Fatigue Damage of Flexible Pavements Under Heavy Loads

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A modified Chevron N-Layer computer program has the capability of calculating the "work" done by the total load on a given load group. Earlier analyses of AASHO Road Test sections and test vehicles had permitted the development of damage factor relationships. This paper presents seven, namely two-tire and four-tire single axles, tandems, triaxles, and four-axle, five-axle, and six-axle groups. The two-tire axle (front or steering axle) has the most severe damage relationship. The 80-kN (18-kip) four-tire single axle was used as the reference axle and was assigned a damage factor of 1.0 for a specific amount of "work". Other axle arrangements and total loads producing that amount of "work" were 63.6 kN (14.3 kips) for the two-tire axle, 166.4 kN (37.4 kips) for eight-tire tandems, 250.2 kN (56.25 kips) for twelve-tired triaxles, 333.6 kN (75.0 kips) for a sixteen-tired four-axle group, 415.0 kN (93.3 kips) for a twenty-tired five-axle group, and 496.4 kN (111.6 kips) for a twenty-four-tired six-axle group.

Using the damage factors for the various axle groupings, one trip of a vehicle having a gross weight of 534 kN (120 kips) can produce up to approximately 17 times the damage of an 80-kN (18-kip) axleload, depending on the particular axle groupings involved. Equally as significant effects can be attributed to the distribution of loads on a given type of vehicle. For example, a 355.9-kN (80-kip) vehicle having 53.4 kN (12 kips) on the steering axle and 151.3 kN (34 kips) on each of two sets of tandem axles has an equivalent damage factor of 1.80 per trip. If the load distribution is changed to 40.0 kN (9 kips) on the steering axle and 157.9 kN (35.5 kips) on each of two sets of tandem axles, the total damage factor per trip is reduced to 1.76. Other configurations and various ranges of loads are presented, evaluated in terms of damage per trip, and discussed.
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by

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ABSTRACT

A modified Chevron N-Layer computer program has the capability of calculating the "work" done by the total load on a given load group. Earlier analyses of AASHO Road Test sections and test vehicles had permitted the development of damage factor relationships. This paper presents seven, namely two-tire and four-tire single axles, tandems, triaxles, and four-axle, five axle, and six-axle groups. The two-tire axle (front or steering axle) has the most severe damage relationship. The 80-kN (18-kip) four-tire single axle was used as the reference axle and was assigned a damage factor of 1.0 for a specific amount of "work". Other axle arrangements and total loads producing that amount of "work" were 63.6 kN (14.3 kips) for the two-tire axle, 166.4 kN (37.4 kips) for eight-tire tandems, 250.2 kN (56.25 kips) for twelve-tired triaxles, 333.6 kN (75.0 kips) for a sixteen-tired four-axle group, 415.0 kN (93.3 kips) for a twenty-tired five axle group, and 496.4 kN (111.6 kips) for a twenty-four-tired six-axle group.

Using the damage factors for the various axle groupings, one trip of a vehicle having a gross weight of 534 kN (120 kips) can produce up to approximately 17 times the damage of an 80-kN (18-kip) axleload, depending on the number of axle groupings and the particular axle groupings involved. Equally as significant effects can be attributed to the distribution of loads on a given type of vehicle. For example, a 355.9-kN (80-kip) vehicle having 53.4 kN (12 kips) on the steering axle and 151.3 kN (34 kips) on each of two sets of tandem axles has an equivalent damage factor of 1.80 per trip. If the load distribution is changed to 40.0 kN (9 kips) on the steering axle and 157.9 kN (35.5 kips) on each of two sets of tandem axles, the total damage factor per trip is reduced to 1.76. Other configurations and various ranges of loads are presented, evaluated in terms of damage per trip, and discussed.
INTRODUCTION

Heretofore, pavement design engineers generally have sought merely to sustain current limits (statutory) on axlesloads -- that is, to avoid destructive and catastrophic damage to pavements and premature depletion, or ruination, of physical assets. Premature (in this context) implies that it occurs before the responsible agency is fiscally capable of restoring and maintaining the system under the newer circumstances. If it were feasible and practical to manufacture highway truck-trains having perfect cornering and guidance capabilities in the trailing axles, bulk raw materials, such as ores, coals, logs, and freight, could be transported on the highways more efficiently than by some simpler styles of trucks presently used and presently being overloaded by some owners or 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 manufacturers of trucks. 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 upon bridges need to be performed. The analyses are predicated upon the concept of 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 upon 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

$$U = \int \tau W d\tau,$$

where

- $\tau$ = a stress component,
- $W$ = volume density of strain energy at a specific point in the pavement structure, strain energy density, or the elastic
potential, and
\[ U = \text{strain energy of the body.} \]

This relationship can be expanded to yield his Equation 26.16 as follows:

\[ W = \frac{1}{2} \lambda \vartheta e_{ii} + G e_{ij} e_{ij} \]

\[ = \frac{1}{2} \lambda \vartheta^2 + G (e_{11}^2 + e_{22}^2 + e_{33}^2 + 2e_{12}^2 + 2e_{23}^2 + 2e_{13}^2), \]

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

Young's modulus, \( E \), and Poisson's ratio, \( \mu \), are input values to the Chevron N-Layer computer program \( (2) \); the strain components, \( e_{ij} \) 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:

\[ \epsilon_w^2 = 2W/E \]  
\[ \epsilon_w = \sqrt{2(\mu W/E)} \]  

where \( \epsilon_w \) = "work strain" and has the same order of magnitude as the strain components \( e_{ij} \).

Since the strain components and the sum of the principle strains are squared, taking the square root as in Equation 4 eliminates any direction and identification as tension or compression. Thus, \( \epsilon_w \) can be used only as an indicator of the total effect of all strain components.

Stress components may be used to calculate \( W \) by Sokolnikoff’s Equation 26.17 \( (1) \):

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

where \( \psi = \tau_{11} + \tau_{22} + \tau_{33} \) and
\( \tau_{ij} = \text{stress component in the ii direction.} \)

Noting that \( W = (1/2) \epsilon_w^2 E \) and \( \tau_w = \epsilon_w^2/2E \), then

\[ \epsilon_w^2 E/2 = \tau_w^2/2E \]  

where \( \tau_w \) = "work stress".
Multiplying both sides by $2E$ gives
\[ \epsilon_w^2 E^2 = \tau_w^2. \]

Work stress is given by
\[ \tau_w = \epsilon_w E. \]

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

Work not yet reported 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 upon the tensile strain component may be directly converted to a "work strain" versus fatigue relationship.

**INPUT PARAMETERS AND COMPUTATIONAL PROCESSES**

The Chevron N-Layer (2) program was modified to perform the strain energy density calculations 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 the subgrade.

Superposition principles (1) apply when deflections, stresses, and strains are sufficiently small so as not to substantially affect the action of external forces. The nine, basic superposition equations are summarized in Figure 1. For this analysis, the input format to the Chevron N-Layer program was modified so that the loads and desired locations for computations are read in terms of a X-Y coordinate system, and all stresses and strains are resolved and 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 4.14 GPa (600 ksi), determined from a typical temperature distribution for the AASHO Road Test site. The Poisson's ratio was taken as 0.4. The subgrade modulus was 41.1 MPa (6 ksi), and the Poisson's ratio was 0.45.

Previous work (4) had shown that changes in tire pressures have such a minor effect as to be negligible compared to effects of other variables. For this analysis, a tire pressure of 80 psi was used. The numbers of tires and axles on a vehicle were varied to simulate
a front steering axle having two tires, a four-tired tractor and(or) trailer single axle, an eight-tired tractor and(or) trailer tandem axle group, and a twelve-tired trailer triaxle group. Analyses were also made to simulate a 16-tired four-axle group, a 20-tired five-axle group, and a 24-tired 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 group. The load ranged from 8.9 kN (2 kips) to 35.6 kN (8 kips) on 2.2-kN (0.5-kip) 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 principle tensile strain at the bottom of the asphaltic concrete layer.

Previous analyses (4) 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. Strain energy density calculations indicate that the most severe location is 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: (1) previously, only one component of strain at each depth had been used as the criterion; and (2) 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 which 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-tired single-axle group was computed and the value of "work strain" for the 80-kN (18-kip) axleload for each respective pavement section was used as the basic value for all other groups for that same pavement section. Thus, Figure 2 shows the ratio of the "work strain" at any given load compared to the "work strain" for the 80-kN (18-kip) axleload. Therefore, the same amount of "damage" is caused by the total load on the group described in Table 1. Since the damage factors for the steering axle on 51-mm (2-inch)
asphaltic concrete sections were five to eight times those on thicker sections, the values in Tables 1, 2, and 3 are averages for the thicker pavements only.

Table 2 compares damage factors by AASHTO and those developed based upon “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, the curves 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 2S1 and 3S2, respectively (2S1 is a two-axle tractor and a one-axle semi-trailer vehicle; 3S2 is a three-axle tractor and a two-axle semi-trailer vehicle). A total of 556,880 vehicle trips (1,113,760 applications) was made in each traffic lane. Thus, the “loaded” axles were the axles on the rear of the tractor and on the trailer. All analyses of relative damage have been based upon 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 have further emphasized the need for damage factor relationships for two-tired axles. Transit-mix and coal- and stone-haul single-unit trucks typically have steering axleloads of 70 to 80 kN (16 to 18 kips). Figure 2 illustrates that these loads are approximately ten times more damaging than the steering axleloads used on the AASHO Road Test.

Figures 3 and 4 illustrate the relationship between AASHO Road Test damage factors and damage factors based upon strain energy density analyses. 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 AASHO damage factors for the two “loaded” axles. Inserts to Figures 3 and 4 illustrate that the steering axleloads were not truly proportional to the “loaded” axles. For example, the steering axleload 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 illustration purposes, a line drawn through the Loop 3 and Loop 6 points provides one way of proportioning the steering axleload to the “loaded” axles.

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

For 2S1 vehicles, the relative accumulated damage per trip was 2.1 times the damage done by the single, four-tired axleload. For 3S2 vehicles, the relative accumulated damage per trip was 2.1 to 3.0 times the damage done by the tandem axleload. If the steering axleloads for 3S2 vehicles had been reduced so as to cause a damage of only 10 percent of the tandem axleload damage, then an increase in the magnitude of the tandem axleload would have been required to cause the same damage as the single, four-tired axleloads of the 2S1 vehicles. Because AASHO (7) equated a 146.8 kN (33 kips) tandem axleload to an 80-kN (18-kip), four-tired, single axleload, the above logic indicates the tandem axleload would be greater than 146.8 kN (33 kips). Thus, by strain energy density methods, a 166.4-kN (37.4-kip) tandem axleload is equivalent to an 80-kN (18-kip) single, four-tired, axleload. Figure 2 illustrates that damage factors appropriate to a four-tired, single axle should not be used for two-tired, single axles.

Figure 2 illustrates that the load-damage factor relationship for a two-tired axle group is roughly parallel to the relationship for the single-axle, four-tired group -- particularly in the range of normal loads. Using 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 -- thus, a severe "punching" action results. However, when another tire is placed quite close to the single tire (thus a dual tire), the sharp bending due to 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 upon 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 upon 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 (Figure 5) indicates that, for four or more axles, the total load can be increased by approximately 83.5 kN (18.8 kips) for each additional axle.
Table 3 shows the effects of (a) different magnitudes of loads (Vehicles 1, 2-4, 5-11, and 12), (b) different configurations (Vehicles 1-6, 7, and 8; 9; 10 and 11; and 12), and (c) differences in the total damage factor due to load distribution for the same total load and configuration (Vehicles 2-6; and 10 and 11). Winfrey et al. (8) gave the gross vehicle weight of 535 kN (120 kips) as proposed by FHWA research for the 1985 proposed weight limits. Careful study of Table 3 illustrates that specifying total load only does not account for accumulated fatigue. Proposals of gross weight limits without some restrictions upon configuration could prove disastrous in terms of fatigue.

Table 3 contains another interesting comparison. Empty weights were obtained from manufacturer’s 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. Empty weights and axleloads shown in Table 3 are representative of vehicles currently in use in Kentucky and the eastern part of the United States and differ considerably from those used in analyses by Layton et al. (9).

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

Figure 7 illustrates the effects of front axleloads upon total load and total damage factor for a five-axle semi-trailer vehicle (3S2). The obvious conclusion is that the front axleload should be minimized, and the remainder of the load should be evenly divided over the other two sets of tandems. The front axleload should range between 31.1 kN (7 kips) to 62.3 kN (14 kips) to provide adequate and safe steering. Figure 2 indicates that the remainder of the load is far less damaging when distributed over tandem or triaxle groups.

In August 1978, 129 vehicles of the 3S2 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.
Over 80 percent of the kingpins were located ahead of the center of the tandem by as much as 457 mm (18 inches). 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 kN (9 kips) to 47.6 kN (10.7 kips) on the front axle causes the damage factor to increase from 0.2 to 0.4. However, a 7.6-kN (1.7-kip) increase of the tandem axle load of 151.2 kN (34 kips) 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 the pavement life significantly. However, the addition of a third axle to form a triaxle trailer group will substantially increase the pavement life if the load is uniformly distributed among the three axles.

**SUMMARY**

Based upon the concept of “equal work”, damage factors have been developed and presented for seven axle groups -- two-tired and four-tired single axles, eight-tired tandem, and twelve-tired triaxle, sixteen tires on four axles, twenty tires on five axles, and twenty-four tires on six axles. The damage factors and equivalent loads for all groupings are based upon the amount of work caused by an 80-kN (18-kip) four-tired single axle load (Figure 2 and Table 1, respectively). Using these damage factor relationships, the total damage was computed for the test vehicles used at the AASHO Road Test and compared to values computed from the 1972 AASHTO Interim Guide (7) (Table 2).

Not only are magnitudes of loads important, but equally as important 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 (Figure 8). Weight shifted to the front axle can be two times more damaging than if 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. The pavement life could be extended considerably if a triaxle group on the trailer were used instead of a tandem group.

If the proposed gross vehicle weight is raised to 535 kN (120 kips), the configuration of the vehicle should be specified to minimize the fatigue damage.
ACKNOWLEDGEMENTS

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REFERENCES

Department of Transportation, Research and Special Programs Administration.
TABLE 1. LOAD GROUPS PRODUCING A DAMAGE FACTOR OF 1.0

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NOTE: 1 kN = 0.225 KIP

TABLE 2. DAMAGE FACTORS FOR AASHO ROAD TEST VEHICLES

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<th>FRONT AXLE</th>
<th>TRACTOR AXLE</th>
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*BY 'EQUAL WORK' CONCEPT
NOTE: 1 kN = 0.225 KIP
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<td>355.9</td>
<td>133.4</td>
<td>314.6</td>
<td>71.2</td>
<td>1.42</td>
</tr>
</tbody>
</table>

NOTE: 1 kN = 0.225 KIP
SUPERPOSITION EQUATIONS

\[ \sigma_x = \sigma_R \cos^2\theta - 2\sigma_{RT} \cos\theta \sin\theta + \sigma_T \sin^2\theta \]

\[ \tau_{xy} = \sigma_R \cos\theta \sin\theta + \sigma_{RT} \cos^2\theta - \sin^2\theta \cdot \sigma_T \sin\theta \cos\theta \]

\[ \tau_{xz} = \tau_{RZ} \cos\theta \cdot \tau_{TZ} \sin\theta \]

\[ \sigma_y = \sigma_R \sin^2\theta + 2\sigma_{RT} \sin\theta \cos\theta + \sigma_T \cos^2\theta \]

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

\[ \sigma_z = \sigma_z \]

\[ \tau_{yx} = \tau_{xy} \]

\[ \tau_{zx} = \tau_{xz} \]

\[ \tau_{zy} = \tau_{yz} \]

Figure 1. Basic Equations by Superposition Principles.
Figure 2. Damage Factors versus Total Load for Various Axle Groupings.
Figure 3. Comparison of Damage Factors by AASHTO Method and by Strain Energy Density Method for Single-Axle Vehicles Used at the AASHO Road Test.
Figure 4. Comparison of Damage Factors by AASHTO Method and by Strain Energy Density Method for Tandem-Axle Vehicles Used at the AASHO Road Test.
Figure 5. Load per Axle versus Number of Axles in the Group.
Figure 6. Total Load versus Damage Factor for Various Vehicle Configurations.
Figure 7. Effects of Front Axleload Damage Factor upon Damage Factor for Total Load.
Figure 8. Front Axleload versus Position of Kingpin Assembly Relative to the Center of Tractor Tandem.