Procedures for Calibration of Eurocode Traffic Load Model 1 for National Conditions

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ABSTRACT: Since April 2010 Eurocode Load Model 1 (LM1) is the prescribed traffic load model to be employed in the design of highway bridges in the European Union (EU). Uniquely, the code permits member states to calibrate the load model, through the application of 'α-factors' to allow for national or regional conditions. Some countries with high volumes of very heavy traffic may find that they require α–factors in excess of unity whilst other less heavily trafficked road networks may require much lesser values. The importance of accurate calibration of the α-factors is clear from a safety and economic point of view. This paper describes procedures for calibration of α-factors using Weigh in Motion (WIM) data. WIM data allows classification of the traffic loads in individual countries, enabling the specific Gross Vehicle Weights (GVWs), axle loads and frequencies of heavy trucks to be taken into account. Simulations calibrated using this data, for a wide range of structural forms (i.e., influence lines, spans and numbers of lanes) and scenario types (i.e., free flowing, congested and mixed traffic conditions); allow comparison of the load effects generated by the site-specific traffic to those obtained when employing LM1. Statistical Extreme Value Distributions (EVDs) are fitted to simulated results to determine characteristic load effect values using the same methodology as was employed in the calibration of LM1 itself. Appropriate α adjustment factors are then determined to cater for variation in predicted characteristic extreme load effects on a network by network basis. Where α<1.0, the prescribed approach delivers significant savings by preventing unnecessary overdesign of bridges. On the other hand, for cases where α>1.0 it allows bridge designers to design bridges with adequate levels of safety.

KEY WORDS: Eurocode; LM1; Weigh in Motion; WIM; Characteristic Loading; Bridge Loading;

1 INTRODUCTION

Over the last number of decades road traffic in Europe, and in particular freight transport, has increased significantly, approximately in line with economic growth (Figure 1).

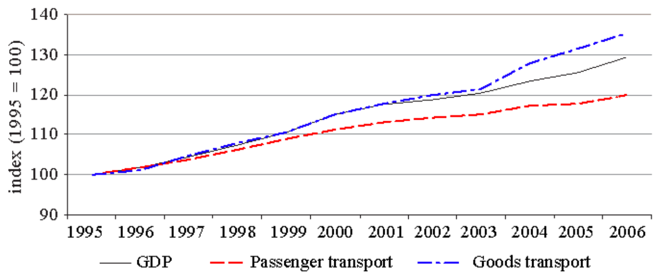


Figure 1: Evolution of transport demand and GDP in the EU-25 for period 1995-2006 [1].

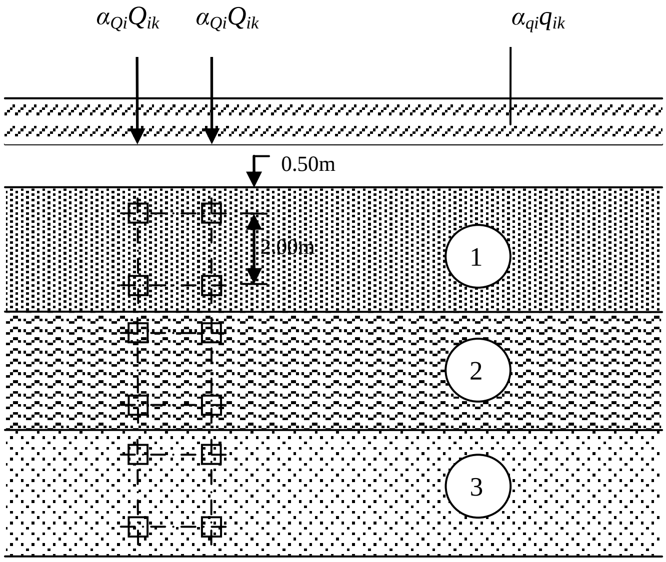
Eurocode 1: Actions on Structures, Part 2 – Traffic Loads on Bridges, is the current design standard employed across the EU. Load Model 1 (LM1) is applied for the design of new bridges with spans of up to 200m. It consists of a tandem axle load, $\alpha_{Qi}Q_{ik}$, and a Uniformly Distributed Load (UDL), $\alpha_{qi}q_{ik}$, where α_{Qi} and α_{qi} are the load adjustment factors for lane number *i*. The tandem axle load is placed at the most adverse location on the influence line under consideration to determine the worst load effect on the bridge. The remaining area of the road (the section outside the defined traffic lanes) is also subjected to a UDL, denoted $\alpha_{qr}q_{rk}$. It allows member states to calibrate the code to their own national traffic conditions. When correctly employed it facilitates a cost effective bridge design that allows for variations between countries in the frequency of heavy vehicles. This is achieved through calibration of the adjustment factors for the specific country under consideration.

The model takes account of traffic scenarios ranging from free-flowing to congested conditions with a high percentage of heavy trucks. The magnitude of the tandem axle loads and UDLs depend on the lane number and are specified in the code, reproduced in Table 1 and Figure 2.

Table 1. Eurocode LM1 [2]

Location	Tandem system Axle loads Q_{ik} (kN)	UDL system q_{ik} (kN/m^2)
Lane Number 1	300	9
Lane Number 2	200	2.5
Lane Number 3	100	2.5
Other Lanes	0	2.5
Remaining Area	0	2.5

As can be observed, as the number of lanes on the bridge increases, the tandem axle load and the UDL in the new lane is reduced. For bridges with more than 3 lanes no tandem axle load is considered.



Lane Nr. 1: Q_{1k} = 300kN, q_{1k} = 9kN/m^2
Lane Nr. 2: Q_{2k} = 200kN, q_{2k} = 2,5kN/m^2
Lane Nr. 3: Q_{3k} = 100kN, q_{3k} = 2,5kN/m^2
*for w_l = 3,00m

Figure 2: Eurocode LM1 for 3 lanes [2]

This paper outlines methods for analysing real traffic data acquired by Weigh-In-Motion (WIM) systems to allow calibration of the Eurocode LM1 α-factors. WIM data allows the individual loads in countries to be classified, enabling the specific Gross Vehicle Weights (GVWs), axle loads and frequencies of heavy trucks to be taken into account. Simulations are calibrated using this real life data, considering a wide range of bridge lengths and influence lines. Statistical Extreme Value Distributions (EVDs) are fitted to simulated results to determine the characteristic load effects. Appropriate α-factors are then determined to cater for the variation in predicted characteristic extreme load effect on a network-by-network basis. As this approach is specifically tailored to the real-life loading, identification of lightly travelled roads can result in significant savings in bridge design. Similarly for heavily trafficked roads, it identifies the need to employ high α-factors, ensuring a safe design.

2 WEIGH IN MOTION DATA

Weigh in Motion technology is the process of acquiring the real loads on bridges through the use of sensors inbuilt into the road. This allows the load effects on bridges to be determined on a network by network basis. WIM systems allow identification of the Gross Vehicle Weights (GVW), axle loads and axle spacings for each truck as well as the inter-vehicle gap data. It enables the frequency of abnormally loaded vehicles, such as that shown in Figure 3, to be identified. Statistical models can be developed using the data obtained from WIM sensors, such as the GVW histogram shown in Figure 4. The bimodal nature is a result of empty and fully laden trucks.

Figure 3: Abnormal vehicle

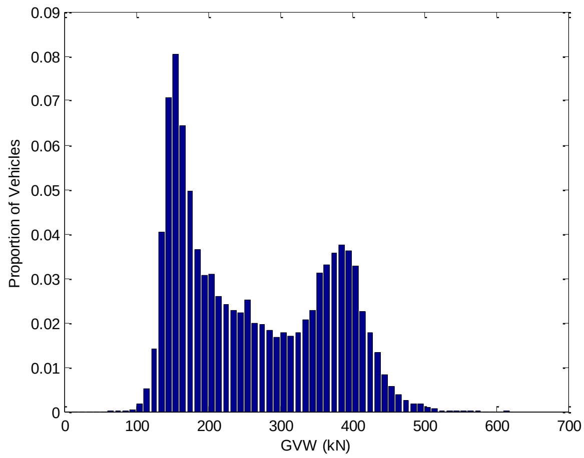


Figure 4: GVW histogram, 5 axle trucks

The authors favour the fitting of a ‘semi-parametric’ distribution to the histogram of measured GVSs. This has been proposed by OBrien et al. [3]. It involves:

- using bootstrapping to directly simulate from the histogram where there is sufficient data to justify this and
- fitting the tail of a Normal distribution to the data for extremely heavy vehicles, as shown in figure 5.

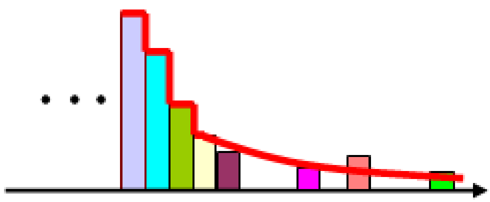


Figure 5: Semi-parametric fitting

This approach provides for significantly improved accuracy in the tail of the histogram allowing for the frequency of very heavy trucks to be accounted for in the analysis. The spacing between trucks is also an important consideration. The fitting of statistical distributions to gap data acquired by WIM sensors has been used to account for this [4].

The critical load cases for short span bridges are governed by individual axle and axle group loads. For shorter bridges free-flow conditions are generally more critically than congestion [5]. Allowance for dynamics is incorporated when free-flowing conditions are dominant using the Dynamic Amplification Factors (DAFs) of the Eurocode, reproduced in Figure 6.

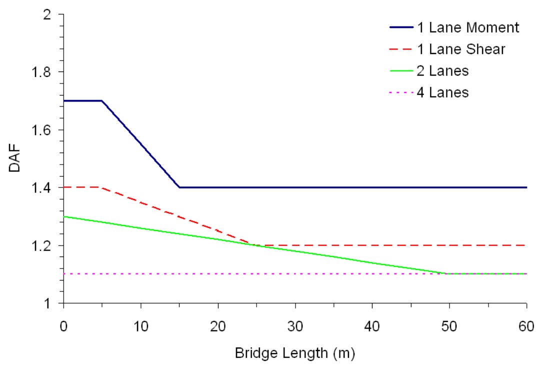


Figure 6: Eurocode DAFs

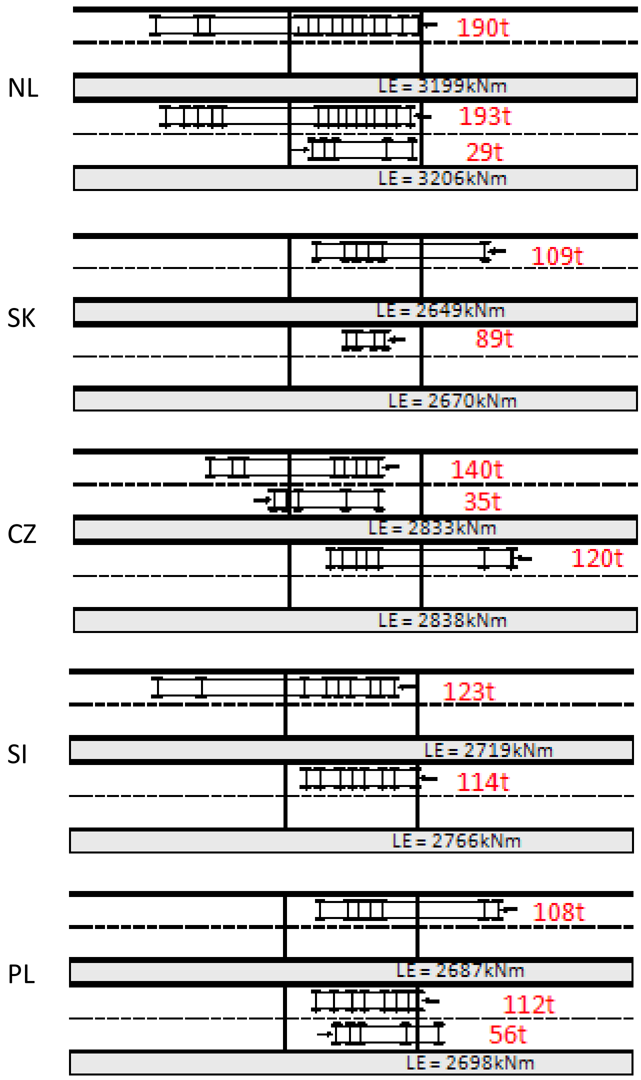


Figure 7: 1 in 1000 year loading scenarios for mid span moment in a simply supported 15m span (NL = Netherlands, SK = Slovakia, CZ = Czech Republic, SI Slovenia, PL = Poland).

Monte Carlo simulations [6] of traffic streams are generated using the acquired WIM data allowing determination of the load effects (shear forces, bending moments etc.) for the bridge under consideration. Characteristic 1 in 1000 year loading events are then determined by extrapolation or by simulating thousands of years of traffic. Enright and O'Brien [7] found typical characteristic maximum loading scenarios based on WIM data from five European countries shown in Figure 7.

The critical load case is sometimes an extreme vehicle on its own and sometimes an extreme vehicle meeting a more typical 5 or 6 axle truck. For example, the second critical loading scenario shown for the Dutch data is a 193 tonne 15 axle vehicle meeting a 29 tonne 5 axle semi-trailer.

3 CHARACTERISTIC LOAD DETERMINATION USING EXTREME VALUE DISTRIBUTIONS

For identification of characteristic load effects using the acquired WIM data, statistical extrapolations can be performed to the required return period (usually 1000 years). A standard Cumulative Distribution Function (CDF) plots the probability of non-exceedance against the load effect (moment or shear force) as shown in Figure 8.

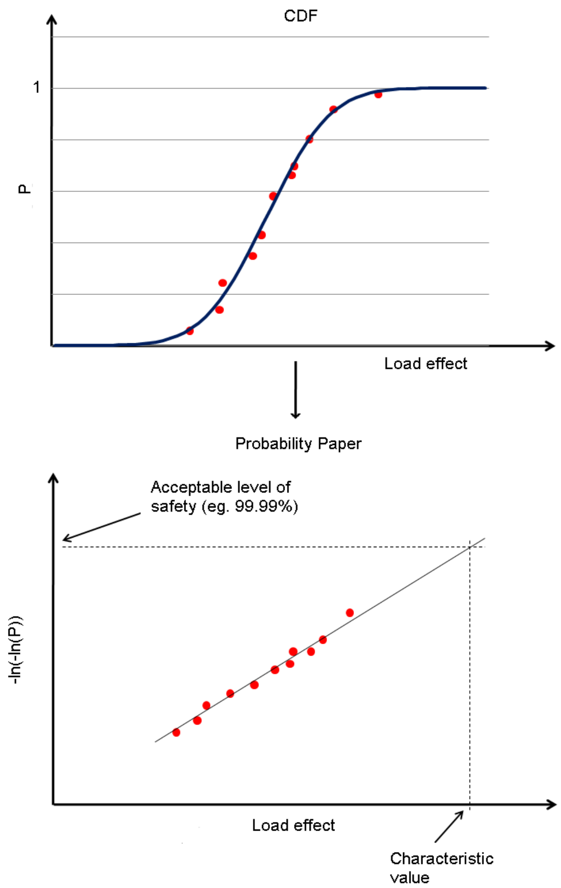


Figure 8: Gumbel probability paper plot

Each point represents a maximum-per-day or maximum-per-month load effect. The CDF has been replotted in the lower graph of Figure 8 to a Gumbel probability scale. The characteristic maximum load effect can then be found by extrapolating this trend to the predetermined acceptable level of safety. An alternative method can be employed whereby thousands of years of traffic can be simulated using Monte Carlo simulation and the 1000 year maximum found by interpolation. This approach is computationally intensive; however, it has the advantage that typical extreme loading scenarios can be identified.

The straight line in Figure 8 indicates that the data corresponds to a Gumbel Distribution. More usually bridge load effect data fits a Weibull distribution, which appears as a concave plot on Gumbel probability paper. A Weibull distribution is given by:

$$y = F(x, \lambda, \beta, \delta) = \exp\left[-\left(\frac{\lambda - x}{\delta}\right)^{\beta}\right] \tag{1}$$

where x = variable in question (i.e. the load effect), λ = threshold parameter, β = shape parameter and δ = scale parameter.

The probability of exceedance of the 1000 year load is given by

$$F(x) = 1 - \frac{1}{R.P} \tag{2}$$

where R.P = Return Period. Rearranging equation 1 and substituting for $F(x)$ allows calculation of the characteristic (i.e., 1000 year) load effect:

$$x = \lambda - \delta\left[-\ln F(x)\right]^{\frac{1}{\beta}} \tag{3}$$

Castillo recommends extrapolation after fitting to the final $2\sqrt{n}$ points, where n = number of points in the dataset [6]. However, it is not clear why this term is chosen and other authors have used others, such as the top 30%.

4 LOAD SHARING IN MULTIPLE LANE BRIDGES

Monte Carlo simulation is used to generate streams of single lane traffic, with the characteristics of the traffic flow (i.e. GVW, axle weight, axle spacing etc.) representative of the WIM measurements. For two lane roads with opposing traffic flow, i.e. a national primary/secondary route, the traffic in the two lanes can be assumed to be statistically independent. This allows simplification of the calculations as the effects of the two streams can be combined and the total load effect calculated for any point on the bridge. The results are sensitive to the transverse stiffness of the bridge: for example, the bending moment in the outer beam of a flexible bridge is less influenced by the traffic in the remote lane than is the case for a stiff bridge. Lane factors are applied to account for this, calculated so as to cover the range of expected transverse stiffness values. A lane factor of unity is applied to the lane making the greatest contribution to the load effect, i.e. the lane directly under the traffic flow. The factor applied for the other bridge lanes reflect their relative contribution to the load effect and ranges from as low as 0.05 for shear force in flexible bridge to 1.0 for bending moments in stiff bridges.

For two lane roads with same direction traffic (i.e. a motorway/dual carriageway), the loading scenario is more complicated. In the slow traffic lane, the frequency and weights of the heavy trucks are greater. The result is affected by a number of correlations. The weight of a lead vehicle is correlated with the weight of a following vehicle. This can be explained by, for example, heavy crane ballast vehicles travelling in convoy with cranes, sometimes without escort vehicles, shown in Figure 9.

Figure 9: Correlated vehicle event (courtesy Rijkswaterstaat)

The correlation is slight – of the order of 2% – but has a significant influence on the results. The weight of a lead vehicle in the slow lane is also correlated with the weight of an adjacent vehicle in the fast lane. This can be explained by overtaking events – the overtaking vehicle tends to be lighter than the vehicle it overtakes. Gaps are a difficult issue – it is possible to generate gaps consistent with measurements in each lane but this results in inter-lane gaps that are not consistent with measurements. This effect also has a significant influence on the results.

All of the issues with same-direction multi-lane simulations can be addressed using 'scenario modelling', as described by Enright and OBrien [7]. Traffic 'scenarios' – weights, within-lane and inter-lane gaps – are selected at random from the WIM database (Figure 10). The gaps and weights are then 'perturbed' using Kernel Density estimators to give a better coverage of all possible scenarios.

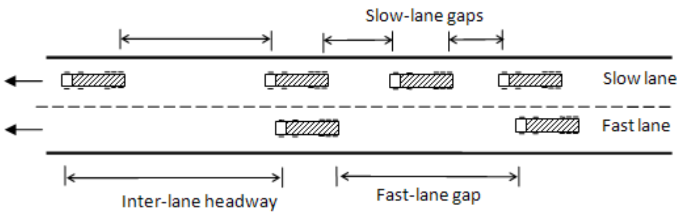


Figure 10. Typical traffic scenario [7]

5 CALIBRATION OF EUROCODE ALPHA FACTORS

The techniques outlined previously can be used to determine suitable adjustment factors (i.e. α factors) for Eurocode LM1. EC1 was originally developed considering a series of spans and influence lines, shown in Table 2. For each influence line, the characteristic load effects are found and compared to the corresponding load effect as calculated from the UDL and tandem axle load of LM1.

Enright and OBrien [7] calculated α–factors for a range of load effects using WIM data from five European countries: the Netherlands (647,000 trucks), Slovakia (748,000 trucks), Czech Republic (730,000 trucks), Slovenia (148,000 trucks) and Poland (430,000 trucks). The number of trucks over 70 tonnes ranged from 892 in the Netherlands to 3 in Slovenia and the number over 100 tonnes ranged from 238 to 1.

Table 2: Influence lines used in EC1 calibration

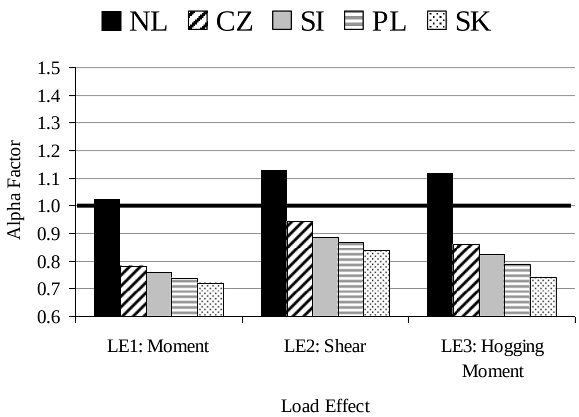
Influence Line Number	Representation	Description of the Influence Line
LE0		Total load.
LE1, LE2		Maximum bending moment of a simply supported and double fixed[1] span, respectively.
LE3		Maximum bending moment at the support of the former double fixed beam[1].
LE4, LE5		Shear force at the ends of simply supported bridge (assuming traffic flowing left to right)
LE6[2], LE7		Minimum and maximum bending moment at mid-span of the first of two spans of a two span continuous beam.
LE8		Continuous support moment of the former two span beam.
LE9		Continuous support reaction of the former two span beam.

[1]with an inertia strongly varying between mid span and the ends
[2]the second span only in loaded

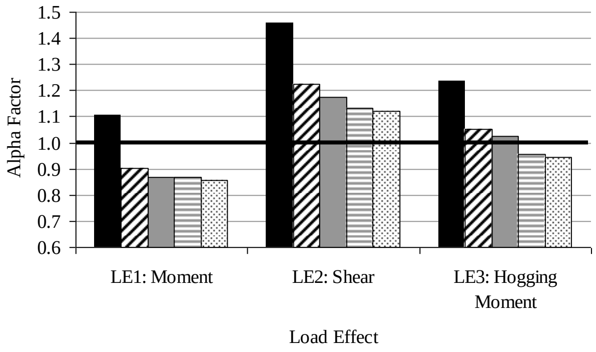
Three load effects were considered from Table 2:

- LE1: Mid-span moment
- LE4: Shear force at support
- LE8: Central support hogging moment in 2-span continuous bridge

For bi-directional 2-lane bridges, the α-factors were calculated for four bridge lengths: 15 m, 25 m, 35 m and 45 m. The results for the four spans are shown in Figure 11. It is observed that for the Dutch traffic, LM1 is non-conservative for the recorded traffic by up to as much as 45% for low lane factors. End shear is a problem for all five countries considered, with α-factors greater than 1.0 required.



(a) High lane factors

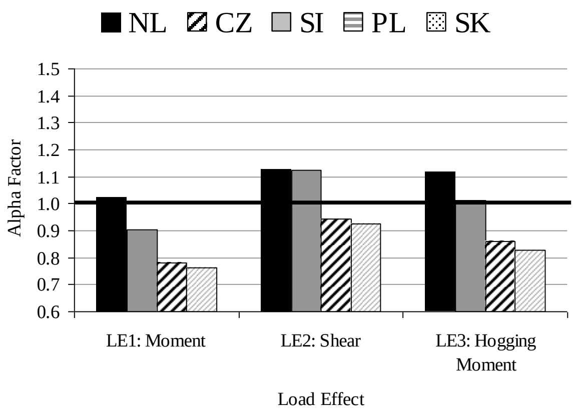


(b) Low lane factors

Figure 11: Maximum α-factor of four spans, bi-directional traffic [7]

It should be noted that both permit and non-permit trucks were included in the WIM database so the Dutch bridges would be expected to be governed by the abnormal load model as opposed to LM1.

The inconsistency between stiff and flexible bridges (high and low lane factors respectively) suggests that the relative loading in the lanes of the load model are incorrect: the slow lane loading of 9 kN/m^2 should be increased to reduce the α–factors in the flexible bridges relative to the stiff bridges. Figure 12 shows the α–factors for a same direction 2 lane bridge. While the results are generally similar, differences of up to 10% exist in some cases.



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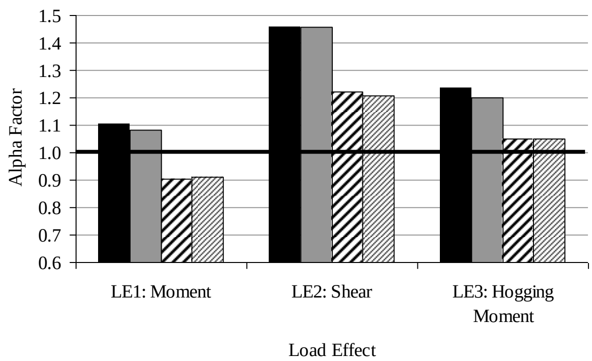

(b) Low lane factors

Figure 12: Maximum α-factor of four spans, same-direction traffic [7]

The α-factors for Ireland and the United Kingdom are listed in Table 3. As can be seen, the uniform loading of 9 kN/m^2 is significantly reduced in the most heavily loaded lane and other lane loadings of 2.5 kN/m^2 are more than doubled. This is contrary to the findings for the five continental European countries considered. If traffic in the British Isles is similar to that elsewhere in Europe, this will result in some bridges being over-designed while others are under-designed.

Table 3: Ireland/United Kingdom α-factors

Location	α_Q for tandem axle loads	α_q for UDL loading
Lane 1	1.0	0.61
Lane 2	1.0	2.2
Lane 3	1.0	2.2
Other Lanes	-	2.2
Remaining Area	-	2.2

6 CONCLUSIONS

This paper outlines techniques for the determination of load adjustment factors for Eurocode LM1 for a specific network, or on a case by case basis. Methods for calculating the characteristic load effects from the WIM data by extrapolation on probability paper are presented, and the alternative of simulating thousands of years of traffic and interpolating. These characteristic maximum load effects are compared to those obtained using Eurocode LM1 to determine appropriate α-factors. It was shown that for a range of load effects and spans, Eurocode LM1 is conservative for four out of five countries except for shear force. It is non-conservative for almost all cases at the Dutch site which is very heavily trafficked.

Furthermore, there is an inconsistency between the factors for stiff and flexible bridges. This could be corrected by using α-factors in excess of unity to the slow lane loading of 9 kN/m^2.

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