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Calibration of bridge fatigue loads under real traffic conditions

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Summary

This paper explains how the conventional fatigue load model n°3 of the Eurocode 1.3 is calibrated versus real measured traffic loads, by comparison of their respective load effects and fatigue damages on an extensive sample of influence surfaces of representative bridges. The calibration procedure is developed for one slow traffic lane and then for several slow traffic lanes. The final calibration and application rules of the Eurocode model are presented, with respect of most relevant parameters to be taken into account.

1. Conventional Fatigue Load Models

The Eurocode 1 part 3 [1] contains conventional load models for the assessment of characteristic values of loads. A special chapter of this document deals with the fatigue loads, to be used for fatigue checking of sensitive details in bridges. In the most recent existing national codes [2,3,4] or in specific recommendations as it is the case in France [5,6,7], similar or simpler fatigue load models were already elaborated; but the calibration of some of these models were not based on rigorous scientific bases. The expert panel of the Eurocode 1.3 worked for 3 years (1988-90) and collected the up-to-date knowledge and tools to elaborate and calibrate the proposed fatigue load models. Further works [5,8] were then carried out in France by the LCPC and the SETRA to complete and make more operational this common work and to prepare the final draft of the document.

The fatigue load models proposed in [1] are mainly devoted to the steel bridges or the steel parts of the composite bridges, which are the most sensitive to fatigue. Five models are defined, n°1 to 5, for various purposes. Models 1 and 2 are a bit « pessimistic » and allow some quick and simple checking to identify the details exposed to fatigue damage. Model 3 is a standard model to be used for most common checking, and will be described in detail in this paper. Models 4 and 5 are more sophisticated and allow full damage calculation using the Palmgreen-Miner law and the S-N resistance curves. Model 4 consists in a set of five lorries (as model 2), but with different axle loads; the proportion of each lorry type depends on the traffic characteristics of the considered road. Model 5, which may only be used if specified in the project requirements, uses a full traffic record, e.g. a sample of many thousands of lorries weighed in motion on a road, and applied by a specific computer software (such as CASTOR-LCPC [9]) on the influence surfaces of the bridge to assess the stress variations and then to compute the fatigue damage. Extrapolation may be carried out to investigate deeper the issue of the structural lifetime.

Model 3 consists of 4 axles, each of them loaded at 120 kN, and grouped in two tandem as shown in figure 1.

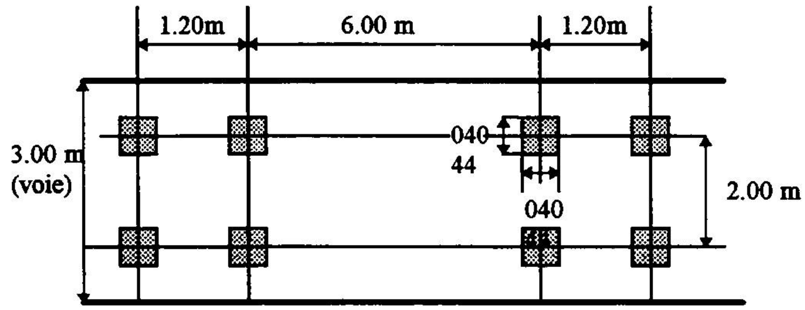

Fig. 1. Model 3 for fatigue load (Eurocode 1.3).

2. Calibration for one traffic lane

The procedure is the same than that used in the French recommendations, described in [5,6]. Only one stress cycle is considered for a given detail during the lorry crossing. Its amplitude is the maximal stress variation. The lorry mass is then calibrated to produce the same damage after 2 millions of crossings as the damage of one hundred years of real traffic. The traffic damage for the detail considered is computed by the CASTOR-LCPC software [9], from any traffic record of the existing LCPC's database « PESAGE » [10]. The detail is represented by an influence surface or two influence lines (one longitudinal and one transversal). The « rain-flow » histogram of the stress variations is computed and used for the damage or lifetime calculation with the Miner law and the relevant S-N curve.

Nine composite bridges with main span lengths from 20 to 102 m have been selected as representative of the existing bridges. The span widths are between 5.5 and 16 m. 64 details have been analysed, sensitive to the longitudinal bending moment. Two traffics were applied, recorded on the A6 motorway near Auxerre (one of the most aggressive in Europe) and on the National road RN23 near Angers. All the details were assumed to be in class 36, in a conservative way and to obtain a more accurate calibration. The S-N curve with two slopes and a truncating at 10^8 cycles was used.

The number of crossings of the 4-axle lorry (model 3), loaded at 30 t to get stress amplitudes in the same range as with the real traffics - e.g. in the slope -1/5 of the S-N curve -, providing a damage equal to 1 was computed for each detail. A graph plotting the results is shown in the figure 2. Each point corresponds to a detail, with the abscissa x equal to the logarithm of the lifetime (in years) computed by CASTOR-LCPC and the ordinate y equal to the logarithm of the number of crossings (in millions) of the lorry. The damage is 1 after y millions of crossings. A linear regression is made on the points and the accuracy of the simple calibration is evaluated by the correlation coefficient (1 in the ideal case). The correlation coefficient is 0.97 with the A6 traffic and 0.954 with the RN23 traffic. The acceptable number of lorry crossings N_{100} (in millions) for an expected lifetime of 100 years is the ordinate of the regression strait line at x=2 (100 years), increased by one standard deviation.

The next step replaces this criteria on the number of crossings by a weighing coefficient c on the lorry mass. The number of crossings is fixed at 2.10^6 and the lorry mass is 4 x 120 kN (model 3). The coefficient c is derived from another coefficient c_{30} applied to the 30 t lorry to give the same damage, after 100 years or 10^8 crossings, than the real traffic:

$$c = c_{30} \times \frac{30 \times 9.81}{4 \times 120} \times \left(\frac{100}{5}\right)^{\frac{1}{5}} \times \left(\frac{5}{2}\right)^{\frac{1}{3}} = 1.515 \times c_{30} \tag{1}$$

with : $N_{100} \times \Delta\sigma_{30}^5 = 10^8 \times (c_{30} \times \Delta\sigma_{30})^5$

and $\Delta\sigma_{30}$ is the stress amplitude induced by the 30 t lorry.

Finally the coefficient c is 2.20 for the A6 traffic (heavily trafficked motorway) and 1.40 for the RN23 (national road). The average coefficient c=1.80 is taken into account for a heavily trafficked road or an average trafficked motorway.

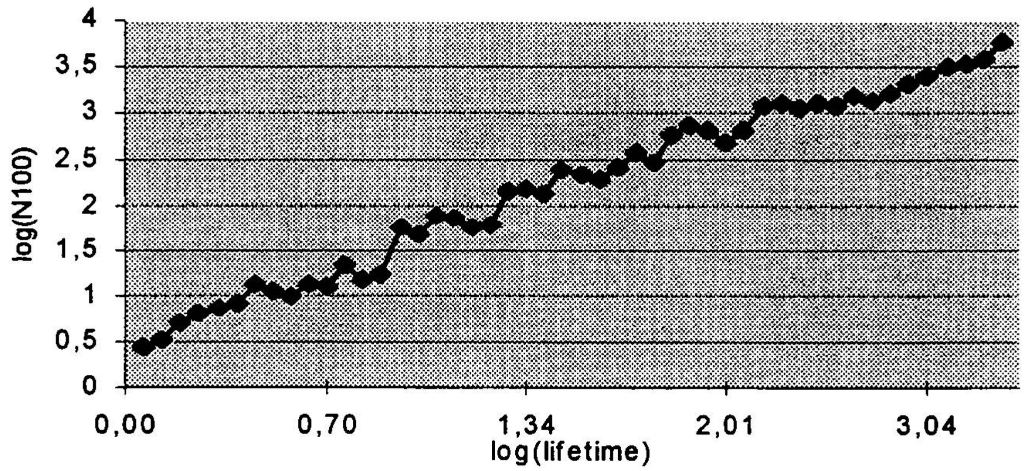

Fig. 2. Calibration of model n°3: number of millions of crossing versus lifetime (in log)

3. Calibration for several slow traffic lanes

Generally a bridge supports at least two slow traffic lanes heavily loaded. The effects of all theses slow lanes must then be added for fatigue assessment. A procedure was proposed in [8]. We briefly present the case of two slow lanes in opposite directions.

The total damage D may be written, because of the linearity of the Miner's law, as:

$D = D_1 + D_2 + D_3$, where indices 1 and 2 correspond to the lane 1 or 2 only loaded, and indices 3 corresponds to both lanes loaded (vehicles passing each other).

In most bridge details, the stress cycle amplitudes under real traffic are in the area of the S-N curve with a slope -1/5. Then the damages may be written:

$$D_i = \alpha\,(1 - p/100)\,\Delta\sigma_i^5 \quad \text{for } i=1 \text{ or } 2, \text{ and } D_3 = \alpha\, p\,(\Delta\sigma_1 + \Delta\sigma_2)^5/100 \tag{2}$$

where $\Delta\sigma_i$ is the stress cycle amplitude when the lorry crosses on lane i, and p is the percentage of « equivalent passing cases».

From Eq. 2, and assuming that p/100 is rather small, we get at the first order:

$$p \approx 100\,(D - D_1 - D_2)/(D_1^{1/5} + D_2^{1/5})^5 \tag{3}$$

and the total damage becomes:

$$D = \alpha\left((1-\frac{p}{100}).\Delta\sigma_1^5 + (1-\frac{p}{100}).\Delta\sigma_2^5 + \frac{p}{100}(\Delta\sigma_1 + \Delta\sigma_2)^5\right) = \alpha\,\Delta\sigma_{tot}^5 \tag{4a}$$

with :

$$\Delta\sigma_{tot} = \left((1-\frac{p}{100}).\Delta\sigma_1^5 + (1-\frac{p}{100}).\Delta\sigma_2^5 + \frac{p}{100}(\Delta\sigma_1 + \Delta\sigma_2)^5\right)^{\frac{1}{5}} \tag{4b}$$

Eq.4a and 4b include the percentage of « equivalent passing cases » p, which depends on two main parameters: the length of the influence line and the traffic density. p will be calculated in the following section.

4. Sensitivity to the influence line

4.1 Simple supported span

4.1.1 Mathematical Model

We will calculate theoretically the percentage p, for a box girder simple supported span of length L, with two slow traffic lanes in opposite directions. In this case, the transverse influence line is constant (equal to 1) and the longitudinal influence line is triangular. Then the effect of vehicle passing may be significant.

An simple idealised traffic model is built for our purpose, with the following assumptions, and the results were validated with real traffic records and the CASTOR-LCPC software:
- all the lorries are identical, with a mass P concentrated,
- all the lorries are at uniform spacing and travelling at constant speed v,
- all the passing situations have the same probability of occurrence,
- the traffic characteristics are the same in both directions.

q is the traffic density on one lane (in veh/sec). If a lorry enters the span in direction 1 at time t_1, and takes T=L/v to cross the span, we have a passing case if another lorry travelling in direction 2 enters the span at t_2, with $t_1 - T/2 < t_2 < t + T/2$. The figure 3 indicates the stress cycle amplitude $\Delta\sigma_{max}$ in this passing case, with respect of the time interval (t_2-t_1):

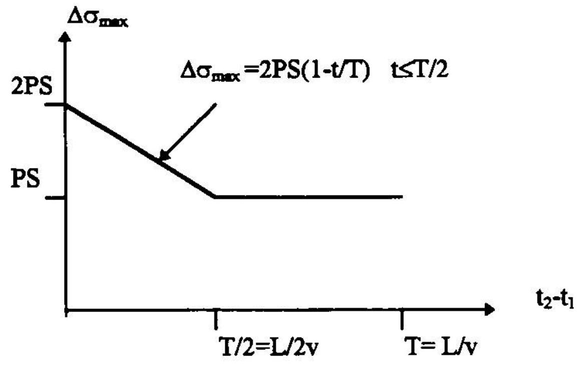

Fig. 3. Stress cycle amplitude for a passing case.

Then the damage due to a passing case is, per second:

$$D_3 = \alpha \times 2q \int_0^{\frac{T}{2}} \left(2PS \times \left(1-\frac{t}{T}\right)\right)^5 \times q dt$$

$$D_3 = \alpha \times 2q \times q \times (2PS)^5 \times \frac{T}{6}\left[1-\left(1-\frac{1}{2}\right)^6\right] = \alpha \times q \times (2PS)^5 \times \frac{63}{64}\frac{qT}{3} \qquad (5)$$

and the percentage p is given by:

$$\frac{p}{100} = \frac{63}{64}\frac{qT}{3} = \frac{63}{64}\frac{q \times L}{3v} \qquad (6)$$

and p is proportional to the span length L and the traffic density q.
For example, with the realistic data:
v=20 m/sec, L=60 m, $q=10^8$ veh/100 yrs = 0.0317 veh/sec, we have : p = 3.1%. An exact calculation with the A6 traffic by CASTOR-LCPC gives p = 2.3% (see 4.1.2).

4.1.2 Calibration with CASTOR-LCPC

With this software and the data of the A6 traffic recorded on all the four traffic lanes during one week in 1986 (we only use here the slow lanes 1 and 4), the damages D_1, D_2 and D are calculated for simple supported spans of various lengths from 3 to 132 m (neglecting the calibration factor α mentioned above). Eq.3 gives the percentages p for each L, and the very good proportionality is shown on figure 4, with an empirical linear relation:

$$p = 0.7 + 0.027\, L \qquad (7)$$

which is adopted for a heavily trafficked motorway;
with the RN23 traffic, Eq.7 is slightly modified into :

$$p = 0.5 + 0.012\, L \qquad (7a)$$

which is adopted for a common highway;
finally for a heavily trafficked highway or a common motorway, an intermediate relation is:

$$p = 0.6 + 0.020\, L \qquad (7b)$$

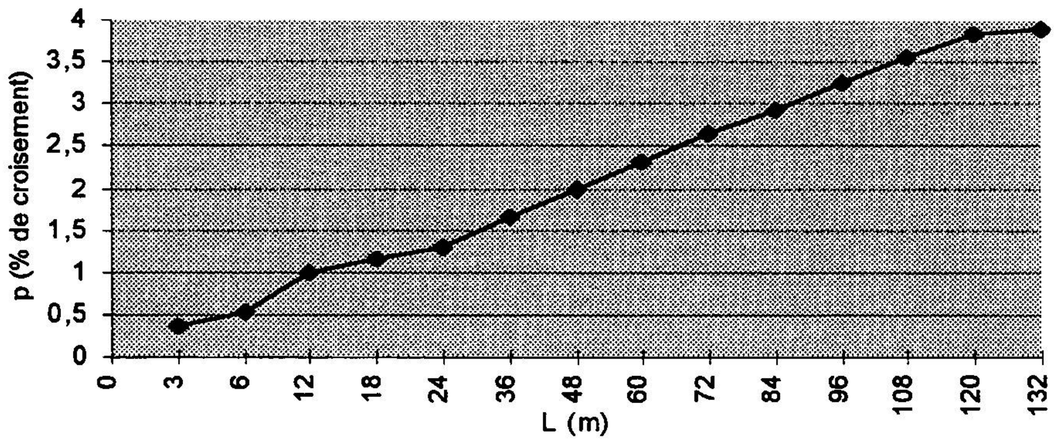

Fig. 4. Variation of p with L (CASTOR-LCPC, traffic A6).

4.1.3 Consequence of the passing cases

In our case the lorry induces the same stress amplitude if travelling on each lane, then the total stress amplitude for two independent crossings (on each lane) is:

$$\Delta\sigma_{tot} = \left(\Delta\sigma_1^5 + \Delta\sigma_2^5\right)^{1/5} = \left(\Delta\sigma_1^5 + \Delta\sigma_1^5\right)^{1/5} = 2^{1/5}\,\Delta\sigma_1 = 1{,}1487\ \Delta\sigma_1 \tag{8a}$$

but for a passing case, with L=60 m and p=2.32 :

$$\Delta\sigma_{tot} = \left(\left(1-\frac{p}{100}\right).\Delta\sigma_1^5 + \left(1-\frac{p}{100}\right).\Delta\sigma_2^5 + \frac{p}{100}\left(\Delta\sigma_1 + \Delta\sigma_2\right)^5\right)^{\frac{1}{5}}$$

$$\Delta\sigma_{tot} = \left(2\,\Delta\sigma_1^5 + \frac{30p}{100}\,\Delta\sigma_1^5\right)^{\frac{1}{5}} = (2{,}696)^{1/5}\,\Delta\sigma_1 = 1{,}22\Delta\sigma_1 \tag{8b}$$

Then the passing case induces an increase of 6% in the total stress amplitude, or an increase of more than 30% in the damage.

4.1.4 Checking the calibration of the fatigue load model

The damage calculations for these triangular influence lines of various lengths also allowed the calibration of the weighing coefficients c_{30} and c applied to the conventional lorry mass (Eq.1). With the same notations as in section 2, if D_1 is the damage computed (neglecting the coefficient α) by CASTOR-LCPC under the traffic loads of the lane 1 of the A6 motorway, during a period T (in years), e.g. the sum of the stress cycle amplitudes to the power 5, then we have:

$$D_1 = \frac{T}{100} \times 10^8 \times \left(c_{30} \times \Delta\sigma_{30}\right)^5 \quad \Rightarrow \quad c_{30} = \frac{D_1^{\ 1/5}}{\Delta\sigma_{30}} \times \left(\frac{10^{-6}}{T}\right)^{\frac{1}{5}} \tag{9}$$

and c is obtained by the Eq.1.

For the triangular influence lines (with a peak value of 2.5 t/m²), from L=3 m to 132 m, the coefficient c remains very constant around 2.40, with a minimum at 2.32 and a maximum at 2.64. It proves that the conventional lorry, properly calibrated, gives a good picture of the real traffic, independent of the span length. The gap of 8% with the announced value c=2.20 is due

to the fact that the truncating threshold of the S-N curve was neglected here. Nevertheless, the values for the short spans (under 35 m) are slightly higher than the average. This phenomenon shows that the lorry is not aggressive enough for the short influence lines for two reasons:
- the counting method underestimate the number of cycles for influence lines shorter than the lorry length; in such a case it would be necessary to consider one cycle for each axle group, e.g. two cycles per lorry;
- the lorry silhouette is not representative of the real heavy vehicles.

Therefore an amplification coefficient λ was introduced for the short influence lines (0.5 to 40 m), defined by: $\lambda = \frac{c}{2.40}$, where the values of c were calculated for all the values of L, by steps of 0.5, 1 and 2 m. Figure 5 shows the variations of λ with L. An analytical approximation was found for λ as a function of L:

$$
\begin{array}{ll}
L \leq 3{,}0\,m & \lambda = 1{,}20 \\
3{,}0\text{ m} < L \leq 15\,m & \lambda = 1 + \dfrac{(L-9)^2}{300} \\
5\text{ m} < L \leq 35\,m & \lambda = 1{,}21 - \dfrac{6 \times L}{1000}
\end{array}
\qquad (10)
$$

For L under 2.40 m, the lorry axles act individually on the span, and therefore the coefficient of 1.20 correspond to 2.5 cycles per crossing.

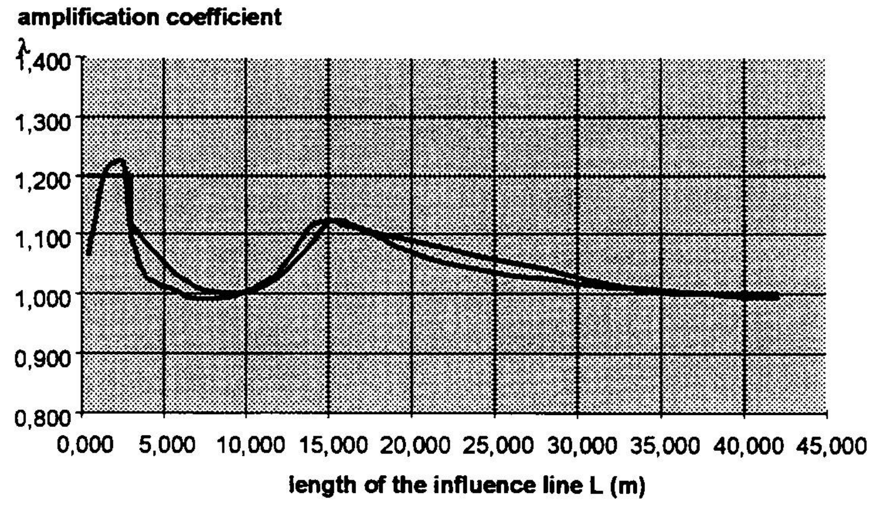

Fig. 5. Amplification coefficient λ for short influence lines (calculated and approx. Eq.10).

4.2 Bridge influence lines

Eq.7 for the calculation of p as a function of L is now simply extended to any type of influence line for real bridges. This rule is tested for 6 existing multiple-span (2 to 5) bridges and 3 to 5 sections per bridge. The span lengths are between 24 and 102 m.

In Eq.7, the length L is now replaced by L_{cal} defined by:
- the span length if the considered section is not on a pier,
- the sum of the two adjacent span lengths if the section is on a pier.

Using these values L_{cal} for each section in Eq.7, p_{cal} are obtained and compared to the p_{ex} directly calculated by CASTOR-LCPC and the real traffic. The fit between both is good as shown in the figure 6, with only one case of underestimation (-0.8% for L_{cal}=79 m) on the unsafe side, and a maximum overestimation of 1.94% for the largest L_{cal} on the safe side. The errors made on $\Delta\sigma_{tot}$ are respectively -1.7% and +3.6%, which justify the simple rule proposed.

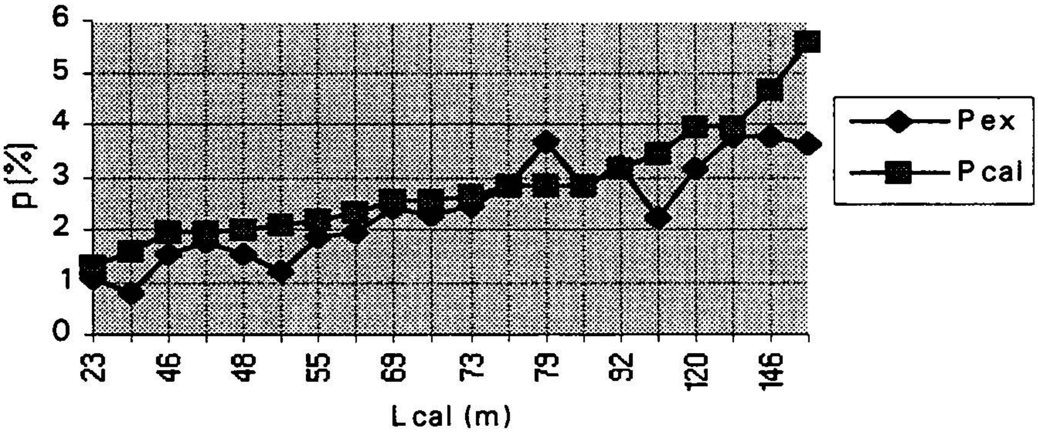

Fig. 6. Comparison of the exact and calculated (Eq.7) values of p for real bridges.

5. Final calibration of the fatigue model (EC 1.3)

The model 3 (lorry) for fatigue of the Eurocode 3.1 given in figure 1 is finally calibrated by a load coefficient λ_e such as 2.10^6 crossings of this calibrated lorry induce the same damage than the real traffic during the reference period of 100 years. λ_e accounts for various parameters related to the traffic and bridge characteristics, and is written as:

$$\lambda_e = \lambda_1 . \lambda_2 . \lambda_3 . \lambda_4 \tag{11}$$

where λ_1 accounts for the influence line length and is given by Eq.10,
λ_2 accounts for the traffic volume and content,
λ_3 accounts for the expected bridge lifetime,
λ_4 accounts for the effect of several traffic lanes.

λ_2 = 2.20 for a heavily trafficked motorway (such as A6 near Auxerre),
λ_2 = 1.80 for a common motorway or a heavily trafficked highway,
λ_2 = 1.40 for a common highway (such as RN23 near Angers);

$\lambda_3 = (DV/100)^{1/5}$ if DV is the expected bridge lifetime (in years);

Finally, for two slow traffic lanes (but this may be generalised), λ_4 is given by:

$$\lambda_4 = \left[\left(1-\frac{p}{100}\right) + \left(1-\frac{p}{100}\right)\left(\frac{\Delta\sigma_2}{\Delta\sigma_1}\right)^5 + \frac{p}{100}\left(1+\frac{\Delta\sigma_2}{\Delta\sigma_1}\right)^5 \right]^{\frac{1}{5}} \tag{12}$$

where p is calculated from Eq.7, 7a or 7b, in which L is the value L_{cal} defined in 4.2.

In conclusion, operational rules are given which allow a unique and simple conventional fatigue load model to be applied, after calibration by the proposed factors, to any type of bridge and detail, and to be adapted to various traffic conditions and expected lifetimes.

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