Strain Energy Analysis of Pavement Designs for Heavy Trucks

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Classical concepts of work, or strain energy, as applied to the analysis of stresses, strains, and deflections under various vehicular load configurations on pavement systems are summarized and controlling equations for strain energy density are presented. When considering strain energy density, strain energy, or work, all components of stresses or strains must be taken into account so that total internal behavior can be evaluated. Previously, pavement thickness design systems have been developed using only one component of strain, typically at the bottom of the asphaltic concrete layer or at the top of the subgrade. Strain energy concepts permit modifications to thickness design systems to account for the net effect of all components of strains or stresses. Effects of loads and distribution of loads on vehicles are summarized. One startling result shows the large increase in fatigue rate due to unequal distribution of loads between the two axles of a tandem group relative to the fatigue rate caused by an equal load distribution. Damage factors and pavement thickness designs for heavily loaded trucks exceeding legal load limits are also discussed. The effects of those vehicles on Interstate pavements are compared to the effects of more normally loaded vehicles.

The work done by a force when its point of application is displaced is the product of that force (parallel to the direction of movement) and the displacement. When work is done on some systems, the internal geometry is altered in such a way that there is a potential to give back work when the force is removed, and the system returns to its original configuration. This stored energy is defined as strain energy. Strain energy per unit volume at a given point in the body is the strain energy density at that point.

STRAIN ENERGY

Strain energy density is a function of Young's modulus of elasticity and Poisson's ratio of the material and the nine strain (or stress) components; however, it is independent of the coordinate system. Stress and strain components, referenced to a local cylindrical coordinate system, for each load are calculated by the Chevron program (1). The classical equation for strain energy density derived by Sokolnikoff (2) is as follows:

$$W = \Sigma\ \Sigma\ [(1/2)\lambda\nu\, \epsilon_{ii} + G\, \epsilon_{ij}\epsilon_{ij}]$$

$$- (1/2)\lambda\nu^2 + G(\epsilon^2_{11} + \epsilon^2_{22} + \epsilon^2_{33} + 2\epsilon_{12} + 2\epsilon^2_{23} + 2\epsilon^2_{13}) \quad (1)$$

where

- W = strain energy density (or energy of deformation per unit volume);
- ϵ_{ij} = i,jth component of the strain tensor;
- G = $E/[2(1 + \mu)]$, the modulus of rigidity (or the shear modulus);
- E = Young's modulus;
- μ = Poisson's ratio;
- λ = $E\mu/[(1 + \mu)(1 - 2\mu)]$; and
- ν = $\epsilon_{11} + \epsilon_{22} + 33$.

Strain energy density may be calculated using stress components by the equation

$$W = -\mu\Theta^2/2E + [(1 + \mu)/2E](\sigma^2_{11} + \sigma^2_{22} + \sigma^2_{33}) +$$

$$[(1 + \mu)/E](\sigma^2_{12} + \sigma^2_{23} + \sigma^2_{31}) \quad (2)$$

where

- $\Theta = \sigma_{11} + \sigma_{22} + \sigma_{33}$ and
- σ_{ij} = i,jth component of the stress tensor.

Inspection of Equation 1 shows that the term $E/[2(1 + \mu)]$ is contained by means of the terms λ and G. Also, it is noted that the strain components are squared. Having calculated strain energy density, work strain (3) may be obtained from

$$\epsilon_w = (2\ W/E)^{0.5} \quad (3)$$

where ϵ_w is work strain. The associated work stress is given by $E\epsilon_w$.

Interpretations of Work Strain

Admittedly, work strain is not a true strain because Poisson's ratio has not been eliminated before taking the square root; however, it is of the same order of magnitude as any of the strain components. Calculating the work strain is a minor effort because all terms of the equations are either required input to, or calculated output of, the Chevron N-layer (1,4) program. Work strain is also the composite, or net effect, of all strain components and thus is an indicator of the total strain behavior. Figure 1 shows that there is a direct correlation between a strain component and work strain.

Uses for Work Strain

Some thickness design systems for flexible pavements are based partly on tensile strain criteria at the bottom of the asphaltic concrete layer. Kentucky's

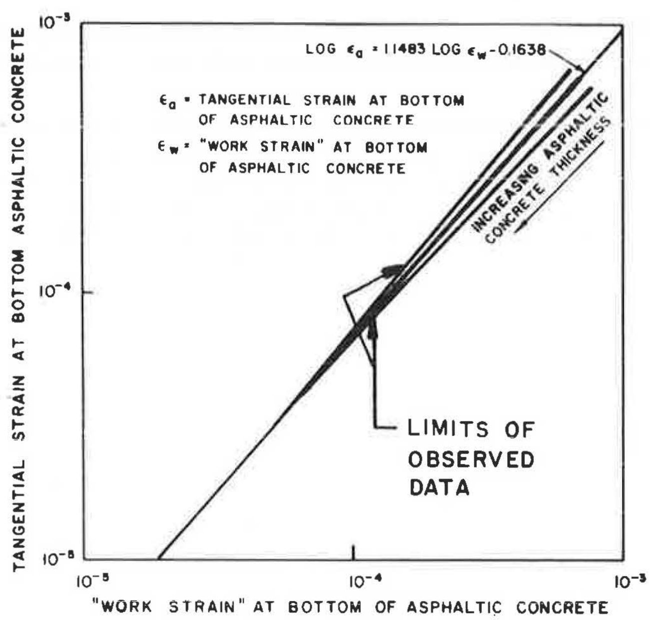

Figure 1. Tensile strain versus work strain.

proposed system (5-7) is based in part on the tangential strain component. The tangential component is generally the largest in magnitude, but the radial component often is nearly as large. Only the tangential component has been used because laboratory test data yield one component of tensile strain. The net effect of all components of strain (work strain) can be correlated with any component of strain. Thus, design systems based on one component of strain may be converted to a design system that uses the net effect of all component strains. The load-damage factor relationships presented in this paper are based on work strain. All comments concerning component strains also apply to component stresses.

Fatigue Concepts

The equivalent axle load (or EAL) approach converts all axle load weights that pass over a pavement during its design life to some reference axle load. The reference axle load weight selected in Kentucky was 80 kN (18,000 lb). Any axle load could have been selected, and the change from one axle load reference to another should not change the results of a design system. The 80-kN (18,000-lb) axle load was probably selected because it represented, at the time the EAL concept was developed, the typical legal axle load limit recognized in many states. The 80-kN (18,000-lb) axle load was also the reference used at the AASHO Road Test in the early 1960s.

The passage of one 80-kN (18,000-lb) axle load results in the application of one EAL. An 89-kN (20,000-lb) axle load is equivalent to applying 1.7 EALs; the 89-kN (20,000-lb) axle load would cause 1.7 times the damage to the pavement as would one 80-kN (18,000-lb) axle load. The EAL for a given group of axles, thus, represents the damage factor (load equivalency) for that particular group.

Figure 2 illustrates how the damage factor for selected axle groups varies with increasing loads on those groups. The load-damage factor relationships shown in Figure 2 were developed from analyses using the Chevron N-layer computer program, which is based on elastic theory. Pavements analyzed were the hundred possible combinations of thicknesses, of which 67 were built and tested, at the AASHO Road Test. The tire loads and axle spacings were those used on the test vehicles at the AASHO Road Test. The load-damage factor relationship is expressed by

$$DF = 10^{[a + b (\log \text{Load}) + c (\log \text{Load})^2]} \quad (4)$$

where

DF = damage factor and
a,b,c = coefficients by regression analyses.

Table 1 gives the numerical values for the coefficients in Equation 4 for each axle configuration. The coefficients have been published previously (8) for the two- and four-tired single axle and eight-tired tandem axle groups.

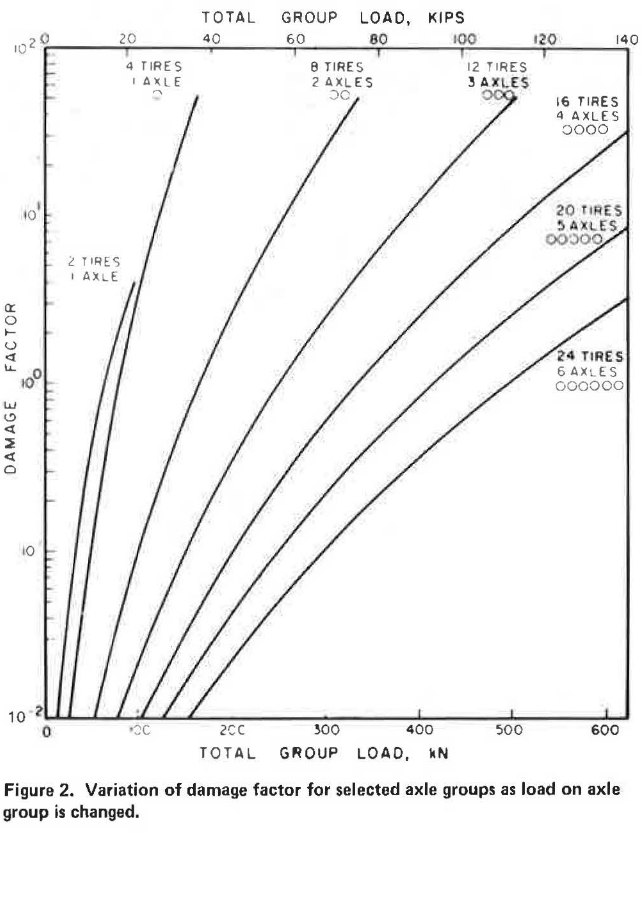

Figure 2. Variation of damage factor for selected axle groups as load on axle group is changed.

Table 1. Regression coefficients to calculate damage factors for various axle configurations.

Log (Damage Factor) = a + b (Log Load) + c [Log Load]^2

	COEFFICIENTS		
AXLE CONFIGURATION	a	b	c
Two-Tired Single Front Axle	-3.540112	2.728860	0.289133
Four-Tired Single Rear Axle	-3.439501	0.423747	1.846657
Eight-Tired Tandem Axle	-2.979479	-1.265144	2.007989
Twelve-Tired Tridem Axle	-2.740987	-1.973428	1.964442
Sixteen-Tired Quad Axle	-2.589482	-2.224981	1.923512
Twenty-Tired Quint Axle	-2.264324	-2.666882	1.937472
Twenty-Four Tired Sextet Axle	-2.084883	-2.900445	1.913994

Figure 3 shows how the damage factor increases due to an increasing difference of load distribution between the axles of a tandom group. The significance of unevenly distributed loads between the two axles of a tandem is indicated by an examination of individual axle loads for 335 vehicles of the 3S2 (five-axle semitrailer) configuration listed in the 1976 W6 tables for Kentucky. Appropriate damage factors were applied to those individual axle loads. Figure 4 shows the large difference between uniform and nonuniform load distributions using factors from Figure 2 and those adjusted by Figure 3 for nonuniform load distributions. AASHTO (9) damage factors also were applied to the same vehicle loads. Figure 4 shows that there is very little difference in the summation of EALs based on AASHTO damage factors and the energy-based factors adjusted for nonuniform loading.

For example, it has been found that only about 10 percent of the tandem axle groups observed in Kentucky have loads uniformly distributed between the two axles. Analyses indicate that the nonuniform distribution between the axles in a tandem group can account for as much as a 40-percent increase in the damage to a pavement. The difference between the

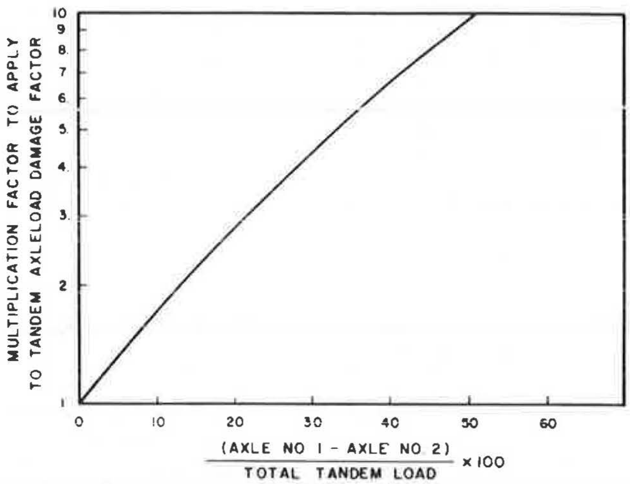

Figure 3. Multiplying factors increasing damage factors due to nonuniform load distribution between axles of a tandem.

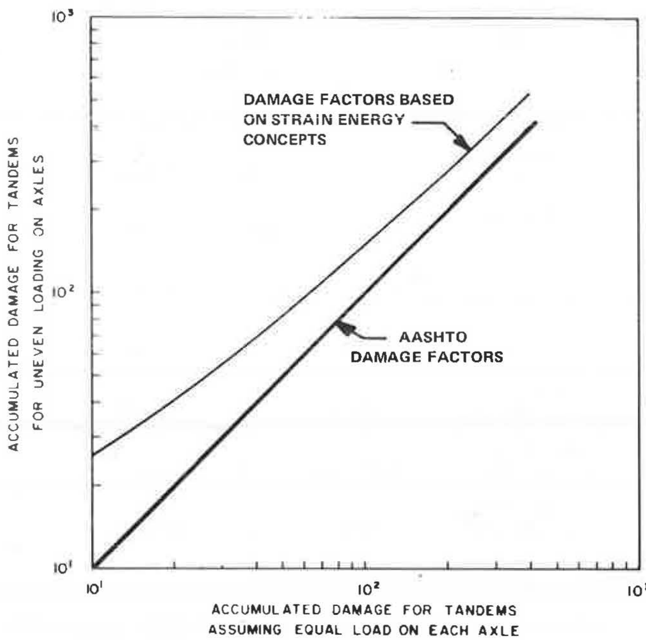

Figure 4. Accumulated fatigue of 335 vehicles from 1976 W6 tables for Kentucky.

axles exceeded 8.9 kN (2,000 lb) for three of 10 tandems on semitrailers and two of 10 tandems on tractors. The use of floating axles also may be undesirable unless a means is found to ensure that the floating axle carries its proper share of the load. It has been observed that loads carried by floating third axles may vary from a low portion of the total load, providing little benefit from the additional axle and shifting the additional load to the two remaining axles in the group, to an unduly large percentage of the load. Both conditions increase the damage significantly over the situation where the load is distributed uniformly among all axles.

Experience indicates that the elastic theory and work concept used in Kentucky predict reliably the number of EALs a given pavement system can support in its lifetime. Conversely, it is possible to design a pavement that will adequately resist the damage of a specified number of EALs. However, the problem of predicting the rate at which EALs will accumulate remains. This involves estimating the numbers and types of vehicles that will use a section of highway as much as 30 years in advance. To illustrate the problem, a section of KY 15 was designed to carry a given number of EALs. The pavement, however, failed after only 8 months. Analyses showed that the pavement did carry the EALs for which it was designed. Unfortunately, the opening of a coal producing operation that created a high-volume of heavy traffic was not foreseen, and the rate of accumulating EALs was underestimated.

HEAVY LOAD DESIGN

In almost any state, some commodity is transported on overloaded trucks. Coal and limestone are two such commodities in Kentucky. In other states, industries that generate overloaded trucks might be logging, pulp wood, minerals, ores, grains, or other agricultural products. Many county roads in Illinois, for example, lead to a grain elevator and have only one paved lane. Typical gross loads are given in Table 2 for three truck configurations in Kentucky coal fields. Table 2 also gives the corresponding damage factors obtained from Figure 2. Classification counts in 1981 on one of the main coal-haul non-Interstate routes were used to obtain the percentages of the three configurations. Note that the 3S3 can carry 111 kN (25,000 lb) more than the 3S2, yet the 3S3 produces slightly less total damage per trip.

Table 3 gives only the design EALs for the three truck configurations of Table 2. Two of the thickness design charts contained in the proposed Ken-

Table 2. Damage factors for typical heavily loaded truck configurations.

		FRONT AXLE		TANDEM		TRIDEM				
CONFIGURATION	GROSS LOAD (kips)	LOAD (kips)	DAMAGE FACTOR	LOAD (kips)	DAMAGE FACTOR	LOAD (kips)	DAMAGE FACTOR	TOTAL DAMAGE PER TRIP	NUMBER OF TRUCKS PER 100 TRUCKS	TOTAL DAMAGE PER 100 TRUCKS
Single Unit Three-Axle Dump	96	20	3.2	76	57.0			60.2	25	1,505
Five-Axle Semi-Trailer 3S2	115	15	1.15	2@ 50	2@ 4.65			10.5	70	732
Six-Axle Semi-Trailer 3S3	140	15	1.15	50	4.65	7.5	4.50	10.3	5	51
Total EALs										2,288

Table 3. Pavement thickness designs for heavily loaded trucks.

NUMBER OF TRUCKS PER DAY	DESIGN YEARS	DESIGN EALs $P_t = 3.5$	DESIGN THICKNESS (in.) 50% AC[a]	100% AC[b]
100	1	617,760	-	-
	5	3,088,800	18.2	11.8
	10	6,177,600	20.1	13.1
	20	12,355,200	22.1	14.5
200	1	1,235,520	-	-
	5	6,177,600	20.1	13.1
	10	12,355,200	22.1	14.5
	20	24,710,400	24.2	15.8

Assumptions:
Sundays = 52
Holidays = 8
Bad Weather = 5

Total Non-work = 65
Working days per year = 365 - 65 = 300

[a]50 percent - half of pavement thickness is asphaltic concrete, half is unbound granular base
[b]100 percent - full-depth asphaltic concrete

tucky thickness design system (6) are shown in Figures 5 and 6. Assuming a design CBR of 5.2, which is typical for many Kentucky soils and is the same soil used at the AASHO Road Test, the required thicknesses are given in Table 3 for the various combinations of truck volumes and design periods. Kentucky assigns a terminal serviceability of 3.5 for pavements expected to support 4 million or more 80-kN (18,000-lb) EALs in the design life.

Comparison with Interstate Traffic

Interstate traffic is a mixture of loaded and empty trucks, as reflected by loadometer studies. Average damage factors (5,6) were calculated and applied to eight classification counts made in 1981 at two locations. The volume of truck traffic was 28.3 percent on I-65 and 39.0 percent on I-71. However, the number of trucks was nearly the same on each route and almost identical regardless of which quarter of the year the count was made. Thus, truck traffic was fairly constant. Table 4 shows that the daily and annual EALs for these two routes were nearly the same. The data in Table 3 indicate that approximately 200 heavily loaded trucks per day can cause the same fatigue as all trucks using I-65 or I-71.

A second comparison was made on the basis of net tonnage and the associated accumulation or fatigue. Table 5 gives the tare weight for typical vehicles for both the heavily loaded trucks and those normally found on Interstates and other routes. This permits a theoretical comparison of net tonnage hauled by the two groups of vehicles. The following assumptions were made:

1. The number of trucks was taken from I-65 data in Table 4 for the corresponding classifications in Table 2. This represents typical use on Interstates.
2. The remainder of the traffic stream would be constant for both comparisons and therefore are not included in this example problem.

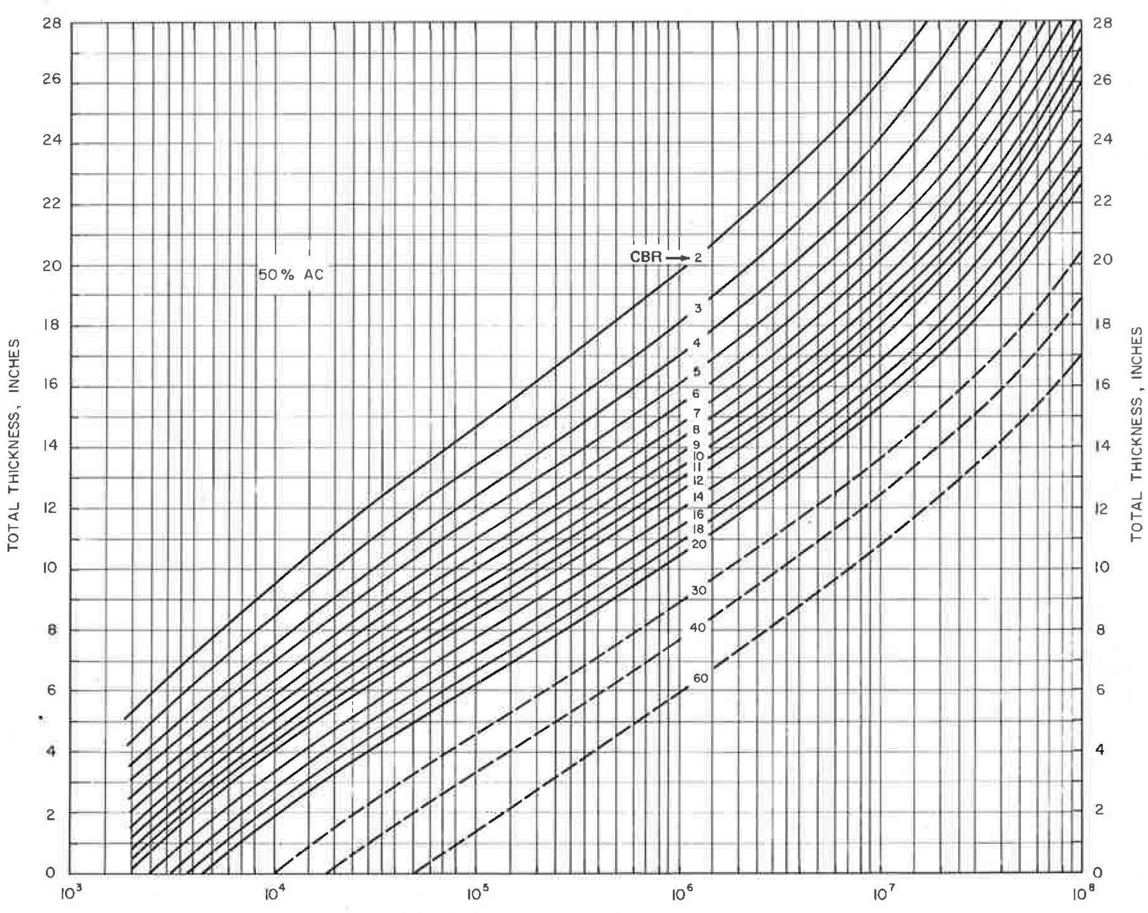

Figure 5. Thickness design curves for pavement structures where 50 percent of the total pavement thickness is asphaltic concrete.

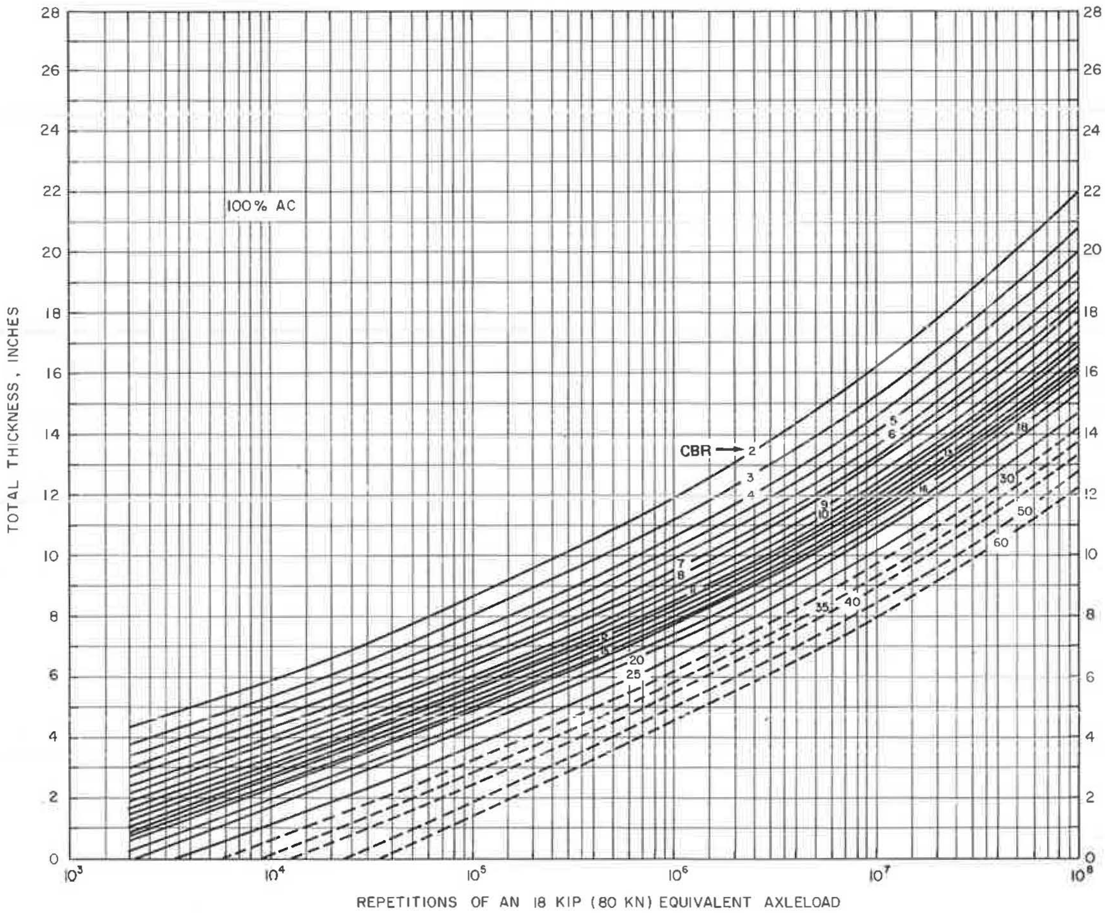

Figure 6. Thickness design curves for pavement structures where 100 percent of the total pavement thickness is asphaltic concrete.

3. Each axle group is loaded to the legal maximum.

4. For an Interstate, 365 days are assumed for EAL calculations because truck traffic does not appear to vary significantly on any given day. However, for coal or similar commodities, there are market slumps and bad-weather days that reduce the total number of working days to approximately 300.

The following methodology was used to calculate the net loads:

1. Legally loaded trucks for the three classifications reported for I-65 were used to calculate the fatigue for 1 year. The fatigue for 1 year for 100 heavily loaded trucks also was calculated. The ratio of the two fatigue calculations multiplied by the original 100 heavily loaded trucks produces the total number of heavily loaded trucks required to produce the same fatigue as the trucks reported on I-65.

2. For each classification of legally loaded trucks, the number of trucks per day were multiplied

Table 4. Vehicle classification counts and corresponding EAL for two sites on Kentucky Interstates.

		SINGLE UNIT TRUCKS				SEMI-TRAILER TRUCKS				
AVERAGE	AUTOS & PICKUPS	TWO AXLES FOUR TIRES	TWO AXLES SIX TIRES	THREE AXLES	FOUR AXLES	THREE AXLES	FOUR AXLES	FIVE AXLES	SIX AXLES	TOTAL
DAMAGE FACTOR	0.0501	0.0605	0.2953	0.6386	0.6386	0.6353	0.7514	0.6267	0.6000	
VOLUME: TOTAL OF FOUR DAILY COUNTS										
I-65	51,026	52	2,435	272	15	266	1,442	15,319	67	70,894
I-71	32,392	356	2,015	426	137	372	945	15,889	150	52,682
EALs										
I-65	2,556.4	3.1	719.1	173.1	9.6	169.0	1,083.5	9,600.4	40.2	14,355.0
Average										3,588.8[a]
I-71	1,622.8	21.5	595.0	272.0	87.5	236.3	710.0	9,957.6	99.6	13,602.6
Average										3,400.6[b]

[a] Annual EAL for I-65 = 365 x 3,588.8 = 1,309,895.
[b] Annual EAL for I-71 = 365 x 3,400.6 = 1,241,235.

Table 5. Gross, empty, and net weights of selected vehicle configurations.

	NORMAL TRUCKS				HEAVILY LOADED TRUCKS			
CLASSIFICATION	EMPTY WEIGHT (kips)	GROSS WEIGHT (kips)	NET WEIGHT (kips)	DAMAGE FACTOR PER TRIP	EMPTY WEIGHT (kips)	GROSS WEIGHT (kips)	NET WEIGHT (kips)	DAMAGE FACTOR PER TRIP
Three- Axle Single-Unit	20	46	26	1.18	30[a]	96	66	60.2
Five-Axle Semi-Trailer	30	80	50	1.80	30	115	85	10.45
Six-Axle Semi-Trailer	32	96	64	1.74	34	140	106	10.30

[a]Different from empty weight of normally loaded trucks.

by the net load and accumulated. The product of the number of heavily loaded trucks and their net loads was also calculated.

3. The total net load per day for the legally loaded trucks was divided by the total net load for the heavily loaded trucks.

For the same fatigue, calculations shown in Figure 7 indicate that the number of heavily loaded trucks is approximately 10 percent of the number of legally loaded trucks. Furthermore legally loaded trucks would transport approximately 7.7 times more payload than would the heavily loaded trucks with only about one-fourth (1/3.72 from Figure 7) of the fatigue damage.

Classification	Number of Trucks	Net Weight[a] (kips)	Total Net Weight (kips)	Average Damage Factor[a]	Total EAL
Normally Loaded Trucks[b] (per day for 365 days per year)					
Three-axle single unit	68	26	1,768	1.18	80.24
Five-axle semitrailer	3,830	50	191,500	1.80	6,894
Six-axle semitrailer	17	64	1,088	1.74	29.58
Total	3,915		194,356		7,003.82
					x 356
				EAL per year	2,556,394.
Heavily loaded trucks (per day for 300 days per year)					
Three-axle single-unit	25	66	–	60.2	1,505
Five-axle semitrailer	70	85	–	10.45	731.5
Six-axle semitrailer	5	106	–	10.30	51.5
Total	100				2,288.0
					x 300
				EAL per year	686,400

$$\text{Ratio of EAL} = \frac{\text{normal trucks}}{\text{heavy trucks}} = \frac{2{,}556{,}394}{686{,}400} = 3.72 \text{ for equivalent fatigue damage}$$

Number of heavy trucks

3.72 x 25 =	93.1	66	6,145
3.72 x 70 =	260.7	85	22,159
3.72 x 5 =	20.7	106	2,194
Total	374.5		30,498

$$\text{Ratio of net load} = \frac{\text{legally loaded}}{\text{heavily loaded}} = \frac{194{,}356 \times 365}{30{,}498 \times 300} = 7.7$$

[a]From Table 5. [b]Daily volume: one-fourth of volumes in Table 4.

Figure 7. Sample calculation sheet to compare fatigue and payloads.

Deterioration of Pavements

Many Kentucky pavements have been subjected to heavily loaded vehicles. Some observations of the effect on pavements are given in the following paragraphs.

Pavements designed for light to medium traffic will deteriorate rapidly under heavy loads, and the paved surface of a rural secondary road may be broken up and even disappear in 1 to 2 years. During construction of 11 km (7 miles) of KY 15, two unanticipated strip mine operations were opened. Eight months later, a 102-mm (4-in.) asphaltic concrete overlay was placed to eliminate severe rutting and some cracking. The overlay was required and laid before the official opening of the new construction to traffic.

On an experimental full-depth asphaltic concrete pavement with cross sections ranging from 254 to 457 mm (10 to 18 in.), cold weather temperature cracking was observed in the passing lane. Those transverse cracks were 1.2 to 1.8 m (4 to 6 ft) apart in some areas. The cracks were evident in the outer lane only at the outer and centerline paint stripes. Evidently, the heavily loaded trucks kneaded the pavement surface together. It is not known whether the cracks extend below the surface layer.

On a 432-mm (17-in.) full-depth asphaltic concrete pavement on the Daniel Boone Parkway, there is a long steep grade that shows progressively deeper rutting as the top of the hill is approached. The change in rutting was pronounced and occurred over a fairly short length where drivers downshift into a lower gear. The amount of rutting then remained relatively constant over a considerable distance. When the driver shifted to an even lower gear, another significant increase in rutting occurred and remained constant over a considerable length. The lengths of constant rutting decreased as the truck approached the top of the hill. Rutting varied from 6.4 mm (0.25 in.) at the bottom of the grade to 76 mm (3 in.) at the top of the hill. Two experiments were conducted to help understand the cause of the rutting.

First, a full-depth trench was excavated across the climbing lane containing the severe rutting. Inspection of the cross section showed that rutting occurred only in the top 152 mm (6 in.) and all construction interfaces below the 152-mm (6-in.) depth were parallel and straight. Above 152 mm (6 in.) construction interfaces were undulating and layer thicknesses varied due to differential densification under traffic. Also in the upper layers, the normally random orientation of aggregate particles was totally reoriented so that the particles were parallel to each other.

The second experiment consisted of making two shallow saw cuts across the lane. One was perpendicular to the centerline, and the other was on a 45 degree angle with the lower end of the cut at the shoulder. Both cuts were filled with small-diameter glass beads used in highway paint stripping. Four weeks later these cuts were inspected. Both cuts in both wheel track areas had been displaced downgrade by 16 mm (0.6 in.). Thus, the high torque at the tire pavement interface caused a downward flow of the surface mix. The lack of stability of the bituminous mixture was determined to be caused primarily by a soft grade of asphaltic cement. An overlay with a stiffer grade of asphaltic cement was placed.

SUMMARY

Pavements can be designed for heavily loaded trucks, but the rate of accumulating fatigue is greatly accelerated. The accumulation of fatigue for heavy trucks is highly disproportionate to the amount of payload transported. For the same fatigue and assumed proportions of trucks, the number of trucks loaded to the legal maximum axle loads is approximately 10 times the number of heavily loaded trucks. For the same fatigue, legally loaded trucks can transport approximately 8.2 times more payload than can heavily loaded trucks.

Pavements designed for normally loaded trucks may deteriorate rapidly and severely when subjected to heavily loaded trucks. Observed deterioration varies from accelerated rutting, both in depth and time, to severe breakup of the paved surface.

ACKNOWLEDGMENT

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Pavement Analysis for Heavy Hauls in Washington State

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An evaluation of the haul routes associated with moving heavy nuclear power plant components over existing state and county roads is described. These routes were associated with the planned construction of the power plants at Satsop (southwestern Washington state) and Sedro Wooley (northwestern Washington state). The procedures for evaluating the proposed moves are provided and include descriptions of the field and laboratory tests and analytical techniques. Ultimately, the haul routes analyzed were not used.

In recent years construction of nuclear power plants instigated analyses of the feasibility of using existing highways for hauling very large and heavy machinery. These hauls require special tractors and trailers to accommodate the machinery as well as to spread the load to minimize damage to pavements and bridges.

A special permit is required by those who perform the heavy hauling. For modestly oversize or overweight vehicles, obtaining a permit is somewhat routine as long as local requirements of wheel load and spacing are met, and the fee is usually nominal. Very heavy loads, however, require considerably more analysis to assess potential damage to the existing facilities, and the fee is commensurate with the expected cost to repair the damage.

Plans for constructing two nuclear power plants in Washington State instigated pavement analysis for the purpose of obtaining permits. Each plant had a different owner, and each owner was required to back up the application with an analysis of the significant damage that would be incurred, if any. For one project, Skagit, the supplier of the reactor equipment was required by the plant owner to deliver the equipment to the job site, so the supplier arranged for a consultant to evaluate the proposed route. The consultant's report was, in turn, presented to the Washington State Department of Transportation (WSDOT). For the other project, Satsop, the plant owner requested that the pavement evaluation be made by WSDOT, but be paid for by the plant.