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Truck Damage Factors Using Dissipated Energy versus Peak Strains

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In this paper, truck factors (how many 18-kips single axle loads is equivalent to the passage of a truck in terms of fatigue damage) were evaluated for different axle types and configurations using six pavement profiles, involving thin, medium-thick and thick AC layers and low and high damping ratios. Three methods were used and compared to the AASHTO equivalency factors: Peak tensile strain, peak and midway strains, and dissipated energy. The SAPSI-M computer program was used to calculate the stress and strain histories within the asphalt concrete layer in longitudinal and transverse directions due to the passage of a set of moving axle loads. The corresponding dissipated energy was determined from the area within the stress-strain hysteresis loop. Fatigue life predictions were then made using empirical relationships, and Load Equivalency Factors (LEF) were determined for each axle configuration. A total of thirteen truck configurations were included in the analysis, including three axle types: Single, Tandem and Tridem axles. Axles were fitted with wide-base single tires to investigate the critical component of strain under this tire configuration. The results showed that the critical response under wide-base single tires is in the longitudinal direction, and that in this direction, the dissipated energy method gives LEFs that are about 20% higher for tandem axles and about 30% higher for tridem axles, for thin to medium pavements. This translates to an increase in Truck Factors of up to 15% relative to the strain-based method. For thick pavements the difference among dissipated energy and strain methods is not significant. The AASHTO method grossly underpredicts the damage caused by wide-base single tires. The underprediction is worse for multiple axles and thin to medium pavements.

1. INTRODUCTION

Truck traffic is a major factor in pavement design because truck-loads are the primary cause of pavement damage. Different trucks cause different damage levels to pavements, however, because of variations in axle loads, number and configuration of axles, types of suspension, tire type and inflation pressure and other factors. To compare the damage caused by different truck and axle configurations, the Equivalent Single Axle Load (ESAL) concept has been widely used in pavement engineering. In this concept, the damage caused by the passage of a given truck or axle group over the pavement is described in terms of a unit damage caused by a standard axle. This standard axle is a single axle, with dual tires, loaded to 80 kN (18 kip). Using this concept, each axle type will have a Load Equivalency Factor (LEF), and each truck can be described by a Truck Factor (TF). The TF is the sum of LEFs corresponding to the different axles of the truck, expressed in ESALs. The most widely used LEFs are those obtained from the AASHO road test. These values are based on empirical methodology, which uses the Pavement Serviceability Index (PSI) as a measure of pavement performance, and includes environmental factors and other variables. Another approach to determining LEFs is the mechanistic approach. In this approach, stresses and strains caused by a given axle group are calculated using a mechanistic model, which simulates the response of the pavement structure. These responses are then input in a damage law. The LEF is obtained as the ratio of the damage caused by a particular axle group with that caused by the standard axle.

In this paper, LEFs were calculated using the mechanistic approach and three different methods: (1) peak strains; (2) difference between peak and valley (midway) strains; and (3) dissipated energy. Results were compared to the AASHTO LEF-values. The analysis was done using longitudinal and transverse stresses/strains, and for different flexible (asphalt) pavement profiles and axle/truck types. The only mode of failure considered is fatigue.

The objective of the analysis presented in this paper is to investigate: (1) the usefulness of the dissipated energy approach in describing the damage caused by the passage of an axle group, and (2) the critical component of strain (longitudinal versus transverse) under wide-base single tire loading.

1.0 METHODS USED

1.1 AASHTO Method

One of the most widely used methods for calculating LEFs is the AASHTO method. AASHTO LEFs are based on empirical data generated from the AASHO Road Test. Empirical relationships were developed to correlate PSI, as a measure of pavement performance, to the number of load repetitions. Because AASHTO ELF-values are purely empirical, they present several shortcomings. For example, they are based on one tire type and one level of tire inflation pressure, whereas several tire types are in use today with significantly higher tire pressures. Also, the AASHO Road Test included only single and tandem axles with dual tires and loads up to 133 kN (30 kip) and 214 kN (48 kip), respectively. Today, axle configurations include super singles, tridem and quad axles with higher axle loads. In this paper, LEF-values for the different axle configurations were determined for three different values of the Structural Number (SN= 4, 5 and 7) and a terminal serviceability index (p_t) of 2.5.

1.2 Mechanistic-Empirical Strain-Based Methods

Because of the shortcomings in the AASHTO method, many researchers have proposed using a mechanistic method to determine LEFs. In this approach, pavement response is calculated using mechanics, and the peak strain at the bottom of the AC layer is used to predict fatigue damage via a regression model that is based on laboratory tests and calibrated to field performance data. In this paper, this method is designated as the Peak Tensile Strain Method. If the method is applied to tandem and tridem axles, they are considered as two and three independent single axles, respectively. This assumption is not correct if there is significant interaction between axles within a tandem or tridem axle. Because of this problem, some researchers have used the difference between peak and midway tensile strains for accounting for successive axles: VESYS (Jordhal and Rauhut, 1983) and KENLAYER (Huang, 1993). For example, the strains to be used for damage analysis of a tridem axle are (see Figure 2): (1) The first peak strain due to the first axle; (2) the difference between the second peak strain due to the second axle and the strain value midway between the first and second axles; and (3) the difference between the third peak strain due to the third axle and the strain value midway between the second and third axles. This second strain-based method is designated as the Peak/Midway Strain Method.

1.3 Mechanistic-Empirical Energy-Based Method

Some researchers have proposed using dissipated energy as opposed to peak strain for predicting fatigue damage of asphalt concrete pavements. Dissipated energy is defined as the area within a stress-strain hysteresis loop, and represents the energy lost in the pavement as a result of the passage of an axle group over the pavement. A clear advantage of this method over the strain-based methods is that the damage caused by the passage of an axle group (say, a truck) is described by a single number: The cumulative dissipated energy. This number represents the response of the pavement during the entire passage of the axle group or truck, and not discrete maximum and minimum peaks. This method is designated as the Dissipated Energy Method.

2.0 ANALYSIS

2.1 Pavement Profiles and Axle/Truck Configurations Used in the Analysis

The three methods described above (peak strain, peak/midway strain and dissipated energy) were used to predict fatigue life for different axle types and axle configurations. LEFs were then calculated and compared with each other as well as those from the AASHTO method. Six different pavement profiles, three axle types and thirteen truck types were used. Pavement profiles used in the analysis are listed in Table 1. They represent the range of conditions that can be encountered in the field, from thin-soft to thick-stiff pavements. Damping ratios of 0.05 and 0.25 correspond to normal traffic and creep speed conditions, respectively. Similarly, dynamic modulus values of 4,800,000 MPa (700,000 psi) and 2,400,000 MPa (350,000 psi) correspond to normal and creep speed conditions, respectively, at normal temperature. The three axle types used are single, tandem and tridem axles with wide-base single tires. Load magnitudes of these axles are 107 kN (24 kip), 214 kN (48 kip) and 321 kN (72 kip), respectively. The distance between axles within a tandem or a tridem is 1.22 m (48 in). Axle configurations and load information of the thirteen trucks used in the analysis were adopted from (Gillespie et al., 1993), and are shown in Table 2. The use of wide-based single tires is for the purpose of investigating the critical component of stress/strain for fatigue damage. It is well recognized that the critical component of strain under dual tires is the longitudinal component. However, for tandem and tridem axles with wide-base single tires, the peak transverse strain can be higher than the longitudinal strain due to the overlapping of the influence functions from the consecutive axles/tires.

2.2 Prediction of Pavement Fatigue Damage Using SAPSI-M Program

Prediction of fatigue damage using the energy dissipation concept requires the use of a computer program that solves for the response of pavement systems with visco-elastic material properties. The SAPSI-M computer program (Chatti and Yun,1995) was used for this purpose. It computes the stress and strain time histories at any point within the asphalt concrete layer due to the passage of a moving load. The dissipated energy was determined by calculating the area within the stress-strain hysteresis loop. The output from SAPSI-M was also used for the two strain-based methods.

2.3 Fatigue Models Used in the Study

As part of the SHRP study, Monismith (Monismith et al., 1994) evaluated the fatigue performance of a thin asphalt pavement section consisting of 9 cm (3.5 in) asphalt concrete layer over 32 cm (12 in) base at FHWA's Accelerated Loading Facility. Beam specimens (6.3 cm x 5.1 cm x 38.1 cm or 2.5 in x 2.0 in x 15 in) were made from the sawed asphalt concrete slab sections for laboratory fatigue testing. All tests were performed under controlled-strain mode of loading, at a frequency of 10 Hz and a temperature of 20 °C (68°F). Fatigue tests were summarized in the form of relationships between fatigue life and initial strain, and initial dissipated energy per cycle. The following equations were developed using linear regression analysis:

[Eq. 1]	$N_f = 8.959*10^{-8}(\varepsilon_o)^{-3.574}$	$R^2=0.987$
[Eq. 2]	$N_f = 425.81(w_o)^{-1.846}$	$R^2=0.987$

where N_f is the fatigue life, ε_o is the initial peak tensile strain, and w_o is the initial dissipated energy density (in psi).

3.0 RESULTS

4.1 Stress - Strain Time Histories

Longitudinal versus Transverse response - Figures 1 and 2 show stress-strain time histories at the bottom of AC layer for the soft-thin pavement subjected to a moving tridem axle load. In the longitudinal direction (Figure 1), the bottom of the AC layer is compressed as the load approaches a fixed point in the pavement, then stretched when the load is near or on that point, and compressed again as the load moves away. So, there is compressions midway between two consecutive peaks. On the other hand, in the transverse direction (Figure 2), there is still some tension between peaks because the bottom of AC layer is stretched as the load approaches. Because there is very little interaction between consecutive axles, the hysteresis loops are essentially superposed on top of each other.

Thick versus Thin Pavement - Figures 2 and 3 show transverse stress-strain time histories at the bottom of the AC layer in thin and thick soft pavements subjected to a moving tridem axle load. For the thick pavement (Figure 3), there is strong interaction between consecutive axles. Because of this interaction, there is high tension midway between two peaks, and the corresponding hysteresis loops become small. On the other hand, for the thin pavement (Figure 2), this interaction is much smaller, as described above.

Soft versus Stiff Pavement - Figures 2 and 4 show transverse stress-strain time histories in soft and stiff thin pavements subjected to a moving tridem axle load. There is little difference in the overall shape of the strain time history, other than the magnitude and the fact that the strain pulses in the soft pavement are asymmetric. The stress-strain hysteresis loops are quite different. It is fat in the soft pavement (high damping) while it is very lean in the stiff pavement (low damping). The stiff pavement behaves more like an elastic material and therefore is damaged less than the soft pavement.

4.2 LEF-Values for Different Axle Types

LEF-values for all pavement profiles were obtained for single, tandem and tridem axles with wide base single tires using the four different methods described above. The unit of damage used in the analysis is the damage caused by the standard 80 kN (18 kip) single axle with dual tires. For the mechanistic analysis, this unit damage corresponds to the fatigue damage caused by the longitudinal strain/stress component because it is the most critical component under a dual tire configuration.

Longitudinal Direction - LEF-values considering longitudinal stresses and strains are shown in Figure 5. Both strain-based methods have the same LEF-values. This is because the midway strain in the longitudinal direction is in compression and so the (tensile) difference between peak and midway strains is equal to the peak strain. The Dissipated Energy method gives higher LEF-values for tandem and tridem axle loads than the strain-based methods. This is because the hysteresis loop includes the area caused by compression and the dissipated energy method counts this area as damage. However the strain-based methods count only peak values, and compression is not counted as damage. For thin to medium pavements, the difference is about 20% for tandem axles and about 30% for tridem axles. However for the thick pavement, this difference vanishes. The effect of AC layer stiffness and damping is negligible for thin pavements. The effect increases somewhat for medium to thick pavements (10% for tandem to 20% for tridem axles). The figure also shows that there is little interaction between consecutive axles for thin to medium pavements. Therefore for thin to medium pavements, a tandem is equivalent to two singles and a tridem is equivalent to three singles. This is not true for the thick pavement and for the AASHTO LEFs. Also, the AASHTO LEF-values grossly underestimate the damage of these axles relative to the mechanistic approach.

Transverse Direction - LEF-values considering transverse stresses and strains are shown in Figure 6. The Peak Strain method significantly overestimates the damage for tandem and tridem axles, and therefore should not be used. The Dissipated Energy method underpredicts the damage because the dissipated energy in the longitudinal direction is 20% to 30% greater than that in the transverse direction for the single axle. The Peak/Midway tensile strain method gives in-between predictions. The AASHTO method again grossly underestimates the damage. The difference in LEF-values from the Peak/Midway tensile strain method and the Dissipated Energy method decreases with the increase in pavement thickness. This is because the interaction between nearby axle loads becomes bigger with the increase in pavement thickness. Stiffness and damping ratio again have essentially no effect on the results in the transverse direction. Finally, the comparison of Figure 6 to Figure 5 shows that the response in the transverse direction is not critical even for the wide base super singles.

4.3 LEF-Values for Different Truck Configurations

Truck factors for the stiff-medium thick pavement (152mm thick, Modulus of 4,800,000 MPa and damping ratio of 0.05) were evaluated using the four different methods. Figures 7 and 8 show truck factors of 13 different axle configurations based on longitudinal and transverse stresses/strains, respectively. As expected from the above results, the AASHTO method gives unrealistically low truck factors (TF). The dissipated energy method gives the highest TFs using the longitudinal response whereas it gives the lowest TFs using the transverse response. The Peak/Midway strain method gives TFs in between. The peak strain method gives unrealistically high TFs when using the transverse response.

The overall trends of TFs along truck types are not so different between methods except for the Peak Tensile Strain method when using transverse response. The two strain-based methods give the same TFs when using the longitudinal response, and for trucks which have only single axles (truck type 1, 5, 9 and 10). The overall conclusion from the two figures is that TFs should be calculated using the longitudinal response (even for wide base single wheels). For this critical orientation, the dissipated energy method gives TFs that are up 15% higher than the strain-based methods.

5.0 CONCLUSION

The following conclusions can be made:

- The critical response under wide-base single tires is in the longitudinal direction.
- When longitudinal strains and stresses are used, the dissipated energy method gives LEFs that are about 20% higher for tandem axles and about 30% higher for tridem axles, for thin to medium pavements. This translates to an increase in TF of up to 15% relative to the strain-based method. For thick pavements the difference among dissipated energy and strain methods is not significant.
- The AASHTO method grossly underpredicts the damage caused by wide-base single tires. The underprediction is worse for multiple axles and thin to medium pavements.
- The damping ratio has little effect on the results.

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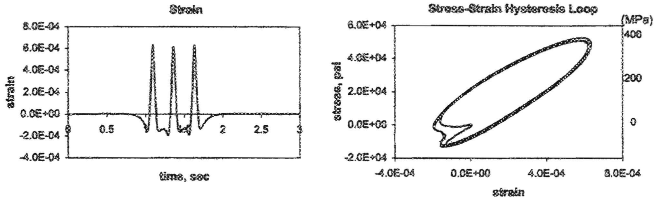

Figure 1. Longitudinal Strain Time History and Stress-Strain Hysteresis Loop for Soft-Thin Pavement under Moving Tridem Axle Load

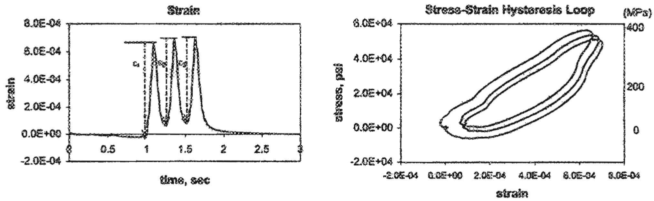

Figure 2. Transverse Strain Time History and Stress-Strain Hysteresis Loop for Soft-Thin Pavement under Moving Tridem Axle Load

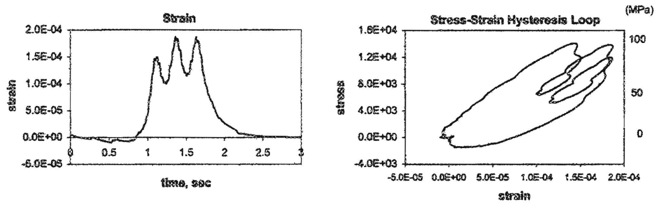

Figure 3. Transverse Strain Time History and Stress-Strain Hysteresis Loop for Soft-Thick Pavement under Moving Tridem Axle Load

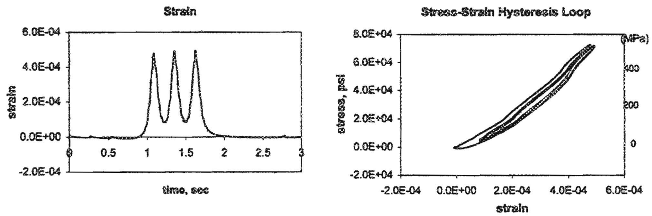

Figure 4. Transverse Strain Time History and Stress-Strain Hysteresis Loop for Stiff-Thin Pavement under Moving Tridem Axle Load

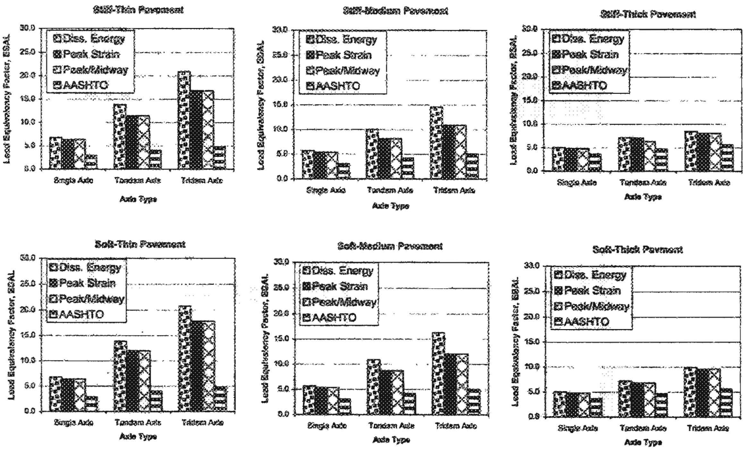

Figure 5. Load Equivalency Factors for Different Axle Types : Longitudinal Direction

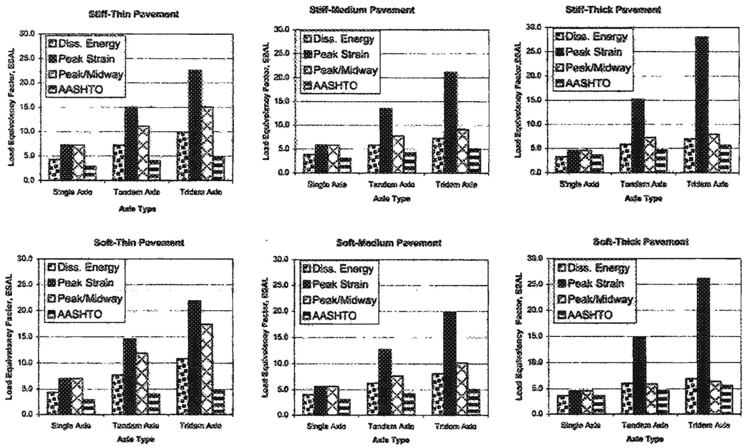

Figure 6. Load Equivalency Factors for Different Axle Types : Transverse Direction