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EVALUATION OF THE EFFECTS OF HEAVY VEHICLES ON BRIDGES FATIGUE

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ABSTRACT

This paper presents and compares bridge lifetimes in fatigue for several heavy traffics, using traffic data recorded by Weigh-In-Motion (WIM) systems, and computed with CASTOR-LCPC software. CASTOR-LCPC was developed to compute traffic load effects on bridges, in order to assess structural design, to calibrate load models to be used in bridge codes, or to evaluate fatigue damages and lifetimes. Load effects (such as stresses) vs time, are computed using multi-lane traffic data files and theoretical or experimental influence surfaces. Among others, CASTOR-LCPC provides a "rain-flow'" histogram of the stress cycles, used to calculate fatigue lifetimes, once combined with Miner's law. One detail of a common bridge structure sensitive to fatigue is considered in this paper: the welded join between a vertical stiffener and the main girder upper or lower flanges, of composite (steel-concrete) bridges. Seven existing French bridges are considered as examples. Three traffics were chosen, with different vehicle flows and mean loads, measured by WIM systems on trafficked motorways in 1997 and 2001; one traffic recorded in 1986 on the A6 motorway at Auxerre, and which was used for the Eurocode "Traffic loads on road bridges" (EN 1991-3) is also used for comparison.

1. INTRODUCTION

Fatigue is a progressive deterioration of a structure by crack growth, due to a series of stress variations (cycles) resulting from the application of repeated loads, such as induced in bridge components under traffic loads and heavy vehicle crossings. The stress amplitudes are much lower than the failure strength of the material, and are experienced very often or even continuously during the structure lifetime. Fatigue damage is a function of the magnitude and frequency of load effect cycles, as well as of the fatigue strength or behaviour of a structural detail. The fatigue strength depends on the geometry of the detail and the parameters and quality of the welds (Bathias and Baïlon, 1997).

In the mid-80's, extensive traffic data were collected in France and in a few other European countries (Bruls, Jacob, Sedlacek, 1989), including WIM (weigh in motion) data, to get figures of the real traffic loads applied on the existing bridges, and to be applied on future bridges. These data, recorded by WIM systems on motorways, heavily trafficked highways or secondary roads, were used for the calibration of load models and fatigue loads (Kretz and Jacob, 1991; Jacob and Kretz, 1996) of the Eurocode EN1991-3 (CEN, 1994) in the late 80's and early 90's. Most of the fatigue lifetime calculations were carried out for composite bridges (Jacob, 1989), using the most sensitive details of the steel structures, i.e. the welds between upper and lower flanges of main girders and the vertical stiffeners of the girders' web. These details are sensitive to vehicle weights and dimensions, and traffic parameters such as vehicle headings, crossings or take over, because they result from longitudinal bending moments coupled with transverse influence lines. Local effects, such as welds between longitudinal stiffeners and deck plate of steel orthotropic decks, widely investigated in ECSC research projects (Bignonnet et al., 1990a & b), are not considered here, because the lifetimes are mostly governed by the number of axles and the axle load distribution.

Ten years later, the freight traffic throughout Europe increased a lot, the truck and tire characteristics changed quickly, e.g. with the increase of wide tires and tridem axles on semi-trailers, the development of air suspensions, a better management of heavy vehicle fleets leading to a reduction of empty lorries travelling on the roads, etc. Also, the WIM systems and their calibration were improved (COST323 2002; Jacob 1999; WAVE 2001), and thus WIM data became more reliable and accurate. Therefore, it seems necessary to re-assess the dynamic effects of heavy vehicles on bridges for fatigue, the safety of bridges in fatigue and the calibration of the fatigue load models.

New traffic (WIM) data were recorded on a few French motorways in 1997 and 2001, in order to be compared to those of 1987, and to analyse the evolution in traffic and lorry aggressiveness for bridges in fatigue. Attention is paid to the influence of individual truck characteristics and traffic parameters.

2. TRAFFICS AND WIM DATA

Traffics

Two highway traffics were chosen to be recorded during one whole week at least, and used for fatigue lifetime computations. Two older highway traffics were chosen in addition.
Each traffic will be apply on each bridges, without any correlation with the real traffic supported by the considered bridge. Indeed, the objective is not to check a particular bridge project, but to verify that some critical details regarding to fatigue in the bridges comply with best practice codes or eurocodes.

Traffic loads were recorded on the four lanes (both directions) of the A9 motorway (Nimes-Montpelliers-Perpignan) in October 2001, close to the Spanish border, by the concessionary company Autoroutes du Sud de la France (ASF). During the same period, the traffic was also recorded on the two lanes of each direction on the A5 motorway (Paris-Troyes-Langres) in Eastern France, by the concessionary company Société des Autoroutes Paris-Rhin-Rhône (SAPRR). The third traffic was recorded in 1997 on the A31 (Luxembourg-Metz-Nancy-Langres) motorway at Bulgnéville, in Eastern France between Nancy and Langres, on the two lanes of both directions.

The traffic of the A6 motorway (Paris-Lyon) was recorded in 1986 at Auxerre, and was widely used for the studies and calibration of the Eurocode EN1991-3. Two lanes of each direction were recorded, but for the 2-lane bridges, only one direction was used (instead of the two slow lanes).

Generally, lorries and cars were recorded, but for bridge loading and fatigue purposes, only lorries with a gross weight above 3.5t are considered. Some coherence tests were carried out on the traffic files, in order to eliminate outliers (for speed, weights, axle spacing, etc...), so that CASTOR-LCPC could compute correct values. The transverse location of the lorries within each traffic lane was not measured by the WIM systems, but simulated afterwards by a truncated normal distribution (so that no wheel could be out of the lane).

The main traffic statistics are shown in Table 1. Among the recent traffics, the traffic on A9 motorway has a lorry flow twice higher than the A5 traffic, which is itself twice than the A31 traffic. The distribution by type of vehicles is very similar for the three recent traffics (A9, A5 and A31), if classified either by number of axles, or by class of lorry (1 = 2-axle rigid, 2 = 3 and 4-axle rigid, 3 = articulated tractor and semi-trailer, 4 = drawbar lorries). More than 75% of the lorries have 5 axles, and almost 80% are tractors with semi-trailer (4, 5 or 6 axles). The second and third largest classes are class 4 (10 to 15%) and class 2 (7 to 9%). The percentage in class 4 highly depends on the location, because drawbar lorries are more common in Germany and northern Europe than in France and Spain. Therefore, this percentage reaches 15% on the A31 motorway, which is a main route from Benelux and Germany to south of France, Italy and Spain, while it drops down to 10% on the A9 motorway near Spain.

The 15 year old traffic of the A6 motorway shows several patterns, which reveals an important time-evolution of the types of lorries used in France and Europe. In 1986, the 5-axles lorries were less than half of the population (43%), and the class 3 contained only 62%. The class 1 contained one fourth of the population. Moreover, at that time, approximately half of the articulated tractors with semi-trailers only had 4 axles, with a tandem axle (and twin wheels) under the semi-trailer, while now almost 85% of these articulated lorries have 5 axles and a tridem axle under the semi-trailer (with wide tires).

It is also well known that the proportion of air suspension highly increased since 15 years, and now it is likely that at least 50 to 60% of the lorries are equipped with such "road-friendly" suspensions.

WIM data

The traffic of the A6 motorway was one of the heaviest traffic in France in 1986, and one of the heaviest recorded in Europe at that time. Therefore, it was the traffic which was mainly used to calibrate the traffic load models of the Eurocode EN 1991-3 (extreme loads). The gross weight distribution always has a tri-modal shape: (i) a first mode is concentrated just above 3.5 t, which contains overloaded vans and small 2-axle lorries, (ii) a second mode is located between 18 and 25 t, which consists of overloaded 2-axle lorries, and fully loaded class 2 lorries, and partially loaded lorries of classes 3 and 4; this mode is the most scattered, (iii) the third mode is concentrated around the highest current legal limit (44 t), while the upper tail of the distribution extends until 55 or 60 t (overloaded lorries and special permits); it contains fully (or over-) loaded classes 3 and 4 lorries.

In 1986, on the A6 motorway, the two upper modes were not well distinguished and the upper tail was longer, even if the legal limit at that time was only 38 t. This is explained by two reasons: (i) the dynamic impact factors were higher with the mechanical suspensions than with the air suspensions, which leads to more scattered impact forces and higher values, (ii) the WIM systems were much less accurate than now, and thus again the scattering was higher and the maxima over-estimated. This overestimation was considered in the studies of the Eurocode, and the extreme load effects calculated were reduced by app. 10%.

The mean gross vehicle weight is 29.5 t on the A9, 29.9 t on the A5, 32.6 t on the A31 and 32.4 t on the A6. Because the A6 traffic was the heaviest measured in 1986, and loads were slightly over-estimated, it confirmed the general trend of a significant increase of the gross weights over the 15-years period.

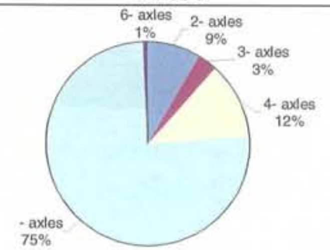
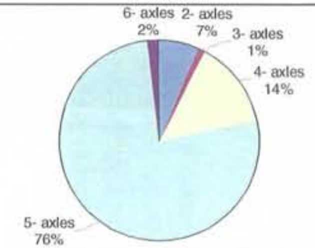
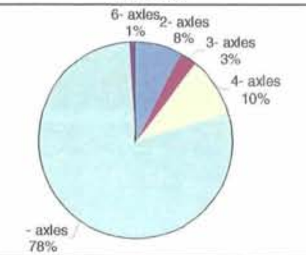
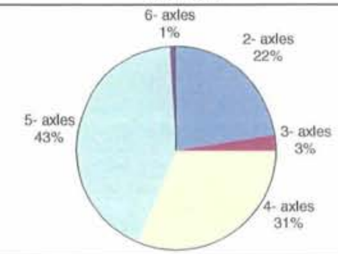
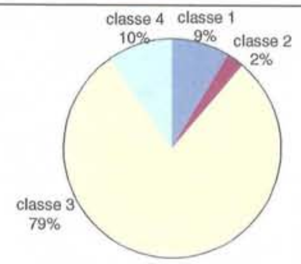
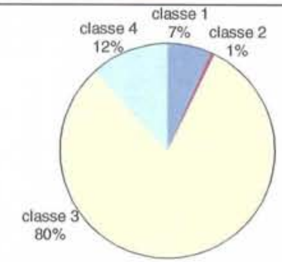
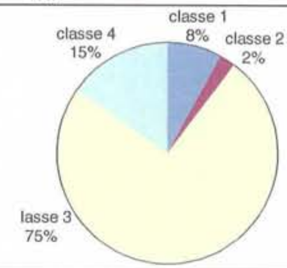
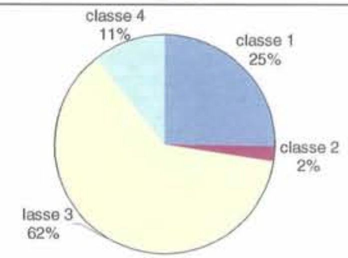
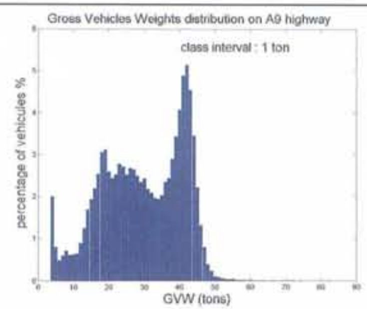
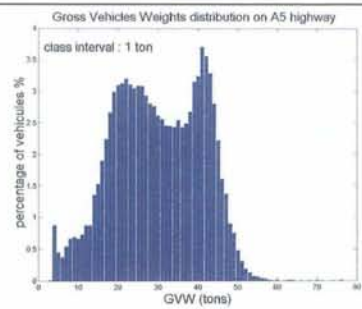
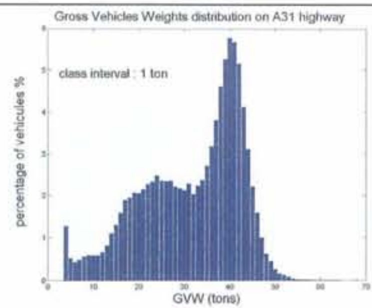
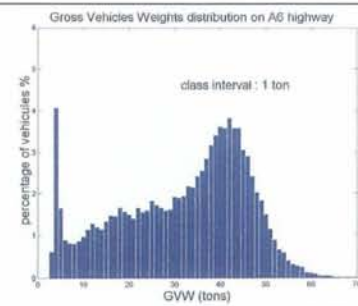
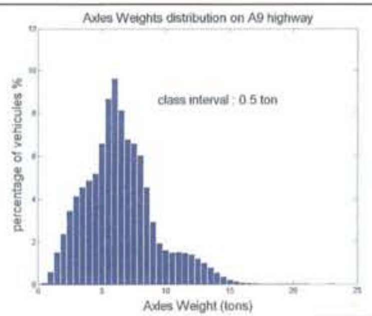
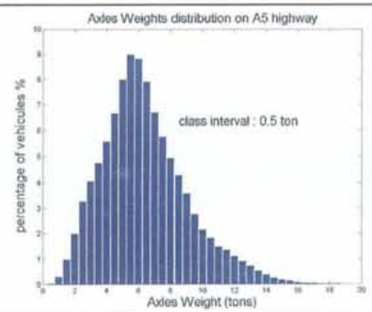
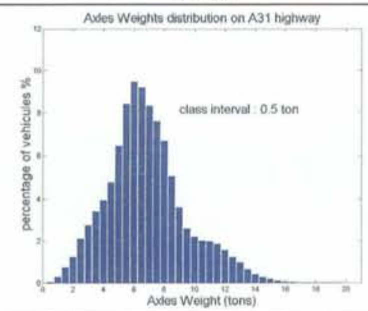
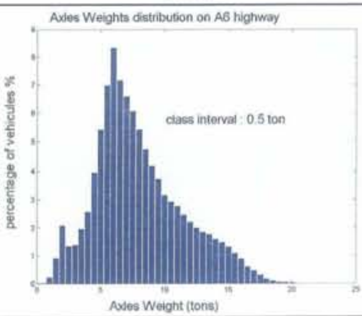
Axles weight distribution presents only one peak, which is always centred around 6 t, and a rather constant shape over time and space. The distribution is more scattered and presents a longer upper tail (until 20 t) for the old traffic of the A6 for the reasons explained above.

Tandem and tridem axles distributions are always bimodal whatever the traffic. Indeed, one peak is related to empty lorries and the second one to fully loaded lorries. A5 traffic shows a very high proportion of axle groups in the first mode, which is in agreement with the proportion of partially loaded lorries - the 2nd mode of the gross weight distribution also exceeds 50% of the population -.

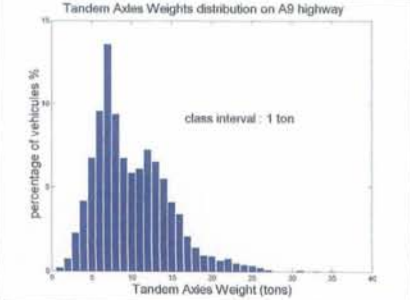
Length distributions reveals an evolution of large lorry design with time, e.g. an increase of the articulated tractor with semi-trailer length from 11 m in 1986 to 12.5 m in 1997 and 2001 (the higher value for the A9 traffic is due to the fact that the total vehicle length is considered instead of the spacing between the front and the rear axles). These class 3 vehicles are almost standardised, and thus the scattering of their length distribution is very low. In 1986, the higher proportion of class 1 vehicles induced a higher proportion of shorter lorries, with an axle spacing from front to rear between 2 and 6 m.

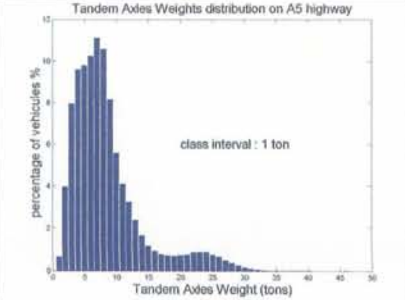
Higher the traffic density, lower the scattering of the vehicle heading distribution.

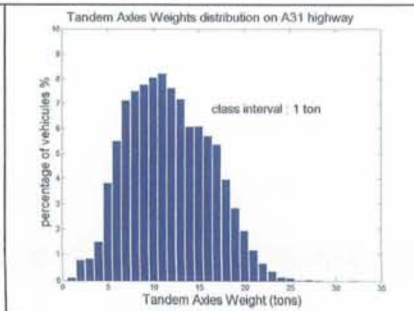
Table 1- Statistics associated to the chosen traffics

Highway	A9	A5	A31	A6 (Aux86)
Trucks flow / day	8 183	4 583	2 101	5 503
Load flow (t/day)	241 390	136 868	68 578	178 360
Percentage of each type of truck (Nb of axles)				
Percentage of each class of truck class 1 : 2-axles rigid vehicles class 2 : >2-axles rigid vehicles class 3 : articulated vehicles class 4 : draw bar vehicles				
Distribution of Gross Vehicles Weight				
Distribution of Axles weights				

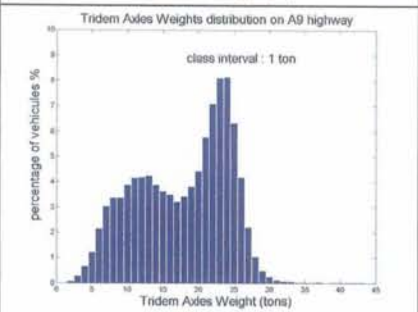
Distribution of tandem axles weights

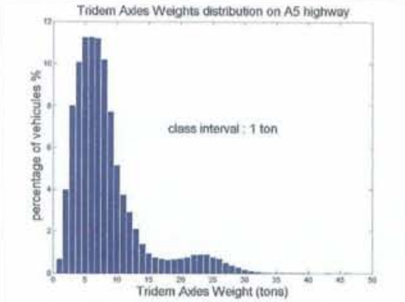


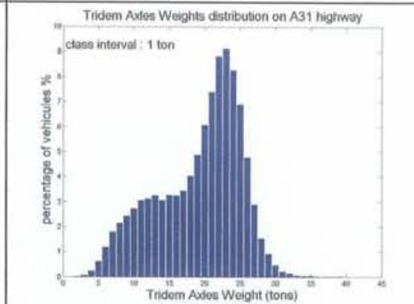




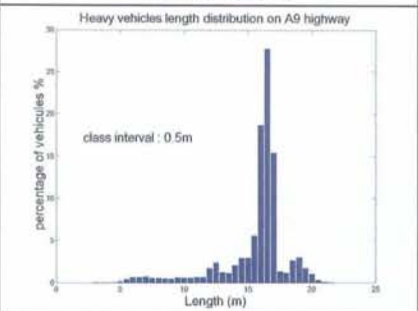
Distribution of tridem axles weights

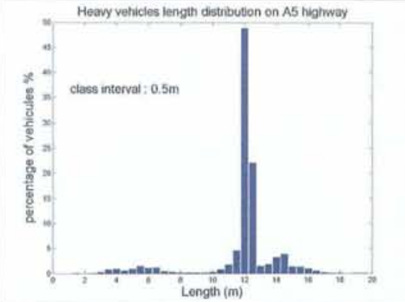


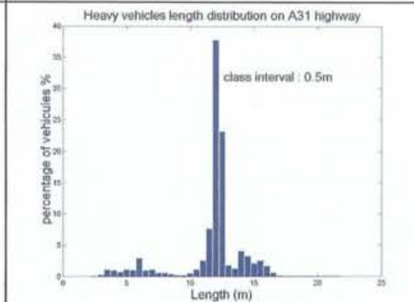


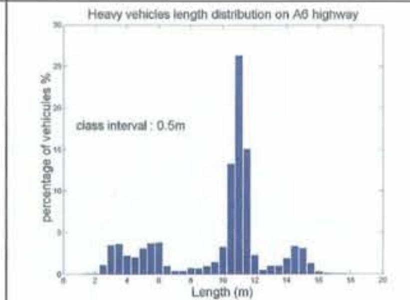


Distribution of heavy vehicles length

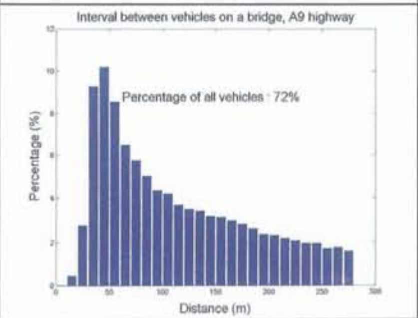


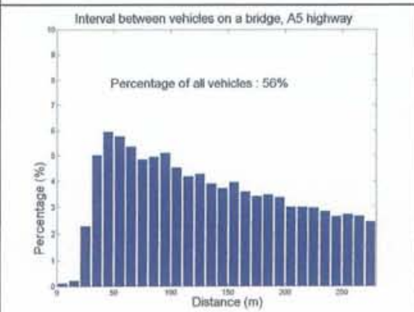


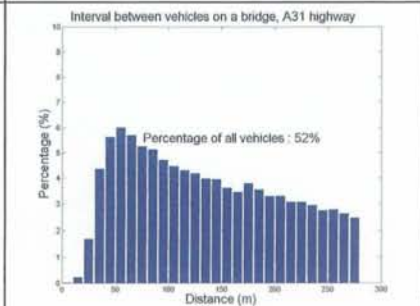




Distribution of distance interval between consecutive heavy vehicles







3. BRIDGES AND DETAILS

Bridges

Seven existing composite bridges, all located in France, are chosen : Libourne, Auxerre, Beaucaire, Joigny, Layrac, Millau and St Denis. All of them but St Denis are two main girder bridges with 2 or 3 traffic lanes, while the last one has four main girders and four traffic lanes. Auxerre and Joigny are simple supported spans, while the other bridges have 4 to 6 continuous spans.

The details considered are the welds between the vertical girder web's stiffener and the lower (at mid span) or upper (on piers) beam flanges. The strains in these details are induced by the general bending of the main girders. The influence lines of the stresses induced by theses bending moments for each bridge are given in Figure 1, with the following indications: name of the bridge, "m" for bending moment effect, a number which represents the section of the detail (generally at mid-span or on a pier), and the letter "i" for lower flange or "s" for upper flange; e.g. "Layrac m3i" means effect in the section n°3 of Layrac bridge, in the lower flange (thus at mid span, here of the second span). The ordinate y (in MPa/kN) gives the stress induced in the detail by a load of 1 kN applied at the abcissa x, right on the main girder. Then, influence surfaces were build using linear transverse influence lines, with an ordinate 1 on the considered main girder, and 0 on the other one (for 2 girder bridges).

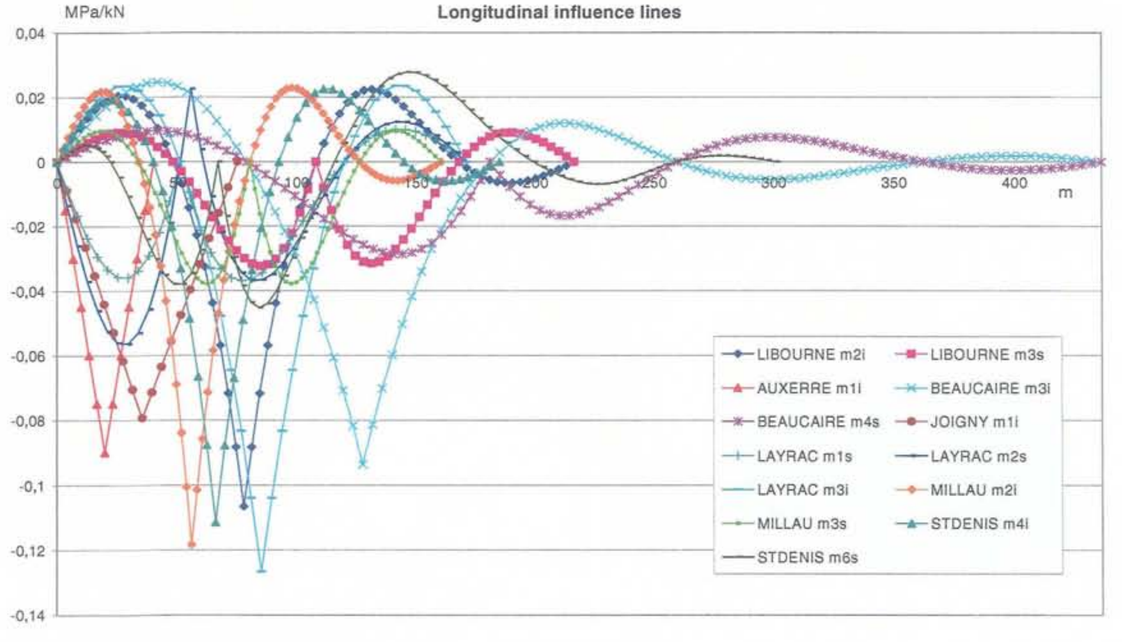


Figure 1 - Longitudinal influence lines of the chosen bridges and details

The fatigue strengths of the details, expressed by their class of fatigue, i.e. the ordinate of the log-log S-N curves for $N = 2.10^6$ cycles, are presented in Table 2.

Table 2 - S-N classes of the details

Bridge/section	Class (Eurocode 3)	Thickness (mm)	Corrected class	Bridge/section	Class (Eurocode 3)	Thickness (mm)	Corrected class
Auxerre m1i	71	70	56	Libourne m3s	-	-	50
Beaucaire m3i	71	30	68	Layrac m1s	50	70	40
Beaucaire m4s	-	-	50	Layrac m2s	50	30	48
Joigny m1i	71	90	50	Layrac m3i	71	26	71
Millau m3s	45	80	34	St Denis m6s	50	45	45
Millau m2i	-	-	50	St Denis m4i	71	30	68
Libourne m2i	-	-	50				

The class, proposed by the Eurocode 3 (Steel constructions) for a given geometry of the weld (join) and the common welding process, is corrected with respect to the thickness of the main steel plate (here the girder flange). The multiplicative factor is $\sqrt[4]{25/t}$, where t is the plate thickness in mm; thicker the plate, lower the class and fatigue strength. In some cases, the data on fatigue strength were missing, and the corrected classes were chosen in agreement with the other ones.

4. SIMULATION SOFTWARE "CASTOR-LCPC"

CASTOR-LCPC is a software developed by the LCPC in 1988 (Eymard and Jacob, 1989), which simulates any traffic flowing on a bridge, described by a set of influence lines or surfaces. The inputs are a traffic data file, i.e. a series of vehicles described by sets of axles, with axle load and spacing, time of passage, traffic lane and lateral position, and the influence surfaces of the considered load effects. The software simulates the passage of the vehicles with respect to their lateral position, speed and headings, and calculates for any given time step, the time history of the load effects (e.g. total load on a span, bending moments, shearing forces, bearing reactions, or stresses) induced by the traffic loads (see Figure 2). The time history of these load effects is not stored, but statistics are computed on real time, and histograms are provided: (i) load effect distribution (computed values), (ii) local minima and maxima, (iii) level crossings, (iv) "rain-flow" cycles, the counting method used for fatigue calculation by Miner's law. CASTOR-LCPC was widely used to produce the target values of load effects (Flint and Jacob, 1996) used for the calibration of the Eurocode "Traffic Loads on Road Bridges" (EN 1991-3).
CASTOR-LCPC automatically proceeds fatigue calculations, using the S-N curves of the given details, the "rain-flow" histograms, and the Miner's law.

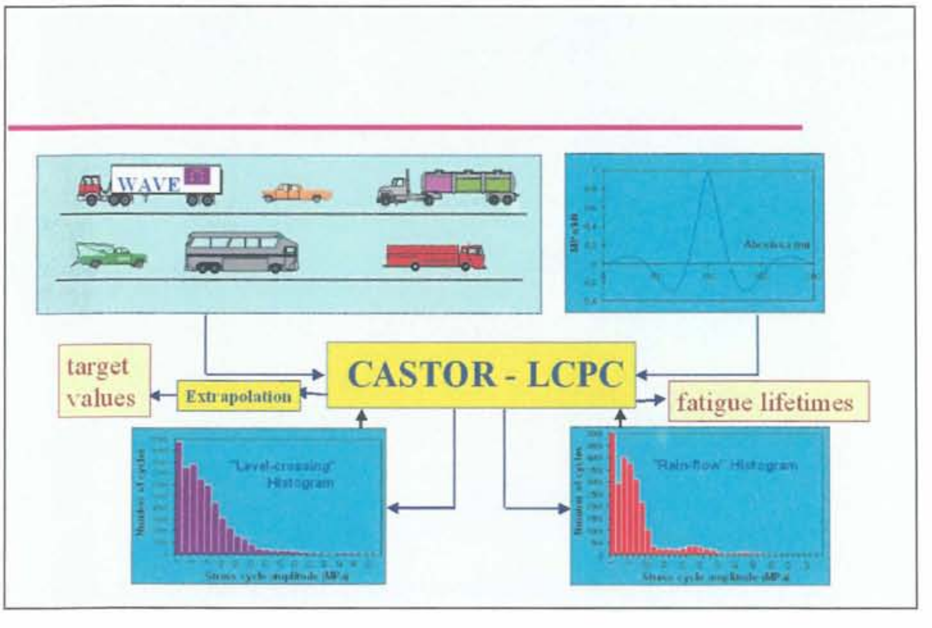


Figure 2 : CASTOR-LCPC software - general flow chart

5. RESULTS

Simulations were carried out with the 13 influence lines (and surfaces) of the 7 bridges described in section 3, for each of the three motorway traffics : A9, A5, and A31. The results are compared to those obtained with the traffic of the A6 motorway (1986) for the same influence lines. The calculations with the A6 traffic on the two-lane bridges were carried out using two lanes in one direction, i.e. a slow lane and a fast lane, because the aim was to be representative of a highway traffic. But the calculations with the A9, A5, and A31 traffics were carried out using the two slow lanes in each direction for the two-lane bridges. Therefore, for the two-lane bridges, the A6 traffic was not that aggressive that it could be.

Rain-flow histograms

Rain-flow histograms for each influence line, with the three traffics of A9, A5 and A31 are given in Figure 3.

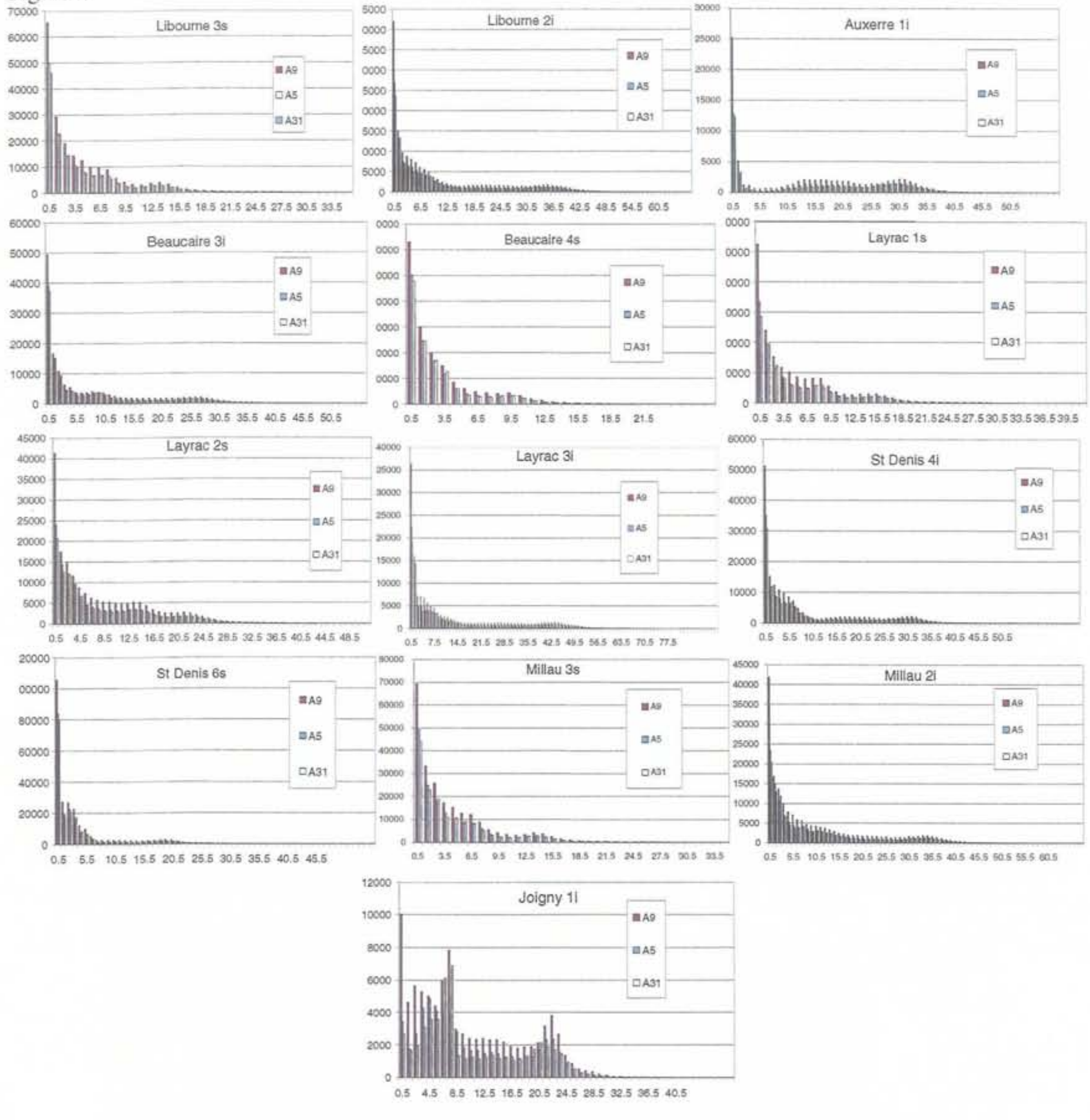


Figure 3 - Rainflow histograms for each influence line

The shape of the histograms are rather independent on the traffic, but the number of cycles in each class and the number of non empty classes vary according to the traffic density, and the vehicle loads. However, the shape of the histograms depends on the influence line. For the simple supported spans (Auxerre and Joigny), the rain-flow histograms show tri-modal distributions, as the gross vehicle weights distribution, because most of the lorries (passing alone on the bridge) induce one stress cycle per vehicle, with an amplitude proportional to its weight. For the continuous span bridges, the rain-flow histograms are smoother, but a second mode is mostly visible, which corresponds to the third gross weight mode.

Lifetimes

The computed lifetimes for each influence line and traffic are given in Table 3. It should be underlined, that these lifetimes are rather conventional, according to the crude hypotheses of the Miner's model. Only the order of magnitude should be considered, in a logarithmic scale. It means that lifetimes under 50 years are much too short for an acceptable bridge design, lifetimes between 50 and a few hundreds years are either acceptable or good, and over 1000 years it means either that the detail is not exposed to any significant fatigue damage, or that the traffic is

not aggressive for this detail. The most interesting is to compare the lifetimes for the same detail and different traffics, or for the same traffic and different details, i.e. to assess the relative aggressiveness of the traffic or the sensitivity of the details.
For four details (Libourne 2i, Auxerre 1i, Layrac 3i and Millau 2i) the lifetimes are unacceptable under each of the considered traffics. However, it doesn't mean that these bridges are unsafe or poorly designed, while the real traffics carried by them are much lighter than those on the motorways (they all carry secondary roads). Only St Denis' bridge carries a motorway (A86, an urban circular motorway around and outside Paris), with a traffic as dense as a motorway, but a high proportion of personal cars. For that bridge, only the traffic of the A5 for "St Denis 6s" leads to a too short lifetime. That is investigated below. The Beaucaire's bridge carries a main highway, but it is clearly well designed for heavy traffics.

Among all the traffics, the A6 is generally the most aggressive, whatever the detail, even if only one slow lane was used for the two-lane bridges. That is because of the heavier weights recorded and the non linearity of the fatigue damage with respect to the stress amplitude (a power 3 to 5 appears in the relationship between the stress amplitude and the damage). Thus, for example with the power 5 (mostly used), an increase of 15% in a lorry weight (in fact stress amplitude) will double the damage! According to the remark done in section 2 about the relative inaccuracy of the old traffic data (A6, 1986) and the overestimation of the upper tail of the GW distribution, we may assume that the fatigue lifetimes are underestimated by 30 to 50%. If so, the A6 old traffic would be approximately as aggressive as the recent A9 traffic.

Table 3 : Lifetimes (years)

	A9	A5	A31	A6 (1986)		A9	A5	A31	6 (1986)
Libourne 3s	1169	1646	1976	682	**Layrac 3i**	18	27	29	13
Libourne 2i	9	14	15	8	**St Denis 4i**	93	144	165	100
Auxerre 1i	35	41	54	23	**St Denis 6s**	86	33	155	85
Beaucaire 3i	247	372	421	100	**Millau 3s**	90	154	176	90
Beaucaire 4s	49217	53739	122032	358800	**Millau 2i**	11	17	18	9
Layrac 1s	125	183	209	70	**Joigny 1i**	108	165	188	85
Layrac 2s	58	84	92	40					

Results for A9, A5, and A31 show, as expected, that heavier (and denser) the traffic lower the lifetime. The case of St Denis 6s, where the A5 traffic is twice more aggressive than the other ones is not so clear. We performed some detailed analysis to try to explain this unexpected result. The assumption was that, according to the influence line shape, with two negative peaks at the abscissa 50 and 80 m, the detail could be more sensitive to a traffic where a high proportion of vehicle headings would be close to 30 m. But nothing confirmed such a specific characteristic of the A5 traffic... A more detailed investigation would be needed to clarify this phenomenon.

The traffic of the A31, which has a high proportion of heavy lorries in the third mode (around 40 t), but a density half than the A5 traffic, has the same aggressiveness for the details of the two-girder bridges with a sharp influence line (Libourne 2i, Layrac 3i, Millau 2i). For such sharp influence lines, the individual lorry weights mainly govern the fatigue lifetime. These details are also those with the shortest lifetimes.

The lifetimes under the traffics of the A9 and A5 motorways, with similar gross weight distributions, but a ratio of 1.8/1 for the lorry density, have generally a ratio of 1/1.5. This is due to a significant reduction of the lorry headings when the density increases, and therefore, more lorries are passing on the bridge together in a queue, being partially on positive and partially on negative parts of the influence line, which reduce the overall effect. Thus, less stress cycles and lower amplitudes are experienced than for the same number of vehicles passing alone.

6. CONCLUSIONS

This study confirms the importance of an accurate and periodical survey of traffic loads on bridges, using WIM systems, to assess and verify the lifetimes of structures exposed to heavy traffics. Moreover, sensitivity studies may be carried out using traffic data of various types of roads and highways, and bridge influence surfaces of different shapes, to identify the most critical situations.

Steel-concrete composite bridges, which are very common in Europe, and their most sensitive details in fatigue, i.e. the weld between vertical stiffeners and main girder flanges, in which stresses cycles are induced by girder bending, may be highly penalised by an increase of the individual lorry loads; that is above all true for the mid-span section of the 2^{nd} span of 3 or more span bridges, and more generally for any details with a sharp longitudinal influence line. This conclusion will have to be considered in the future evolution of lorry design and in the weight limits. The tendency over the last 20 years in Europe, was a continuous increase of the maximum allowed gross weights (from 36 t until 44 t, and even more in northern Europe). It should be underlined that, because of the non linearity of the fatigue damage with respect to the loads, an increase of 15% of a gross vehicle weight may lead to double the damage, and thus reduce the lifetime of the structure by a factor 2 !

Conversely, the quick increase of the heavy traffic flow seems, at least for long and continuous span bridges, not to reduce the bridge lifetime proportionally, as expected. In our examples, an increase of the lorry density by a factor 1.8 only lead to a reduction of the lifetime by a factor 1.5. When the vehicle headings become smaller than the bridge length, several lorries pass simultaneously on the bridge being in the same traffic lane, and thus their effects are not fully cumulated, and even sometime are reduced, because of the changes of the influence line ordinate sign.

For bridge safety, it is important to divide the loads between more lighter lorries, than to concentrate them on heavier lorries. That is may be neither the main tendency, nor the wish of the transport companies, but the cost of the freight transport should likely also account for the bridge design and maintenance...

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