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► **To cite this version:**

Xiao Yi Zhou, Franziska Schmidt, Bernard Jacob, François Toutlemonde. Accurate and up-to-date evaluation of extreme load effects for bridge assessment. TRA - Transport Research Arena, Apr 2014, France. 8p. hal-00983768

**HAL Id: hal-00983768**

**<https://hal.science/hal-00983768v1>**

Submitted on 25 Apr 2014

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## Accurate and up-to-date evaluation of extreme load effects for bridge assessment

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### Abstract

In the 1990's, during the background works of Eurocode 1991-2 (Traffic loads on bridges), extreme loads and extreme load effects have been evaluated by using WIM data recorded at various European locations. The most used WIM data file is a WIM data record, 2-week long, recorded at Auxerre on a French heavy trafficked motorway in 1986. Today, WIM records are longer and much more accurate, thanks to the fast progresses of the WIM technology. Thus they give a better account of the traffic variations along time. After the action COST323, self-calibration of WIM system has been generalized and the sensor and software technologies were improved. Therefore, uncertainties in the calculation of traffic effects on bridges are lesser than 25 years ago.

To up-date the maximum load effects calculated in the late 1980's and used for the calibration of the load model LM1 of the Eurocode 1991-2, using the most recent WIM data, but also advanced extrapolation methods, extrapolations are made using various methods (Gaussian fitting, Gumbel fitting, Rice formula, Generalized Extreme Value, ..). Confidence intervals on the extremes that are found are derived. Among the several extrapolations methods found in the literature, a choice was made according to the objectives and the chosen methods were applied to traffic loads and traffic load effects. Results are discussed with respect to the method robustness vs the traffic data, the period of extrapolation and the load effect considered, as well of the likelihood of the final results.

*Keywords:* Bridge ; Extreme effects ; Extrapolation ; Assessment of structures.

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### Résumé

Dans les années 1990, durant les travaux préparatoires à l'Eurocode 1991-2 (Charges de trafic sur les ouvrages d'art), les charges extrêmes et les effets extrêmes des charges ont été évalués en utilisant des données de trafic enregistrées sur divers sites européens. L'enregistrement de trafic le plus utilisé correspond à deux semaines de données, enregistrées sur l'autoroute A6 à Auxerre en 1986, avec un trafic lourd intense. Aujourd'hui, les fichiers de trafic dont nous disposons sont de durées plus longues et de précision supérieure, grâce aux améliorations apportées à la technologie du pesage en marche. Ainsi ils donnent une meilleure vision des variations de trafic au cours du temps. Après l'action COST323, l'étalonnage automatique des stations de pesage en marche a été généralisé et les technologies des capteurs et de traitements ont été améliorées. Tout ceci a réduit les incertitudes des mesures de trafic, aujourd'hui très inférieures à celles d'il y a 25 ans.

Afin d'actualiser les charges extrêmes du trafic calculées à la fin des années 1980 et utilisées pour le calage du modèle de charge LM1 de l'Eurocode 1991-2, des enregistrements récents de trafic et des méthodes d'extrapolation différentes ont été utilisées. Des intervalles de confiance ont pu être déterminés. Parmi les différentes méthodes trouvées dans la littérature, un choix a été réalisé qui a été appliqué aux charges de trafic et effets des charges de trafic. Les résultats sont discutés en fonction de la robustesse de la méthode par rapport aux données et l'effet considérés.

*Mots-clé:* Pont ; Effets extrêmes ; Extrapolation ; Evaluation de structures.



## 1. Introduction

A bridge structure should have the capacity to withstand the load expected with a given probability over the design life: it is stated in Eurocode 1 [AFNOR, 2003] that the structures should be able to resist to the characteristic values for 1000-year return period, which means events with a probability of crossing of 5% in 50 years.

But it is impossible to collect enough data to determine the characteristic value of load effect expected over lifetime of loading. Even getting sufficient data for short return periods would require several samples of short period data in order to assess the corresponding probability, which is not currently available. Therefore, some extrapolation should be performed.

To develop the live load model of AASHTO, Nowak [Nowak & Hong, 1991] proposed a method that uses normal probability paper. This method had and still has great influence on other American researchers, for example [Kozikowski, 2009], [Sivakumar et al., 2008]. Straight lines are fitted to the tails of the load effect distributions plotted on normal probability paper. The extreme value of load effect can be easily determined by the inversed normal distribution, and the cumulative distribution of maximum load effect is calculated by raising the fitted distribution to a certain power according to the extreme value theory. Although the method is extensively used, the choice of the tail fraction is empirical and subjective: Nowak [Nowak, 1993] does not state how he selects the beginning of the tail and Sivakumar uses the upper 5%, see [Sivakumar et al., 2008].

In the background studies for developing the traffic load model of Eurocode 1, five methods have been proposed to predict extreme traffic load or traffic load effect [Jacob et al., 1989], [Flint and Jacob, 1996]. These are:

- a half-normal curve fitted to the end of the histogram,
- a Gumbel distribution fitted to the tail of the histogram,
- the asymptotic extreme distribution obtained with extreme value theory,
- Rice's formula for stationary Gaussian processes,
- Monte-Carlo simulation of artificial traffic and Gumbel extrapolation.

Among these methods, Rice's formula is different from the others as it uses the full history of the load effect. It has been proved that if the process is Gaussian and stationary, the up-crossing intensity can be expressed by Rice's formula [Rice, 1944]. In practice, the load effect is a mixed Gaussian process, therefore the level crossing rate has a Gaussian tail. Cremona [Cremona, 2001] proposed an automatic method to select the optimal threshold from which the tail can be expressed by Rice formula. But the mathematical assumption of Gaussian stationary process is a strong requirement, as the required length of the influence line of interest is large compared to the length occupied by the single vehicles [Ditlevsen, 1994]. The approach may be not suitable to common load effect of short- to medium-span bridge as it has sharply varying nonzero influence area.

In recent years, the extreme value theory has been used for modelling traffic load effect. Many authors approach the problem by identifying the maxima load effect recorded during a loading event or in a reference period such as a day or a week, and then fit these maxima to an extreme value distribution. Bailey and Bez [Bailey & Bez, 1999] determined that the Weibull distribution is the most appropriate to model the extreme traffic load effect. Caprani et al. [Caprani et al., 2008] classified the loading events by the number of trucks involved in the maximal load effect, and then the maxima of each loading event are modelled by GEV distribution. This block maxima approach is wasteful of data as only one data point in each block is taken. The second highest value in one block may be larger than the highest of another block and this is generally not accounted for.

A peaks-over-threshold (POT) approach exists that avoids this drawback, by using the Generalized Pareto Distribution (GPD). Indeed, due to the advances in extreme value theory, the GPD emerged as a natural family for modelling crossings over a high threshold. The POT approach has shown its importance and success in a number of statistical analysis problems relating to finance, insurance, hydrology, geographical phenomena, and other domains [Holmes & Moriarty, 1999]. However, despite the sound theoretical basis and wide applicability, fitting of this distribution in practice is not a trivial exercise. Two main factors, the choice of threshold and the choice of the parameter estimator, affect the accuracy of the return values estimations. An extensive discussion of the various parameter estimation methods has been given by Zea Bermudez and Kotz [de Zea



Bermudez & Kotz, 2010a], [de Zea Bermudez & Kotz, 2010b]. Scarrott and MacDonald [Scarrott & MacDonald, 2012] reviewed the threshold estimation methods. While each methodology has its advantages and disadvantages, traditional parameter estimator such as maximum likelihood is undefined in some regions of the parameter space. Due to these difficulties, the POT approach has not gotten much attention for modelling extreme bridge load effects [James, 2003].

The purpose of this paper is to introduce the use of the extrapolation methods on recent WIM data and the data used in the 1980's during the background works of Eurocode 1991-2 in order to assess the effect of changing traffic on bridges. The rest of the article is organized as follows: section 2 provides some comparison between traffic of the 1980's as recorded in Auxerre in 1986 and recent WIM data. Section 3 applies various extrapolation methods to these two WIM data files and summarizes the results. Discussions are carried out and conclusions are drawn in Section 4. More information on the extrapolation methods used in this article can be found in [Zhou, 2013].

## 2. WIM data files

The first WIM data used in this study have been collected in 1986 at a WIM station, in Auxerre on the heavy trafficked A6 motorway. In addition, recent traffic data, recorded by a piezo-ceramic weigh-in-motion (WIM) system on the A9 motorway near Saint Jean de Vedas, in South-Eastern France, was used. The traffic of these two locations can be compared, to assess that they represent the national traffic.

The data of 1986, recorded in Auxerre, have been used in the 1990's to calibrate the Eurocode 1, part 2, on traffic loads on bridges.



Figure 1: Location and length of WIM data files used in this study.

Weights and dimensions were collected for trucks travelling in the slow and fast lanes in one direction of the 4-lane motorway from April 1986 to May 1986, and from January 2010 to May 2010 in St Jean de Vedas on the A9 motorway.

As shown in Table 1, significant changes occurred in weights and dimensions of trucks from 1986 till 2010. In 2010, 835468 trucks have been recorded; after cleaning, 581011 trucks over 86 days are drawn from the original data by excluding obvious false recordings, week-ends and system inactivity days.

Nowadays, long and reliable data files may be recorded (e.g., a 138-day long traffic data in 2010). Moreover, as shown Table 1, the mean flow has been more than doubled since 1986.



	Auxerre, A6, 1986	Saint Jean de Védas, A9, 2010
Number of days	7	138
Number of trucks	46049	83546
Mean flow (veh/hour)	107	259
Mean flow (veh/day)	2558	6217

Table 1: Comparison of the WIM data from 1986 and 2010.

Thus the mean flow significantly increased since 1986, and the hour by hour daily flows are also rather different between the two traffic records (Figure 2). Both patterns are not only affected by the traffic increase along the time, but by the differences of location and type of traffic. In Auxerre 1986, a country side location with only long distance transport, the hourly flow rate varied between 80 and 220 vehicles/hour with two peaks in the morning and in the evening. In St Jean de Vedas in 2010, with a combined local and long distance traffic in a peri-urban area, the hourly flow is low at night and much higher along the day, with two peaks in the middle of the morning and afternoon.

Because of all these differences in the traffic patterns, but also in the load patterns, the extreme load effects experienced by the bridge have to be re-assessed.

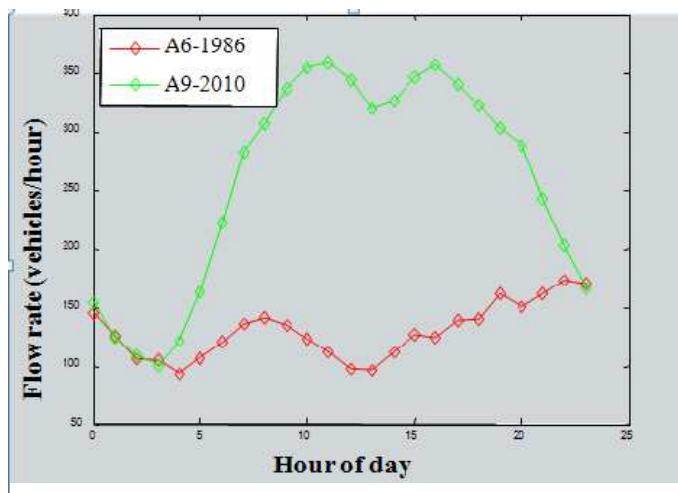


Figure 2: Hourly flow rates comparison Auxerre 1986/St Jean de Vedas 2010.

The gross vehicle weight histograms of both traffic records are presented in Figure 3. As usually, there are two main modes, centred around 15 and 40 t. The first mode contains the smaller trucks (2 and 3-axle) and not fully loaded large trucks, while the second mode close or just above the legal limit contains fully loaded 5-axle and more trucks. The second mode is much more concentrated because it contains a homogeneous population of trucks. It is highlighted that the maximum allowed GVW was 36 t in 1986, and 40 t in 2010. The overload rate was much higher in 1986, as well as some measurements errors due to the early WIM systems, which induced a more scattered weight distribution. In addition a first class just above the 3.5 t lower limit of heavy commercial vehicle is highly populated with overloaded vans. But these vehicles do not influence the extreme load effects on bridges.

Finally the GVWs were modelled by a bi-modal Gaussian distribution.

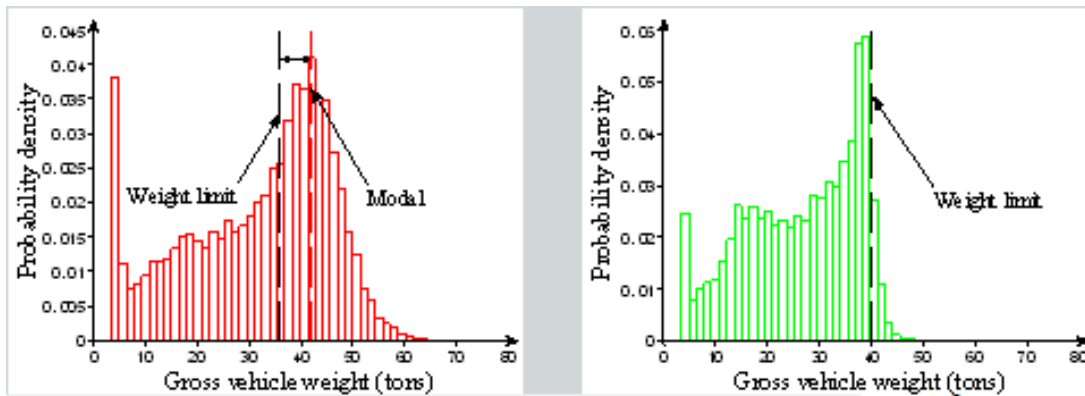


Figure 3: GVW (Gross Vehicle Weights) histograms in Auxere 1986 and St Jean de Vedas 2010.

The traffic composition (Figure 4) shows that 5-axle trucks are the most frequent trucks, with a proportion which increased since 1986. The proportion of articulated trucks (4 and 5-axle) remained very stable, with a switch from 4 to 5-axle (2 to 3-axle semi-trailer). The characteristics of the trucks affect the load effect on bridges (the tridem is the most important element to take into account).

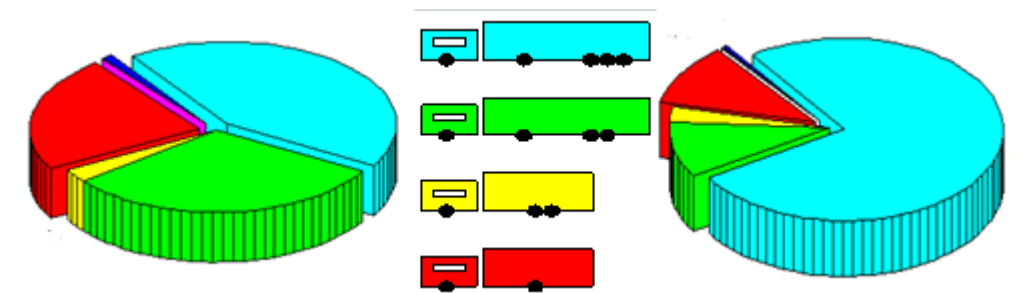


Figure 4: Traffic composition in 1986 (Auxerre, left) and in 2010 (St Jean de Vedas, right).

All these elements prove that it is important to re-assess the existing bridges, built according to Eurocodes calibrated with the traffic of 1986, by using recent traffic data files.

### 3. Extrapolated values for the considered WIM data

The results of the calculations done, both with the traffic data of 1986 and of 2010, are reported here for various extrapolation methods.

The first extrapolation method is fitting the level-crossing histogram to Rice formula, to assess the load effect level being exceeded with a given probability, which is called the characteristic values.

The second method is the Generalized Pareto Distribution (GPD) using the mathematical property that crossings of a given threshold follow a statistical distribution called Pareto distribution. That allows assessing the characteristic values.

The third method is named Generalized Extreme Value (GEV). The maximum values of the load effects on bridges are distributed as one of the generalized extreme value function, i.e. Gumbel, Fréchet and Weibull.

These methods give different results shown in Table 2, provided by [Zhou, 2013]. Variations between the extrapolated effects with these various methods can be observed. This is a fact that has also been observed in other domains, as hydrology or fiancé. But it has been shown [Zhou, 2013] that these different results are quite



similar when the traffic data is accurate and long (several months). But it also highlights the fact that choosing the extrapolation methods is still an issue.

	St Jean de Vedas, A9, 2010
Rice formula	10229
GPD	9631
GEV	9455

Table 2: Extrapolated effect values on a given bridge, for the various extrapolation methods and WIM data (1986 and 2010).

When comparing the effect of these two traffic files with the effect of the load model 1 of Eurocode 1, two cases can be found: spans under 30 meters and spans over 30 meters. For spans smaller than 30 meters the effect of actual traffic is higher than the effect of the traffic recorded in 1986. For spans longer than 30 meters, in which the governing case is the congested traffic, the extrapolated value of 1986 is higher than the extrapolated effect of the actual traffic. This is due to higher scattering of the “old” traffic data.

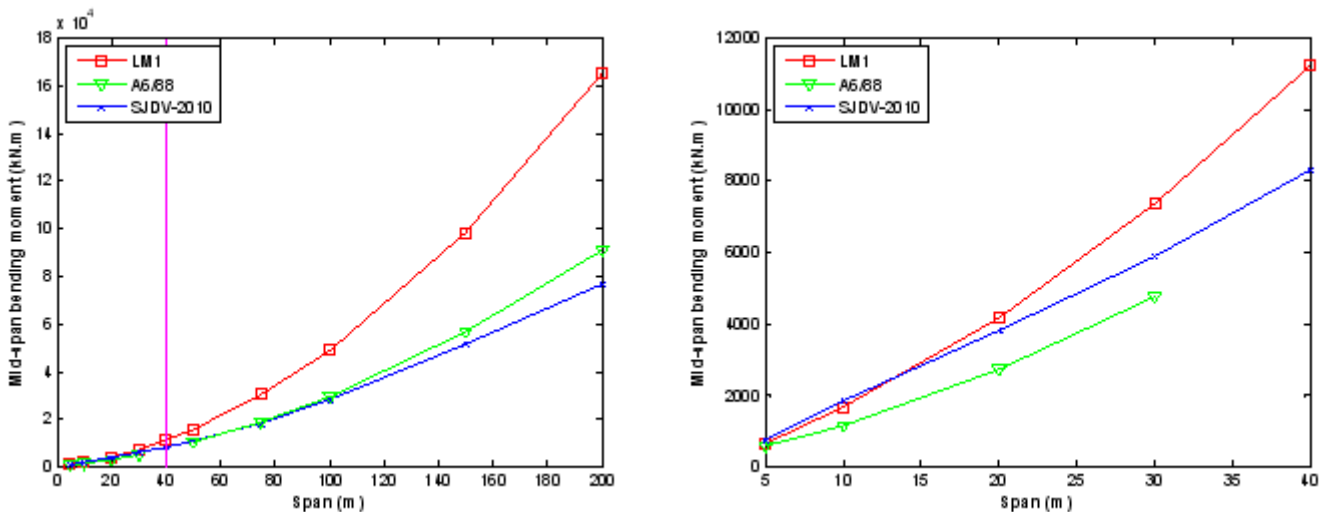


Figure 5: Extreme mid-span bending moment for simply supported bridges of various span lengths, according to various methods.

In all cases, it may be found that the effect induced by the load model 1 of Eurocode 1 is higher than the effect of the measured traffic. The safety margin seems to be reduced. But one issue remains to be solved: which dynamic amplification factor should be applied? Indeed, there is already some dynamic amplification included in the WIM data, but it should be assessed. And which remaining amplification factor should be taken into account when assessing a bridge?

### 5. Conclusion

Bridges have been built according to existing regulations, while the traffic is evolving in volume and frequency along the time. Extreme load effects and fatigue effects need to be assessed when reassessing bridges designed by a code or a past traffic, against the effects induced by the current traffic.

This article relates some works done on the issue of extreme load effects. Two WIM data files have been used, one recorded in 1986 which has been used to calibrate the Eurocodes, and another measured in 2010, while



regulations on weights and dimensions had changed. Several extrapolation methods have then been used and compared to the load model of the Eurocode 1.

The safety margin seems to have been reduced, but the issue of the dynamic amplification remains.

### **Acknowledgements**

The authors greatly acknowledge the financial support provided by the Marie Curie Initial Training Network TEAM (Training in European Asset Management) project.

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