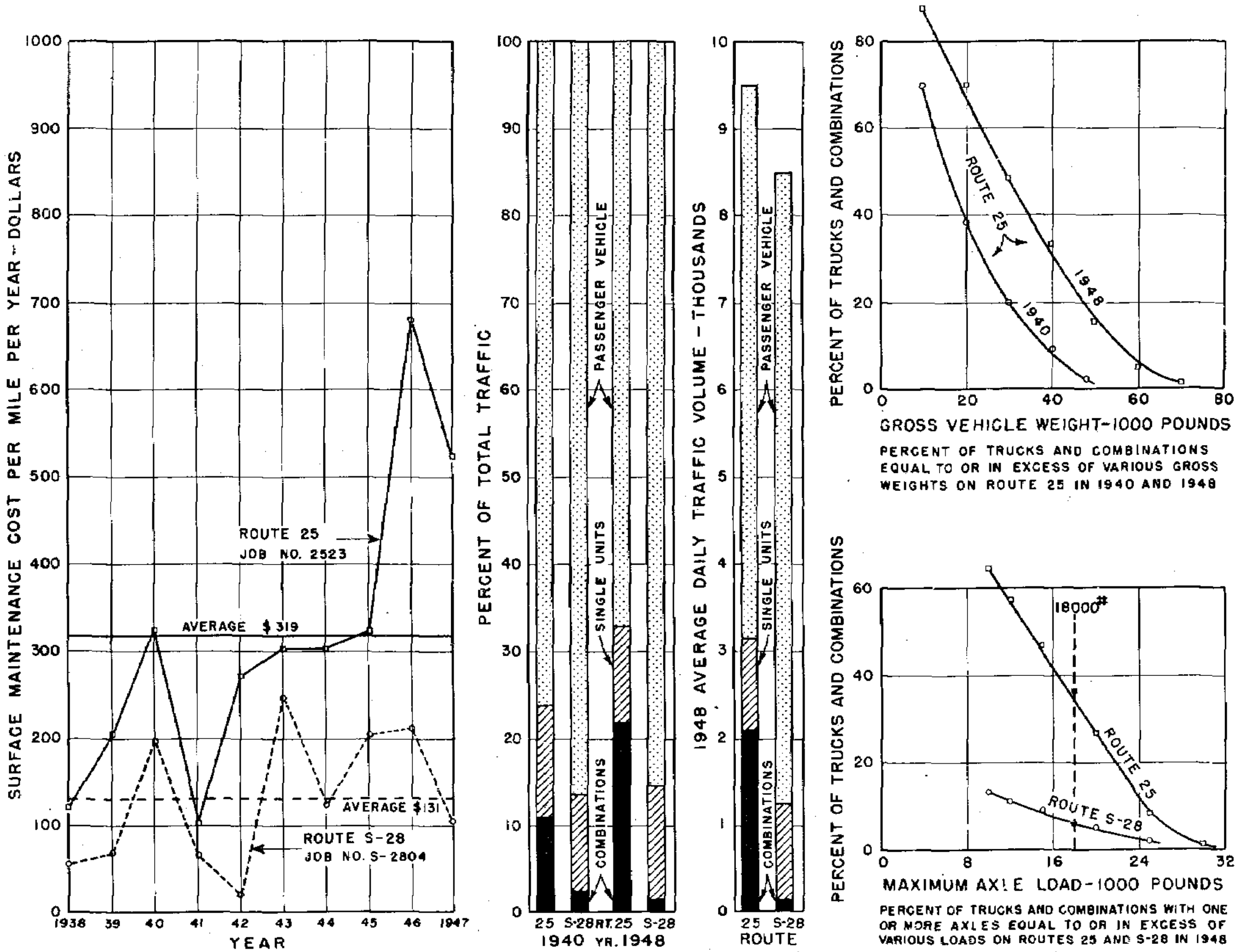


FIGURE 4.-PAIR "B"-COMPARISON OF NEW JERSEY STATE ROUTES 25 AND S-28

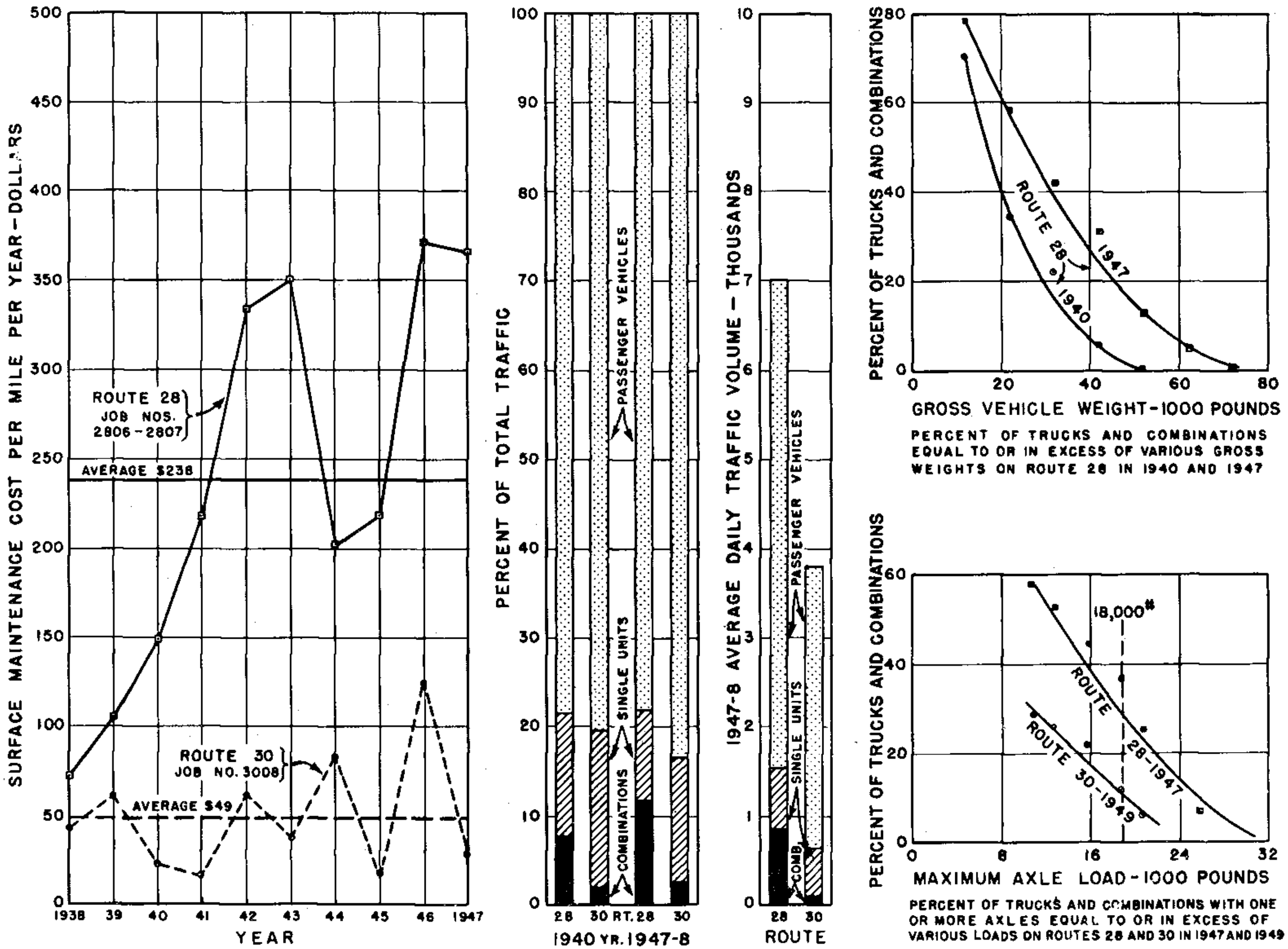


FIGURE 5-PAIR "C"- COMPARISON OF NEW JERSEY STATE ROUTES 28 AND 30

WHY 18,000 LB? AXLE LOAD EFFECT ON HIGHWAY DESIGN AND OPERATION

Herbert S. Fairbank, Bureau of Public Roads

This paper was presented at the SAE Nat'l Transportation Mtg., New York City, Oct. 16, 1950.

IN the question which serves as the principal title of this paper, an attentive ear may detect overtones of skepticism. The instinctive response of one firmly convinced of the reasonableness of 18,000 lb as a limit of the weight to be carried by a single axle of a motor vehicle might conceivably be a somewhat bickering, "Well, why *not* 18,000 lb?"

The speaker will eschew the bickering response. Instead, he will attempt a reasoned answer to what he will assume to be a sincere question.

Some part of the heat that is generated in many discussions of the question doubtless arises out of a misunderstanding between the disputants as to the precise nature and purpose of the limitation.

The 18,000-lb axle load limit *is* a limit prescribed by law in 34 states as a regulation binding upon the operation of present vehicles over present roads, its purpose being the protection of the existing road system against undue wear and tear. It may also be regarded, and is so regarded by many who have no other than the public interest in view, as a limit of the weight which roads should now be designed to support, and hence a continuing limit upon the design and loading of vehicles.

It will be of advantage in our discussion clearly to distinguish these two concepts of the nature and purpose of the limitation. Accordingly, let us first consider the necessity, or may we preferably say the advisability, of 18,000 lb as a limit regulatory of present vehicle operation for the prevention of undue wear and tear of existing roads.

What are the roads which the 18,000-lb axle load limit is intended to protect? What are their character and their condition?

In some of the comment of opponents of the limit the assumption seems implicit that all, or the only considerable part of all, heavy vehicle movement is confined to the primary highways. It is apparently assumed also that the primary highways are preponderantly of such design as to withstand, without undue distress, the application of axle loads exceeding 18,000 lb in such numbers and frequency as they are likely to occur. There is some vagueness as to just where the limit above 18,000 lb is to be placed, and observation indicates that there are operators of vehicles who may suppose that the only limit to be respected should be one of their individual choice, be it 20,000 or upwards of 40,000 lb.

But, for the moment let us confine our attention to the particularity and the character and the condition of the roads which the 18,000-lb axle load limit is intended to protect.

Certainly they consist of the upwards of 350,000 miles of primary state highways. But they do not consist of these only. They include a substantially greater mileage of secondary and even tertiary roads, over which the heavier vehicles are regularly operated in significant numbers. There are, for example, some 500,000 miles of secondary and lesser roads over which milk collection trucks operate daily. These trucks are definitely not light vehicles. Their axle loads may, and do, reach and surpass the limit of 18,000 lb. There are also the tank trucks that regularly deliver gasoline and heating oil to farms and communities on local roads. The mileage of such roads affected by these operations cannot be closely dimensioned, but it is considerable; and these vehicles also have the potential and the actuality of axle loading up to and beyond 18,000 lb.

Coal is moved regularly by truck from mines to consumers in heavy loads over secondary and lesser roads, as well as primary highways. Sand and gravel pits and stone quarries are very often located on local roads, and the loads of these construction materials – among the heaviest observed on our highways – must perforce be moved over the local, as well as the primary roads. In parts of the country logging operations, likewise generative of heavy axle loading, utilize secondary and lesser roads to perhaps a greater extent than primary highways.

Nor can it presently be assumed, as once it could with some assurance, that the movement of farm produce, arising largely from origins on local roads, is a movement accomplished in light vehicles. Many of the vehicles operated by farmers' cooperative organizations and by the middleman buyers of farm produce, are heavy vehicles and vehicles of heavy axle loading, as, also, is the modern mechanized equipment of agriculture itself, which is by no means confined to the fields and farm lanes.

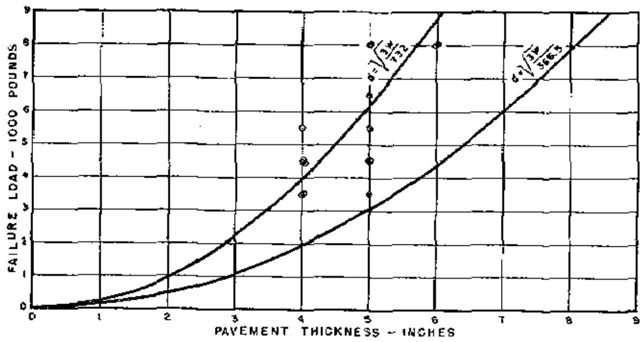


Fig. 1 – Relation of concrete pavement thickness to load causing corner break (Bates road test)

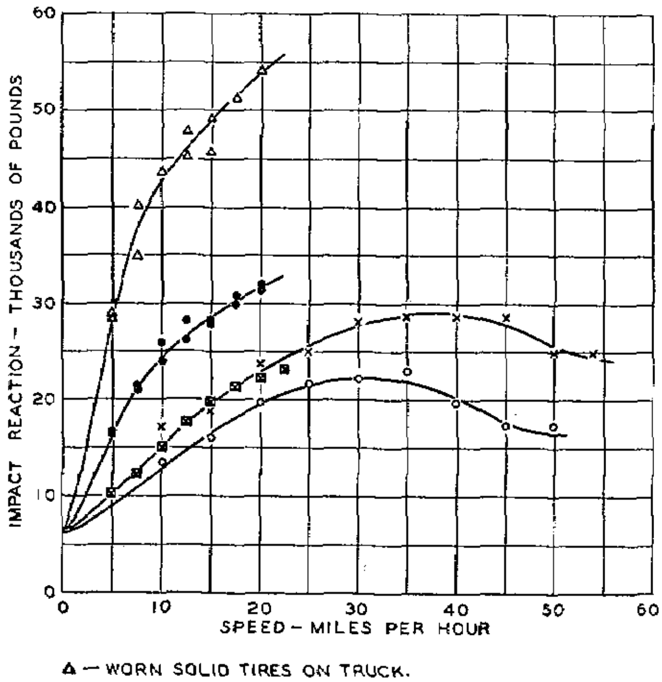


Fig. 2 – Comparison of data from separately conducted truck and bus impact tests, showing reactions produced by various types of tire equipment – plotted points denote impact reactions caused by drop after 1½ by 30 in. inclined plane

And, then, there are times when, with seasonal load restrictions enforced on primary highways in recognition of their temporarily frost-weakened condition, drivers of vehicles that would be rated as too heavy in their axle loads for the primary roads find other and less diligently patrolled routes to their destinations via the lesser roads.

So, it is definitely not correct to assume that a limit of axle loading is required solely for the protection of primary highways upon which the heavier vehicle loading may be presumed to be confined. The need of protection extends also to a large mileage of local secondary and lesser roads.

Turning now to the character of the roads that require protection – roads which, as we have observed, are of secondary and lesser, as well as primary, classification, it is perhaps unnecessary to labor the point that a great part of the secondary and lesser mileage is of relatively frail construction. That is a matter of common knowledge.

However, there appears to be an impression abroad that the primary highway system of the United States is rather uniformly improved in such manner as to enable it to serve, without undue distress, a heavy vehicle traffic of considerable proportions. More particularly, there appears to be the impression that axle loads exceeding 18,000 lb, in such numbers as they may and do occur, do not actually constitute a threat of undue wear and tear of the primary highway system. Again, it may be observed in passing, the magnitude of the excess over 18,000 lb and the frequency of such excessive loading presumed to be feasible are apparently not particularized in the minds of those who believe that the primary roads will withstand such applications, whatever they may be.

This impression is markedly erroneous. The primary highway system of the country is not all of one kind. It is not all of one condition. It is not all of one age. Its character and its qualities are the antithesis of these. It is a system of wide diversity in type of construction, in the dimensions of its design, in the condition of its surfaces and foundations, and (particularly relevant to the present discussion) in its load-supporting capacity. The variation is not a condition of regional occurrence. The roads of one state are not all of strong design, those of another of lesser strength. The age, the type, the condition, the strength of the highway system in every state, the primary, as well as the secondary and lesser roads, varies from short section to relatively short section of every individual route composing the system.

Some of these widely variant sections of road doubtless have strength sufficient to enable them to withstand without appreciable effect applications of axle loads exceeding 18,000 lb in high frequency. Among these the magnitude of load they will so withstand varies. Large parts of the highway system, more particularly the primary highway system, are believed to be able to withstand, without undue wear and tear, the operation of vehicles with axle loads of 18,000 lb in practically unlimited frequency. Still larger parts suffer definite damage when subjected to axle loads of 18,000 lb and less, the extent of the damage varying with the season and the frequency of the heavier load applications.

If, then, the highway system that requires for its protection a regulation of axle loads of vehicles is of such diversity of strength and condition, how does it occur that a particular limit of axle loading – 18,000 lb – is chosen to afford the desired protection? The question appears to be reasonable. Obviously, considering the qualities of the situation as described, it can receive no wholly indisputable answer. It can, and does, find a reasonable answer.

As a limit of vehicle axle loading, 18,000 lb is not, as some have said, just a figure materialized out of thin air. As a measure of road protection, it has a greater validity than another limit for which some preference is expressed. I refer to the limit of 22,400 lb, which is established by law in six states. That limit has its origin in nothing other than the fact that long years ago the desirable limit of loading of a solid rubber tire was considered to be 800 lb per in. of width. The width of the widest tire then manufactured being 14 in., the maximum desirable weight per tire turned out to be 11,200 lb, and the desirable combined loading of two tires on one axle, 22,400 lb. This limit, which had some relevance to a type of tire no longer extensively used, has not now, and never has had, any rationally predetermined relation to the supporting capacity of existing roads.

In contrast, the 18,000-lb axle load limit has definite basis in the estimated safe supporting capacity of a particular type of road of a particular dimension. The type is a widely prevalent type – concrete. The dimension is a preponderant dimension of roads of that type – an edge thickness of 9 in.

The estimate of the safe axle load capacity of concrete pavements of 9-in. edge thickness is based upon the mathematical theory of the behavior of slabs supported on elastic foundations, as developed particularly by the late Dr. H. M. Westergaard, confirmed and supplemented by numerous tests and experiments made both before and after Westergaard's demonstrations.

The Bates road test, conducted by the Division of Highways of the Department of Public Works and Buildings of Illinois in 1922 and 1923, was one of the earliest, and is perhaps the most widely known, of the many experiments that have been made. It is only one of many experiments that have been made, all with the same purpose and similar results, including an extended series of tests by the Bureau of Public Roads at Arlington, Va.

To attempt a recital of the findings of these tests in detail would unpardonably extend the length of this paper, and for engineers such a recital is assumed to be unnecessary. Reports of the more significant tests have been published. They can be studied and understood by engineers.

THE 18,000-lb axle load limit is prescribed by law in 34 states to protect our roads against undue wear and tear.

The philosophy and reasoning behind the imposition of this limit are discussed by the author, who is a public official.

HERBERT S. FAIRBANK has been deputy commissioner of research, Bureau of Public Roads, since 1943. Joining the Bureau in 1910 as a civil engineer student, he has since been editor of "Public Roads," a journal of highway research published by the Bureau, and chief, division of information. Mr. Fairbank graduated from Cornell University with a degree of civil engineer.

It will suffice here to describe the nature of the evidence developed by the tests and the mathematical theory.

Bates Road Test

The pioneer Bates road test was a traffic test of a road constructed for the experiment. Included in the road were 68 experimental pavement sections of varying material composition and design. Twenty-nine of the sections were paved with concrete of various thickness, design, and composition, some with, and some without, reinforcement.

These varying sections were subjected to a controlled test traffic consisting of Liberty trucks equipped with solid rubber tires. Starting with a loading of the vehicles which resulted in an application of 2500 lb by each rear wheel, a number of trips over the several sections was made with that loading. Subsequently, the loading was increased to apply successively by a substantial number of trips at each load, various wheel loads, ranging up to 13,000 lb, corresponding to an axle load of 26,000 lb.

Some of the pavement types represented were severely damaged and virtually destroyed under the lighter increments of load. In the case of some of the types it was difficult to discern a relation between the pavement behavior and the magnitude of the axle load. In the case of the sections involving concrete either as a base or a surface, however, such a relation could be observed, and it was most clearly discernable in the case of the concrete pavement sections. These sections could be observed to crack under the loading, and the increments of loading at which cracks formed in sections of the several thicknesses and designs represented could be taken as an approximate measure of their strength or load-supporting capacity.

Analyzing the results of the tests at their conclusion, Clifford Older, chief engineer of the Division of Highways, drew a relation (Fig. 1) between

Table 1 – Combined Stresses for Load at Slab Corner and Partial Subgrade Support (Corner Warped Upward)

Slab Thickness, in.	Dual Wheel Load, lb.		Tire Size-Dual, in.	Stress, psi		
	Static	Impact		Load	Warping	Combined
7	8,000	10,000	10.00-20	373	29	402
	9,000	11,250	11.00-20	404	29	433
	10,000	12,500	12.00-20	436	29	465
	11,000	13,750	12.00-22	456	29	485
8	8,000	10,000	10.00-20	304	32	336
	9,000	11,250	11.00-20	330	32	362
	10,000	12,500	12.00-20	357	32	389
	11,000	13,750	12.00-22	381	32	413
9	8,000	10,000	10.00-20	255	34	289
	9,000	11,250	11.00-20	278	34	312
	10,000	12,500	12.00-20	300	34	334
	11,000	13,750	12.00-22	319	34	353
10	8,000	10,000	10.00-20	217	37	254
	9,000	11,250	11.00-20	237	37	274
	10,000	12,500	12.00-20	257	37	294
	11,000	13,750	12.00-22	278	37	315

Westergaard corner formula (empirically modified):
$k = 200$
$E = 4{,}500{,}000$
$\mu = 0.15$

Table 2 – Combined Stresses for Load at Interior of 12-Ft by 20-Ft Slab with Full Temperature Warping (Afternoon of Hot Day)

Slab Thickness, in.	Dual Wheel Load, lb.		Tire Size-Dual, in.	Stress, psi		
	Static	Impact		Load	Warping	Combined
7	8,000	10,000	10.00-20	150	232	382
	9,000	11,250	11.00-20	165	232	397
	10,000	12,500	12.00-20	178	232	410
	11,000	13,750	12.00-22	192	232	424
8	8,000	10,000	10.00-20	117	254	371
	9,000	11,250	11.00-20	128	254	382
	10,000	12,500	12.00-20	139	254	393
	11,000	13,750	12.00-22	150	254	404
9	8,000	10,000	10.00-20	94	274	368
	9,000	11,250	11.00-20	104	274	378
	10,000	12,500	12.00-20	113	274	387
	11,000	13,750	12.00-22	122	274	396
10	8,000	10,000	10.00-20	79	284	363
	9,000	11,250	11.00-20	87	284	371
	10,000	12,500	12.00-20	94	284	378
	11,000	13,750	12.00-22	102	284	386

Westergaard formula for interior loading:
$k = 200$
$E = 4{,}500{,}000$
$\mu = 0.15$
$Z = 0.05$
$L = 1.75$

the edge thickness of the slab-type pavement sections and the magnitude of the respective wheel loads at which significant cracking occurred in the slabs of each thickness. This relation he found to conform closely with the equation:

where:

$$d = \sqrt{\frac{3W}{s}}$$

d = Depth of pavement, in.

W = Wheel load, lb

s = Modulus of rupture of material of slab in cross bending

The determined modulus of rupture of the concrete of which the slabs were formed averaged 700 psi or better. This, according to the relation expressed, would indicate that a slab of 6-in. edge thickness should be cracked by a wheel load of 9000 lb, and the 6-in, slabs cracked under wheel loads of that magnitude or a little less.

Effect of Fatigue

It was recognized that the cracking or failures observed in the tests were the result of a comparatively infrequent application of load. Most of the increments of load were applied only 3000 times. In the whole test, with wheel loads increasing from 2500 to 13,000 lb, a total of 50,000 load applications was the maximum experienced by any test section.

It was known that concrete, in common with other materials, is subject to fatigue, and will eventually fail under some repetition of stress that it will withstand once or a few times repeated.

To test the ability of concrete to withstand repeated stress, a machine was devised to apply repeated loads to concrete beams. From the tests made with this device, Older drew the following conclusions, which he reported in a paper presented before the American Society of Civil Engineers in 1924:

"Plain-concrete beams or slabs will sustain without failure from bending an indefinite number of repetitions of a load if the tensile fiber stress induced is less than 50% of the modulus of rupture. At the present time (Dec. 1, 1923) there are in the fatigue machine test beams that have withstood without failure about 5,000,000 repetitions of a load sufficient to produce a fiber stress of approximately 50% of the modulus of rupture.

"For loads causing fiber stress in excess of 50% of the modulus of rupture, the tendency to failure increases rapidly with the increase of this excess of stress. For instance, loads causing fiber stresses of about 60% of the modulus of rupture, repeated a few thousand times (rarely more than 30,000) will cause failure; for stresses in excess of 70% of the modulus of rupture, only a few hundred repetitions (rarely more than 5000) are required."

In view of these findings Older suggested that the value of S that should be used in the equation $d = \sqrt{\frac{3W}{s}}$, in the design of concrete pavements expected to withstand numerous applications of specific maximum loads, should be a value no greater than 50% of the modulus of rupture of the concrete. If, then, the modulus of rupture be assumed at the common value of 700 psi, the indicated slab thickness required for the safe support of 9000-wheel loads (18,000-lb axle loads) would be 8.8 or, practically, 9 in.

In disparagement of the Bates road test, it has often been remarked that the test pavement sections were laid directly on a typical Illinois black soil, imperfectly drained. Let it here be observed that a large part of the existing Illinois highway system and similar parts of the systems of other states have foundations of about the same character.

It is also remarked that the Bates road test vehicles were equipped with solid rubber tires, not with low-pressure pneumatic tires such as we use today. The Bates road vehicles were equipped with solid-rubber tires; and the vehicles were driven at a speed between 12 and 15 mph. It is one of the findings of later tests, particularly the impact tests conducted at Arlington, Va., by the Bureau of Public Roads, that the impact force delivered to a road surface by a wheel passing over an obstruction on the road is approximately the same for a solid-tired vehicle driven at 12 to 15 mph and for a high-pressure pneumatic-tired vehicle driven at 40 mph (Fig. 2). The impact delivered by a balloon-tired vehicle is of a slightly lower order.

Bates Road Conclusions Confirmed

The Bates road test was a pioneer test. In many respects it did not measure up to the requirements of a thoroughly scientific test. But, let me add at once that the principal pavement design conclusions drawn from this pioneer test have been remarkably confirmed by all later tests much more scientifically conducted, and by the mathematical theories of slab design of later development.

Failure from Load, Warping Stresses Combined

We now know that the critical stresses developed in concrete pavement slabs are not those engendered by load alone, but the conjunction of load stresses with temperature warping stresses. We know this from many measurements of the actual strains produced in pavements by loads and by warping. And we know that the combined stresses in various parts of a pavement slab reach fatiguing magnitudes for pavements of various thickness under approximately the same loads that Older concluded to be critical. This statement is made with reference to pavements as they are now built, laid on foundations of the better sort now existing and subjected to balloon-tired traffic. It is instanced by Tables 1 to 4, which give stress values calculated by the Westergaard formulas, empirically modified to accord with actual strain measurements to be expected in slabs of various thickness when subjected to various static loads and corresponding impact forces.

The great majority of the concrete pavements now existing are of a quality no better, and rest upon support no more firm than is assumed in these tables. The preponderant cross-sectional design is of the 9-7-9-in. dimensions. Many existing pavements are of lesser supporting strength; few will support a heavier load.

Concrete Roads Overtaxed

It seems clear to a highway engineer that the great majority of the country's existing concrete pavements are overtaxed by axle loads exceeding 18,000 lb. Accordingly, highway engineers are not surprised when their observation and daily experience indicate that, as the numbers of such excessive loads have multiplied in recent years, the occurrence of concrete pavement failure has alarmingly increased, and the cost of maintenance of the existing pavements has increased in like disturbing progression.

Without detail of description reference is made here to Figs. 3, 4, and 5, which compare the maintenance cost experience on pairs of New Jersey concrete highways of closely similar physical characteristics but differing in each pair in the magnitudes of traffic loads applied to them. A fuller description of these charts may be found in Appendix III, entitled "Road Damage by Trucks in New Jersey," of a statement made by Commissioner T. H. MacDonald of the Bureau of Public Roads in hearings before the subcommittee of the Senate Committee on Interstate and Foreign Commerce pursuant to S. Res. 50, June 27, 1950.

The generation of increased maintenance cost of concrete pavements by the operation of increasingly heavy vehicles as indicated in these New Jersey cases is the result commonly experienced in various degrees in all states. The increased costs tell the same tale as the scientific tests and mathematical analyses, and as many observations of the difference of behavior of roads and parts of roads subjected to moderately and excessively heavy vehicles in all parts of the country. The tale is that our concrete roads – most of them – are overloaded,

Table 3 – Combined Stresses for Load at Transverse Edge of 12-Ft by 20-Ft Slab with Full Temperature Warping (Afternoon of Hot Day), No Load Transfer across Joint

Slab Thickness, in.	Dual Wheel Load, lb.		Tire Size-Dual, in.	Stress, psi		
	Static	Impact		Load	Warping	Combined
7	8,000	10,000	10.00-20	304	41	345
	9,000	11,250	11.00-20	333	41	374
	10,000	12,500	12.00-20	358	41	399
	11,000	13,750	12.00-22	389	41	430
8	8,000	10,000	10.00-20	237	38	275
	9,000	11,250	11.00-20	260	38	298
	10,000	12,500	12.00-20	280	38	318
	11,000	13,750	12.00-22	307	38	345
9	8,000	10,000	10.00-20	191	36	227
	9,000	11,250	11.00-20	211	36	247
	10,000	12,500	12.00-20	227	36	263
	11,000	13,750	12.00-22	246	36	282
10	8,000	10,000	10.00-20	158	31	189
	9,000	11,250	11.00-20	173	31	204
	10,000	12,500	12.00-20	187	31	218
	11,000	13,750	12.00-22	203	31	234

Westergaard formula for edge loading (modified to provide full tire area on slab):
$k = 200$
$E = 4,500,000$
$\mu = 0.15$

Table 4 – Combined Stresses in 12-Ft by 20-Ft Slab of Thickened-Edge Design (9-In. Edge 7-In. Center)

Slab Thickness, in.	Dual Wheel Load, lb.		Tire Size-Dual, in.	Stress, psi		
	Static	Impact		Load	Warping	Combined
			Corner			
9-7-9	8,000	10,000	10.00-20	311	31	342
	9,000	11,250	11.00-20	339	31	370
	10,000	12,500	12.00-20	381	31	412
	11,000	13,750	12.00-22	388	31	419
			Interior			
9-7-9	8,000	10,000	10.00-20	150	232	382
	9,000	11,250	11.00-20	165	232	397
	10,000	12,500	12.00-20	178	232	410
	11,000	13,750	12.00-22	192	232	424
			Transverse Edge			
9-7-9	8,000	10,000	10.00-20	304	41	345
	9,000	11,250	11.00-20	333	41	374
	10,000	12,500	12.00-20	358	41	399
	11,000	13,750	12.00-22	389	41	430

Westergaard formulas adapted to thickened-edge cross-section:
$k = 200$
$E = 4,500,000$
$\mu = 0.15$
$Z = 0.05$
$L = 1.75\ l$

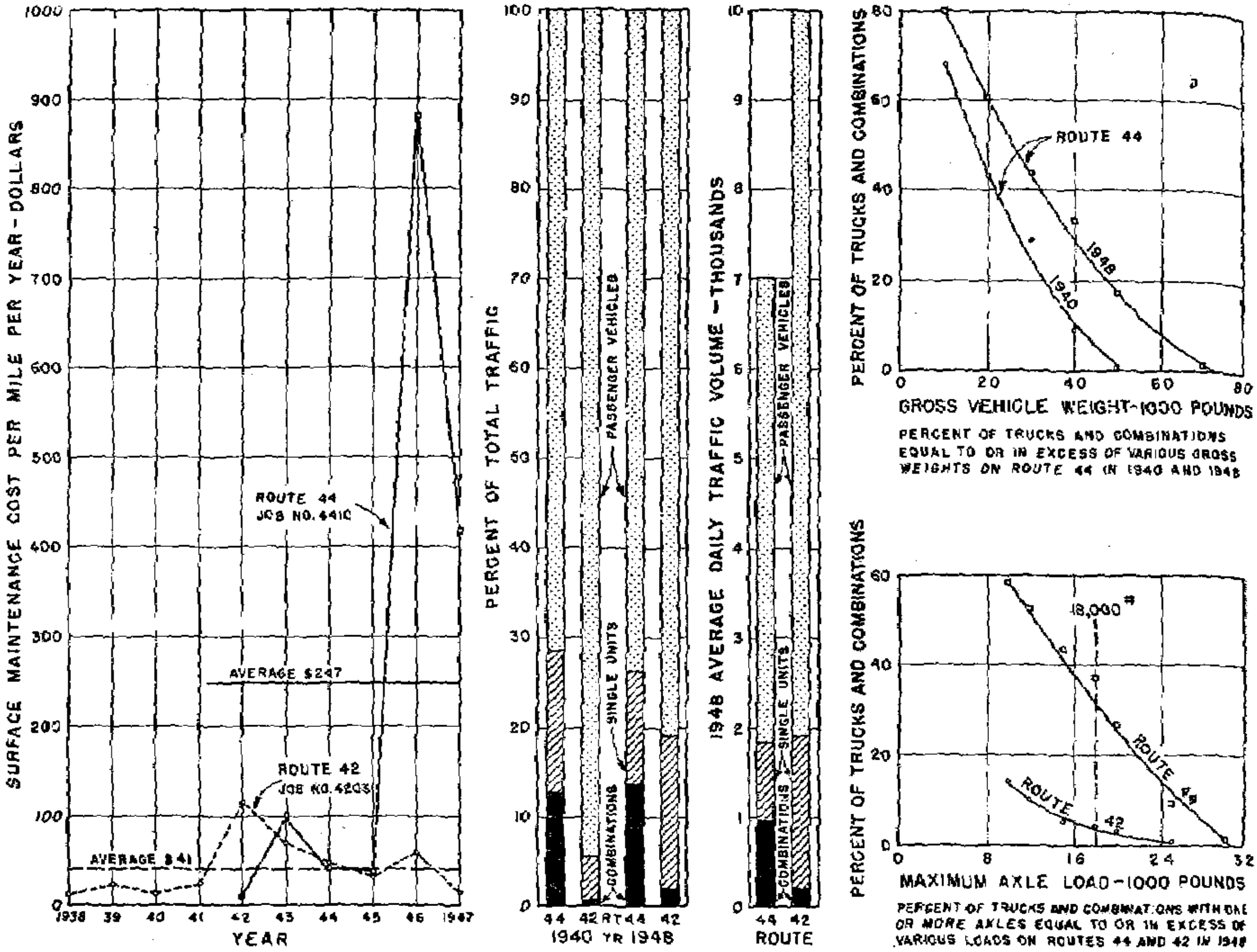


Fig. 3 – Pair A – comparison of New Jersey routes 44 and 42

their lives shortened, and their maintenance costs largely increased by the multiplication of axle loading over 18,000 lb.

Maryland Road Test

At this moment the attention of motor manufacturers (and I presume their automotive engineers), truck operators, and highway engineers the country over is focused on an accelerated traffic test of a road in southern Maryland. The road is a typical mesh-reinforced concrete road with 12-ft lanes of 9-7-9-in. cross-section, laid on a subgrade of about average character. It is being subjected in four of its parts to a controlled traffic of vehicles, which motor manufacturers have donated and petroleum producers are fueling. The vehicles operating over the four separate parts are, respectively, 2-axle vehicles with 18,000- and 22,400-lb maximum axle weights and 3-axle vehicles with 32,000- and 44,800-lb tandem-axle weights. I trust it will not be deemed a prejudgment of the results of this test, which has still some two months to run, if I restate here the expectation I held before the test was begun, that it will simply confirm the conclusions that have been drawn from the previous tests and observations.

It has not escaped my notice that all that has been offered as reason for the 18,000-lb axle load limit as a measure of protection for existing highways has been based on an accumulated knowledge of the behavior of one type of highway. This has been necessary if the reasons were to be stated in quantitative terms. The effects of load on other types of pavement have not been quantitatively determined as they have for the concrete type. Although a general knowledge of the behavior of flexible-type surfaces suggests no likelihood that they react to differences in loading in a manner markedly different from concrete pavements, the obvious fact that comparative tests of a satisfactory nature have not been made is not calculated to discourage the free assertion that all would be different were all our roads of the flexible-surface type.

Belatedly seeking the facts in this regard, state highway officials intend to arrange for at least one, and perhaps two, controlled traffic tests of flexible-type pavement at an early date. The devising of appropriate methods of measurement of the effect of load in this case presents some problems which probably can be satisfactorily solved. When suitable measures are applied, it is, in my opinion, to be expected that they will reveal relations not essentially different from those demonstrated to exist in the behavior of rigid pavements.

In the meantime, there is the evidence that our pavements of an extensively used type – pavements that rate among all of the existing pavements certainly in the class of the stronger – that these pavements in the greater part of their existing mileage are overtaxed, are shortened in their useful lives, and are maintainable only at materially increased expense when the axle loads of vehicles rise in substantial frequency above the 18,000 lb for which most of them have actually been designed. This, as it appears to a highway engineer – I may add, to nearly all highway engineers, to a substantial segment of the American public, to its lawmakers, and to its governors – is a sufficient answer from one point of view to the question, "Why 18,000 lb?" It seems to supply sufficient reason to justify the 18,000-lb axle load limit as a measure for protection of existing highways from undue wear and tear.

18,000 Lb as Design Limit

If, now, we may briefly consider the 18,000-lb limit in its other aspect – as an assumed axle weight to be used by engineers as a basis of future road design – we will speak in less positive accents.

New roads can be built for heavier loads more cheaply than old roads can be operated under them. The building of the new roads will be extended over a somewhat prolonged period. The greater capital outlay will probably make possible a reduction of the current expense of the highway system which climbs higher and higher by the propulsion of excessive loads on highways built for lighter loads.

This other aspect of the question presents a complex economic problem which should receive careful attention.

At present, about 5% of all trucks and combinations as they are operated have axle loads exceeding 18,000 lb. To a certain extent this percentage is affected by the presence of the legal limits, though only recently has there been much evidence that these limits are widely noticed.

It may be that if the legal constraint were removed more vehicles would be operated with axle loads of greater magnitude. The number, in any case, would be but a minute percentage of all the vehicles operating over the highway system, in-

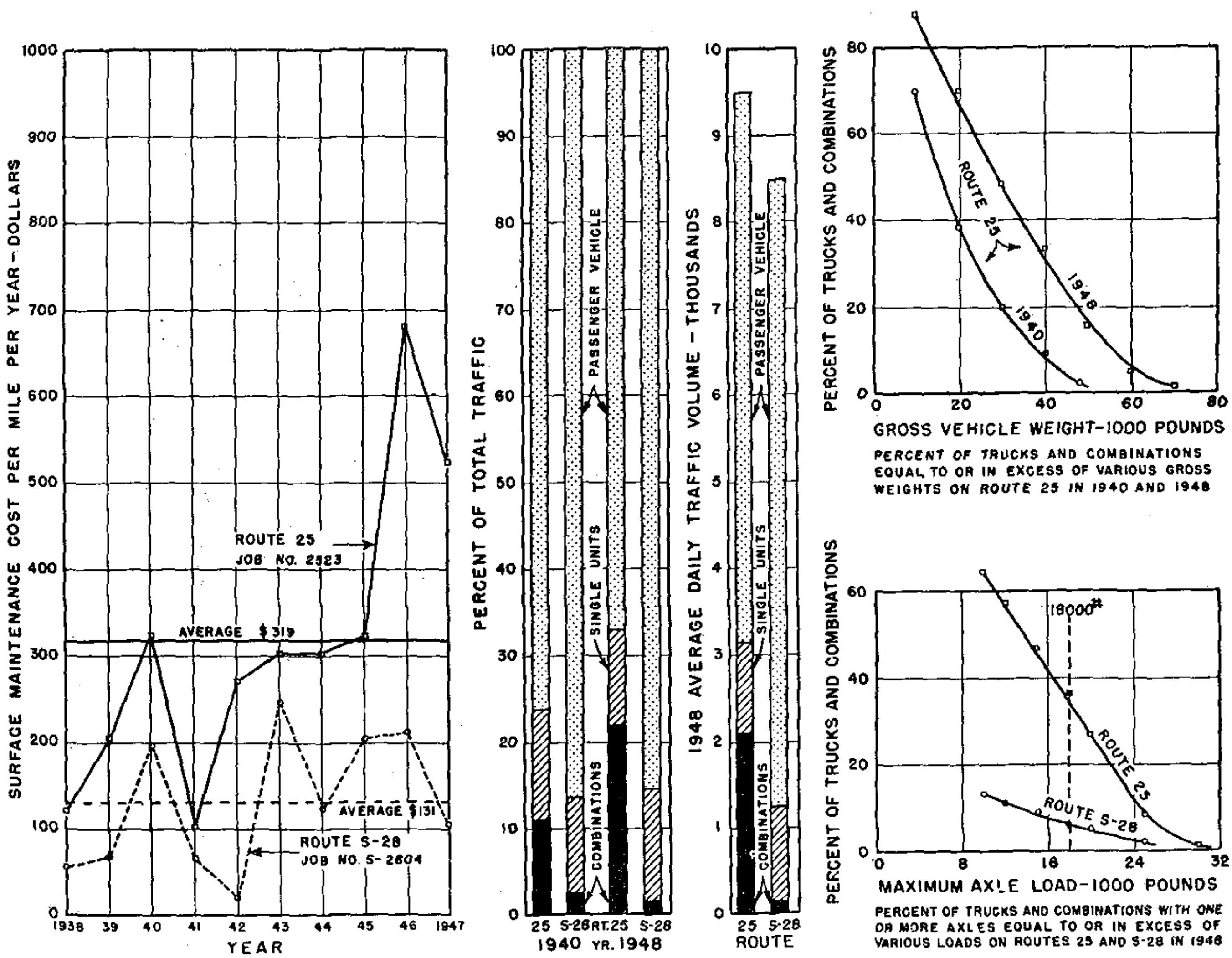


Fig. 4 – Pair B – comparison of New Jersey routes 25 and S-28

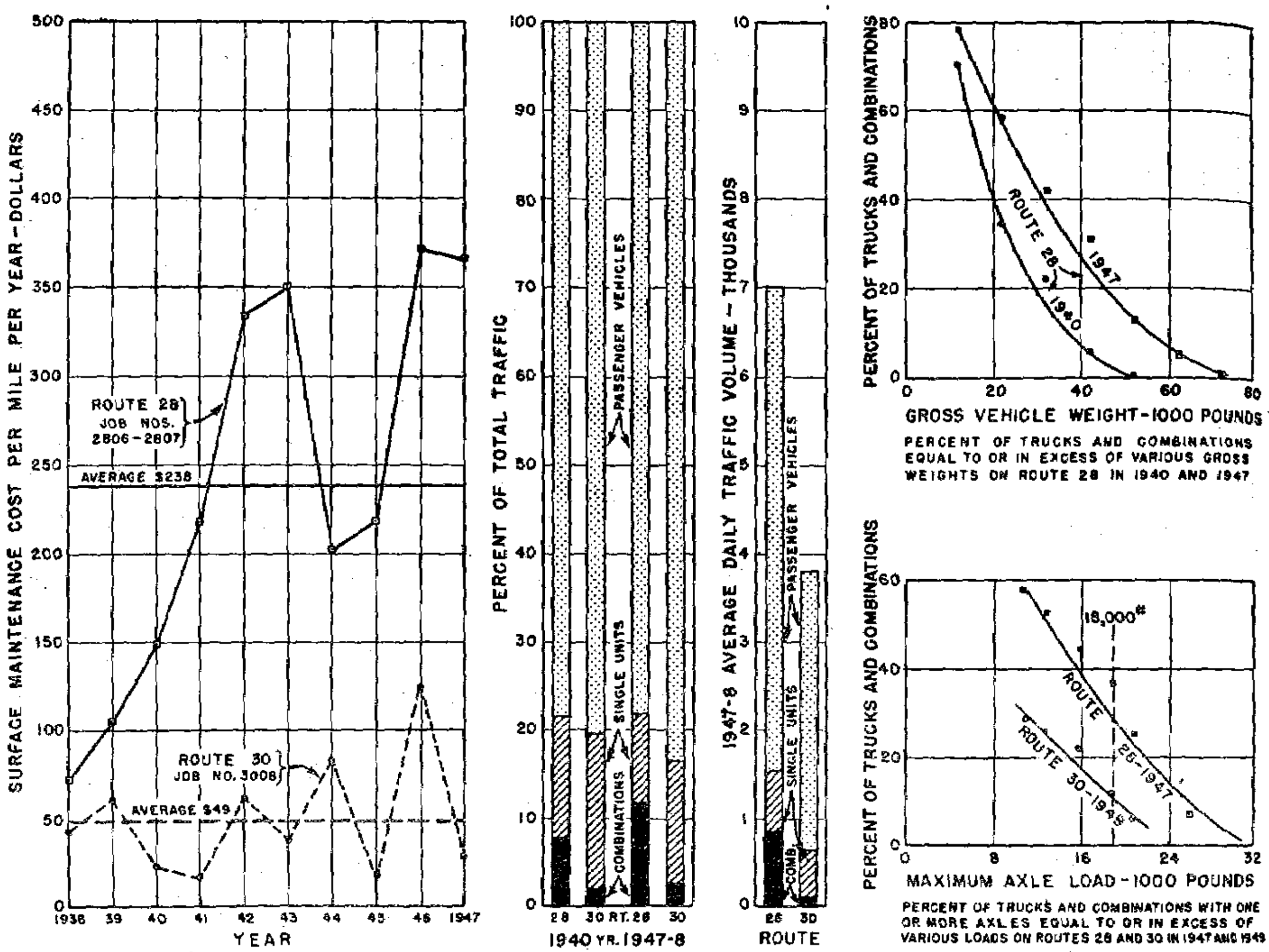


Fig. 5 – Pair C – comparison of New Jersey routes 28 and 30

cluding passenger cars – for all of which the highways are provided.

The root incentive to heavier axle loading would remain, as it is, the desire to move more payload in one vehicle.

The first question to be answered – and it is a question that automotive engineers are most competent to answer – is whether it is necessary to increase axle loading in order efficiently to increase payload. On 2-axle vehicles the answer is obvious; but what is the economic future of the 2-axle vehicle?

Operating Savings Offset by Higher Road Costs

If the answer to this first question indicates that some increase of axle loads is desirable in relation to the economy of vehicle operation, then how much increase is desirable? We will remember, of course, that with increase of axle load, in closer relation than with increased payload achieved without axle load increase, the cost of road building will increase. The increased highway cost must be accepted on many thousands of miles of highway. It will be necessitated solely by the heavier vehicles – relatively few in number at most – that utilize the increased axle loading. Who, but the owners of these few vehicles, are to pay this increase of road cost? Will the realizable vehicle-operating economies be sufficient to compensate the heavier charge for road use? These are the economic questions, extremely complex in their manifold implications, that must be puzzled out before we can come to satisfactory conclusions regarding the second aspect of our topical question.

If, in closing, I need give earnest of my interest in the finding of a satisfactory answer to this larger question, I need only mention, I hope, the research that has been undertaken with precisely that object, under the guidance of a committee of the Highway Research Board of which I am chairman, a committee on which distinguished members of your Society are serving in cooperation with representative truck and bus operators and highway engineers. Results of a first phase of this research, conducted in Pennsylvania, have been presented before the SAE by Carl Saal. A second and more difficult phase is just beginning. It is of the utmost importance, in my opinion, that we find means to accelerate our somewhat lagging steps; and I pledge you my earnest best to do so.

DISCUSSION

Compares Truck Usage Over Highway and in City

—Howard L. Willett, Jr.
Willett Co.

WE know that we all have the same end in view. Mr. Fairbank as a representative of the Federal Government is charged by the Constitution with encouraging commerce between the states. We commercial members of the Society make our bread and butter from the commerce between the states, so we are all trying to encourage and promote it. With this common goal in mind, our only point of disagreement or controversy, then, is, how this can best be done.

Mr. Fairbank says, in essence, that it is cheaper to build new roads designed to carry loads in excess of 18,000 lb than it is to repair the present system when it is damaged by the pounding of overloaded trucks.

He further states that these roads built to carry heavy loads should be paid for by the heavy trucks that make them necessary. This is certainly a logical approach, but when we hear about trucks paying for something, we become very allergic to it because for years we have been paying for things we never received. I am not going to touch on the diversion of highway funds, which is only prohibited by law (although not by practice) in 21 states, but rather explain the difference between truck usage over the highway and in the city.

My company is primarily engaged in local and contract cartage in metropolitan Chicago, the charter motor coach business, and, as a member of the National Truck Leasing System, the truck leasing business. We operate in the Chicago metropolitan area and use the streets of the contiguous municipalities that comprise our area. We do not use the highways that Mr. Fairbank is talking about except for the few open miles between Gary and Indiana Harbor, and so forth. We are not alone in this usage of our streets since there are 84,000 trucks domiciled in Chicago that use these same streets. There are an additional 50,000 trucks in the nearby suburbs whose occupation keeps them in this metropolitan area almost exclusively. There are only 10,000 to 12,000 trucks that enter and leave the area daily to use the highways that the author is talking about.

Thus, 90% of the trucks in the area use the metropolitan streets and only 10% use the highways. We, in this metropolitan area, have been paying for the highways downstate for a long time, and would dislike very much to pay for extra-special highways that we would never use since they are to be built for special trucks that we don't even possess. I am sure this same condition exists throughout the country.

The number of trucks that could use these highways is strictly limited. Contrary to the author's statement, milk from the farmers is picked up in cans by 1- or 1½-ton trucks, brought to a country collecting station, where it is tested for butter fat and cooled before being brought to the city in big bulk tank trucks, which use only the main highways.

Large, heavily loaded gasoline trucks do not deliver to farmers and therefore do not ordinarily use the secondary or tertiary roads. They deliver to bulk plants, where the fuel is loaded into small trucks for ultimate delivery to the consumer.

As a matter of fact, only a small percentage of the trucks built in the United States are large enough to carry 18,000 lb on an axle. This small percentage could be stretched to 8% only by extreme and severe overloading.

Our plea, then, is to consider where the bulk of the trucks operate, how large most trucks are, and spend our time and effort in this direction.

Let us not tar all trucks with a brush that fits only a very few. Let us, in spending, get the bestest for the mostest.

Pledges Cooperation of Truck Operators In Program to Determine Best Limitation

—Juluis Gaussoin
Silver Eagle Co.

AS a truck operator and the president of a state trucking association, it is unthinkable that I would be disinterested—when the very continuation of my occupation depends on the existence of, and permission to use, a reasonably good highway system—which is now a sizeable portion of the established trucking industry's investment in business.

The author has not started a direct condemnation proceedings against the truck operators, the highway engineers, or the highway builders, but his paper may start movements in such directions—to the end that all highway users will be alerted, some with reasonable, and others with radical attitudes.

It is our duty as citizens—and particularly as an engineering society—to concern ourselves with the economic impact of unreasonably reducing the useful life of our present highways and legislating out of use all vehicles that appear to be abusive of highways.

Fundamentally, there are two approaches that may be used to solve this controversy, and they appear to spring from extreme viewpoints:

1. Determine the optimum axle weight that will permit the most economical movement of a ton-mile of payload; then build all highways to accomodate such axle loads. Of course, present highways must be repaired or replaced as they deteriorate.

2. Determine what axle weight causes highway deterioration, then make all such axle weights unlawful.

At first, it may appear that such determinations would be unreasonably and irreconcilably far apart, but it is to be hoped that such is not the case.

This discusser believes that strains imparted by extremely heavy axle loads to tires, springs, frames, axles, and highways—to the point that all are stressed to near their yield point—will bring about such short life that low-cost transportation will not be achieved.

The optimum economic axle weight should be studied and an attempt made to make a definite determination; and other studies made to find out what, if any, additional highway costs would permit the use of optimum economical axle loads. The economics of gross loads have been studied, but this does not supply the answer to the axle load problem.

The reasonable trucker, surely, should be willing to compromise, if necessary, so that his total cost of highway use, depreciation of highway equipment investment, and operating expenses would permit him to move ton-miles of payload at lower cost—if and when such determinations have been reasonably and reliably determined.

Since both truck equipment and highways are made by man, and serve no useful purpose unless used, they can be considered expendable, with maximum economic use from both. We should be careful not to make a determination based entirely on what we now have, which includes errors of the past and could close the door on future progress and efficiency.

The highways and the trucking industry serve the people as a whole, but the best interests of these people will not be served if we tie ourselves so tightly to the past that there is no room to take advantage of improvements in highway and vehicle design. The maximum ability of minimum-strength highways should not be used to set axle load limitations – and, on the other hand, the maximum ability of the largest axles probably would be an unreasonable basis upon which to set highway construction standards.

When the best overall axle weight has been determined, great savings can accrue to the truck operator, such as the possibility of eliminating conflicting state load laws, uniform and cheaper tires and parts, easier procurement of parts and lower inventory, better designed and lower cost equipment, higher resale value, lower depreciation cost because of the present obsolescence probability with changing state laws, and the possibility of eliminating gross load laws, as such, so that the maximum economical use could be made of each axle.

The truck operator is now in a vulnerable position, and he is vitally concerned in this matter. He can quit buying trucks or tires of any particular make that do not serve him well, but he must use the only highways.

I express the view of many truck operators, and of at least one state trucking association, when I pledge our continued interest in and support of studies to determine a best overall economic axle load limitation. I pledge further that we will support legislation and promote programs to reduce the frequency of overloading.

We can probably agree that illegal loads may not be actual overloads in certain cases, and, in some instances, overstressing is actually not illegal, due to improper legislation. Some are definitely of the opinion that certain states, through the acts of the legislators, have so restricted types of equipment that greater than normal highway deterioration has been the actual end result.

Let us look forward, constructive in criticism, cooperative, open to the views of others. Let us season our judgment in studying how to build and maintain highways and equipment to operate upon these highways. Let us do these things to the end that the public will be better served and at a lower cost – permitting a capable, sufficient, and profitable highway trucking industry.

West Coast Operators Favor 18,000-Lb Axle Load Limit

– L. E. Kassebaum

Consolidated Freightways, Inc.

IN commenting on such a controversial subject, it is questionable if much more could be added to the volume of information that has already been published. Mr. Fairbank has outlined to us the reasons why a definite limit is proposed as an individual axle load limit. It can very briefly and simply be expressed also by a sentence in a subtitle of an article appearing in "Western Construction News," dated June 15, 1950, which read, "Because most concrete pavements are 9 in. thick and 9-in. pavements are designed for 9000-lb wheel loads." Perhaps this explanation also emanated from Mr. Fairbank's office.

It is commendable that the purpose of the 18,000-lb axle limit, prescribed by law in 34 states, is for the protection of the existing road system against undue wear and tear. A more liberal view is not inconceivable for axle limits in the future. More comment on this phase may be in order later.

No exception can be taken to the fact that all our country's highways are in need of protection. There must be thousands of miles of roads within the category of 500,000 miles of secondary and lesser roads feeding the rural districts that would not at the present time withstand the 18,000-lb axle presently proposed. The expanding economy of our country requires that highway facilities follow the population. The present-day mechanized farms require better roads to enable the farmer to use trucks of a capacity that will allow him to operate efficiently. It is realized that the expenditure to bring secondary roads up to standard would be staggering.

In the Northwest we are faced with the problem of maintaining highways to stand up under the wear and tear imposed by logging trucks. Most operations of these vehicles are on secondary highways which in many cases do not stand up under normal or 18,000-lb axle loading, but overloading and weather also take their toll. Some of the larger logging operators have built private roads, thereby getting around the restrictions, regulations, licenses, and taxation imposed by governmental agencies. One such road is a 20-mile stretch in Oregon built with 12-in. gravel and a light bituminous surface. Equipment grossing 142,000 lb is operated over the route. Another private road 35 miles long is being constructed in northern California, which will accommodate gross loads up to 200,000 lb. Of course the axle loadings are far in excess of 18,000 lb. The mention of private roads is not with the thought of increasing axle limits on primary or other highways but as a matter of information only. It is entirely possible that some worth-while data could be developed from the methods of construction and effect of extreme axle weights.

Please do not assume from what has already been said that axle weights in excess of 18,000 lb are being advocated at the present time. We of the West Coast are advocates of the 18,000-lb axle and diligently try to live within the law. It is true that almost any operator at some time or another will find himself in violation of axle overloading, regardless of all precaution taken. Western carriers as a group, using Western equipment, are the lesser violators of overloading and are proponents of rigid enforcement and adequate penalties. In trying to live within the law (the 18,000-lb axle) it has been necessary to experiment with and develop equipment that will produce the most revenue per mile, consistent with operating costs.

At the present time you will find in the West some 4-wheel trucks with 4-wheel trailers, a considerable number of dual or 6-wheel tractors with a dual-axle semi-trailer, and also some 6-wheel trucks and 6-wheel full trailers. There is a tendency at the present time to go to a 4-wheel tractor, a single-axle semitrailer, and 2-axle full-trailer combination, commonly known as doubles. Size and weight are two of the primary factors governing the efficient operation of motor transportation. Both are essential for the hauling of general freight.

All 11 of the Western states have adopted the 18,000-lb axle limitation and all but two of our states officially permit at least 32,000 lb on tandem axles. The variations come in the limitation of loadings on axle groups and on overall combination grosses. The Western Highway Institute, represented by John L. Springer, president, which represents the operators in that area, has presented to the Western Association of State Highway Officials the following:

1. The 18,000-lb limitation for single axles.
2. A graduated scale ranging from 32,000 lb to 46,400 lb for axle group spacing between 4 ft and 18 ft.
3. A graduated scale up to a maximum of 76,800 lb for gross loads based on the overall spacing between the first and last axles of combinations.

Somewhere recently appeared an article to the effect that the 18,000-lb axle load restriction is the maximum that ever will be considered by AASHO and the PRA, even for the 40,000 miles of new interstate highways to be constructed. In referring to Mr. Fairbank's original remarks that the 18,000-lb limitation was for the protection of existing highways, it would appear that 18,000 lb would not necessarily be the maximum capacity desired. If progress is to continue in this country, with further increases in population, and with technological improvements, there should be no maximum that would stifle advancement.

If the highway officials and legislatures of some states feel that the people's best interest would be served by exceeding the limits of an 18,000-lb axle, there should be no opposition.

Further, it might be well to quote an article from a booklet entitled "Highway Transportation Story," published by the National Highway Users Conference. It mentions roads on Federal Aid Systems, as follows: "The Federal Government is interested in many of these roads because of the obligation imposed in the U. S. Constitution to provide for the national defense, to establish post roads, to encourage commerce among the states, and to promote the general welfare." On July 3, 1950, in "Transport Topics" there was an article by Henry C. Flynn, who quoted Thomas H. MacDonald, Commissioner of the U. S. Bureau of Public Roads, as follows: "The minimum requirements of structural and capacity design of the major routes to serve national interests must be equated to the foreseen needs of the national defense."

Unquestionably all the members of AASHO have been fully informed of axle limits necessary for defense needs; likewise the Bureau of Public Roads staff must have the same information. Knowing this, and also having in mind their duty to the public, and considering all the economic factors that must be observed, one cannot help but feel that they have done their best to arrive at a practical solution to the axle problem.

It is only fitting that all interested groups, organizations, committees, and individuals help to secure the adoption of axle weights as outlined as a national program and put an end to the "war of the axles."

Fig. A – Section of Merritt Parkway, Connecticut

Why Not More Than 18,000 Lb?

– A. B. Gorman
Esso Standard Oil Co.

I THINK Mr. Fairbank's paper has been very well prepared. It is concise, definite, and well argued, and I am sure has been very informative to all of us. Before touching on it, I will discuss some other material.

Fig. A shows the Merritt Parkway in Connecticut, which is about 12 years old. No trucks are allowed on this road. Notice the large crack in the slab and the spalled surface.

Fig. B shows another view of the same Parkway. Notice particularly the long longitudinal cracks – again the spalled surface.

In Fig. C we see asphalt concrete being placed on the pavement to put it back in shape.

Fig. D is a view of the approach to Interborough Parkway at Northern Boulevard in New York. See how the spalled concrete has been patched with asphalt and then the disintegration continued behind the patch. This road is about 13 years old. No trucks – just passenger cars – use it.

Fig. E shows the entrance to Hutchinson River Parkway, Westchester. This piece of road is about 11 years old. Again just passenger cars – no trucks use it.

In Fig. F, we show a section of the old Pelham Bay Parkway in Mt. Vernon. This concrete is about 25 years old. No trucks – just passenger cars use it. Notice the bad disintegration.

Fig. G is a view of the Henry Hudson Parkway. This road is about 12 years old. No trucks use it – just passenger cars. Notice the transverse cracks in the slabs.

Now we are finished with the purely passenger-car roads.

The pavement shown in Fig. H is used by both trucks and passenger cars. It is the entrance to the Brooklyn Battery Tunnel here in Manhattan. The reason I am showing it is that this concrete is only six months old. I believe that no one will blame this damage on trucks – nor can the condition of these road surfaces: buckled pavement in Reading, Pa. (Fig. I), buckled pavement in Pittsburgh, Pa. (Fig. J), pavement in Pittsburgh, Pa., damaged by water (Fig. K).

The pavement shown in Fig. L collapsed before it was opened to the public. As some wag remarked, "It collapsed before even a velocipede rode over it." No passenger car nor truck had touched it. The explanation was butter clay under the surface.

After a quick look at these pictures, I think we can safely draw this generalization: **various forces damage pavements.** Regardless of specific causes, it is quite obvious that other forces than truck axle loadings do break up pavements. Please note I say "pavement" instead of "road." Propaganda against trucks is trying to establish two myths. The first is: big trucks are breaking up our roads. Now it may be true that some of the trucks are breaking up some of the pavements some of the time, but it is not true that all of the trucks are breaking up all of the pavements all of the time, which is what the propagandists would have us believe when they echo the chorus: big trucks are breaking up our highways.

We've seen some of the bad examples, let's see some of the good ones.

The sign shown in Fig. M tells its own story and that of Fig. N, which shows the oldest concrete road in New Jersey, built in 1912. Please note the longitudinal cracks. This old road need make no apologies for them; for remember the Merritt Parkway, a passenger-car road, also had them, and this old road is still doing duty as Jersey highway No. 24 – 38 years old.

Fig. O gives a view of the famous Pennsylvania Turnpike. A beautiful road over which you can travel from one end to the other at a mile a minute. Fig. P shows another part of the same road.

U. S. highway No. 1 in New Jersey, near Elizabeth, is shown in Fig. Q. This road has very heavy truck concentration. The slab in the foreground is 10 in. thick laid in 1928, doing a wonderful job.

The same road southbound and the same story about the slab is illustrated by Fig. R.

Now I want to show a road that is unique. Fig. S shows a section of U. S. 22 in Pennsylvania just going out of Easton toward Bethlehem. The section of concrete under the truck is a new section laid three years ago when the street was widened. The concrete I am referring to is to the left of the truck. This original piece of pavement was laid in 1915, originally a single slab 16 ft wide and about 6 in. thick. So here we have two adjacent pavements, one three years old where the truck is standing, and the other one on the side of the truck, 35 years old, built before anyone thought of truck transportation. U. S. 22 has very heavy truck traffic of the kind that you see in the picture.

Outside the city, the pavement has been covered with

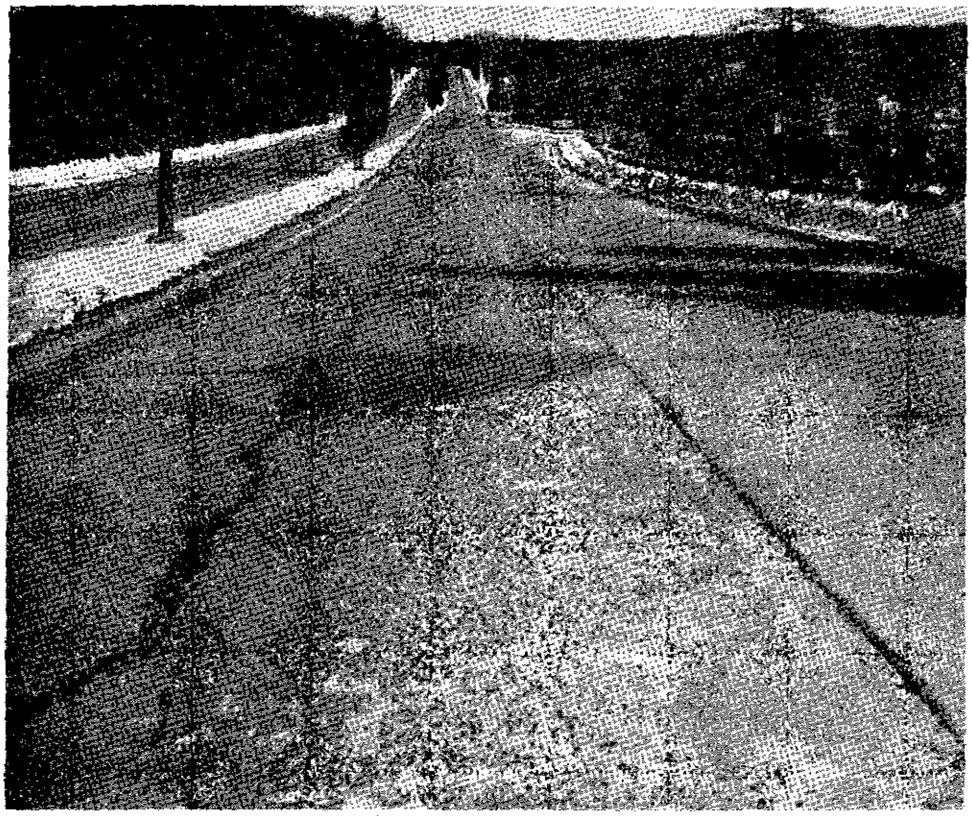


Fig. 8 – Another section of Merritt Parkway

asphalt and made 20 ft wide. The line on the left in Fig. T shows the original edge of the concrete, and there has been a layer of asphalt extended 2 ft beyond that. There is a similar addition of 2 ft on the other side of the concrete pavement.

Fig. U is another view. The strip on the left is the new 3-year-old pavement. The strip on the right is the 35-year-old pavement.

Fig. V gives a close-up view of the two pavements. The one on the left is the old one, the one on the right is the new 3-year-old pavement. Notice the quantities of stone in the surface of the old pavement. The question as to why this pavement has lasted so long and has been so serviceable, so strong, and carried such a burden of truck traffic seems to be answered by the fact that when the pavement was built, the custom was to use a coarse ground cement, and not to wash the sand. This has stood the test of time, weather, and very heavy truck traffic. Later on, road builders discontinued the use of coarse ground cement and used other techniques.

From the entire series of pictures, I think we can draw another generalization: **some pavements are more durable than others.** Assuredly, as you can see, they are.

Now after seeing such a variety of pavement conditions, one first wonders what was the source of the idea of an 18,000-lb axle limitation. In all the diversity of quality which I have shown you, where is the unity among these various pavements to give rise to the concept of an 18,000-lb axle limitation? Obviously it isn't there. Now, if it's that difficult to see in the pavements I've shown you (all of which, except the three at Pittsburgh, are within a 75-mile radius of New York), how much more difficult is it to see it in the pavements of the six-million square mile area of the United States.

So, let us refer to the paper that has been presented. Mr. Fairbank takes as his criterion the Bates road test made in Illinois in 1922 and 1923. He mentions other tests but he devotes most space to the Bates test and the formulas it, plus later tests, produced; and of the Bates test, he says, "The principal pavement design conclusions drawn from this pioneer test have been remarkably confirmed by all later tests much more scientifically conducted, and by the mathematical theories of slab design of later development." Mr. Fairbank gives as the important formula evolved from the Bates test the following:

$$d = \sqrt{\frac{3w}{s}}$$

where:

d = Depth of pavement, in.

w = Wheel load, lb

s = Modulus of rupture of material of slab in cross-bending

The curve at the left of Fig. 1 of Mr. Fairbank's paper is taken from the actual data of the Bates tests and the modulus of rupture established by these data was 732. However, later tests made on concrete beams established a decision that concrete beams will stand indefinite repetitive loads if the load is not over 50% of the indicated modulus and so from this, the curve at the right was developed; and this seems to be the basis for the 9000-lb wheel or the 18,000-lb axle as a maximum load on a 9-in. pavement. The curve runs out of bounds above 9 in. in thickness for the reason I assume that there was no pavement used in the Bates test of greater thickness than 9 in. Notice that, in the formulas, the denominator of the fraction in the curve on the right is only half of the value in the one on the left, 366. This is the accepted formula. I want to make clear what this formula represents, and I am now drawing on Mr. MacDonald's statement before the Myers Committee, known as Senate Committee 50. It expresses, "the relation between the depth of a simple cantilever beam and the magnitude of the weight it will support at its extreme free end." This formula is used because it was found that the corners of the test section were often warped upward as a result of the difference in temperature of the upper and lower surfaces of the slabs. At such time the corners of the slabs were without support of the subgrade, hence the use of the cantilever beam formula. A rough illustration of the idea is shown in

Fig. W and Fig. X. So you can see that this formula applies to corners of the pavement when the pavement is not resting on the subgrade. As to the formula, I have nothing to say. *Mr. Fairbank takes it as his criterion and attests* to its validity.* What I do say is that if the formula is valid, certain conclusions inevitably follow.

The Bates test constituted a very progressive step. It was a real effort to get facts and, as a result, many states began building heavier pavements than they had been and also permitted lifting axle weights from 15,000 and 16,000 lb to 18,000 lb. This was genuine progress and has contributed much to the development of lower cost distribution of goods throughout the country.

As much as we have enjoyed this progress, however, the viewpoint seems now to have changed and, far from the hope of further advancement, we are now faced with the prospect of a nation-wide limitation of 18,000 lb per axle. It is this notion that I want to discuss. I also want to point out some of the harm it will do to our country and to say that it is negative thinking.

Automotive engineering thought in load-carrying capacity, as expressed by actual results, is alreay more than 50% *ahead of highway engineering thought, as expressed* by the Bureau of Public Roads in terms of a nation-wide axle limitation of 18,000 lb. Trucks with 28,000- and 29,000-lb axles are being operated with speed and safety. The question is economic – not strictly engineering. It is economic with the need of expert engineering assistance. Engineering-wise, there is nothing to prevent the manufacture of stronger pavements, as can be easily seen from *the Bates formula:*

$$d = \sqrt{\frac{3w}{s}}$$

and the formula raised to the second power:

$$d^2 = \frac{3w}{366} = \frac{w}{122}$$

$$w = 122d^2$$

Those who remember their "analyt" will recognize this as their old friend the parabola. Working out values from the formula and plotting the curve horizontally for each inch of depth and extending it past the limit of the 9-in. slab, we arrive at the curve shown in Fig. Y. It is obvious from the nature of the curve that strength varies much *more rapidly than thickness.* Notice also the weight value for a 9-in. slab is a 9900-lb wheel or an axle load of 19,800 lb, not 18,000 lb. Those interested in the measure of the strength gained by each additional inch of thickness can ascertain it by taking the first derivative of the equation, which gives the formula for the rate of change of slab strength for each inch of depth:

$$w = 122d^2$$

$$\frac{dw}{dd} = 244d$$

This again brings out the fact of the proportionately greater increase in strength for each increase of unit thickness. Thus, the gain from 9 to 10 in. would be approximately 4600 lb per axle and a 10-in. slab would support a 24,400-lb axle, and the increase from 10 to 11 in. in slab thickness would give an increase in strength of over 5000 lb per axle, thus permitting a 29,500-lb axle for an 11-in. slab. So, if the formula is valid, it is quite possible to make stronger pavements and a great gain in strength is achieved from a slight increase in depth.

One of the iniquities of a nation-wide limitation of 18,000 lb is the penalties it imposes on intrastate traffic. I do not have space to develop this phase of the subject except to say that the penalties are severe on any state which has a strong internal economy. An attempt to set up a nation-wide limitation of 18,000 lb would seem to imply that we have come to the end of an era. In Table A are shown investments in representative roads of certain different times. The one marked A is from Louisiana roads *built in the Twenties* and typifies that period. There was

Fig. C – Asphalt concrete repair

Fig. D – Approach to Interborough Parkway in New York

Fig. E – Entrance to Hutchinson River Parkway

tremendous expansion in automobile production and hard-surface road programs were in motion all over the country. The idea was to get the people out of the mud. A job was done with tremendous haste – either hard surfaces were placed over existing roads built for horse and buggy speeds or new roads were laid with some advance in curves and visibility. Altogether, it was a grand job. The automobiles of the day were, generally speaking, able to utilize most of their power capacity and the roads as built took care of the situation.

But now the advancing technologies of the rubber, automotive, and petroleum industries have created automobiles which have made most of these roads obsolete. In multitudinous instances, curves are sharp, sighting distance for passing is inadequate, safety conditions with moderate traffic density are poor, and modern automobiles cannot be used at anything like their power capacity. Consequently, most of these roads are obsolete today irrespective of any consideration about axle loading.

Also, these three industries have created the modern heavy-duty truck and brought to an end a period unique in the world's history. About 125 years ago, our railroads put the stage coach, the carters, and most of the canals out of business. But now the modern truck is taking much tonnage from the railroads. Most of us grew up when the highways were used only for private passenger traffic, except for short team delivery, and some of us feel irked when a truck gets in front of us on the highway, as though it had no right there, but the fact is the modern truck has restored to the highway one of its ancient functions. Due to trucks, highways are again what they have been since time immemorial – arteries of commerce.

Mr. Fairbank's paper poses two questions. One is, "What axle loads shall generally be carried on existing highways?" As I showed from the number of pictures of various roads, many of these old pavements are disintegrating anyway, so that in substantial measure these roads, if traffic requires it, will have to be rebuilt irrespective of possible truck damage. Such being the case, I feel that any state that wants to help its own internal economy, when it repairs these old roads, should aim for not less than 22,400 lb, and if its present limit is 22,400, for a higher mark. Many old concrete roads, if still usable from the standpoint of visibility, curves, and so on, can have the pavements renewed by leveling the slabs and filling the voids with liquid asphalt and surfacing with asphalt concrete. Recent bids in Pennsylvania for such work were $23,000 a mile for a 20-ft width. We must remember, in dealing with

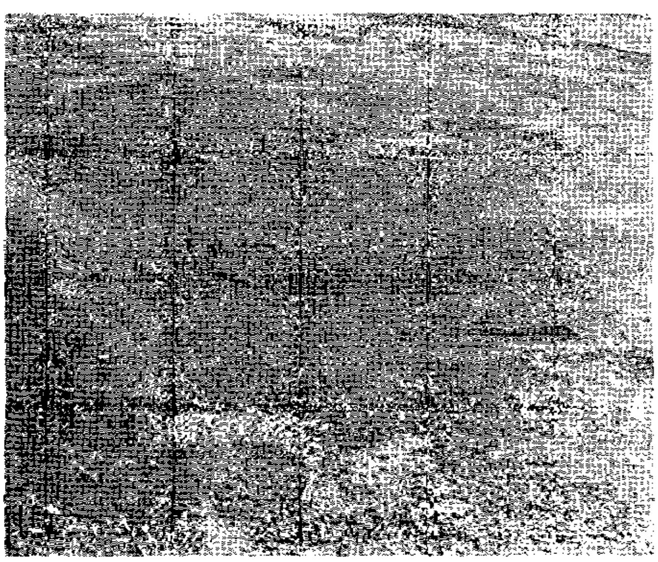


Fig. F – Section of old Pelham Bay Parkway

Fig. G – Section of Henry Hudson Parkway this question, that we are talking about the vital supply of a vast segment of our population. In many states, such as Tennessee, two-thirds of the towns and villages have no other supply but truck.

Any increase in truck expense by axle restrictions must be passed on to the consumer, not as truck freight, but as truck freight plus wholesaler and retailer markups. Forced to choose between increased taxation to provide roads to carry the traffic on the one hand and rising truck costs and markups on the other, I believe I would vote for the better roads because low truck rates benefit ALL the people. Somewhere between producer and consumer, a truck handles the product – sometimes all the way. The first step in such a program of better roads would be absolute non-diversion of all highway funds. The second, the ruthless overhauling of many agencies that dispense the money for road building – to prevent a repetition of the many errors of the past – such as that road down in Maryland, of which state I happen to be a native – I refer to U. S. 40. A section of it was built over a swamp. I have driven over that road many times and heard the slabs rattle from the weight of my car. Mistakes like this and inadequate drainage are tough on the taxpayers. Preventing them should help relieve the tax burden. As to the roads that are obsolete and have to be replaced with new highways, this poses the second question, and I will come to that a little later.

The road identified as B in Table A is the Pennsylvania Turnpike. The investment per mile, $462,000, is many times that of the Louisiana road. When the turnpike was built ten years ago, it was the most advanced design in the United States for safe, high-speed operation. Why did the turnpike come into existence? Because public facilities financed through taxation were not keeping pace with the growth of traffic, and the turnpike appeared to supply the need. I think it is safe to assume that the more the public facilities lag behind traffic needs, the more numerous will be the toll roads. The turnpike furnishes us with evidence to attack the other myth the propagandists want us to believe, and that is that big trucks do not pay their way. A big truck pays 6¢ per mile to use the turnpike, and yet the truck pays it because of its great savings per hour. Trucks are glad to use the turnpike. Last year about 60% of the toll revenue of the Pennsylvania Turnpike came from trucks. Trucks not only paid their way, but in addition, there was collected on the turnpike more than one-half million dollars in gasoline taxes from turnpike users. This tax money was turned over to the State of Pennsylvania and turnpike users received absolutely no return for it. Will the authors of the myth – big trucks do not pay their way – assert that they do not pay their way when they use the Pennsylvania Turnpike?

The road designated as C is the New Jersey Turnpike currently being built. The investment will be close to two million dollars a mile, and it should perform a superb service of expediting traffic through northern Jersey.

Now let us look at the cost of the pavement in relation to the total investment in the highway shown in Table A. In the Louisiana Highway, investment in pavement represented 71% of the investment in highway. This tremendous percentage no doubt gives rise to the belief that the pavement is the road and creates the illusion of the sanctity of pavements. Highway engineers who built these roads can justifiably think of the pavement as the road, and when they think of a truck breaking up a piece of pavement, they declare big trucks are breaking up our highways.

In the Pennsylvania Turnpike, the investment in pavement is only 15% of the total investment. There is a lot of highway here beside the pavement. In the New Jersey Turnpike, it is estimated that the investment in pavement will be only 8% of the total investment. Isn't it obvious from this that a vast change has taken place in the relative importance of the pavements? Isn't it apparent that the structure of the highway is now analagous to the structure of the truck, that the pavement now is simply the wearing surface of the highway, just as tires constitute the wearing surface of the truck? And as such shouldn't

Table A – Investment in Highways

	Highways		
	A	B	C
Total Investment per Mile, $	$29,000	$462,000	$1,900,000 (est.)
Investment in Pavement as % of Total Investment	71	15	8 (est.)

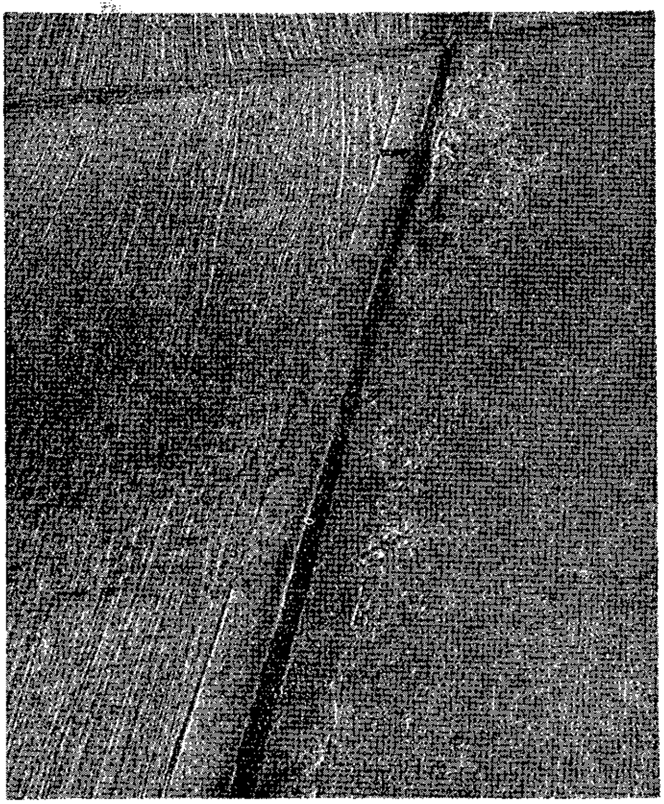


Fig. H – Entrance to Brooklyn Battery Tunnel

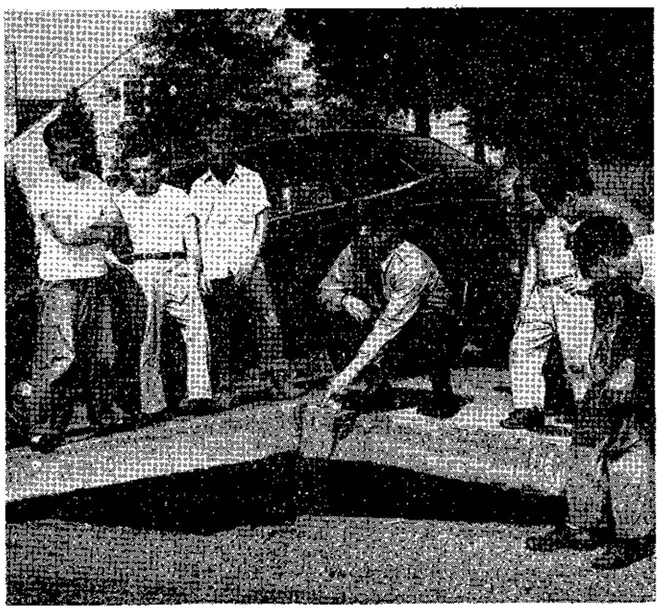


Fig. I – Buckled pavement in Reading, Pa.

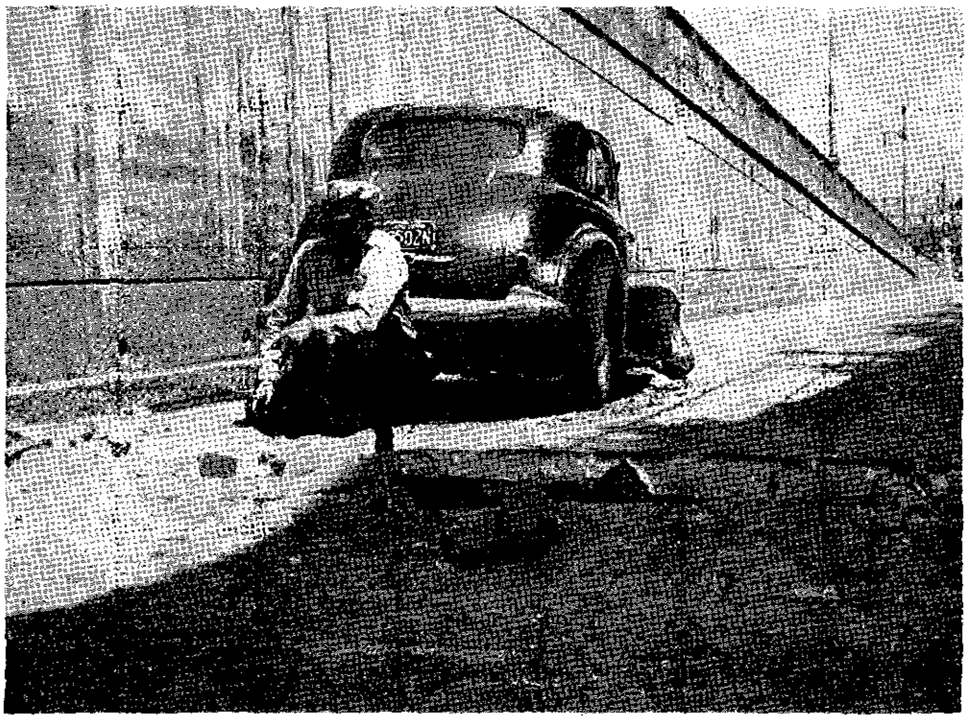


Fig. J – Buckled pavement in Pittsburgh, Pa.

it be relatively just as expendable as the tires of the truck, in the service of providing the consuming public with lowest cost transportation by highway?

In this structure the pavement is no longer the highway. it is only the wearing surface of the highway, and it loses its air of sanctity and descends to the prosaic atmosphere of just another capital item to be used for the production of further wealth and, as such, it can stand inspection on whether it should be 9 in. thick, 10, 11, or 12 in. thick, or whichever one is necessary to support the traffic of the most efficient design that automotive engineers can create. People in the business assert that it would cost 19% more to lay an 11-in. slab as compared with a 9-in. slab, and according to the formula as shown before, an 11-in. slab would carry approximately a 29,500-lb axle load. Any time we can get about 50% increase in strength for a 19% increase in investment, it sounds to me like mighty good business, and even if the slabs generally should break after 10 or 15 years of service, the whole pavement, New Jersey Turnpike, could be leveled and resurfaced with asphalt concrete at current prices for just about 3% on the original investment.

Now, answering the second question raised by Mr. Fairbank's paper as to new roads, I think we should shoot for 35,000 or 36,000-lb axle loadings. Automotive engineering thought is already 50% ahead of expressed opinions in the form of the 18,000-lb axle, and some room should be left for future development. The pavement is the bottleneck.

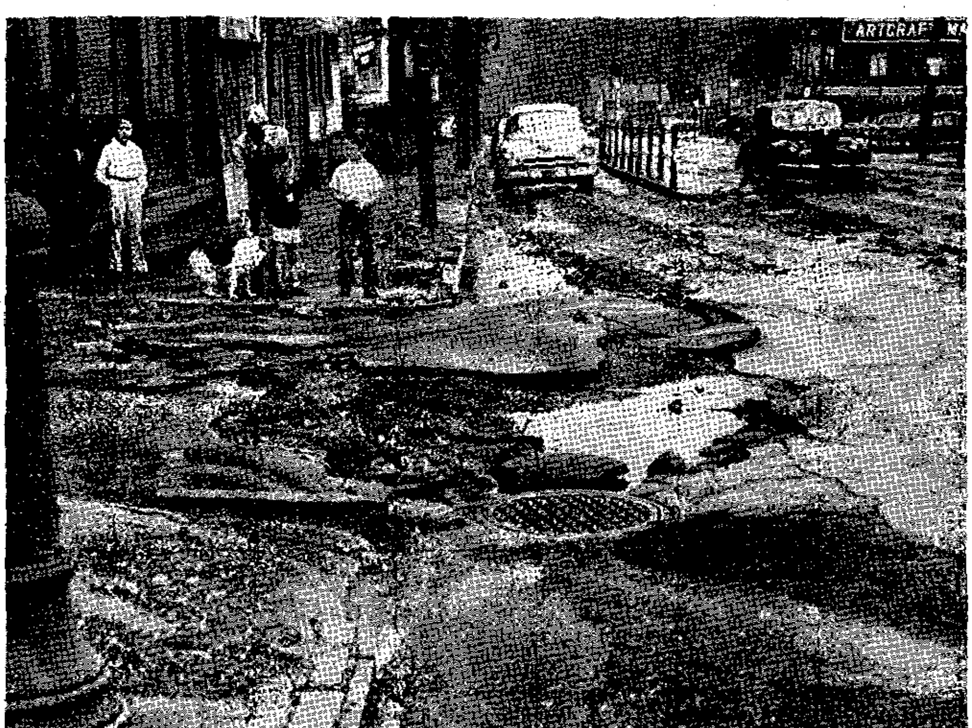


Fig. K – Pavement in Pittsburgh damaged by water

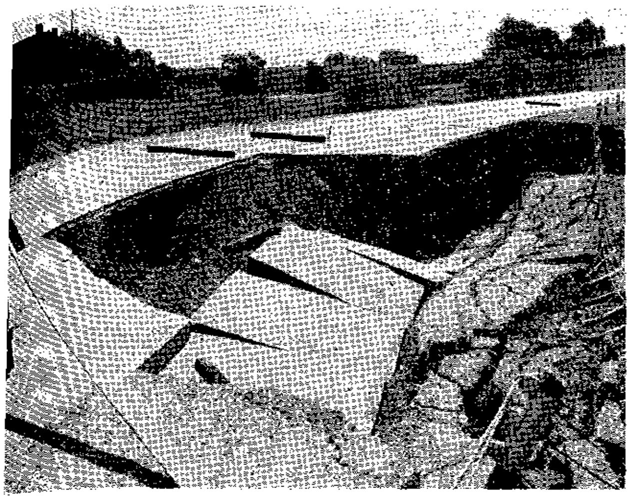


Fig. L – Pavement collapse before use

Fig. M – Sign marking first concrete highway built in New Jersey

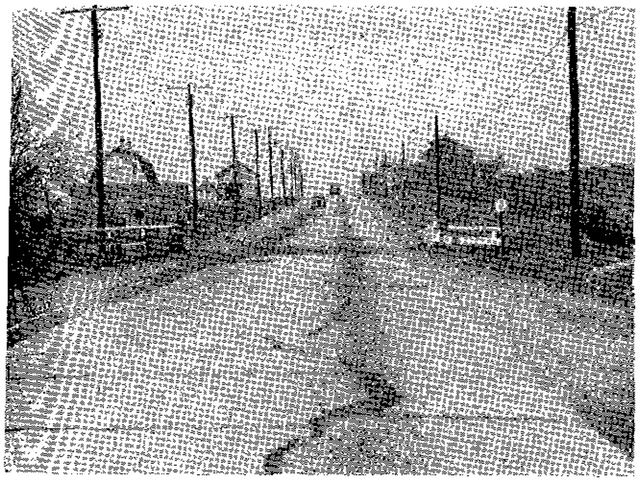


Fig. N – Section of oldest concrete road in New Jersey

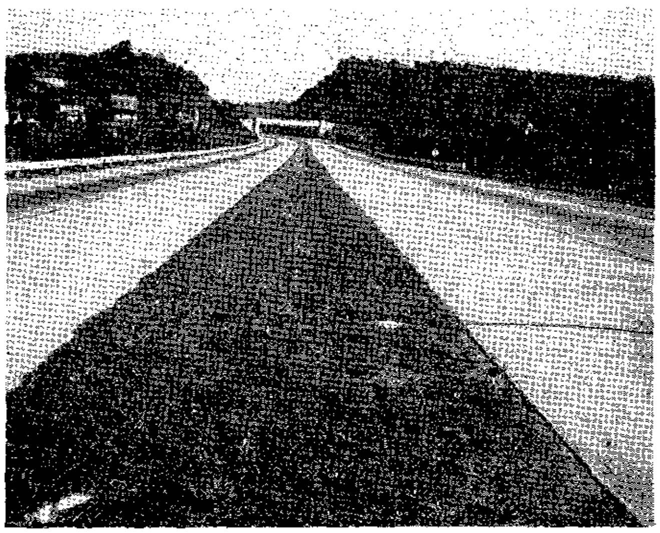


Fig. O – View of Pennsylvania Turnpike

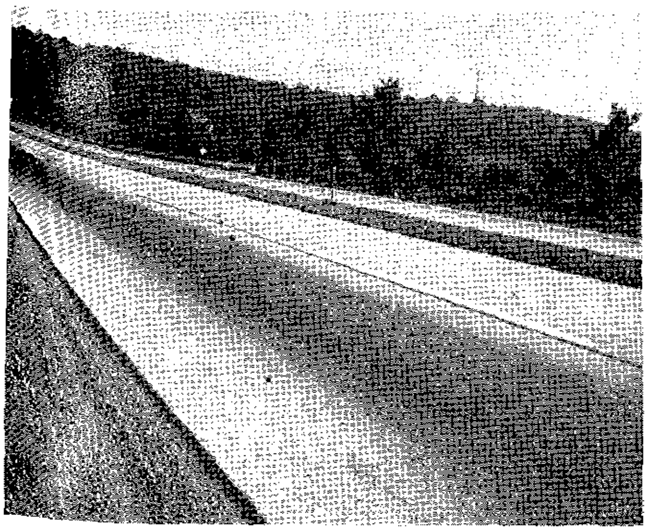


Fig. P – Another section of Pennsylvania Turnpike

Fig. Q – U. S. No. 1 near Elizabeth, N. J. (northbound)

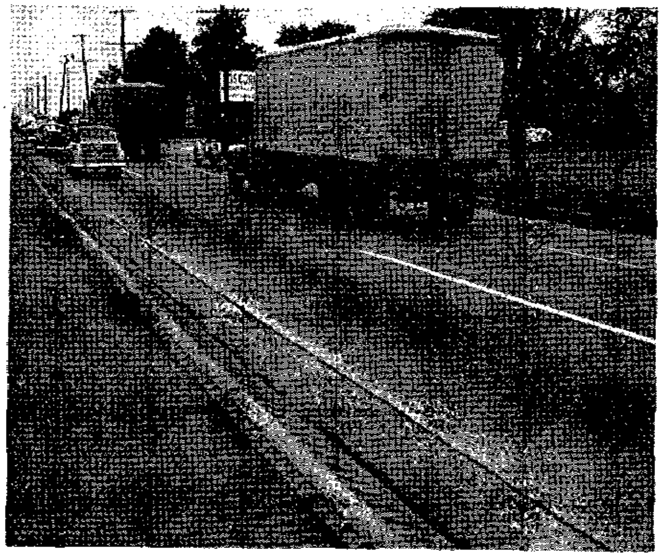


Fig. R – U. S. No. 1 near Elizabeth, N. J. (southbound)

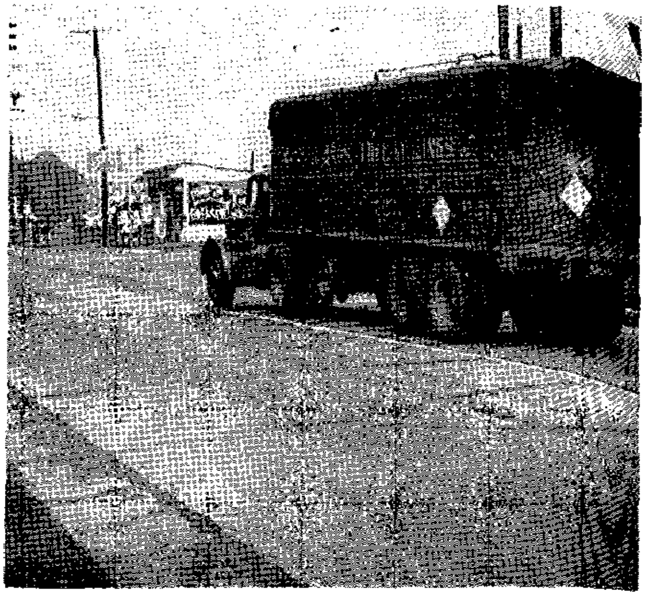


Fig. S – Section of concrete on left was laid in 1915, near Easton, Pa.

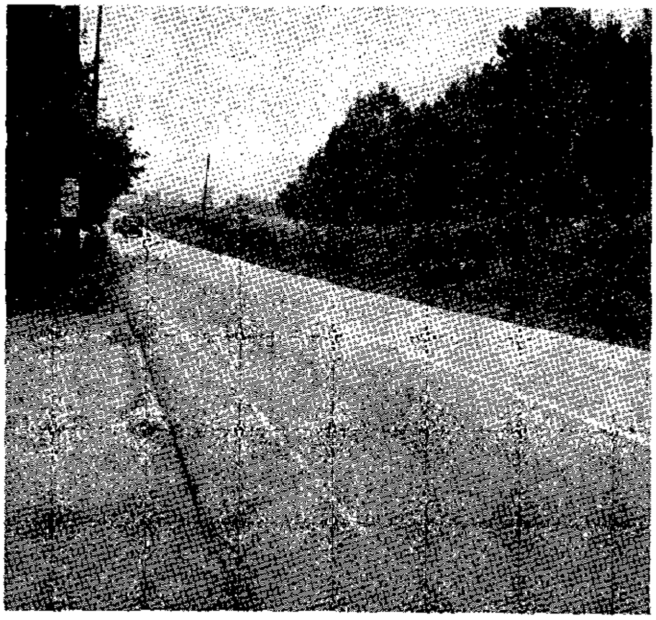


Fig. T – Section of pavement outside of Easton, Pa.

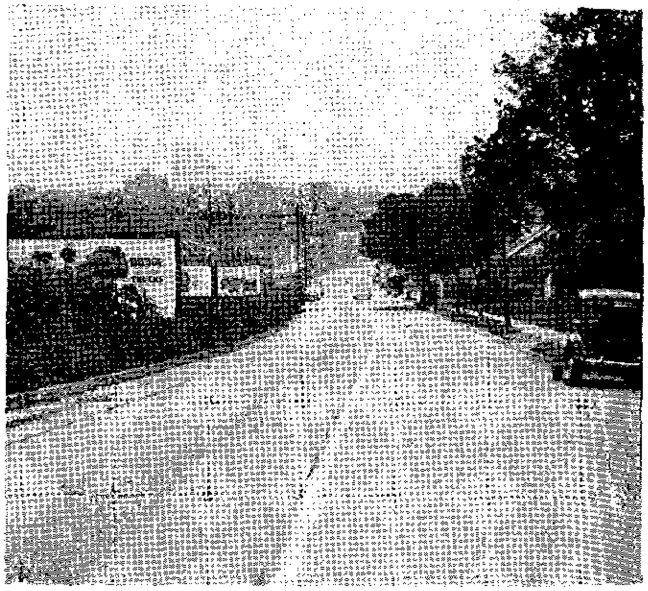


Fig. U – Another section of pavement outside of Easton, Pa.

So, as American highways have again become arteries of commerce, what shall we do? Shall we be realistic and build the kind of pavements needed to carry the traffic, or shall we quietly acquiesce to a nation-wide axle limitation and by default help put these shackles on the wheels of American transport and help set up this road block in the path of American economic progress?

The economic aspect of the limitation is the disturbing one. I think the greatest objection to the nation-wide axle limit is that it is out of step with the dynamic character of the American economy. Our free enterprise system is the greatest one ever devised by the mind of man for the abundant supply of people's needs and, briefly, this is the way it works. American technology, with its genius for making better things cheaper, operating through mass production and mass distribution, reduces costs; and then American competition, with its thirst for sales outlets and volume markets, reduces prices. This is the way that markets are expanded and more and more people receive the benefits of the goods and services created. It isn't all peaches and cream because inherent in the process is the elimination of the obsolete, the inefficient; but the net result is a higher standard of living for all the people.

The key to it all is the increase in the productivity of the individual, brought about by the increased efficiency of each capital item at the time of its replacement. A truck is in this class – so is a pavement. The pattern can be traced through industry after industry. At first, production was low, quality poor. Technology improves quality, which increases sales. Increased volume gives technology the opportunity to reduce costs. Profits increase, which attracts additional capital into the business. Competition increases, prices fall. It has happened over and over again, and the most recent case is the orange juice concentrate business in Florida, which in a half dozen years has greatly improved the quality, rendered a superior service, and cut in half the price of orange juice delivered to the American consumer. The process is now going on in the television business.

A nation-wide 18,000-lb limitation would be bad enough from an economic point of view if it were of limited duration, but apparently the thinking is otherwise. I quote from a recent Congressional Report entitled, "Highway Needs of the National Defense," to the preparation of which the Bureau of Public Roads contributed: "Since the necessities of efficient design and administration of the highway system require fixation of axle loading, the conclusion is strongly supported that 18,000-lb should be adopted as the maximum axle load permissible under the laws of all states, **that this limit without future increase should be rigidly enforced,** and that highways built in the future should be designed for the normal support of axle loads of that magnitude." So the 18,000-lb nation-wide limit is not of a temporary nature but is expressed in terms of fixation.

Just think about that for a moment and let's use our memories. Suppose in 1922, at the time the Bates test was made, that the rubber industry, aviation, automotive, petroleum, steel, chemical, and a number of others had decided on a policy of fixation. Where would we be today and what would we be doing and using? Well, for one thing, the tires on our automobiles would last 4000 miles each, if they didn't blow out sooner. For airplanes we would have something a little better than the boxlike structures that the Wright brothers created, for automobiles most of us would be driving the Tin-Lizzie of sainted memory, for gasoline we would be using the Hammer brand, the magnificent development in the metallurgy of steel would not have been available to us, the wonder drugs and synthetic compounds that the chemical industry has given us would have been denied us. Shall I go on? Whence came the avalanche of bombs that contributed so much to our victory in World War II? The explosive used was TNT, and the toluol contained therein was made by synthesis from petroleum, by a process developed since 1930. Without it, we would not have had the TNT because byproduct coke-ovens could have produced only a fraction of what was needed. Fixation – the word has no place in the vocabulary of the American economy. The American economy is a living, moving, expanding, creative thing. Fixation means stagnation – it means decay. By contrast, 60% of the sales of one American corporation – a very large and old one, which I will not identify except to say that it is not the one with which I am affiliated – are of products which were unknown 21 years ago. This policy of fixation seeks to pour a very important segment of our economy into a permanent mold, one that would deter and handicap the technical development, which is the life blood of American industry, and in hampering the free flow of goods from producer to consumer would exact tribute from every American citizen. This policy stands in the way of progress and says, STOP! THIS IS THE END!

I am sure that among highway engineers there are just as many capable and conscientious men as there are among automotive engineers, and I believe that they are sincerely trying to do their best from their point of view for what they think is the good of the country. But I think it should begin to be apparent to them that the building of pavements is not something which is separate and apart from the dynamic nature of the American economy, that any part of it which holds back must of necessity in its way hold back the totality – that it is just as necessary for the paving business to evolve to a higher level of efficiency and benefit to the public as it is for any other industry. I would like to suggest a new objective for road engineers and allied groups. It is this: **How to make better pavements at lower cost.**

I hope that road engineers and their associates will accept this suggestion from a layman in the same spirit of desire for public betterment in which it is given. In speaking of better pavements, there are two ways in which it can be done. The first is the way I mentioned before by making the slab thicker, and as one of the previous charts showed, a 12-in. slab would carry a 35,000-lb axle. The additional thickness would cost more money, and I believe it would pay off in many places, but I think the right way to get added strength is to improve the quality of the slab without increasing the thickness. Fig. Z shows the weight per axle that a slab would carry if the modulus of rupture were doubled. If the modulus of rupture can be doubled by improving the quality of the slab, then a 6-in. slab, according to the formula, will carry a 17,500-lb axle and a 9-in. slab will carry a 39,500-lb axle. Don't you think this is an objective worth shooting for? Do you think it is impossible of achievement? I don't. If any one should tell me that the technology of America cannot succeed in this attempt, I would simply say that I don't believe it. American technology has solved too many difficult problems to be stopped by a pavement. But we don't have to wait for developing technology to take us past an 18,000-lb nation-wide limit. There are a number of quality measures, such as coarse ground cement, already within the range of present technology by which forward steps, at least experimental ones, may be taken. How foolish to impede progress with an arbitrary nation-wide limit when we already have many advantages at our disposal.

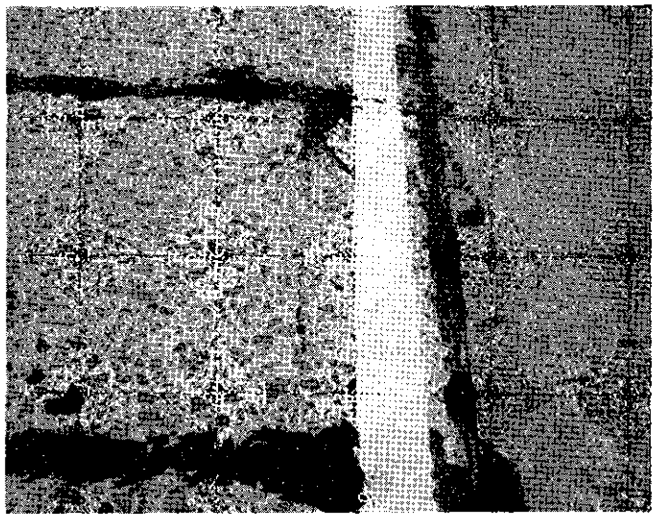


Fig. V – Close-up view of pavements shown in Fig. U – pavement on left is 35 years old, that on right is 3 years old

I would like to mention a number of quality suggestions, but space does not permit except for the most important, one which I have labeled **"quality jack pot."** It deals with the element that amazes me about this whole question. As a result of the Bates tests in 1922, pavement builders raised their sights. Now in 1950 the Bureau of Public Roads is still looking through the same sights that were raised way back yonder, not only looking through them now, but plans to keep on looking through them into the indefinite future. Remember the words in the Congressional Report, "This limit without future increase." What has been happening since 1922? Where are the ideas for better pavements that must have arisen? Are we to believe that among the paving contractors, equipment manufacturers, material manufacturers, state highway and county highway boards there were no people that have any ideas for betterment? Surely there must have been many suggestions for improvements. From this small army of men over a span of so many years there must have been thousands, literally thousands, of suggestions for betterment. What has become of them? More important, what has been done about them? Well, that is water over the dam, and there isn't anything we can do about the past, but there is something that should be done about the future.

The American people are entitled to the benefit of the dreams, the imagination, the creative ideas, the cold, hard judgment based on facts and experience of these men about better pavements, just as they are entitled to and receive the same from other industries. Not only is the public entitled to what I have mentioned, but the men themselves are entitled to the right of recognition for their contribu-

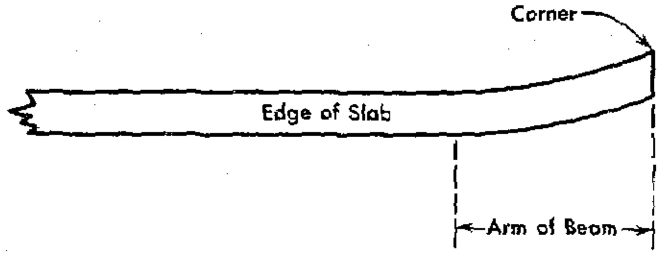


Fig. W – Application of Bates test formula

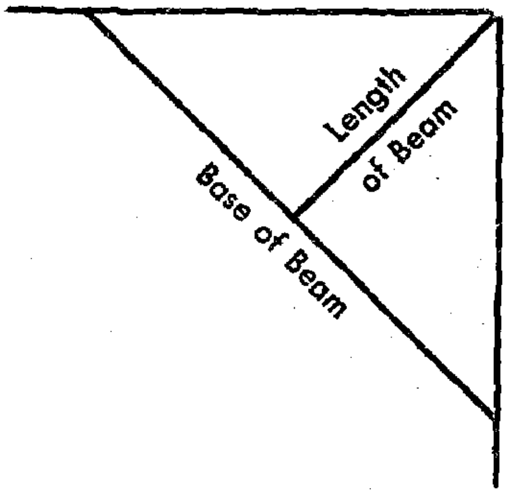


Fig. X – Application of Bates test formula

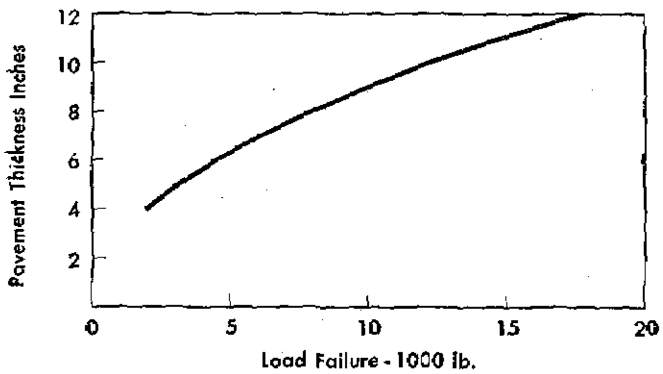


Fig. Y – Indicated concrete pavement thickness versus load, according to Bates test formula

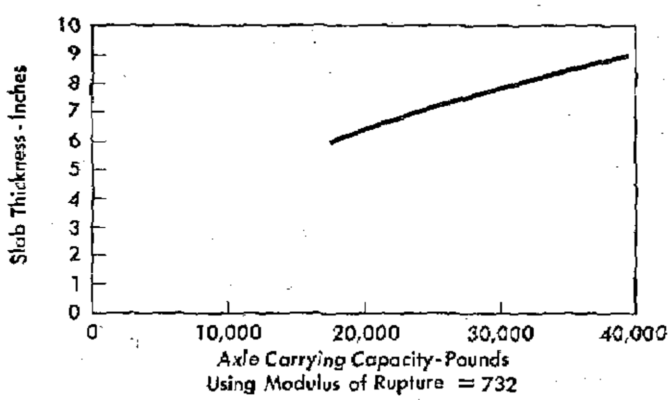


Fig. Z – How to make better pavements at lower cost

tions. There must be some incentive to pull the light from under the bushel.

In all good faith, I suggest to the Bureau of Public Roads that it annually set aside $100,000 of the American taxpayers' money to be set up as a prize fund for the best ideas from whatever source for making better pavements at lower cost. With this sort of incentive, whether the Bureau of Public Roads provides it or someone else provides it, an atmosphere will be created that will encourage people to put their best efforts into the solution of this problem. What is necessary is the concentration of enough of the right kind of brain power on this problem to solve it. I believe this kind of incentive will start the ball rolling, and then we will see highway engineers side by side with automotive engineers moving forward together in the evolution of low-cost highway transportation for a more bountiful livelihood for all Americans.

Author's Closure
To Discussion

THESE facts remain: That there exists a $40,000,000,000 highway system of limited weight-supporting capacity in all its parts. To maintain it, replace it, and modernize it in the state and at the rate required, that it may continue to render a reasonably efficient service to a rapidly increasing traffic is a task that overreaches the revenues thus far raised by road users and other beneficiaries. Every avoidable expense must be avoided.

It is idle to say that road surfaces should be regarded as expendable; they are so regarded. The question is, how fast can they be expended, and replaced? It is equally idle to insist that foundations should be better. The foundations exist; we must get along with them until, in time, they can be bettered.

With respect to the capacity of road surfaces and foundations, the critical vehicular factors are the axle loads and the manner in which they are applied through wheels and tires.

By every test of highway administrative experience, engineering analysis, and experiment, the 18,000-lb axle load has been found to be the greatest that can be frequently supported by the majority of our roads, consistent with the conservative policy forced upon us by the revenues available.

The latest of the experiments – Road Test One – MD – performed on a road of surface type, dimensions, and foundation conditions typical of large parts of the existing highway system, resolves all doubts as to the accuracy of the judgment that 18,000 lb is the practicable limit of supportable axle weight.

When most of the existing road system was built, a limit of 18,000 lb covered most truck operators' desires, as evidenced by actual truck operation. It is exceeded now in a minute fraction of the total operation.

If axle loads heavier than 18,000 lb have an advantage more worthy of consideration than the private gain of a minority of truck operators; if such heavier axle loads are truly "in the public interest," new roads can be built to support them. Highway engineers await the establishment of the fact.

This highway engineer clings to the belief that truck operating economy is more closely associated with the weight of the payload than with the weight that is concentrated on a single axle. All costs of highway transport considered – the costs of the road and the costs of vehicle operation – his conviction is strong that highest economy is to be sought in the increase of payload without increase of axle load. As to the soundness of this judgment, investigations now in progress should provide an answer.

For the present, the question that might be more usefully weighed by truck operators, manufacturers, and automotive engineers, as a highway engineer views it, at least, is: Why not 18,000 lb?