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A peaks-over-threshold analysis of extreme traffic load effects on bridges

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Abstract

For purposes of design of new structures or safety assessment of existing structures, extreme effects need to be assessed, for example through calculation of characteristic values of high quantile. Indeed, these values make it possible to determinate stresses for extreme events (extreme weather impacts like temperatures or rain, but also extreme traffic events). This paper focuses on modeling and estimating tail parameters of bridge traffic load effects by generalized Pareto distribution (GPD) to obtain these characteristic values. Its main advantage is that it makes use of all relevant data on the high load effect induced by the passage of traffic, not just the daily maxima used for generalized extreme value (GEV) distribution. However, two critical problems of parameter estimation and threshold selection complicate the use of GPD in practice. A Kolmogorov-Smirnov (KS) statistic based threshold selection method is used to choose the optimal threshold, and the maximum likelihood estimator is adopted to estimate the parameters in this study. Results show that the GPD method is a theoretically well supported technique for fitting a parametric distribution to the tail of an unknown underlying distribution.

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[1] that the structures should be able to resist to the characteristic values for 1000-year return period, which means events with a probability of exceedance 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 the short return period would require several samples of short period data in order to assess the corresponding probability, which is not currently available. Therefore, some form of statistical projection should be performed.

In development of live load model of AASHTO, Nowak [15] proposed a method that uses normal

probability paper. This method had and still has great influence on other American researchers, for example [11], [19]. 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 [14] does not state how he selects the beginning of the tail and Sivakumar uses the upper 5%, see [19].

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. These are:

- i. a half-normal curve fitted to the end of the histogram,
- ii. a Gumbel distribution fitted to the tail of the histogram,
- iii. the asymptotic extreme distribution obtained with extreme value theory,
- iv. Rice's formula for stationary Gaussian processes,
- v. 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 [16]. In practice, the load effect is a mixed Gaussian process, therefore the level crossing rate has a Gaussian tail. Cremona [5] 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 [8]. 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 modeling 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 [3] determined that the Weibull distribution is the most appropriate to model the extreme traffic load effect. Caprani et al. [4] classified the loading events by the number of trucks involved in the maximal load effect, and then the maxima of each loading event are modeled 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. Indeed, due to the advances in extreme value theory, the GPD emerged as a natural family for modeling exceedances 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 [9]. 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 estimations of the return values. An extensive discussion of the various parameter estimation methods has been given by Zea Bermudez and Kotz [6], [7]. Scarrott and MacDonald [17] 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 modeling extreme bridge load effects [10].

The POT approach makes full use of all the data present in the tail as Nowak's approach, but it approximates the tail through extreme value distribution. Therefore, the POT approach is a natural family for modeling exceedances over a high threshold. The purpose of this paper is to introduce an efficient procedure for using POT approach to determine the extreme bridge traffic load effect. The rest of the article is organized as follows: In Section 2, we provide key distributional properties of the GPD. In Section 3, we fit the GPD to the bridge traffic load effects and summarize the results. Discussions are carried out and conclusions are drawn in Section 4.

2 THE PEAKS-OVER-THRESHOLD METHOD AND GENERALIZED PARETO DISTRIBUTION

Let $\{X_n\}_{n \geq 1}$ be a sequence of independent and identically distributed random variables with common distribution function F , and let's M_n denote its maximum:

In theory the distribution of M_n can be derived exactly for all values of n :

But in most cases, the distribution function F is unknown. The value of F^n can be approximated by extreme value distribution if the maximum, x_n , belongs to a maximum domain of attraction. In this case:

where α , β and μ are shape, scale and location parameters, respectively. The events that exceed some high threshold u can be regarded as extreme events and the behavior of these extreme events is given by the conditional probability:

For large enough u , the distribution of $x_n - u$, conditional on $x_n > u$, is approximated with the extreme value theory by:

In extreme value theory, the previous distribution belongs to the generalized Pareto family. The cumulative distribution function (CDF) of the GPD with shape, scale and location parameters α , β and μ , respectively, is defined as:

The probability density function of the GPD is given by:

3 APPLICATION OF THE GPD TO THE ANALYSIS OF TRAFFIC LOAD EFFECTS

3.1 Bridge Traffic Load Effect

Traffic load effects can be measured directly on a bridge, or can be calculated and simulated through a convolution of traffic data with the influence lines of the effect of interest. This last possibility is what has been done here.

3.1.1 Traffic Data

Traffic data, taken from a piezo-ceramic weigh-in-motion system on the A9 motorway near Saint Jean de Vedas, in the South-East of France, is used to validate the POT method on the estimation of characteristic bridge traffic load effects. Weight and dimensional data were collected for trucks travelling in the slow and fast lanes in one direction of the 6-lane motorway from January 2010 to May 2010. The reliable loading data are useful for estimating extreme traffic load effect on bridge. The unreliable data (trucks with single axle, "0" axle weight and etc) can be eliminated from records with some chosen criteria [19]. For operational reasons, on some days the WIM system may not be active for some hours, it is important to exclude these days to ensure having continuous traffic.

581011 trucks for 86 days were drawn from the original data excluding errors, weekends and system inactive days. The histogram of gross vehicle weight of the remaining trucks is presented in Figure 1: the quality of the records is good, as it can be seen at the high percentage of trucks with GVW around the weight limit. The traffic composition plot shows that 5-axle trucks are the most frequently trucks used in France, and the characteristic of this truck affects the load effect on bridges.

Bridges supporting bi-directional four lanes are common in France. An artificial synthesis approach is used to create a sample with four lanes traffic from the records measured on these two lanes.

3.1.2 Influence lines

Previous studies have demonstrated that the critical influence lines for developing load models the bending moment at mid-span of a simply supported bridge, the bending moment at first mid-span of two-span continuous bridge and the hogging moment at middle support of the former. In this study, these three types of load effect are studied. In addition to these, three load effects for the three-span continuous bridge are studied as it is an usual type of bridge in France. A complete list of the influence lines are indicated in Table 1.

Thus three types of bridge structure are investigated: simply supported, two-span continuous with equal span length, and three-span continuous with span configuration of $0.75 L + L + 0.75 L$. In the calculations four span lengths were considered: 20, 30, 40, and 50 m.

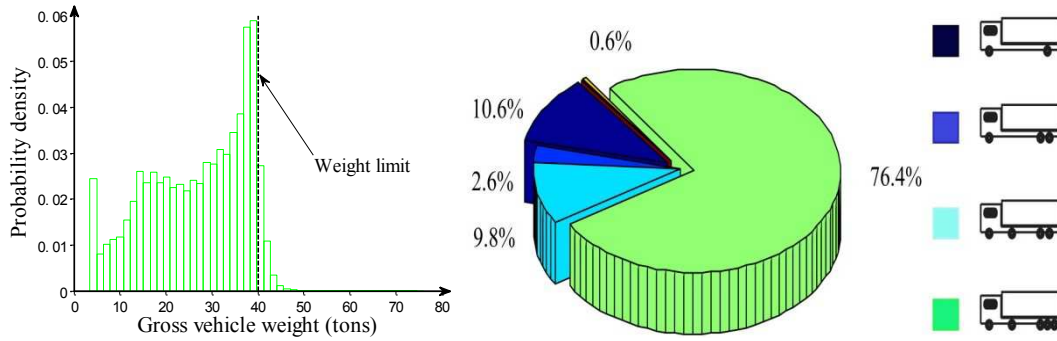


FIGURE 1 Traffic composition and histogram of GVW

TABLE 1 Influence lines used in calculation of load effect

| Item | Description | Representation |
|---------|--|----------------|
| I1 | Bending moment at mid-span of a simply supported bridge | |
| I2 | Bending moment at middle support of a two-span continuous bridge | |
| I3 & I4 | Minimum and maximum bending moment at first mid-span of a two-span continuous bridge | |
| I5 | Bending moment at first mid-span of a three span continuous bridge | |
| I6 | Bending moment at second support of a three-span continuous bridge | |
| I7 | Bending moment at second mid-span of a three span continuous bridge | |

3.2 Preliminary study

In this section, we fit the GPD model to the bridge traffic load effects resulting from combination of traffic data and influence lines, which has been extensively studied in the literature by using other extrapolation methods (see, e.g. [5]). In the first stage, we detail the application of GPD to the moment induced by the four lanes of traffic at mid-span of a simply supported bridge with span of 50 m. The standard exponential Quantile-Quantile (Q-Q) plot in FIGURE 2(a) gives evidence of lighter than exponential (LTE) distribution nature of the hourly maximum traffic load effects as the curve has a convex shape. This becomes even more apparent in the Mean Excess (ME) plot given in FIGURE 2(b) with a negative slope ratio. This asymptotic linear tail on the ME plot indicates a Pareto type distribution can reasonably fit to the tail from the turn point.

3.2.1 Estimation of The GPD Parameters

The last decade has seen development of a number of approaches for parameter estimation in

GPD applications. The maximum likelihood (ML), the probability weighted moments (PWM) and the method of moments (MM) are often used. Previous studies have demonstrated that the maxima of traffic load effect converge to Gumbel or Weibull distribution [2]. Therefore, the three extensively used estimators are available for traffic load effects. An extensive discussion of the various methods has been presented by de Zea Bermudez [6]. The main advantages and disadvantages of each one of these methods mentioned are thus known. Moharram et al [13], Singh and Ahmad [18], and Mackay et al [12] utilized Monte Carlo simulations to evaluate the performance of the estimators for GPD. All of the authors concluded that no method is preferable to another one for all simulated numerical samples. The ML estimator is asymptotically efficient, but for small samples the ML estimators do not always exist and when it does exist, it has a larger bias and variance than other estimators. The PWM and MM estimators are straightforward to compute, but the existence of PWM estimator is restricted to shape parameter less than 0.5 for the PWM estimator and 1.0 for the MM estimator.

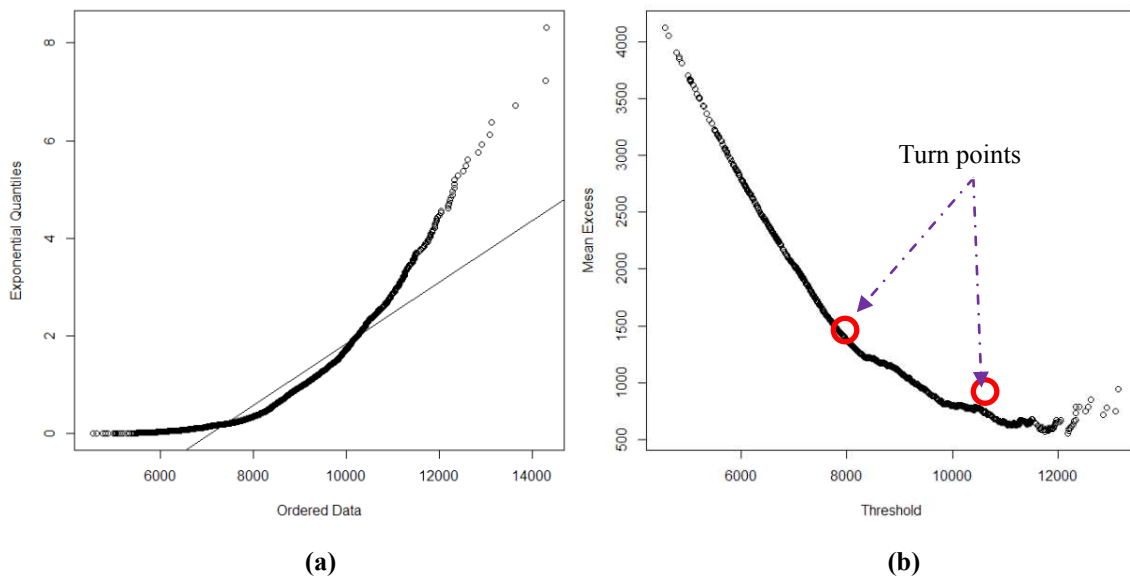


FIGURE 2 (a) Standard Q-Q plot and (b) Mean Excess plot for hourly maximum bending moment

3.2.2 Choice of The Optimal Threshold

The complex shape of the ME plot in FIGURE 2 indicates a variation of the properties for excesses over a high threshold. We need a refined method for choosing an optimal threshold. The determination of such a threshold still remains a delicate point of the whole set-up of the GPD-fitting to distribution tails. The recommendation to use the Mean Excess function for this purpose is not suitable here. The automatic threshold selection method by KS test proposed by Cremona [5] has shown its success in the optimal extrapolation for the level crossing method. It may be a good solution

for the choice of optimal threshold for the use of the POT approach. The Kolmogorov Distance (KD) between the tail histogram and the fitted GPD is thus used as a value to choose the optimal threshold. This statistical test compares two probability functions corresponding respectively to the reference and the tested distribution. If F and G are the probability functions, the KS-test studies the statistics of the variation D :

For a value d , the probability $P(D \leq d)$ is approximated by the Kolmogorov function $K(d)$:

$$K(d) = 1 - \exp(-2d^2)$$

Where n is the total number of observations blocks. This is the discrete Kolmogorov-Smirnov test.

Figure 3 shows the estimates of the shape parameter and the value of P using the ML, MM and PWM estimators with threshold value. It is clear that the PWM estimator is very sensitive to the threshold value as shown in Figure 3, as the value of the shape parameter shows great changes. The ML estimator is slightly less sensitive than the PWM and MM estimators, displaying a slightly lower variation of shape parameter with threshold value. At a threshold of $u=11000$ the shape parameter appears to reach a plateau. The corresponding value of P with a KS test kept at a high level over 0.8 means the GPD model fits the excesses well. The fitting is quite sensitive to the endpoints, as the threshold closing to the tail, the shape parameter and value of P fluctuate display some irregular fluctuations. Therefore, the optimal threshold should be selected from the plateau around $u=11000$. Table 2 summarizes the results of the application. The results include the optimal thresholds selected for each parameter estimator, corresponding estimates of return level for 1000 years return period.

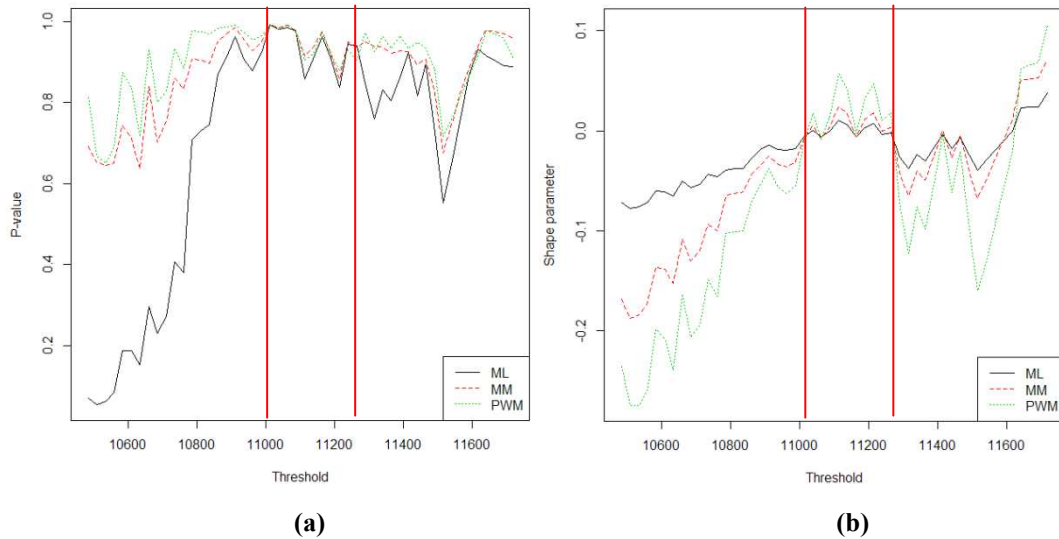


FIGURE 3 (a) Threshold vs. P-value and (b) threshold vs. shape parameter

TABLE 2 ML, MM and PWM estimates

| Method | Threshold | No. excesses | P-value | Shape | Return level |
|--------|-----------|--------------|----------|----------|--------------|
| ML | 11012.07 | 117 | 0.99046 | -0.00087 | 22575.21 |
| MM | 11012.07 | 117 | 0.994234 | 0.003436 | 23004.72 |
| PWM | 11012.07 | 117 | 0.993113 | 0.012504 | 23960.33 |

3.3 Results

The availability of GPD has been illustrated in the previous preliminary study, and then we extend its application to other types of load effect and span lengths. The load effects are determined by combining a four lane free flowing traffic and influence lines for span length from 20 to 50 m. Characteristic values of the load effects for 1000-year return period are extrapolated using the GPD. The results are compared with those found by the conventional GEV method, and also compared with the design values calculated from LM 1 of Eurocode 1. The GEV is fitted to daily maxima to avoid correlation, while the GPD is applied to hourly maxima ensuring more data can be involved. In order to reduce possible difference arising from parameter estimator, parameter estimator of ML is used to GPD and GEV.

A summary of the results is presented in Table 3. So one first comment is that the predictions by using GEV and POT methods are less than the design effects in all cases. Interestingly, the differences compared to design values for various type of load effect are around 40% (columns 6 and 7 of Table 3). The predictions obtained by fitting the daily maxima to the GEV, are slightly less than those obtained by the GPD approach. Comparisons of the POT results with the 1000-year GEV results are given in Figure 4.

TABLE 3 Comparison of POT results

| Load effect | Span length (m) | Characteristic load effect (kN.m) | | | Percentage difference (%) | | |
|-------------|--------------------|-----------------------------------|-------|-------|---------------------------|------------------|------------------|
| | | LM1 | GEV | POT | GEV ^a | POT ^a | POT ^b |
| I1 | 20 | 8115 | 4527 | 4481 | -44.21 | -44.79 | -1.03 |
| | 30 | 14209 | 7801 | 8254 | -45.10 | -41.91 | 5.82 |
| | 40 | 21540 | 12267 | 11915 | -43.05 | -44.68 | -2.86 |
| | 50 | 30109 | 17386 | 22575 | -42.26 | -25.02 | 29.84 |
| I2 | 20 | -4775 | -2779 | -5081 | -41.80 | 6.40 | 82.83 |
| | 30 | -9027 | -4689 | -6432 | -48.06 | -28.75 | 37.17 |
| | 40 | -14514 | -6960 | -7589 | -52.05 | -47.71 | 9.05 |
| | 50 | -21239 | -9355 | -9671 | -55.95 | -54.46 | 3.38 |
| I3 | 20 | -1769 | -1101 | -1249 | -37.74 | -29.40 | 13.41 |
| | 30 | -3121 | -1874 | -1875 | -39.97 | -39.94 | 0.05 |
| | 40 | -4782 | -2853 | -3361 | -40.35 | -29.72 | 17.81 |
| | 50 | -6752 | -3888 | -3806 | -42.42 | -43.63 | -2.10 |
| I4 | 20 | 6402 | 3847 | 3771 | -39.91 | -41.09 | -1.95 |
| | 30 | 11157 | 6140 | 6810 | -44.96 | -38.96 | 10.91 |
| | 40 | 16841 | 8735 | 9211 | -48.14 | -45.31 | 5.45 |
| | 50 | 23455 | 12477 | 13431 | -46.80 | -42.74 | 7.64 |
| I5 | 20 | 6452 | 5226 | 3804 | -19.00 | -41.04 | -27.21 |
| | 30 | 11325 | 4457 | 4051 | -60.64 | -64.23 | -9.12 |
| | 40 | 17188 | 6815 | 7480 | -60.35 | -56.48 | 9.77 |
| | 50 | 24042 | 7386 | 7607 | -69.28 | -68.36 | 3.00 |
| I6 | 20 | -4763 | -1951 | -2098 | -59.04 | -55.95 | 7.54 |
| | 30 | -8886 | -3376 | -5904 | -62.01 | -33.56 | 74.87 |
| | 40 | -14162 | -5446 | -5738 | -61.54 | -59.48 | 5.36 |
| | 50 | -20592 | -7122 | -8877 | -65.41 | -56.89 | 24.65 |
| I7 | 20 | 5338 | 3482 | 3433 | -34.76 | -35.70 | -1.43 |
| | 30 | 9290 | 4667 | 4762 | -49.77 | -48.74 | 2.04 |
| | 40 | 13986 | 7287 | 7641 | -47.90 | -45.37 | 4.87 |
| | 50 | 19426 | 9980 | 10333 | -48.62 | -46.81 | 3.54 |

a Related to load effects from LM1 of EC1.

b Related to GEV predictions.

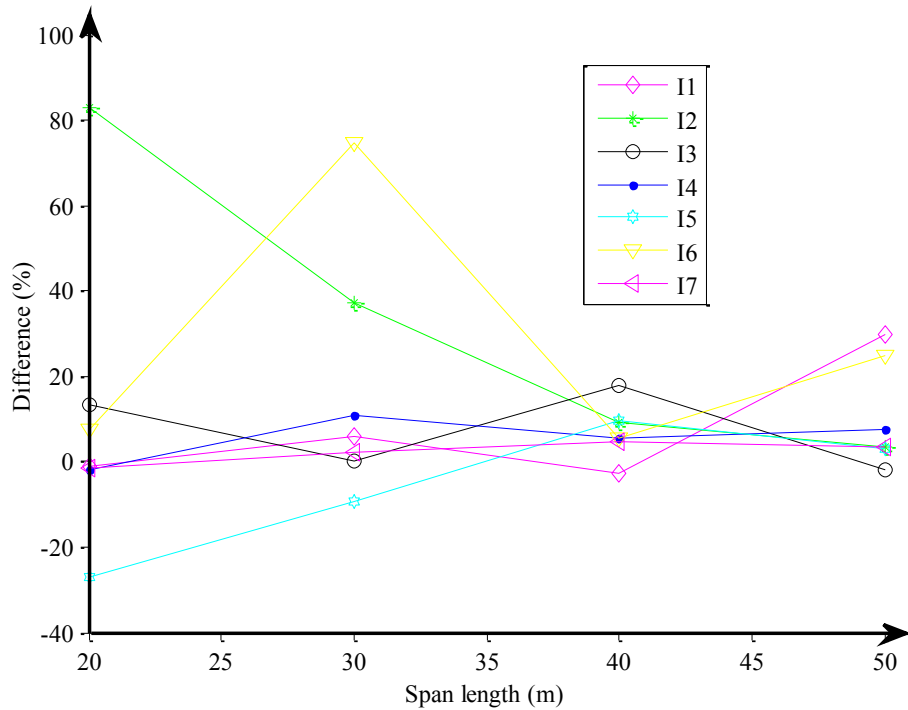


FIGURE 4 Difference

4 DISCUSSION AND CONCLUSIONS

In this article, we have introduced the Peaks-over-threshold method for statistical analysis of traffic load effects on bridges. It is based on the excesses over a high threshold which can be modeled by the generalized Pareto distribution. Its main advantage is that it uses all relevant data of the high tail of the effects induced by the passage of traffic, and not just daily or annual maxima. The two difficulties of threshold selection and parameter estimation for using this method have been discussed in the case of bridge traffic load effects. Some remarks can be made:

- The automatic approach based on KS test can efficiently identify the optimal threshold for the use of POT method.
- The GPD model has shown its success on predicting characteristic bridge traffic load effects as it captures the tail behavior very well.
- The almost same differences indicate the Load model 1 (LM1) of Eurocode 1 has a consistent safety margin for various types of load effect.
- Based upon the results it is reasonable to conclude that the LM1 of Eurocode is sufficient for modern free flowing traffic.

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