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Summary

The paper describes some of the preliminary statistical analysis of traffic data from heavily trafficked European highways which led to the derivation of vehicular loading models in Eurocode 1 part 3. The studies indicated reasonable compatibility between extrapolations to extreme loads and load effects using diverse methods despite differences in modelling and assumptions. The dominance of the effects of congested traffic for medium and long spans indicated the need for better data on traffic jam characteristics.

1. Introduction

The comparison and the calibration of conventional traffic load models proposed for the Eurocode 1 part 3 [1], required a complete set of target values of both axle and vehicular loads, and load effects on representative influence lines and surfaces. A large representative selection of spans and bridge elements was defined providing more than 800 influence lines and surfaces. A complete survey of European traffic data, recorded by Weigh-In-Motion (WIM) systems in D, E, F, I and UK, provided weeks of full traffic measurements vehicle by vehicle over the main motorways and highways [2]. Among these traffic records, the most aggressive for bridges according to the loads an the intensity were selected.

The studies described below primarily made use of comprehensive data from the A6 motorway at Auxerre, collected over a representative week. Those undertaken by different organisations were conducted independently and as a result employed a variety of methods and assumptions [3].

2. Return period and fractile

The occurrence of lorries on a bridge may be described by a stationary time series X_1, X_2, ...,X_n, the i[th] lorry having a gross weight X_i. It is additionally assumed that one event occurs at each time unit, counted by i, and that the X_i are independent and identically distributed (iid), with a cumulative distribution function (CDF) F. The return period R_x of a specified value x of X_i is defined as :

$R_x = E[N_x]$, where $N_x = \inf\{n / X_1<x, X_2<x, ..., X_{n-1}<x, X_n \geq x\}$. (1a)

It is easy to show that : $R_x = (1 - F(x))^{-1}$, for $F(x) < 1$. (1b)

If the time series is replaced by a stationary time random process $(X_t)_{t\in R+}$, we have :

$R_x = E[T_x]$, where $T_x = \inf\{t / X_u<x, \forall u<t, \text{ and } X_t \geq x\}$. (1c)

For any $\alpha<1$, the α-upper fractile x_α of X_t is derived from : $\alpha = 1 - F(x_\alpha)$. (1d)

The maximum $Y_N = \text{Max}_{0<i\leq N}(X_i)$, if N is the expected number of lorries passing during a reference time period T, representing the expected lifetime of a structure. Because the X_i are iid, the CDF of Y_N is $F(x)^N$. If y_α is the α-upper fractile of Y_N, it is possible to show that for N and T $\to +\infty$:

$$R = R_{y_\alpha} \cong \frac{-T}{Ln(1-\alpha)} \cong \frac{T}{\alpha} \qquad \text{if } 0<\alpha<<1. \qquad (1e)$$

This relationship is independent of the value of y_α and of the density of X. For example, if T=50 years and α=0.05, we get R=975≅1000 yrs.

3. Extreme Axle and Lorry Loads

The objective was to compute the probability distribution function (PDF), mean value, standard deviation and the single, double and triple axle loads, gross weights and weights per unit length with given return periods, from the experimental histograms of these variables measured over a week and the traffic flow. Three methods were employed :

3.1 Method 1: Half-normal distribution

With this method it was assumed that the upper tails of the distributions of the local extrema of the variables have a Gaussian shape [4]. Half-normal PDF's were fitted to the part of the histogram for $x \geq x_0$, where x_0 is chosen in order to minimise the mean square error in a Henry's diagram.

The standard Gaussian PDF was adopted with a standardised variable z : $z = (x - m)/\sigma$, where the mean m and the standard deviation σ were fitted on the Henry's diagram, for $x \geq x_0$.
The value with a return period R is given by $x_R = x_0 + \sigma.Z_R$, with Z_R being the α-upper fractile of Z for $\alpha=1/2N_\tau$. N_τ is the total number of events in a histogram for the period R, computed from the total number N_S in the measured histogram by $N_\tau=N_S.R/D$ (D= period of measurement).

3.2 Method 2: Multimodal Gumbel distributions

A bimodal (or a trimodal) Gumbel PDF was fitted to the experimental data [5]; each distribution was obtained by a linear regression on a sub-population of the whole histogram. The conditional PDF of the maximum load of N axles, axles groups or vehicles was computed. The α-upper fractile x_α of these maxima is given by :

$$1 - (1 - p)^N = \alpha \qquad \text{and} \qquad x_\alpha = F_Y^{-1}(\alpha) \qquad (2)$$

where p is the proportion of the distribution considered and F_Y the fitted CDF of this distribution.

3.3 Method 3: Multimodal Gaussian distributions

A trimodal Gaussian PDF was fitted by a least mean square method and the α-fractile of this distribution computed [5].

3.4 Method of the asymptotic extreme distributions

As for method 1 it was assumed that the upper tails of the load PDF's have a Gaussian form [6]. The asymptotic distributions of the maxima were derived as Gumbel PDF's with the parameters [7] :

$$a_n = \frac{\sqrt{2Ln(n)}}{\sigma} \qquad \text{and} \qquad u_n = m + \sigma\left(\sqrt{2Ln(n)} - \frac{Ln(Ln(n)) + Ln(4\Pi)}{\sqrt{2Ln(n)}}\right) \qquad (3)$$

in which m and σ are the parameters of the normal distribution governing the maximum, and n=p.N, where p is the proportion of this distribution in the whole distribution of the considered load and N the total number of loads. This method provides a full PDF of the maximum instead of only a fractile, and defines explicitly the variation of this maximum with n.

3.5 Comparisons and conclusions

Table 1 shows predictions obtained by the methods for single axle, double axle and triple axle and gross vehicle weights for different return periods. The results show very consistent trends. The biggest differences between the predictions appears not to be due to the methods, but rather to the actual parameters of the distributions used to match the tails of the data histograms.

Methods 2 and 3 give high extreme lorry weight predictions since they are based upon the distribution of the uppermost mode of the best fit curve to the Type 4 vehicle data. Predictions based on the entire data sample become dominated by the large numbers of Type 3 vehicles, whose upper mode has less variance than Type 4. In several cases, the best fitting set of distributions contains one which has a relatively low mode and total proportion, but whose high variance leads to its dominating the extreme values. In these cases only the uppermost mode was used.

R	Item	Method 1	Method 2	Method 3	Method 4
20 weeks	Axle Double Triple Lorry	224 * 356 * 469 * 737 *	226 353 436 711 $^{+}$ 728 $^{++}$	234 348 439 736 $^{+}$ 750 $^{++}$	252 332 442 690
20 years	Axle Double Triple Lorry	236 ** 380 ** 504 ** 782 **	249 394 459 775 $^{+}$ 819 $^{++}$	249 376 474 758 $^{+}$ 800 $^{++}$	273 355 479 736
2000 years	Axle Double Triple Lorry	245 *** 397 *** 527 *** 811 ***	278 442 487 850 $^{+}$ 925 $^{++}$	264 403 508 787 $^{+}$ 900 $^{++}$	295 379 517 782

R = return period, * R=50 weeks ** R=50 years *** R=1000 years
Based on distribution for : $^{+}$ = Type 3 vehicles, $^{++}$ = Type 4 vehicles.

Table 1. Comparison of the Extrapolated Maximum Loads (kN).

4. Extreme Total Load on a Lane Length

The maxima of the total load (or the uniformly distributed load : UDL) on a lane length were computed by various methods for various lengths from 5 to 200 m, for a return period R. The traffic used was again that in a slow lane of Auxerre.

4.1 Method 1: Half-normal distribution

The method described in 3.1 was applied to the histograms of the local extrema of the total loads. The traffic was randomly generated by the use of its characteristic parameters and measured inter-vehicle spacing, and a Gaussian distribution was fitted on the local extrema histogram, for free traffic (case (a)). Congested traffic with cars (case (b)) and without cars (case (c)) were also considered. In the case (b), the proportion of lorries was taken equal to 25%. In both jam cases (b) and (c), the spacing between vehicles (from axle to axle) was taken as 5 m. It was assumed that 1% of the vehicles would be involved in jams occupying the chosen lane length.

4.2 Method 2 : Monte-Carlo simulation

The Monte-Carlo method was used to create artificially and randomly composed jammed traffic with 5 m inter-vehicle spacing for simulation purposes [8] and the parameters of Gumbel distributions were derived.

The 'garages' used in random generation were derived for Auxerre traffic, with and without cars with eight classes of vehicle each with a derived distribution of gross weight, proportions of weight on each axle and axle spacings.

For each span length, 50 sequences of 1000 simulations were performed, the Gumbel distributions being derived from the maximum values found in each of the 50 simulation sequences. It was assumed that such maxima were annual extremes from 4 traffic jams per working day.

4.3 Method 3 : Analytical modified Poisson model

This model [6] also adopted a bimodal gross weight distribution, with two Gaussian modes, and was applied to flowing traffic with measured vehicle spacings and to congested traffic with and without cars.

The analytical convolution of the flow process and the gross weight distribution led to the expression of the total load density $f_Q(x)$ on lane length L :

$$f_Q(x) = P(N=0)\delta_0 + \Sigma_{n>0} P(N=n)\, \Sigma_{i=0,\dots,n} C_n^i\, p^i (1-p)^{n-i}\, g(m_{ni},\sigma_{ni},x) \quad (4)$$

where : δ_0 is the Dirac distribution in 0,
p is the proportion of vehicles in the second mode,
g is the Gaussian standardised distribution,
$m_{ni} = i\, m_1 + (n-i)\, m_2$ and $\sigma_{ni}^2 = i\, \sigma_1^2 + (n-i)\, \sigma_2^2$,
$m_1, \sigma_1, m_2, \sigma_2$ are the parameters of the two modes of the gross weight distribution.

Flowing traffic flow and vehicle weight distributions were described by a modified Poisson process, in which the lengths of the vehicles (taken constant) were introduced in order to avoid overlapping. The exponential law of the times of arrival was shifted to the right of $\tau_0 = L_0/S$, L_0 (10 m $\le L_0 \le$ 15 m) being the mean length of the vehicles plus the minimum spacing and S the mean speed.

This model is briefly defined by :

- the distribution of the inter-vehicle time intervals :

  $P(\Delta t=t) = \mu\, e^{-\mu(t-\tau_0)}$, $\mu = \phi / (1-\phi\, \tau_0)$, with ϕ= traffic flow rate,

- and the deduced cumulative distribution of the total number of vehicles on the length L :

  $P(N \le n) = P(\Sigma_{i=1,\dots,n+1} \Delta t_i > \tau)$, with $\tau = L/S$.

The α-upper fractile of Q was obtained by solving numerically the equation :

$$1 - F_Q(x) = 1 - (1-\alpha)^{1/N_T} \cong \alpha / N_T \quad (5)$$

where N_T is the total number of vehicles expected in T ($N_T = \phi T$).

For congested traffic, $f_Q(x)$ becomes a binomial distribution if : $P(N=n)= \delta_{n,k}$, where $k=[L/L_0]$ is the mean number of vehicles on the lane length L, in case of jam.

The number of independent load configurations considered was : $[N'_T/k]$, with N'_T the total number of vehicles involved in a jam on L during T, such that each vehicle belongs only to one configuration.

4.4 Method 4: Simulation and extrapolation from real traffic

Method 3 was also used for providing ***extrapolation coefficients*** [6] from a reference period T of 1 week to those of 1 month, 1 year, 50 and 500 years. The modified Poisson model gives the 5%-fractiles of the total load Q for different periods T, noted Q(T), and the extrapolation coefficient is defined by : Q(T)/Q(1 week).

The traffic recorded during a week was passed over the influence lines of the total load by the simulation program CASTOR-LCPC [9], and the maximum values obtained for each length L were magnified by the corresponding extrapolation factor for each T or R.

Congested traffic was also simulated by compressing the spacings between measured vehicles (with or without cars), and passing the traffic over the same influence lines. The 5% upper-fractiles of the maximum total loads for the target value calculations were derived, the number of load cases with standing traffic on the lane length taken into account being assumed to represent those which would occur during 100 years.

4.5 Method 5 : Jams simulation program

Another Monte-Carlo simulation program was used to generate traffic jams and to compute bridge load effects [10], based on the Auxerre data. Vehicle weights were modelled by bi- or tri-Gaussian distributions.

Traffic jam rates were based upon UK studies showing breakdown rates of 60 incidents per million vehicle kilometres (I/m veh.km) for HGV, and 30 (I/m veh.km) for light vehicles. The accident rate was 4 I/m veh.km in the simulation, with 26% of accidents blocking more than one traffic lane.

The assumed flow in vehicles per hour above which congestion will occur were :

Blockage	Number of lanes per carriageway 1	2	3	4
No blockage	1500	3700	5500	7400
1 lane blocked	0	1300	2700	4300
2 lanes blocked		0	1200	2600

The flow rate was taken to be 1200 vph for 10 hours, 5 days per week, on a two lane carriageway, and vehicle spaces in traffic jams were assumed to be log-normally distributed, with : $\mathrm{mean}(\log_e(\mathrm{space}))=0.647$, and standard deviation of $\log_e(\mathrm{space}))=0.578$.

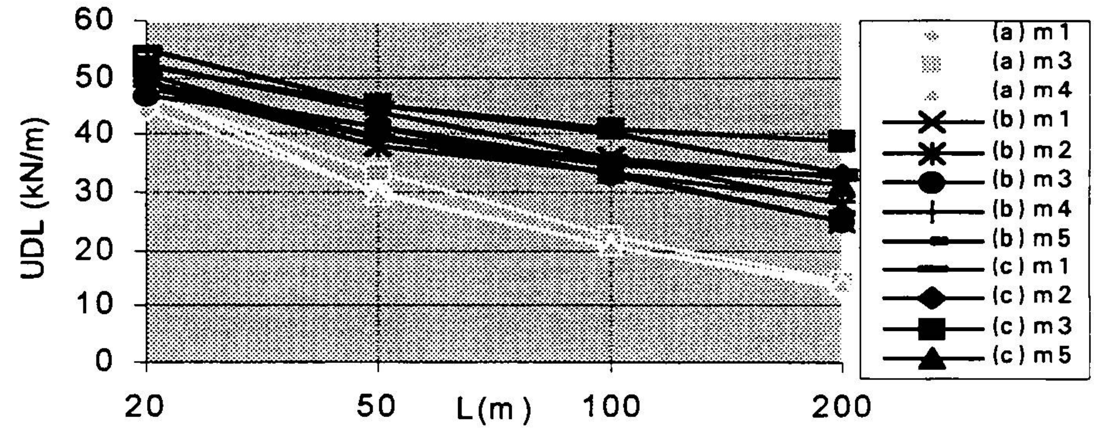
These data were used to model the build up, passage and depletion of vehicles in queues past obstructions. Vehicle kilometres per incident were found by inverting the incident rate to give the mean separation between successive obstructions during any desired return period for a particular flow rate.

Successive jam location points were chosen, spaced according to the return period and flow rate until the jam initiation point has not arrived at the bridge, the effect of the traffic on the bridge influence line being calculated for each and the maximum in each return period recorded. These maxima were then used to derive extreme value distributions. The 10^{-6} fractile values were taken to have a 2000 years return period.

The program also modelled flowing traffic by using the same vehicle types and flow rates as for jammed traffic using variable inter-vehicle spacing and without light vehicles.

4.6 Comparisons and discussion

The 50 years return maxima for different traffic scenarios calculated by the above methods are illustrated in Figure 1. The congested traffic results dominated for most spans and discrepancies between these for the various methods are mainly due to differences in assumptions concerning vehicle length and spacing and in jam frequency.



Maximum of the total load
(a) flowing traffic, (b) congested traffic with cars, (c) congested traffic without car
m1 = half-normal distribution, m2 = Monte-Carlo simulation, m3 = analytical Poisson, m4 = simulation + extrapolation by m3, m5 = jam simulation.

Fig. 1. Comparison of the extrapolation methods for flowing and congested traffic.

5. Extreme Load Effects

Extreme values of bending moments in a simple supported bridge at midspan for various span lengths and bending moments of two continuous bridges (Pont à Mousson and La Nive) were derived by five methods. Methods 1, 2, 4 and 5 were broadly as described in 4. above applied to the relevant influence lines.

Method 3 was based on the crude assumption that the load effect is a Gaussian stationary process X(t). For this Rice's formula gives the level crossing distribution, with the Gaussian density :

$$p(x) = \frac{1}{2\Pi}\frac{\sigma_{\dot{x}}}{\sigma_x}\exp\left(-\frac{(x-\bar{x})^2}{2\sigma_x^2}\right) = k.\exp\exp\left(-\frac{(x-m)^2}{2\sigma^2}\right) \qquad (6)$$

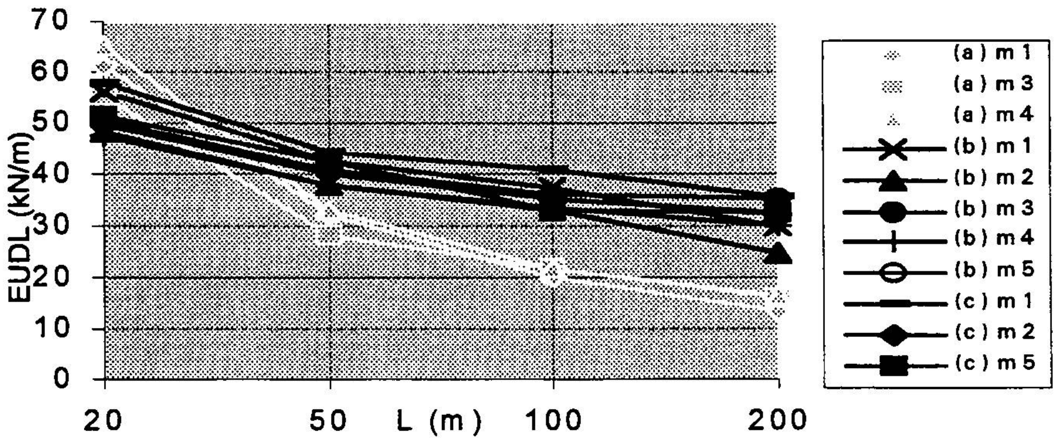
k, m and σ are fitted on the level crossing histogram of the load effect computed by simulation (CASTOR-LCPC) for a traffic record over a time period τ. Then for a reference period T and an α-upper fractile : $p(a) = \alpha\tau/T$, which gives :

$$a = m \pm \sigma\sqrt{2\ln(kT/\alpha\tau)} \qquad (+ \text{ if } a>0, - \text{ if } a<0). \qquad (7)$$

Table 2 shows results for the continuous bridges, by methods 1 and 3 for flowing traffic and by methods 4 and 5 for congested traffic. Figure 2 illustrates the results for simply supported spans for 50 years return values.

		Flowing traffic		Congested traffic	
Bridge	Moment	Method 1	Method 3	Method 4	Method 5
Pont à Mousson	positive	9740	9800	10460	11037
	negative	-3060	-3960	-3954	-3540
La Nive	positive	-	46.6	43.3	47.9
	negative	-	-42.0	-27.4	-28.1

Table 2. Comparison of the 5%-fractiles of the extreme bending moment of real bridges (kN.m).



Maximum of the simply supported span bending moment
(a) flowing traffic, (b) congested traffic with cars, (c) congested traffic
m1 = half normal distribution, m2 = Monte-Carlo simulation, m3'= Rice's formula,
m4 = simulation + extrapolation by Poisson, m5 = jam simulation.

Fig. 2. Comparison of the extrapolation methods for flowing and congested traffic.

6. Conclusions

The results obtained by the different extrapolation methods were generally in reasonably close agreement. Having in mind that the return periods for the characteristic values of loads and load effects are far in excess of the period of records used, it was concluded that any of the methods could be applied. Those described in 3.4 and 4.3 were used in European traffic samples and 800 influence surfaces to provide target values for calibration of candidate loading models for the Eurocode 1 part 3. It was evident that the congested traffic scenarios dominate the maxima for loaded lengths in excess 50 m. However in the subsequent development of the loading model dynamic magnifiers were applied to the flowing traffic effects for the lower lengths and this altered the transition.

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