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Fatigue Damage to Flexible Pavements Under Heavy Loads

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A modified Chevron N-Layer computer program has the capability of calculating the "work" done on pavements by the total load of various types of trucks. Seven truck groups are examined: two-tire and four-tire single axles, tandems, triaxles, and four-, five-, and six-axle groups. The two-tire (front steering) axle has the most severe damage relationship. Damage factors based on the AASHO Road Test and factors based on the concept of strain energy density are compared in the analyses. Various vehicle configurations and ranges of loads are discussed and evaluated in terms of damage per trip.

In the past, pavement design engineers have generally sought merely to sustain current statutory limits on axle loads—that is, to avoid destructive or catastrophic damage to pavements and premature depletion or ruination of physical assets (premature in this context implies that the damage occurs before the responsible agency is fiscally capable of restoring and maintaining the system under the changed circumstances). If it were feasible and practical to manufacture highway truck-trains that had perfect cornering and guidance capabilities in their trailing axles, bulk raw materials such as ores, coal, logs, and freight could be transported on highways more efficiently than they can by some of the simpler types of trucks, which are currently being overloaded by some owners and operators. These ideas issue from the "centipede concept", which fostered railroads and freight trains. These factors should be, and perhaps are being, considered by automotive designers and truck manufacturers. Inputs may take the form of comparative analyses of damage factors and optimization of tire and axle sizes and configurations.

Flexible pavement designs for heavy loads are primarily a function of traffic volume, material characteristics, and the relative damage caused by various load configurations. Material characteristics and traffic volume are assumed to have been determined, and variations in thicknesses would be a function of relative damage factors. The effects revealed are specific for flexible pavements, and further analyses of effects on bridges need to be performed. The analyses are predicated on the concept of the "strain energy density" exerted by the pavement to resist the loadings. Strain energy is the work done internally by the body and is equal to and opposite in direction to the work done on the body by the external force. Strain energy is the integral of strain energy density.

STRAIN ENERGY DENSITY

Sokolnikoff's Equation 26.8 (1) defined strain energy as

$$U = \int_\tau W d\tau \qquad (1)$$

where

- U = strain energy of the body,
- τ = a stress component, and
- W = volume density of strain energy at a specific point in the pavement structure, strain energy density, or elastic potential.

This relation can be expanded to yield Sokolnikoff's Equation 26.16, as follows:

$$W = (1/2)\lambda\vartheta e_{ii} + G e_{ij} e_{ij}$$
$$= (1/2)\lambda\vartheta^2 + G(e_{11}^2 + e_{22}^2 + e_{33}^2 + 2e_{12}^2 + 2e_{23}^2 + 2e_{13}^2) \qquad (2)$$

where

- e_{ii} = strain component in the ii direction,
- ϑ = $e_{11} + e_{22} + e_{33}$,
- λ = $E\mu/(1 + \mu)(1 - 2\mu)$,
- E = Young's modulus of elasticity for the material in which W is to be calculated,
- G = $E/2(1 + \mu)$ and is called the modulus of rigidity or the shear modulus, and
- μ = Poisson's ratio.

Young's modulus E and Poisson's ratio μ are input values to the Chevron N-Layer computer program (2); the strain components (e_{ii}, etc.) are outputs of the program.

Noting that Young's modulus E and the fraction (1/2) are present in each term of Equation 2, Equations 3 and 4 can be obtained as follows:

$$\epsilon_w^2 = 2W/E \qquad (3)$$

$$\epsilon_w^2 = (2W/E)^{1/2} \qquad (4)$$

where ϵ_w = "work strain" and has the same order of magnitude as the strain components e_{ii}. Since the strain components and the sum of the principal strains are squared, taking the square root, as in Equation 4, eliminates any direction and identification as tension or compression. Thus, ϵ_w can be used only as an indicator of the total effect of all strain components.

Stress components can be used to calculate W by using Sokolnikoff's Equation 26.17 (1):

$$W = \mu\psi^2/2E + (1 + \mu)(\tau_{11}^2 + \tau_{22}^2 + \tau_{33}^2)/2E + (1 + \mu)$$
$$(2\tau_{12}^2 + 2\tau_{23}^2 + 2\tau_{31}^2)/2E \qquad (5)$$

where $\psi = \tau_{11}^2 + \tau_{22}^2 + \tau_{33}^2$ and τ_{ii} = stress component in the ii direction. Noting that $W = (1/2)\,\epsilon_w^2 E$ and $W = \tau_w^2/2E$, then

$$\epsilon_w^2 E/2 = \tau_w^2/2E \qquad (6)$$

where τ_w = "work stress". Multiplying both sides by 2E gives

$$\epsilon_w^2 E^2 = \tau_w^2 \qquad (7)$$

Work stress is given by

$$\tau_w = \epsilon_w E \qquad (8)$$

Squaring the stresses and taking the square root of a summation eliminate, as before, any direction and identification as tension or compression.

Research that has not yet been published indicates that there is a direct correlation between the tensile strain component at the bottom of the asphaltic concrete layer and work strain. Thus, fatigue calculations based on the tensile strain component can be directly converted to a relation between work strain and fatigue.

INPUT PARAMETERS AND COMPUTATIONAL PROCESSES

The Chevron N-Layer (2) program was modified to perform calculations of strain energy density for specified depths and radial distances from the center of the load. Computations were requested for the bottom fiber of the asphaltic concrete and the top fiber of of the subgrade.

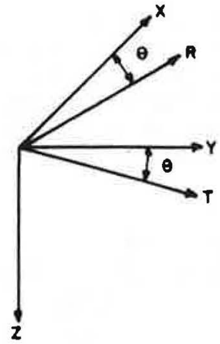
Superposition principles (1) apply when deflections, stresses, and strains are sufficiently small that they do not substantially affect the action of external forces. The nine basic superposition equations are summarized in Figure 1. The input format to the Chevron N-Layer program was modified for this analysis so that the loads and desired locations for computations are read in terms of an X-Y coordinate system and all stresses and strains are resolved and are compatible with the coordinate system.

Layer thicknesses of the asphaltic concrete pavement sections used in this analysis were those used at the AASHO Road Test (3), and the matrix resulted in 100 combinations. Only 67 of the possible combinations were constructed at the Road Test. The modulus of the asphaltic concrete was assumed to be 4140 MPa (600 000 lbf/in^2), determined from a typical temperature distribution for the AASHO Road Test site, and the Poisson's ratio was 0.4. The subgrade modulus was 41.1 MPa (6000 lbf/in^2), and the Poisson's ratio was 0.45.

Previous work (4) had shown that changes in tire pressures have an effect so minor as to be negligible in comparison with the effects of other variables. For this analysis, a tire pressure of 551 kPa (80 lbf/in^2) was used. The numbers of tires and axles on a vehicle were varied to simulate a front steering axle with 2 tires, a 4-tire single-axle tractor and/or trailer, an 8-tire tractor and/or trailer tandem-axle group, and a 12-tire trailer triaxle group. Analyses were also made to simulate a 16-tire, four-axle group; a 20-tire, five-axle group; and a 24-tire, six-axle group. Dimensions between tires and axles were the average of test vehicles used on loops 3-6 of the AASHO Road Test (5).

Tire loads were the same for every tire in a given

Figure 1. Basic equations by superposition principles.



$$\sigma_x = \sigma_R \cos^2\theta - 2\tau_{RT} \cos\theta \sin\theta + \sigma_T \sin^2\theta$$

$$\tau_{xy} = \sigma_R \cos\theta \sin\theta + \sigma_{RT}(\cos^2\theta - \sin^2\theta) - \sigma_T \sin\theta \cos\theta$$

$$\tau_{xz} = \tau_{RZ} \cos\theta - \tau_{TZ} \sin\theta$$

$$\sigma_y = \sigma_R \sin^2\theta + 2\tau_{RT} \sin\theta \cos\theta + \sigma_T \cos^2\theta$$

$$\tau_{yz} = \tau_{RZ} \sin\theta + \tau_{TZ} \cos\theta$$

$$\sigma_z = \sigma_z$$

$$\tau_{yx} = \tau_{xy}$$
$$\tau_{zx} = \tau_{xz}$$
$$\tau_{zy} = \tau_{yz}$$

group. The load ranged from 8.9 to 35.6 kN (2000-8000 lbf) on 2.2-kN (500-lbf) increments.

COMPARATIVE RESULTS

Deacon (6) also used superposition principles, but he assumed one circular loaded area to represent a dual tire arrangement. His fatigue criteria were based on the maximum principal tensile strain at the bottom of the asphaltic concrete layer.

Previous analyses (4) have indicated that the location of the most severe strain is under the center of a single tire or the center of the inside tire of a dual arrangement and at the top of the subgrade. Calculations of strain energy density indicate that the most severe strain is located at the bottom of the asphaltic concrete layer beneath the outer edge of the inside tire. Thus, the location shifted from the center of the inner tire to the outside edge. This significant change was the result of two conditions: (a) Previously, only one component of strain at each depth had been used as the criterion, and (b) the shear component is zero under the center of the load but becomes significant at the outer edge of the loaded area. In the case of two tires per axle, the critical point is the inside edge of the tire print. Thus, when all components of stress or strain are included, the location of the highest magnitude of total strains has shifted both vertically and horizontally within the pavement structure from the location that was previously thought to be the most severe.

The average work strain of the 100 structures and the load matrix described above for the four-tire, single-axle group was computed, and the value of work strain for the 80-kN (18 000-lbf) axle load for each respective pavement section was used as the basic value for all other groups for the same pavement section. Thus, Figure 2 shows the ratio of work strain at any given load to work strain for the 80-kN axle load. Therefore, the same amount of damage is caused by the total load on the group described in the table below (1 kN = 225 lbf):

Axle Group		Load (kN)	
Number of Axles	Number of Tires	Total	Per Axle
1	2	63.6	63.6
1	4	80.0	80.0
2	8	166.4	83.2
3	12	250.0	83.3
4	16	333.6	83.4
5	20	415.0	83.0
6	24	496.4	82.7

Since the damage factors for the steering axle on 5-cm (2-in) asphaltic concrete sections were five to eight times those on thicker sections, the values given in the table above and in Tables 1 and 2 are averages for the thicker pavements only.

Table 1 compares damage factors by the American Association of State Highway and Transportation Officials (AASHTO) and those developed based on "equal work" for the test vehicles used at the AASHO Road Test. Because the curves in Figure 2 represent the mean of the pavement thicknesses and vehicle dimensions, they are not necessarily those related to optimum conditions. Lanes 1 and 2 were the inner and outer lanes, respectively, and the test vehicles were classified as 2-S1 and 3-S2, respectively (2-S1 is a two-axle tractor and one-axle semitrailer; 3-S2 is a three-axle tractor and two-axle semitrailer). A total of 556 880 vehicle trips (1 113 760 applications) were made in each traffic lane. Thus, the loaded axles were the axles onthe rear of the tractor and on the trailer. All analyses of relative damage have been based on the magnitude of the loaded axles. Therefore, the fatigue damage caused by steering axles was included as a part of the damage of the loaded axles. The advent of wide tires and heavily loaded steering axles has further emphasized the need for damage-factor relations for two-tire axles. Transit-mix and coal- and stone-haul single-unit trucks typically have steering axle loads of 70-80 kN (16 000-18 000 lbf). Figure 2 shows that these loads are approximately 10 times more damaging than the steering axle loads used on the AASHO Road Test.

Figures 3 and 4 show the relation between AASHO Road Test damage factors and damage factors based on analyses of strain energy density. The circled points are the sum of the damage factors for all axle groups for the particular test vehicle by the strain energy density method versus the sum of the AASHTO damage factors for the two loaded axles. Inserts to Figures 3 and 4 show that the steering axle loads were not truly proportional to the loaded axles. For example, the steering axle loads for vehicles of loops 4 and 5 were the same for the respective vehicle classifications, yet the loaded axles were greater on loop 5 than on loop 4. For purposes of illustration, a line drawn through the loop 3 and loop 6 points provides one way of proportioning the steering axle load to the loaded axles.

Analyses by the strain energy density method indicate that damage factors for the steering axle on 2-S1 vehicles used on lane 1 of loops 3-6 were approximately 4 percent of the damage factor for a single, four-tire, loaded axle of those vehicles. However, damage factors for the steering axles of the 3-S2 vehicles used on lane 2 of loops 3-6 were approximately equal to 10-100 percent of the damage factors of a tandem axle load of those vehicles. Thus, the steering axles of the 3-S2 vehicles caused a far greater proportion of the damage per trip than the steering axles of the 2-S1 vehicles.

For 2-S1 vehicles, the relative accumulated damage per trip was 2.1 times the damage done by the four-tire, single-axle load. For 3-S2 vehicles, the relative accumulated damage per trip was 2.1-3.0 times the damage done by the tandem axle load. If the steering axle loads for 3-S2 vehicles had been reduced so as to cause a damage of only 10 percent of the tandem axle load damage, an increase in the magnitude of the tandem axle load would have been required to cause the same damage as that caused by the four-tire, single-axle loads of the 2-S1 vehicles. Because AASHTO (7) equated a 146.8-kN (33 000-lbf) tandem axle load to an 80-kN (18 000-lbf) four-tire, single-axle load, the above logic indicates that the tandem axle load would be greater than 146.8 kN. Thus, by strain energy density methods, a

Figure 2. Damage factors versus total load for various axle groupings.

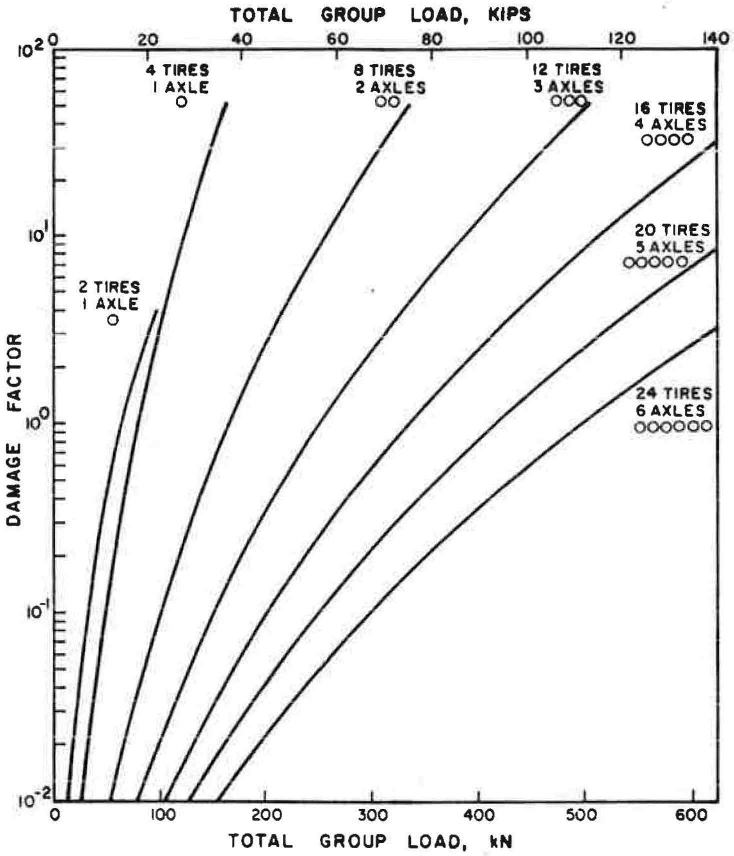


Table 1. Damage factors for AASHO Road Test vehicles based on concept of "equal work".

		Front Axle		Tractor Axle		Trailer Axle		Total Vehicle		Total AASHTO
Loop	Lane	Load (kN)	Damage Factor	Load (kN)	Damage Factor	Load (kN)	Damage Factor	Load (kN)	Damage Factor	Damage Factor
2	1	8.9	0.005	8.9	0.003			17.8	0.010	0.0004
3	1	18.7	0.025	54.3	0.016	54.3	0.016	126.8	0.345	0.440
4	1	24.9	0.045	80.5	1.01	81.4	1.05	186.8	2.105	2.09
5	1	24.9	0.045	101.4	3.45	100.5	3.30	226.9	6.795	4.75
6	1	39.6	0.205	134.8	17.50	133.0	16.0	306.9	33.705	13.90
2	2	8.9	0.005	26.7	0.055			35.6	0.060	0.010
3	2	24.5	0.043	108.1	0.132	109.9	0.144	242.4	0.319	0.63
4	2	39.1	0.20	143.2	0.480	144.6	0.500	326.9	1.18	1.85
5	2	39.1	0.20	177.5	1.39	179.3	1.47	395.9	3.06	4.11
6	2	48.5	0.40	217.1	4.12	214.8	3.90	480.4	8.42	8.35

Note: 1 kN = 225 lbf.

Table 2. Damage factors and payloads for various vehicle configurations.

	Total Vehicle Load (kN)			Front Axle (2 tires)		Single Axle (4 tires)			Tandem Axle (8 tires)			Triaxle (12 tires)			Total Vehicle		
Configuration Number	Gross Weight	Tare Weight	Payload	Axle Load (kN)	Unit Damage Factor	Axle Load (kN)	Number of Units	Unit Damage Factor	Axle Load (kN)	Number of Units	Unit Damage Factor	Axle Load (kN)	Number of Units	Unit Damage Factor	Total Vehicle Damage Factor	Total Number of Axles	Payload per Unit of Damage kN
1	326.0	115.7	210.3	41.3	0.24				142.3	2	0.465				1.17	5	179.7
2	355.9	133.4	222.5	41.3	0.24				157.3	2	0.750				1.74	5	127.9
3	355.9	133.4	222.5	53.4	0.56				151.2	2	0.620				1.80	5	123.6
4	355.9	133.4	222.5	40.0	0.24				157.9	2	0.770				1.755	5	125.0
5	533.8	186.8	347.0	53.4	0.56				240.2	2	7.10				14.76	5	23.5
6	533.8	186.8	347.0	40.0	0.24				246.9	2	8.40				17.015	5	20.4
7	533.8	186.8	347.0	53.4	0.56							240.2	2	0.810	2.18	7	159.2
8	533.8	186.8	347.0	40.0	0.24							246.9	2	0.940	2.095	7	165.6
9	533.8	186.8	347.0	40.0	0.24				123.4	4	0.240				1.175	9	295.3
10	533.8	169.0	364.8	40.0	0.24	89.0	2	1.70	202.4	2	2.80				5.815	7	62.7
11	533.8	169.0	364.8	40.0	0.24	80.1	2	1.00	166.8	2	1.00				4.215	7	86.5
12	355.9	133.4	222.5	71.2	1.42				284.7	1	19.3				20.72	3	10.7

Note: 1 kN = 225 ft.

166.4-kN (37 400-lbf) tandem axle load is equivalent to an 80-kN four-tire, single-axle load. Figure 2 shows that damage factors appropriate to a four-tire single axle should not be used for two-tire single axles.

Figure 2 also shows that the relation between load and damage factor for a two-tire axle group is roughly parallel to the relation for the single-axle, four-tire group, particularly in the range of normal loads. If one uses the concept of "influence lines" from structures, the single tires on either end of an axle are far enough apart that one tire has little influence on the other and a severe "punching" action results. However,

Figure 3. Comparison of damage factors by AASHTO method and strain energy density method for single-axle vehicles used at the AASHO Road Test.

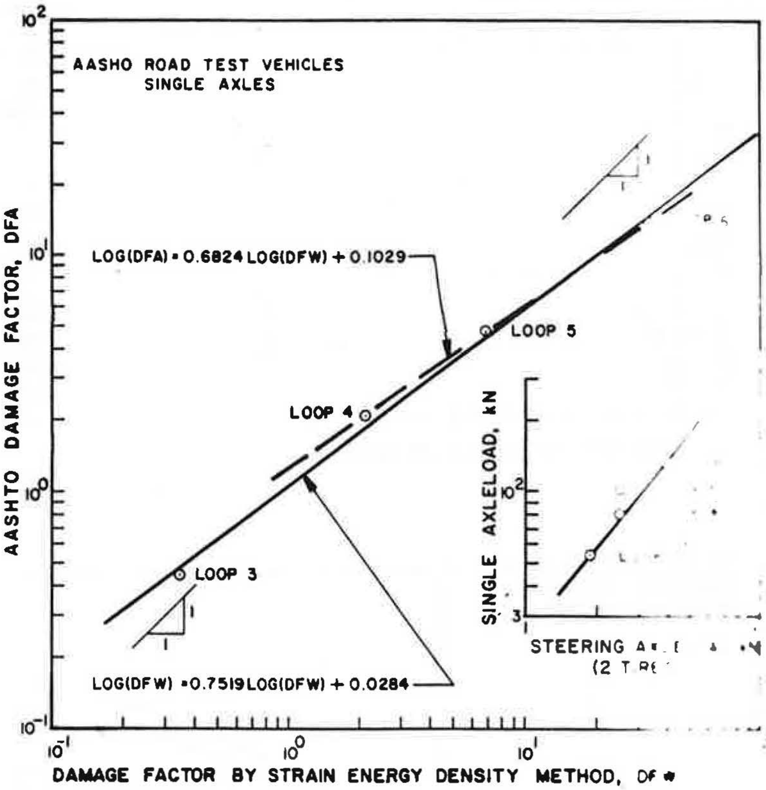
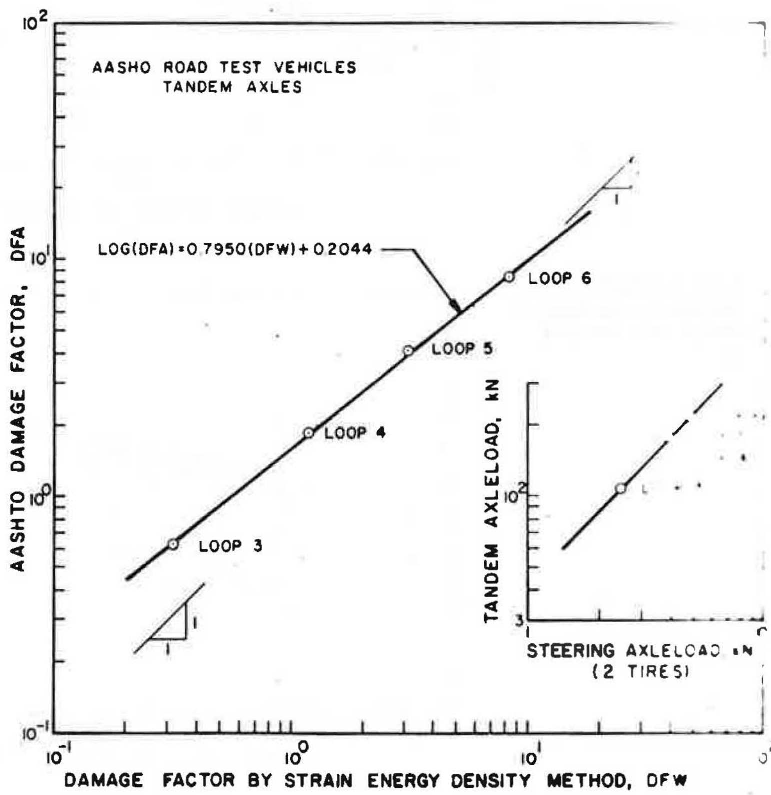


Figure 4. Comparison of damage factors by AASHTO method and strain energy density method for tandem-axle vehicles used at the AASHO Road Test.



when another tire is placed quite close to the single tire (to constitute a dual tire), the sharp bending caused by one tire is considerably reduced, or flattened, by the adjacent tire, and the deflection bowl is extended horizontally. For most highway vehicles, the deflections caused by a set of dual tires will be influenced by the dual tires on the opposite end of the axle. Similarly, the addition of another axle has a modifying influence on the deflection bowl of the single axle. In a three-axle group, maximum deflection will occur beneath the inner tire on the center axle. However, fourth and/or succeeding axles are located far enough from the "center" axle of the triaxle group as to have almost no effect on the magnitude of the deflection, but such additional axles do affect the horizontal dimension of the deflection bowl. Thus, the total load on a given group divided by the number of axles (see Figure 5) indicates that, for four or more axles, the total load can be increased by approximately 83.5 kN (18 800 lbf) for each additional axle.

Table 2 gives the effects of (a) different magnitudes of loads, (b) different configurations, and (c) differences in the total damage factor attributable to load distribution for the same total load and configuration. Winfrey and others (8) give a gross vehicle weight (GVW) of 535 kN (120 000 lbf) as proposed in research by the Federal Highway Administration for the 1985 proposed weight limits. Careful study of Table 2 illustrates that specifying total load only does not account for accumulated fatigue. Proposals of GVW limits without some restrictions on configuration could prove disastrous in terms of fatigue.

Table 2 gives another interesting comparison. Empty weights were obtained from manufacturers'

Figure 5. Load per axle versus number of axles in group.

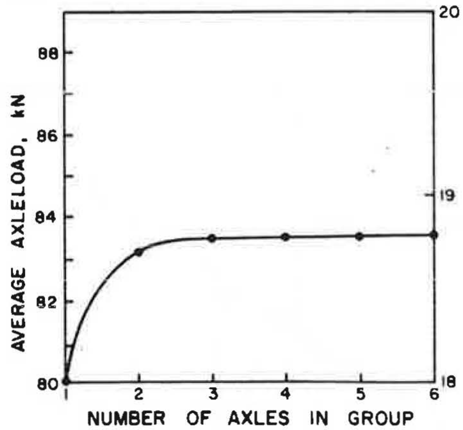


Figure 6. Total load versus damage factor for various vehicle configurations.

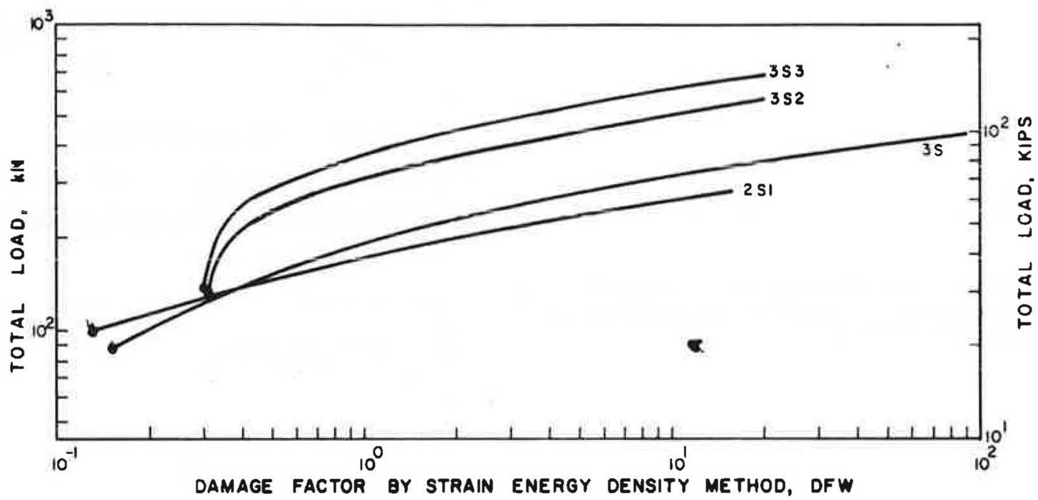


Figure 7. Effects of front axle load damage factor on damage factor for total load.

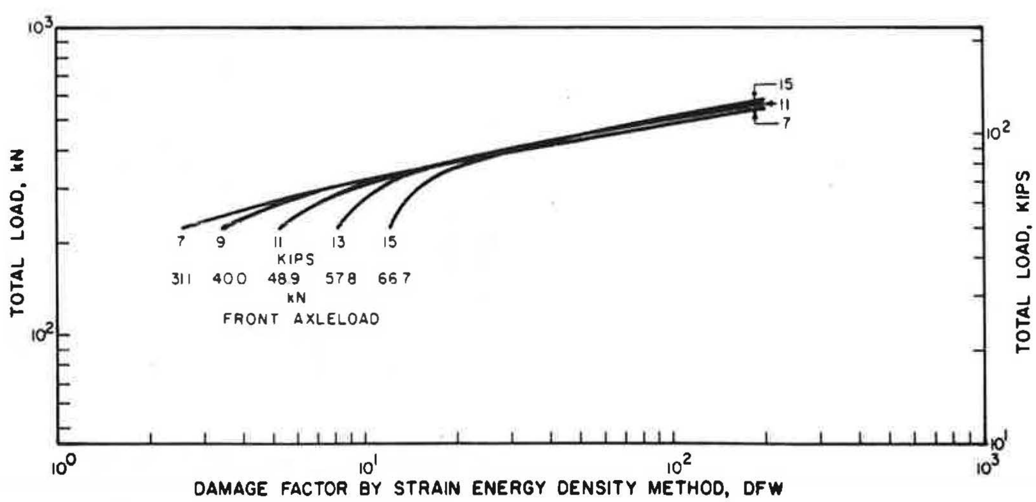
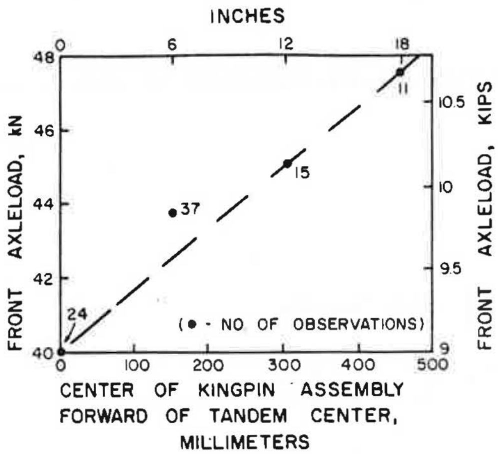


Figure 8. Front axle load versus position of kingpin assembly relative to center of tractor tandem.



published data, and corresponding payloads were selected to be within a realistic range. Thus, the payload per unit of total damage certainly shows some optimum load distributions as well as configurations to minimize damage. The empty weights and axle loads given in Table 2, which are representative of vehicles currently in use in Kentucky and the eastern part of the United States, differ considerably from those used in analyses by Layton and others (9).

Figure 6 shows the relation between total load and damage factor for several configurations. The circled points at the lower end of each curve represent empty weight for that vehicle. Two curves are shown in Figure 6 for the single-unit, three-axle truck to illustrate the variability among manufacturers in the intended use of the vehicle. The two curves are so close together, however, that one curve can be used for both vehicles.

Figure 7 shows the effects of front axle loads on total load and total damage factor for a five-axle semitrailer (3-S2) vehicle. The obvious conclusion is that the front axle load should be minimized and the remainder of the load should be evenly divided over the other two sets of tandems. The front axle load should range between 31.1 and 62.3 kN (7000 and 14 000 lbf) to provide adequate and safe steering. Figure 2 indicates that the remainder of the load is far less damaging when it is distributed over tandem or triaxle groups.

In August 1978, 129 vehicles of the 3-S2 classification were inspected and weighed at a scale on I-64 in Kentucky. The axles were weighed individually, and the location of the kingpin assembly relative to the center of the tandem on the tractor was measured. More than 80 percent of the kingpins were located ahead of the center of the tandem by as much as 46 cm (18 in). Figure 8 shows that the front axle load generally increased as the kingpin assembly was located farther from the center of the tandem. The increase from 40.0 to 47.6 kN (9000-10 700 lbf) on the front axle causes the damage factor to increase from 0.2 to 0.4. However, a 7.6-kN (1700-lbf) increase of the tandem axle load to 151.2 kN (34 000 lbf) causes an increase in the damage factor of only 0.18. Analysis indicates that simply moving the kingpin assembly back to the center of the tandem on the tractor will not increase pavement life significantly. However, the addition of a third axle to form a triaxle trailer group will substantially increase pavement life if the load is uniformly distributed among the three axles.

SUMMARY

Based on the concept of "equal work", damage factors have been developed and presented for seven axle groups—2-tire and 4-tire single axles, 8-tire tandem axles, 12-tire triaxles, 16 tires on four axles, 20 tires on five axles, and 24 tires on six axles. The damage factors and equivalent loads for all groupings are based on the amount of work caused by an 80-kN four-tire, single-axle load (see Figure 2 and text table given earlier, respectively). These damage-factor relations were used to compute the total damage for the test vehicles used at the AASHO Road Test and to compare it with values computed from the 1972 AASHTO Interim Guide (7) (Table 2).

Not only are magnitudes of loads important, but so is the way the load is distributed on a given type of vehicle. Additional load is placed on the front axle when the kingpin assembly is shifted forward of the center of the tandem of the tractor (see Figure 8). Weight shifted to the front axle can be two times more damaging than if it were placed on the tandem axles. Approximately 80 percent of the three-axle tractors have the kingpin assemblies located forward of the center of the tandem. Pavement life could be extended considerably if a triaxle group were used on the trailer instead of a tandem group.

If the proposed GVW is raised to 535 kN (120 000 lbf), the configuration of the vehicle should be specified to minimize the fatigue damage.

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Factorial Study of Relations Between Pavement Cost and Legal Axle Loads

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Results are presented of a study conducted to estimate lifetime costs for flexible pavements as a function of legal axle-load limits by using an improved version of the VESYS IIM computer program. VESYS IIM was modified to include capabilities for (a) seasonal characterizations of pavement materials, (b) a discretized representation of axle-load distribution, and (c) predictions of low-temperature cracking. A literature survey and a laboratory testing program were combined to produce definitions of the variations in permanent deformation parameters as important material characteristics vary seasonally with the environment. These data and other information and experience were applied to produce input data that would yield realistic performance predictions. A factorial of 64 solutions was obtained by using the input data and the improved version of VESYS IIM to study the effects of truck traffic for four levels of legal axle-load limits, two levels of traffic, two levels of pavement-section thickness, and four environmental zones. When failures were predicted, an overlay was applied and a new solution obtained until a pavement life of at least 20 years was attained. Initial and overlay costs were estimated, and these costs, for 20 years of pavement service, were related to legal axle-load limits. Estimated costs for 20 years of pavement service were considerably increased by increasing legal axle loads, and estimated cost increases were more severe for the northern than for the southern environmental zones of the United States.

Significant efforts are under way to evaluate the effects on pavement performance and maintenance costs of the increasing levels of traffic being imposed on U.S. highway systems. The results of one study in this overall effort are reported here.

This study was conducted by using an improved version of the Federal Highway Administration computer program VESYS IIM for predicting pavement distress and performance (1, 2). Briefly, VESYS IIM consists of a set of mechanistic models that are uniquely integrated for use in analyzing the structural integrity and performance of flexible highway pavements. The working hypothesis for the VESYS model assumes that all responses of the pavement can be stated in terms of the geometry of the pavement structure, the physical properties of the material layers, and the effect of climate and load on these properties. The material properties can be characterized for primary response behavior as linear elastic and/or linear viscoelastic, and temperature and stress in the appropriate layers are accounted for.

Laws of cumulative damage exist for several distress mechanisms that cause pavement damage. These laws are formulated from observations of the distress behavior of the materials. The serviceability of a pavement is hypothesized to be represented by the linear accumulation of the distress parameters (cracking, rutting, and roughness), which can be expressed similarly as the American Association of State Highway and Transportation Officials definition of present serviceability index (PSI).

More precise verification of the model was necessary in this study than had previously been attained (3-6). However, such precise verification requires more realistic measurement of traffic and environmental effects. To account for these effects, the program was modified to include all the capabilities of VESYS IIM plus capabilities for (a) seasonal characterizations of stiffness and permanent deformation properties of materials, (b) a discretized representation of axle-load distribution for more accurate axle-load characterization, and (c) predictions of low-temperature cracking (1). This new version of VESYS (currently called VESYS A) is believed to provide greatly improved predictions of rutting, slope variance, PSI, and expected life.

Verification of the modified program and its associated sets of input data was accomplished by comparing predicted distress and performance with measured values from four sections of the AASHO Road Test, four sections from the Brampton Test Road, and data available for sections of I-80N in Utah and I-10 in Florida. This verification effort involved an iterative procedure that required exercising the model to arrive at predictions, comparing the predictions with measured performance, analyzing differences to assess their cause, and making rational modifications to problem input where they were indicated to sharpen up the predictions. The only revisions made to input values were those that could be justified through analysis.

Once the modified VESYS IIM subsystem had been verified and rational material, traffic, and environmental characterizations established, a factorial of 64 solutions was developed in order to arrive at a basis for establishing relations between cost and legal axle load. This factorial included four levels of legal axle load [80, 89, 98, and 107 kN [18 000, 20 000, 22 000, 24 000 lbf (18, 20, 22, and 24 kip)]}, two levels of pavement section called thin and thick, two levels of truck traffic called low and high, and four different environmental zones, including wet-freeze, dry-freeze, wet/no freeze, and dry/no freeze. The solutions were run as a full factorial of 64. The environmental zones were repre-