Application of ASTM E1049-85 in Calculating Load Equivalence Factors from In Situ Strains

T. Papagiannakis, A. Oancea, N. Ali, J. Chan, and A. T. Bergan

A comparative overview of the methods used to calculate mechanistic load equivalence factors (LEFs) is provided. In addition, an application of the rainflow/range-pair counting method (ASTM E1049-85) in calculating LEFs from in-situ pavement strains is demonstrated. The experimental program involved two test vehicles, with a BB truck providing the reference axle load. Asphalt concrete (AC) interfacial strains were measured at three vehicle speeds and three levels of axle load. Counting fatigue cycles according to the ASTM standard has shown that (a) the calculated LEFs decrease with vehicle speed, and (b) the LEFs for entire vehicles are substantially higher than the sum of the LEFs of their individual axle groups. This trend becomes more pronounced at higher vehicle speeds. The LEFs obtained by the rainflow/range-pair counting method were compared with those obtained by the Roads and Transportation Association of Canada method. The two sets of mechanistic LEFs were also compared with the empirical LEFs recommended by AASHTO. This comparison, however, was inconclusive and could not verify that one of the two mechanistic LEF methods best describes the fatigue cycles caused in AC by multiple axle loads.

Load equivalence factors (LEFs), defined as ratios of pavement life, have been the subject of study since the AASHO road test. They are calculated as follows:

$$LEF_x = \frac{N_{18}}{N_x} \qquad (1)$$

where LEF_x is the equivalence factor of load x and N_{18} and N_x are the pavement lives (i.e., number of repetitions to terminal serviceability) for the BB axle and axle load x, respectively. LEFs obtained from empirical observations at the AASHO road test are still in use with few modifications (*1*).

A group of methods has been developed on the basis of mechanistic estimates of pavement life. Typically, a relationship is adopted relating pavement life to a pavement response parameter, as follows:

$$N = k_1\left(\frac{1}{\varepsilon}\right)^{k2} \qquad (2)$$

where ε is a selected pavement response parameter [usually interfacial asphalt concrete (AC) strain or surface deflection] and k_1 and k_2 are material constants determined through regression on fatigue test data. Substituting Equation 2 into Equation 1 gives the following:

$$LEF_x = \left(\frac{\varepsilon_x}{\varepsilon_{18}}\right)^{k2} \qquad (3)$$

Pavement response parameters are analytically calculated or measured using instrumented pavement sections. A variety of researchers (*2–10*) have proposed alternative methods for calculating mechanistic LEFs. Most of these studies (*2–4,6–8,10*) used only discrete (i.e., peak and valley) values of the pavement response curves. The main difference is in the way these peaks and valleys were processed to determine the damaging effect of multiple axles. There have been exceptions to the use of discrete pavement response values. Southgate and Deen (*5*) used strain energy to index pavement fatigue, whereas Govind and Walton (*9*) used the rate of change of strain for the same purpose. However, no evidence has been presented to date suggesting that such integral methods are more suited for describing pavement fatigue than are discrete methods.

In 1986 a standard for counting cycles in fatigue analysis was published (ASTM E1049-85). Four methods were documented:

- Level crossing method,
- Peak counting method,
- Simple-range counting method, and
- Rainflow counting and related methods.

The fourth method listed encompasses three procedures, namely, range-pair counting, rainflow counting, and simplified rainflow counting. Although the ASTM standard does not recommend one method over another, certain methods are clearly best suited for particular applications. The simplified rainflow method, for example, is best for prolonged and repeated load histories.

Two of the studies mentioned previously used methods documented by ASTM. Hutchinson et al. (*7*) applied the rainflow/range-pair counting method to calculate LEFs from surface deflections, whereas Hajek and Agarwal (*8*) applied the peak counting method to calculate LEFs from surface deflections and AC interfacial strains. As described in the following paragraphs, the difficulty in counting strain cycles results because AC interfacial strains go into compression under an approaching tire, peak in tension when the tire is directly over

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the sensor, and turn again into compression after the tire has passed over the sensor. This pattern repeats as subsequent tires go over the sensor (see Figure 1).

Oancea (*11*) presents a comparative assessment of all the methods used in the literature for calculating mechanistic LEFs (see Table 1). Among the methods described in the ASTM standard, the rainflow/range-pair counting method is best suited for counting pavement strain cycles under multiple axle loads. As shown in Figure 2, this method provides a direct relationship between strain history (shown as linear segments) and the stress-strain behavior of the AC. Indeed, Ranges 1–2 and 2–3 are directly related to stress-strain cycle 1–2–3, Ranges 3–4 and 4–5 are directly related to stress-strain cycle 3–4–5, and so on.

OBJECTIVES

To date, there have been no efforts to apply the rainflow/range-pair counting method for calculating LEFs from interfacial AC strains. Another issue that has not been addressed is the contribution to pavement fatigue from the strain history between the axles and axle groups of a vehicle. This role is fulfilled by addressing the following objectives:

- Demonstrate the application of the rainflow/range-pair counting method of ASTM E1049-85 in calculating LEFs of multiple axles from interfacial AC pavement strains.
- Use the rainflow/range-pair counting method to compare the LEFs of an entire vehicle with the sum of the LEFs of its individual axles and axle groups.

RAINFLOW/RANGE-PAIR COUNTING METHOD

The terminology used in explaining the range-pair counting procedure of the rainflow method is shown in Figure 3. The value of a range is equal to the sum of the absolute values of its peak and valley strains. As specified in ASTM E1049-85, the idea is to count a range as a cycle if it can be paired with a subsequent loading in the opposite direction. The steps involved in determining the cycles to be counted lead to a simple algorithm that takes into account all cycles, large and small. These steps are described as follows, naming the current range as n and the immediately preceding range as $n - 1$:

1. Read next peak or valley. If out of data, go to Step 5.
2. If there are less than three points, go to Step 1. Form ranges n and $n - 1$ using the three most recent points (i.e., peak and valley) that have not been discarded.
3. Compare the absolute magnitude of range n to that of range $n - 1$:

- *If* $|n| < |n - 1|$, go to Step 1.
- *If* $|n| \geq |n - 1|$, go to Step 4.

4. Count range $n - 1$ as one cycle and discard the points that define it.
5. If any cycles remain, start at the end of the sequence and count backwards. If a single peak remains, count it as one cycle.

This procedure does not differentiate between positive and negative ranges. It is clear, however, that the mode of fatigue failure should determine the type of cycle counted. That is, valley-peak-valley cycles should only be counted for tensile failure, whereas peak-valley-peak cycles should only be counted for compressive failure (e.g., rutting). ASTM E1049-85 presents an example of applying this method in counting fatigue cycles (see Figure 4).

Figures 5 and 6 show the application of this method for a single and a tandem axle, respectively. In accordance with the ASTM standard, full ranges are taken into account (i.e., from the compression trough to the tension peak), as opposed to previous methods in which the compressive strains were completely ignored (*4,6*). Whether this is appropriate for AC pavements may be disputed along with other fatigue concepts originally developed for metals. Only laboratory fatigue experimentation can verify that such fatigue concepts are indeed applicable for pavements as well as for metals.

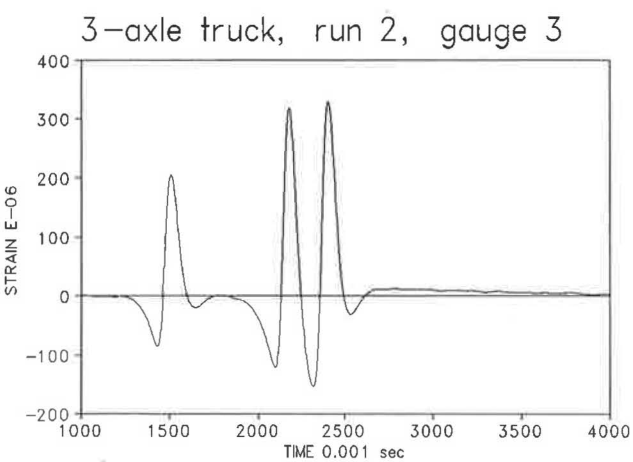
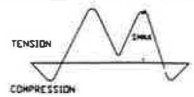
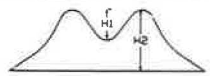
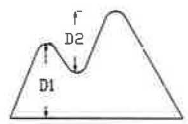
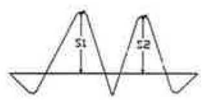
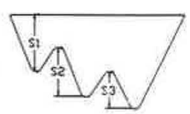
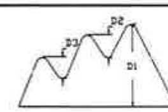
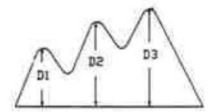
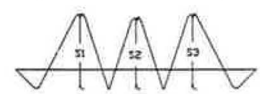


FIGURE 1 Strain pattern under a three-axle truck (*11*).

THE EXPERIMENT

The experiment was conducted in the summer of 1990 at the instrumented pavement site located on HW-16 north of Saskatoon, Canada. The site is equipped with a number of deflection, strain, and temperature transducers (*12*). The pavement structure at the site consists of 175 mm of AC, 100 mm of base, and 100 mm of subbase, laid on a glacial till subgrade. Two vehicles were tested: a three-axle single unit truck and a five-axle semitrailer truck (see Figure 7). Each test run was accompanied by a Benkelman beam truck, which provided the reference axle load. Vehicle runs were performed at three speeds (20, 40, and 50 km/hr) and for three levels of static axle load (see Table 2). A replicate run was performed for each test vehicle, speed, and axle load combination, bringing the total number of runs to 54 (two replicates × three speeds × three loads × three vehicles). Replicate runs were intended

TABLE 1 OVERVIEW OF MECHANISTIC LEF METHODS (*11*).

Method	Basis	Formula	Diagram
Deacon (1969)	Calculated AC strain	$F = 2*\left(\frac{SMAX}{S18}\right)^{c}$	
Ramsamooj (1972)	Stress intensity factors based on measurements	$F = \left(\frac{H1}{H18}\right)^{4} + \left(\frac{H2}{H18}\right)^{4}$	
Christison (1978)	Measured deflection	$F = \left(\frac{D1}{D18}\right)^{c} + \left(\frac{D2}{D18}\right)^{c}$	
	Measured AC strain	$F = \left(\frac{S1}{S18}\right)^{c} + \left(K\frac{S1}{S18}\right)^{c}$ K= average ratio $\frac{S_2}{S_1}$	
Treybig (1983)	Calculated subgrade strain	$F = \left(\frac{S1}{S18}\right)^{c} + \left(\frac{S2}{S18}\right)^{c} + \left(\frac{S3}{S18}\right)^{c}$	
	Calculated AC strain	$F = \left(\frac{S1}{S18}\right)^{c} + \left(\frac{S2}{S18}\right)^{c} + \left(\frac{S3}{S18}\right)^{c}$	
Southgate (1985)	Calculated strain energy density	$F = \frac{N18}{N}$	$\log(N) = \frac{\log(\epsilon_{w}) + 2.6777807}{-0.15471249}$
RTAC (1986)	Measured deflection	as Christison (1978)	
	Measured AC strain	as Treybig (1983)	
Hutchinson (1987)	Measured deflection	$F = \left(\frac{D1}{D18}\right)^{c} + \left(\frac{D2}{D18}\right)^{c} + \left(\frac{D3}{D18}\right)^{c}$ ASTM/Range-Pair Counting	
Hajek (1989)	Calculated & measured deflection	$F = \left(\frac{D1}{D18}\right)^{c} + \left(\frac{D2}{D18}\right)^{c} + \left(\frac{D3}{D18}\right)^{c}$ ASTM/Peak Counting	
	Calculated & measured AC strain	$F = \left(\frac{S1}{S18}\right)^{c} + \left(\frac{S2}{S18}\right)^{c} + \left(\frac{S3}{S18}\right)^{c}$ ASTM/Peak Counting	
Govind (1989)	Calculated AC stress	Damage Factors (LEF's) were calculated based on the rate of change of stress.	
Tseng (1990)	Calculated AC strain	The AC strain pattern was used to modify the value of the exponent C.	

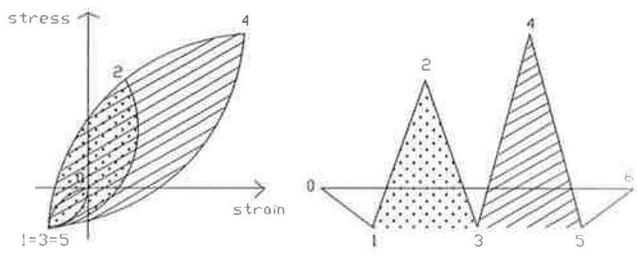


FIGURE 2 Fatigue cycles in a stress-strain diagram (*11*).

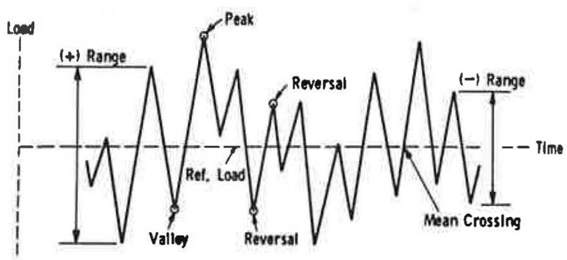
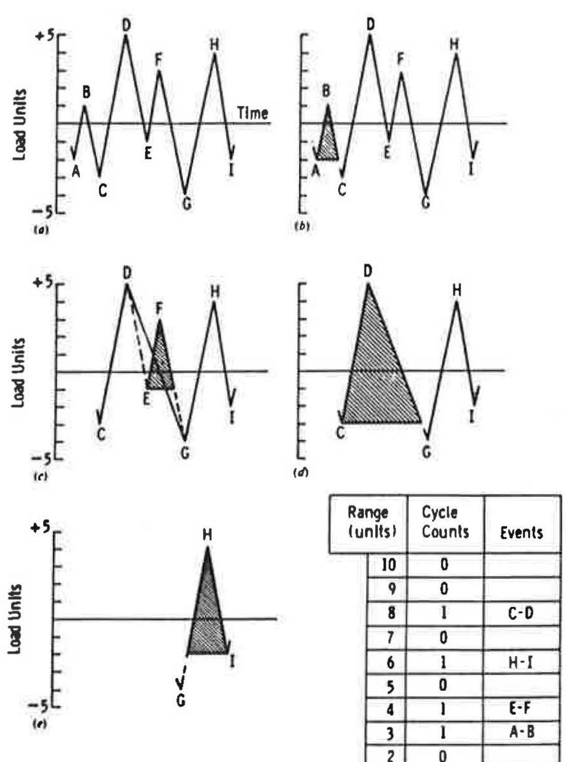


FIGURE 3 Rainflow counting terminology (ASTM E1049-85).



Range (units)	Cycle Counts	Events
10	0	
9	0	
8	1	C-D
7	0	
6	1	H-I
5	0	
4	1	E-F
3	1	A-B
2	0	
1	0	

FIGURE 4 Example of rainflow/range-pair counting method (ASTM E1049-85).

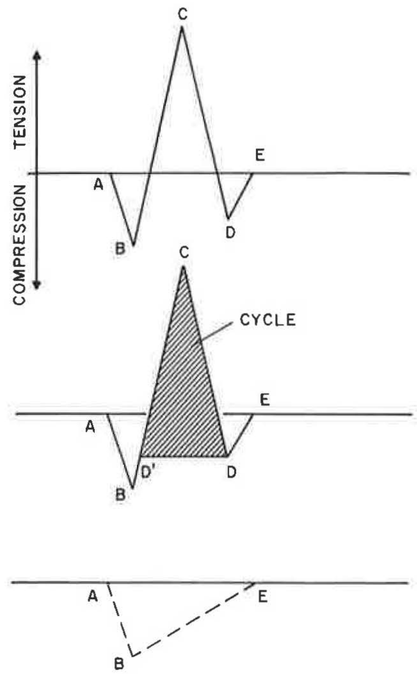


FIGURE 5 Strain cycle counting under a single axle.

to increase the chances of achieving equal lateral placement of the test vehicles and the BB truck with respect to the sensors. Lateral placement was determined by videotaping the passing vehicle axles and the pavement edgeline and scaling off the distance from the still image. The test lasted 2 days, during which the pavement temperature ranged between 26°C and 30°C. As a result, the pavement temperature was not considered a variable in the analysis.

DISCUSSION OF RESULTS

LEF values were calculated according to Equation 3 by following the strain counting method and selecting a k_2 value of 3.8. LEF calculations were limited to strains recorded by a particular sensor to avoid the measurement variability between sensors. Because of the small number of vehicle runs available, LEF calculations were made irrespectively of vehicle lateral placement, despite the observed sensitivity of the measured strains to lateral placement (see Figure 8). An effort was made to select the sensor that happened to be nearest to the outside tire of the pair of axles compared.

As expected, the measured strains exhibited large sensitivity to vehicle speed (see Figure 9). Therefore, only strains obtained at vehicle speeds within 10 percent were compared. Another source of variation in the calculated LEFs is vehicle dynamics. It is expected, however, that vehicle runs performed at roughly the same vehicle speeds will produce precise strain measurements, all other conditions (e.g., temperature and lateral placement) being equal. Replicate vehicle runs were shown to produce dynamic axle load waveforms repetitive in space (*13*). On the other hand, vehicle dynamics are expected to result in discrepancies when comparing mechanistic LEFs and empirical LEFs because the latter are

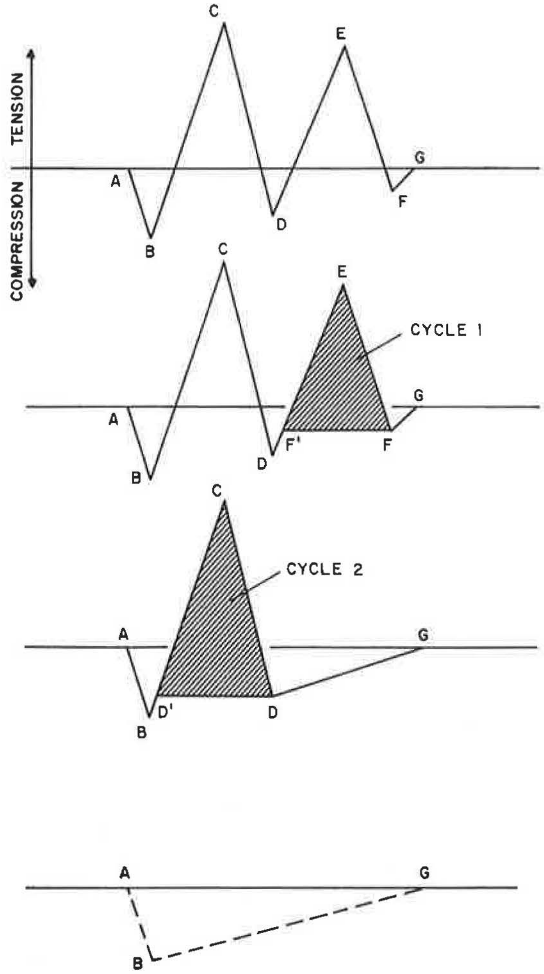


FIGURE 6 Strain cycle counting under tandem axles.

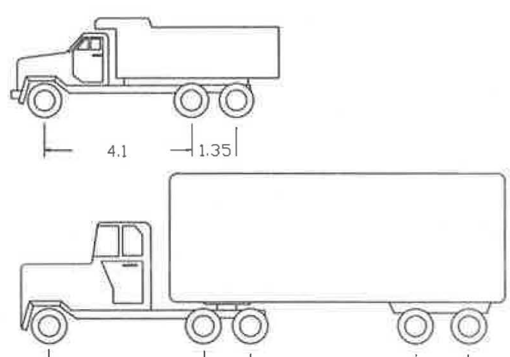


FIGURE 7 Axle spacing of test vehicles in meters.

based on static axle load values. No effort was made to account for this discrepancy. The results of the LEF calculations are presented in Tables 3 and 4 for the three-axle truck and the five-axle truck, respectively.

Two observations can be made:

- In general, the calculated LEFs decrease with vehicle speed.
- LEFs calculated for entire vehicles can be substantially higher than the sum of the LEFs of their individual axle groups (i.e., either single axles or tandem axles in this experiment). This trend becomes more pronounced as vehicle speeds increase.

The dependence of in-situ strains on vehicle speed is a direct result of the viscous properties of the AC. For a given pair of axle loads, strain ratios decrease with increasing vehicle speed and, as a result, LEFs decrease. Thus, mechanistic LEFs should be viewed as speed-specific. This conclusion agrees with the findings of Hutchinson et al. (*7*) but disagrees with the Roads and Transportation Association of Canada (RTAC) study (*6*), which states, "the magnitude of the response ratios did not exhibit a consistent trend with velocity" and, therefore, "the average of the three response ratios [obtained at 6, 13, and 50 km/hr] was used in the load equivalency predictions."

The second observation suggests that the damaging effect of a vehicle is not fully accounted for simply by adding the LEFs of its individual axle groups. This procedure ignores the strain cycles between axle groups, which are shown as cross-hatched areas in Figure 10. Obviously, the larger the number of axle groups in the vehicle, the larger this difference will be. The difference increases with increasing vehicle speed because the unloading time between axle groups decreases. It is therefore concluded that simply adding the damaging effect of axle groups underestimates the damaging effect of a vehicle.

The LEFs obtained at 50 km/hr using the rainflow/range-pair counting method were compared with two sets of values: (a) mechanistic LEFs obtained by the RTAC method (*6*) using the strain measurements at hand and (b) AASHTO LEFs based on the static axle loads measured, a terminal serviceability of 2.5, and a structural number (SN) of 3 in. (*1*). The comparisons are shown in Figures 11–14. In general, the differences between the two groups of mechanistic LEFs (i.e., ASTM and RTAC) are quite significant but exhibit no definite patterns. There is no doubt that the method used for counting fatigue cycles affects the magnitude of the strain cycles counted and the resulting LEFs. In general, there is a better agreement between the two sets of mechanistic LEFs than between any one of them and the empirical LEFs obtained from AASHTO. However, no quantitative assessment was attempted to determine which set is closer to the AASHTO LEFs because such a comparison would not be meaningful. As a result, no conclusive evidence could be produced to support one cycle counting method over another. Indeed, only laboratory fatigue testing can address this issue and specifically determine whether or not the compressive part of the strain history contributes to the fatigue of AC.

CONCLUSIONS

Counting fatigue cycles according to the rainflow/range-pair method of the ASTM E1049-85 standard has shown that

- The calculated LEFs decrease with vehicle speed.
- LEFs for entire vehicles are substantially higher than the sum of the LEFs of their individual axle groups. This trend becomes more pronounced at higher vehicle speeds.

TABLE 2 STATIC LOADS OF TEST VEHICLES IN KILOGRAMS

	3-AXLE TRUCK		5-AXLE TRUCK		
LOAD CODE	STEERING	TANDEM*	STEERING	TANDEM1	TANDEM2
1	4200	16300	4790	16890	17550
2	4160	13450	4500	10950	9250
3	4020	11240	4320	5020	2940

* Load values are suspect due to improper weighing procedure

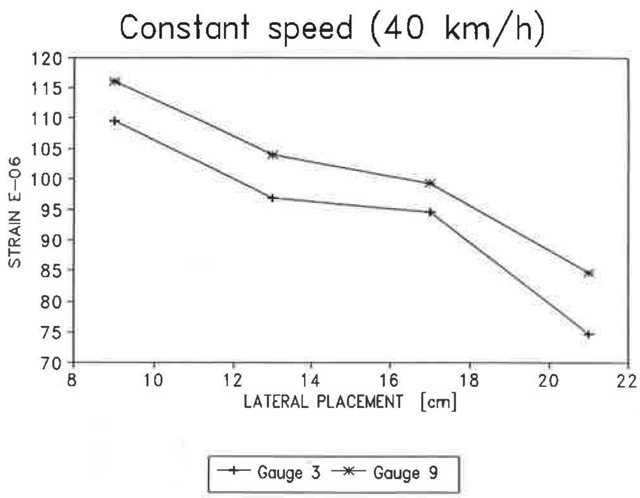


FIGURE 8 Strain versus lateral placement with respect to a sensor.

TABLE 3 LEFs FOR THREE-AXLE TRUCK

RUN	LOAD CODE	NOMINAL SPEED kmh	STEERING	TANDEM	AXLE SUM	WHOLE TRUCK
2		20	-	-	-	-
6	1	40	0.02	74.65	74.67	74.77
8		50	2E-06	3.39	3.39	3.39
11		20	-	-	-	-
14	2	40	7E-06	0.36	0.36	0.39
17		50	0.07	1.08	1.15	1.15
20		20	-	-	-	-
23	3	40	0.31	3.05	3.36	4.04
27		50	0.08	1.47	1.55	1.97

\- Speed difference between test truck and BB truck > 10%

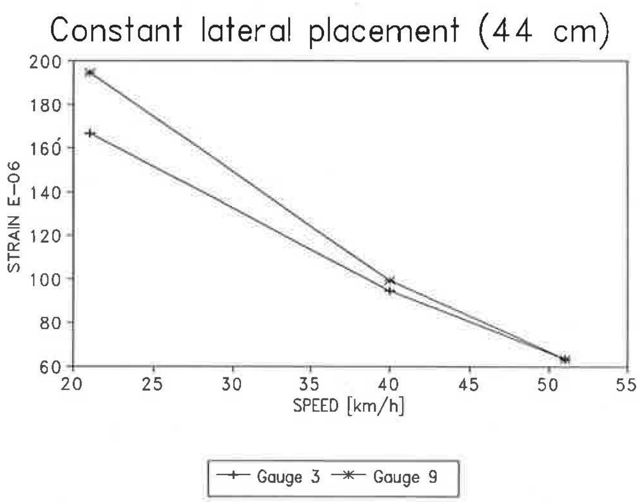


FIGURE 9 Strain versus vehicle speed.

TABLE 4 LEFs FOR FIVE-AXLE TRUCK

RUN	LOAD CODE	NOMINAL SPEED kmh	STEERING	TANDEM1	TANDEM2	AXLE SUM	WHOLE TRUCK
30		20	0.58	4.79	7.74	13.11	16.30
32	1	40	0.31	2.68	5.33	8.32	11.38
35		50	0.10	1.51	2.98	4.59	6.54
38		20	0.20	1.88	1.71	3.79	4.90
42	2	40	0.29	0.38	0.27	0.94	1.63
44		50	0.01	0.26	0.24	0.51	0.91
48		20	0.20	0.03	0.007	0.24	0.42
50	3	40	0.10	0.06	0.004	0.17	0.33
54		50	0.29	0.01	0.001	0.30	0.31

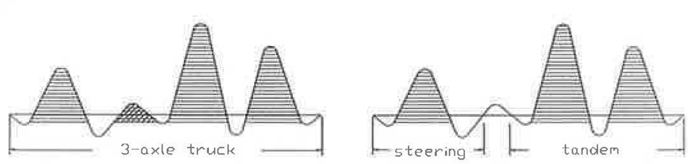


FIGURE 10 Strain cycles for the vehicle and individual axles and axle groups for three-axle truck.

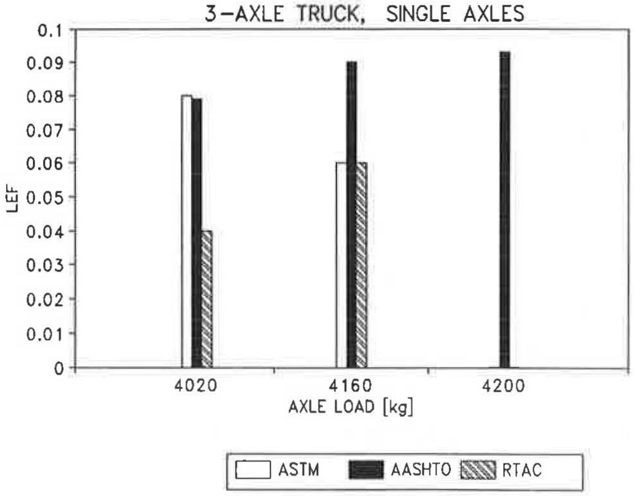


FIGURE 11 Comparison of LEFs for three-axle truck, single axle.

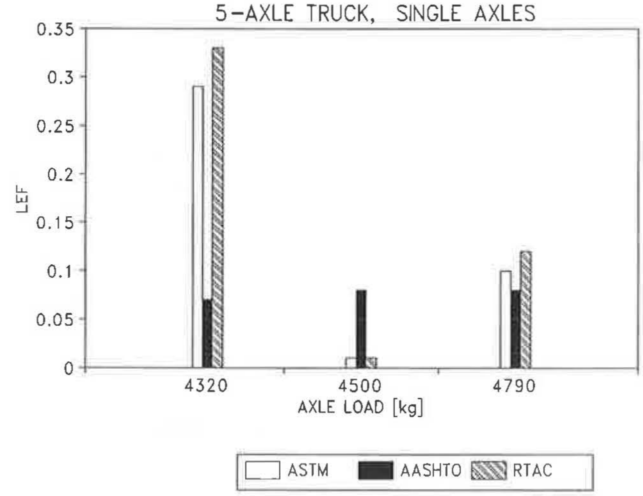


FIGURE 13 Comparison of LEFs for five-axle truck, single axle.

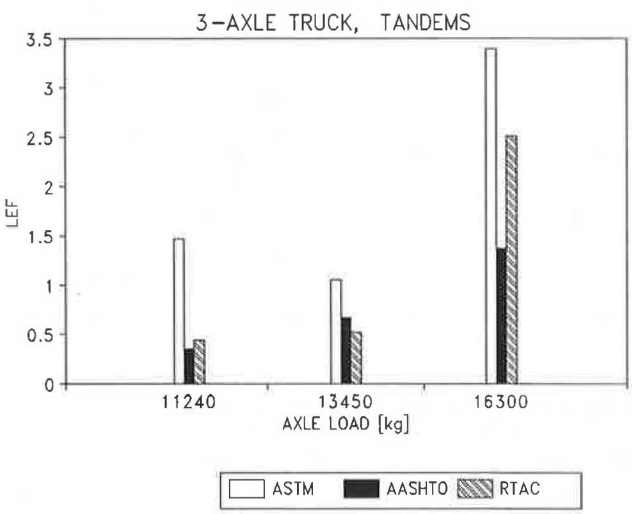


FIGURE 12 Comparison of LEFs for three-axle truck, tandem axle.

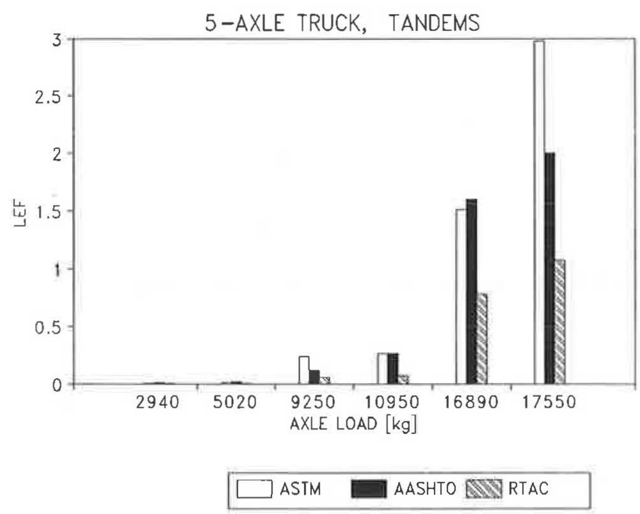


FIGURE 14 Comparison of LEFs for five-axle truck, tandem axle.

The LEFs obtained by the rainflow/range-pair counting method were compared with those obtained by the RTAC method. The two sets of mechanistic LEFs were also compared with the empirical LEFs recommended by AASHTO. This comparison, however, was inconclusive and could not verify that one of the two mechanistic LEF methods best describes the fatigue cycles caused in AC by multiple axle loads.

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