Fatigue Load Spectra For Bridges

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ABSTRACT

To effectively evaluate highway bridges, the load spectra experienced must be determined. A fatigue live load model has been developed for girder bridges which reflects site specific conditions. Five bridges were tested to determine site-specific truck parameters and component-specific stress spectra. The data base includes gross vehicle weight (GVW), axle weights and axle spacing as well as stress cycles in the bridge girders. The weigh-in-motion measurements confirm that truck loads are strongly site-specific. A dual fatigue truck model is proposed. The developed model is verified using fatigue damage analysis to compare the model to measured results and existing models.

INTRODUCTION

The objective of fatigue load research has largely been to establish an equivalent fatigue truck that will cause the same cumulative fatigue damage as the normal traffic distribution. A single, equivalent fatigue truck is an attractive and useful tool for the practicing engineer. In this paper, a fatigue load model is presented based on weigh-in-motion (WIM) measurements (Laman 1995). Statistical parameters of stress are calculated for girder bridges. The results indicate that magnitude and frequency of truck loading are strongly site-specific and component-specific. Based on the WIM data, a design fatigue truck is developed. The model is calibrated against measured dynamic strains to achieve uniform reliability against fatigue failure.

SELECTED BRIDGES AND TEST PROCEDURE

Field measurements were conducted on five steel girder bridges. The important parameters of the selected bridges are summarized in Table 1. Strain transducers were attached to all girders at the lower, mid span flanges for each of the five bridges Strain cycles were measured and counted under normal traffic using the rainflow algorithm. The data was collected and recorded using a WIM system from Bridge Weighing Systems, Inc. and a data acquisition system from the SoMat Corp.

The WIM system calculates truck gross vehicle weight (GVW) and axle weights from the strain record by utilizing influence lines. The truck configuration is determined from lane sensors attached to the pavement in each lane. GVW was determined within 5 percent, and axle weights were determined within 20 percent.

Table 1, Parameters of the Selected Bridges.

| No	ADTT	Span	No of Grdrs	Girder Spac'g	Girder Size
1	2000	23.9 m	6	1.9 m	W36X194
2	2500	9.9 m	10	1.5 m	W27X102
3	5000	10.5 m	10	1.5 m	W24X68
4	5000	15.8 m	9	1.7 m	W36X150
5	1500	16.0 m	8	1.8 m	W30X99

TRUCK WEIGHT DATA

The results of truck weight measurements are presented by Laman (1995). The histograms of GVW are summarized in Fig. 1 for the five bridges selected for this study. The median values of GVW are similar for all locations, varying from 150 kN to 210 kN. However, the maximum values of GVW recorded at the five sites vary from 600 kN to 1,200 kN. The most important factors which influence the distribution of GVW are traffic density (average daily truck traffic, ADTT) and proximity of stationary truck weigh stations. The heaviest trucks were observed on busy interstate highways, with large ADTT, and far away from the stationary truck weigh stations.

The histograms in Fig. 1 confirmed that truck traffic is site-specific. The variation increases for larger percentiles of GVW. The difference between the highest and the lowest median value is approximately 40 percent, but the variation is 100 percent for the extreme values of GVW.
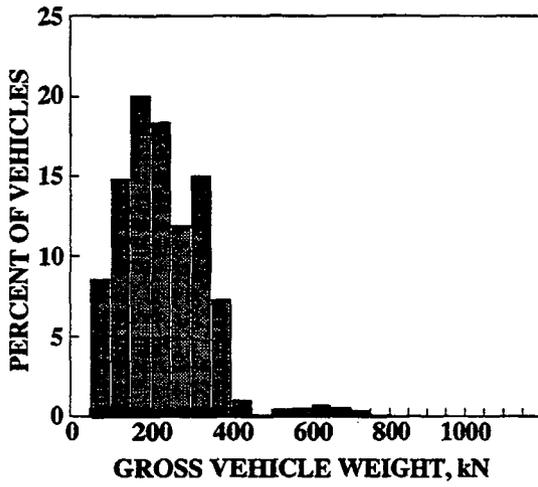
STRAIN DATA

Strain histories were collected continuously for one week periods and reduced using the rainflow algorithm. Data was collected for each girder in the bridge. The number of girders in each bridge vary from 6 to 10 as seen in Table 1. The average strain is less than 50×10^{-6} for all
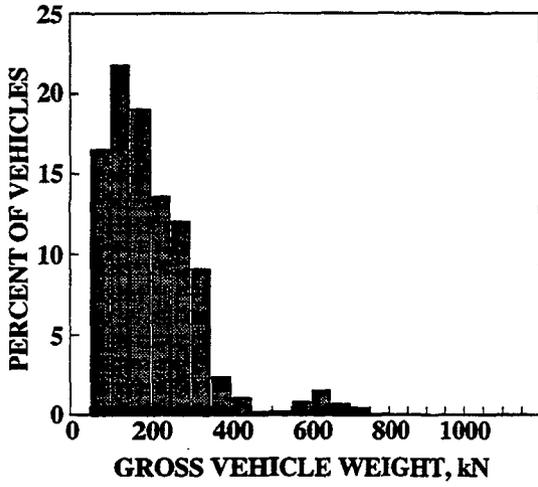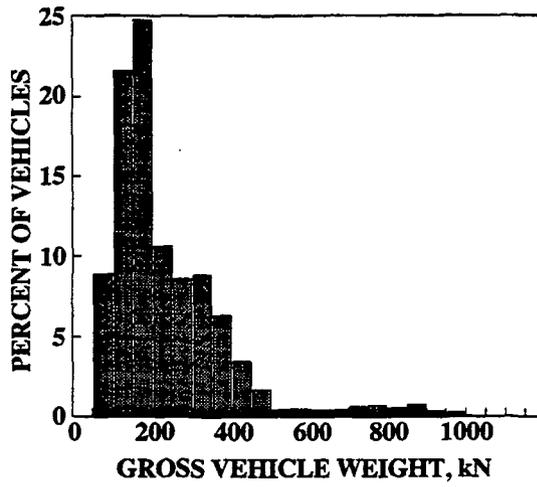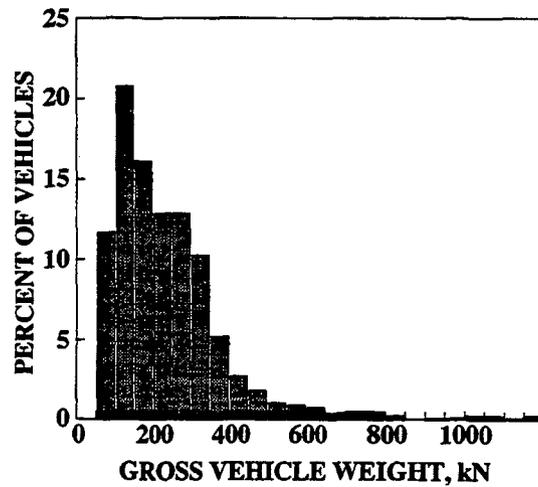
a) Bridge 1, GVW Histogram
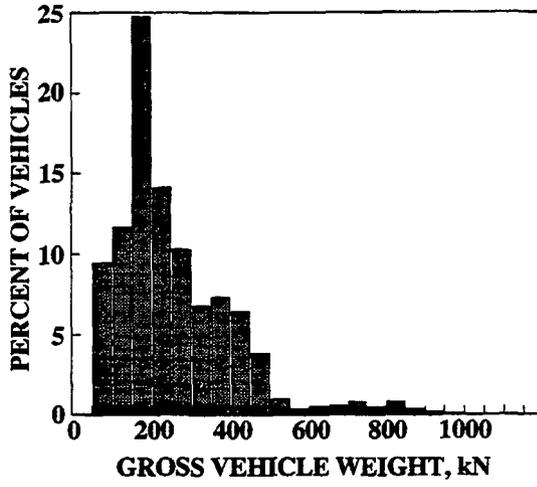
b) Bridge 2, GVW Histogram

c) Bridge 3, GVW Histogram

d) Bridge 4, GVW Histogram

e) Bridge 5 GVW Histogram

Fig. 1, Gross Vehicle Weight Histograms.

girders and all bridges, however, the largest strains were observed in girders supporting the right traffic lane (girder numbers G3, G4 and G5) and nearest the left wheel of traffic in the right lane. As expected, the exterior girders of each bridge experience the lowest strain extremes in the spectrum.

FATIGUE DAMAGE ANALYSIS

Fatigue damage is normally estimated using Miner's rule of linear damage accumulation. Applying the stress life approach, the level of damage induced by a single stress cycle increases significantly with higher levels of stress. Therefore, fatigue behavior of bridges is predominately a function of truck traffic parameters. The histograms of truck GVW obtained in this study are shown in Fig. 1 for each bridge.

The AASHTO Guide Specification (1989) suggests that the equivalent weight (W_{eq}) of trucks be calculated and the GVW distributed to the three axle of the fatigue truck in the same proportion at the AASHTO design vehicle. This is expected to result in a more accurate fatigue model for the particular sight than the standard AASHTO fatigue truck. This study found that accuracy is not improved by this method.

The percent of truck types (by number of axles) is given in Table 2. The data indicates that between 40 percent and 80 percent of the truck population are 5 axle vehicles, depending on the bridge location. Vehicles with 3 and 4 axles are often configured similar to 5 axle vehicles, and when included with 5 axle vehicles, account for between 55 percent and 95 percent of the truck population. Table 2 shows between 1.7 percent and 7.4 percent of the population are 11 axle vehicles. In states where vehicles with more than 5 axles are permitted, this may be of importance. While these vehicles do not account for a significant proportion of the truck population, the extent these vehicles contribute to the total fatigue damage is generally more than 50 percent.

Table 2, Distribution of Truck Types by Axles .

No.	Bridge				
Truck Axles	1 %	2 %	3 %	4 %	5 %
2	9.5	9.5	7.7	8.0	8.3
3	11.0	6.0	5.2	6.2	7.7
4	14.5	6.9	5.6	5.7	11.6
5	54.3	63.5	72.6	69.1	61.2
6	3.4	3.6	3.8	2.6	4.6
7	2.0	0.8	0.9	0.8	1.3
8	1.0	1.0	1.3	1.4	2.2
9	0.0	0.8	0.7	1.2	0.7
10	1.1	1.3	0.4	0.8	0.5
11	3.2	6.6	1.7	4.1	2.0

In addition to the magnitude of the stress cycles, the number of load cycles, n, is an important parameter in the fatigue life prediction. Static load cycles have been determined both analytically by counting the stress cycles for different spans, and experimentally for the tested

bridges. Each vehicle type in the WIM data base was analyzed and average stress cycles per vehicle type calculated for spans of 6 m to 60 m. The resulting average numbers of load cycles are shown in Fig. 2 for different vehicle types by axle number. The results demonstrate that there is a relationship between the number of axles and average significant stress cycles induced per vehicle for simple spans less than 24 m. Also evident from Fig. 2 is the decrease in the average number of stress cycles per vehicle to 1.0 as the span increases. Therefore, the parameter of stress cycles in relationship to vehicle type becomes less important as the span of the bridge under consideration exceeds 24 m, depending on the distribution of vehicle types in the normal traffic flow.

The experimentally measured stress cycles are also a measure of the average number of cycles induced per vehicle. Using an estimate of ADTT and excluding small cycles attributable to light trucks, cars, and noise, Fig. 4 was constructed. The dynamic cycles induced due to truck and bridge interaction do not appear to be significant since the average number of cycles calculated from the static WIM and the dynamic strain data collection are nearly the same. For comparison, the number of average stress cycles per vehicle specified by AASHTO is shown. Because the accumulated fatigue damage is directly related to the number of stress cycles, it can be seen that the AASHTO criteria may not be accurate for some span lengths, particularly for spans between 5 and 20 m.

An analysis was performed using WIM results as a data base to determine the contribution to the total fatigue damage by each vehicle type. Truck traffic flow was simulated over an analytical, simple span, bridge model of 6 to 60 m spans to calculate the static stress history of each truck. The analytical model was calibrated using captured strain files of weighed trucks enabling accurate distribution of load to the girders in the model and accurate calculation of stresses. A rainflow analysis was performed for each vehicle stress record. and damage was calculated using the stress-life approach. The damage was accumulated by Miner's Rule in a matrix of vehicle types and span lengths. Results of this damage accumulation analysis demonstrate that vehicles with 10 and 11 axles dominate. The corresponding percentages of accumulated fatigue damage caused by 10 and 11 axle trucks are shown in Fig. 3.

FATIGUE LOAD MODEL

A fatigue load model has been developed for each site based on the analysis of gross vehicle weight, damage accumulation, stress cycles, axle spacing, and moment peaks (Laman and Nowak, 1995). For the development of a fatigue truck load model, vehicle characteristics were analyzed to determine the statistics of axle spacing, axle load, and significant stress cycle locations. Analysis of the distribution of single axle locations and closely spaced axle group locations revealed that vehicles with 3 to 7 axles are accurately modeled by a 3 axle vehicle, while 10 and 11 axle vehicles can be better modeled by a 4 axle vehicle. Other vehicle types in the distribution are not well represented by either the 3 or 4 axle model, however the damage caused by 2, 8, and 9 axle vehicles was found to be very low for the study data base.

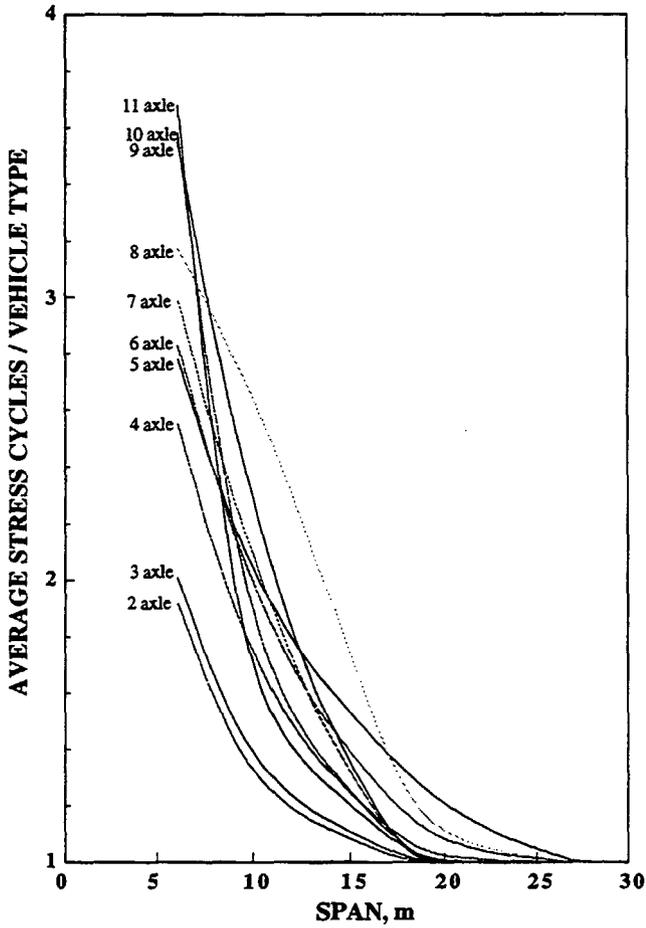In order to determine the appropriate number of axles

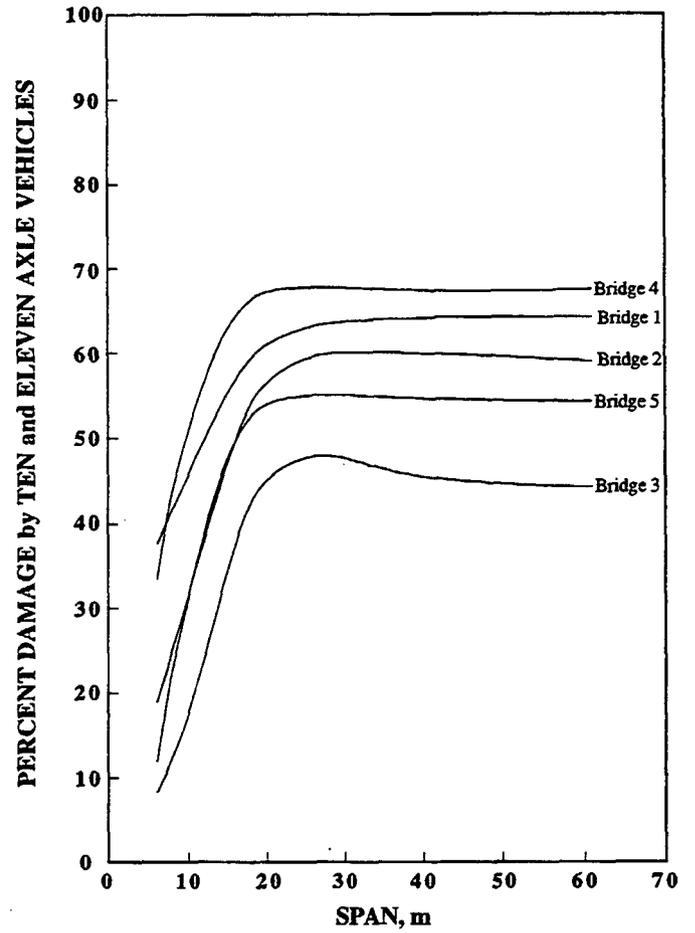Fig. 2, Percent Damage by Veh. Type vs. Span Length.

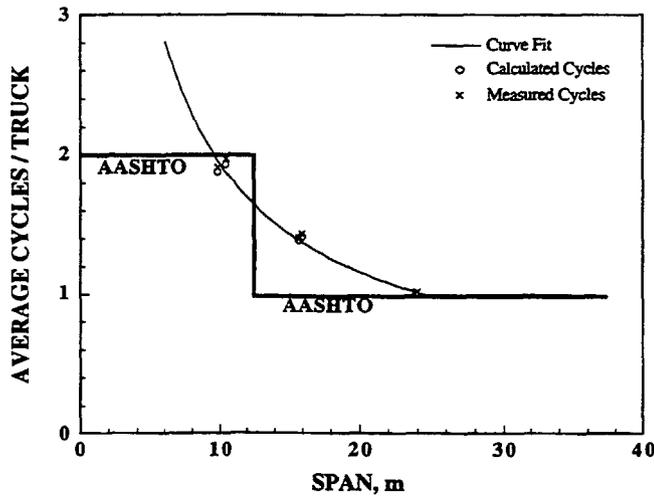Fig. 3, Average Cycles / Veh. Type (by Axles) vs. Span.

Fig. 4, Calculated and Measured Avg Stress Cycles /Veh.

and axle spacing for the fatigue load model, locations of axles and axle groups were studied. Axles on 10 and 11 axle vehicles tend to be arranged in groups of 2, 3, and 4. This corresponds well with the analysis results presented in Fig. 2 where these vehicles induce between 3 and 4 significant stress cycles, on average, per vehicle for short (6 m) spans.

The proposed fatigue truck model is developed to envelope the damage caused by measured vehicles. Due to the site specific nature of the distribution of vehicle types by axle, a single truck model for fatigue loading is not the most accurate approach. For sites with traffic consisting of 2-6 axle trucks, the fatigue truck is shown in
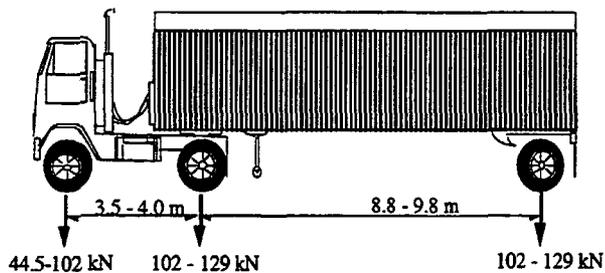
Fig. 5. For locations with significant fatigue damage caused by trucks with more than 6 axles a four axle truck, shown in Fig. 6, establishes an improved fatigue load model. Damage caused by the passage of all trucks with 2 to 9 axles is equivalent to the damage caused by an equal number of passes of the 3 axle fatigue truck over the bridge. Likewise, the damage caused by the passage of 10 and 11 axle trucks is equivalent to the damage caused by an equal number of passes of the 4 axle fatigue truck over the bridge. Combining the two trucks results is an accurate representation of the actual truck population at the particular bridge.
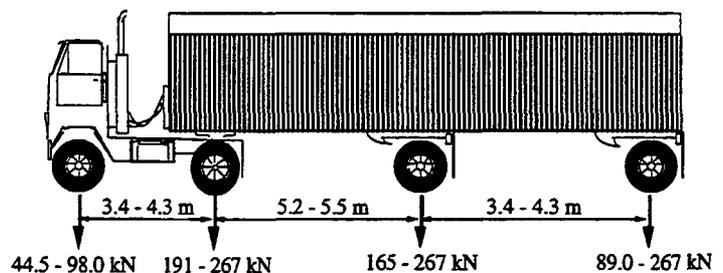

Fig. 5, 3 Axle Fatigue Truck

44.5-102 kN   102 - 129 kN   102 - 129 kN

3.5 - 4.0 m   8.8 - 9.8 m

Fig. 6, 4 Axle Fatigue Truck

44.5 - 98.0 kN   191 - 267 kN   165 - 267 kN   89.0 - 267 kN

3.4 - 4.3 m   5.2 - 5.5 m   3.4 - 4.3 m

Fatigue damage was calculated based on four load models; (1) the actual WIM data base, (2) idealized fatigue trucks, (3) the fatigue truck specified in the AASHTO Guide (1989), and (4) fatigue truck specified in the LRFD AASHTO (1994) and compared. Using the WIM fatigue damage as the benchmark for comparison, the calculation of fatigue damage by the AASHTO fatigue vehicle is generally overestimated by a factor of 2 to 6 for shorter spans and underestimated by a factor of between 2 to 4 for longer spans. The dual fatigue truck load model induces damage very close to that caused by the simulation of the actual WIM truck traffic flow. The damage due to the dual truck model is in most cases within 95% of the damage caused by the WIM data base.

CONCLUSIONS

The truck load spectra for bridges are strongly site-specific. Bridges located on major routes between large industrial metropolitan areas will experience the highest extreme loads. Routes where vehicles are able to circumvent stationary weigh stations will have very high extreme loads. Bridges not on a major route, that are very near a weigh station, or that are within a metropolitan area experience much lower extreme loads.

Live load stress spectra are strongly component-specific. Each component experiences a very different distribution of strain cycle ranges. The girder that is nearest the left wheel track of vehicles traveling in the right lane experiences the highest stresses in the stress spectra and decreases as a function of the distance from this location. This information can be useful to target bridge inspection efforts to the critical members.

A vehicle type that dominates the distribution of vehicle types does not necessarily dominate the fatigue damage of the particular component. A vehicle type that dominates the distribution of lane moments will likely dominate the fatigue analysis. This has been

demonstrated in this study by the ten and eleven axle vehicles at each bridge and for several span lengths. Eleven axle vehicles dominate the extreme values of the load spectra.

The fatigue load models based on a three axle truck may overestimate the fatigue damage for bridges with a simple span shorter than 12 to 18 m and underestimate the fatigue damage for longer spans. The proposed dual fatigue truck load model more accurately predicts the fatigue damage caused by normal truck traffic passing over a bridge. The model is site-specific and is characterized by the load spectra of the bridge.

ACKNOWLEDGMENTS

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