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# Bridge weigh-in-motion on steel orthotropic decks and application to bridge assessment

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**Abstract**

Bridge weigh-in-motion uses an instrumented bridge as a scale to weigh vehicles. Several types of bridges may be used, if being sensitive to wheel or axle loads. Here some strains of steel orthotropic deck bridges are measured by extensometers and analyzed by software, to calculate axle loads and gross vehicle weights. Between 2009 and 2011, several large scale tests were done on the Millau viaduct (France), the tallest cable stayed bridge in the world. These tests showed that the system meets the accuracy class C(15)/D+(20) of the European WIM Specifications.

The data obtained can be used for fatigue checks, because it assesses truck sizes and weights of the traffic and the behaviour of the bridge. We show here that bridge lifetimes under current and possible future traffic loads, after an increase of the GVW limit from 40 tons to 44 tons in France, could be reduced by 20%.

# 1. Introduction

## *1.1. Concept of bridge weigh-in-motion (B-WIM)*

The basics of Bridge Weigh-In-Motion (B-WIM) were first introduced by Moses (Moses 1979). Concrete simple supported multi-girder bridges with span length between 10 and 30 m were instrumented by extensometers, which measured the bending strains at mid span under moving heavy vehicles. Axle detectors were installed on the pavement to count the axles, measure the vehicle speed and axle spacing. A simple algorithm determined axle loads and gross vehicle weight by a back calculation using the bending moment influence lines of each girder. The accuracy of gross weight was in the range of 15 to 20%, but the axle loads were inaccurate.

## *1.2. Bridge WIM on orthotropic steel decks*

In 1996 the LCPC launched the idea of using steel orthotropic deck instrumentation as a B-WIM option. This type of structure is rather flexible and the longitudinal stiffeners' bending between two cross beams, spaced by 4 to 4.5 m, are sensitive to wheel and axle loads. These stiffeners are generally spaced by 0.6 m, and thus mainly responding to a wheel or twin wheel load.

Strain gauges or extensometers are fixed on the bottom of each stiffener under the traffic lanes, and record the strains while the vehicle crosses the short span between two cross beams. The principle of “free of axle detector” (FAD) B-WIM, introduced by (Žnidarič et al. 1999) is applied. Instead of road sensors to detect axles and measure the vehicle speed, some additional strain gauges or extensometers are fixed on a previous short span, 4 to 8 m up-stream the instrumented short span. They deliver a signal when the first axle of a truck comes, which initiates the data acquisition of the system and allows calculating the vehicle speed and axle spacing.

A global optimization and identification algorithm was developed by (Dempsey et al. 1999) to calculate these parameters and the axle loads, which is more efficient and robust than Moses’ algorithm. A test was carried out on the Autreville bridge (Figure 1), supporting the motorway A31 (Luxembourg-Nancy) over the Moselle river in eastern France (Figure 1), which showed that the prototype B-WIM system was in the accuracy class D+(20) if using a 1-D bridge model, and in the accuracy class C(15) if using a 2-D bridge model (Dempsey et al. 1999), according to the European WIM Specifications (Jacob et al. 2002).

After the completion of the WAVE project, the Slovenian company Cestel developed a marketed B-WIM system named SiWIM which can be used on several types of bridges. In 2005, the Laboratoire Central des Ponts et Chaussées (LCPC) acquired a SiWIM to test it and assess its performances and reliability on integral concrete slab bridges and orthotropic decks (Bouteldja et al. 2008).

## *1.3. Bridge fatigue assessment by WIM data*

Bridge load effects, stresses, damage and lifetime in fatigue are assessed either by measurements, using strain gauges, extensometers and other techniques, or by calculation, using traffic load data and bridge models such as influence line or surfaces, if the dynamic interactions are neglected (Bailey & Bez 1996, Nassif & Nowak 1996, Jacob 1998, Jacob & Labry 2002). The development and implementation of WIM techniques allowed to collect traffic load data on a large scale and to use them for bridge assessment (Jacob et al. 2002), instead of using simulated data (Hwang & Nowak 1991).

In the late 1980’s and early 1990’s, some extensive works were developed in Europe using traffic data of various EU member states (Vrouwenvelder & Waarts 1993, Bruls et al. 1996, O’Connor et al. 1998) to design the Eurocode “Traffic loads on bridges” (CEN EN1991-2, 2003). Fatigue calculations were performed to design the fatigue load models (Jacob & Kretz 1996).

All these models and assessment methods assume that the traffic loads are stationary. But the traffic loads and volume increase with time because of the development of the road freight transport, and the increases of the truck legal weight limits. Thus it is necessary to periodically recalibrate the bridge code load models and to reassess the reliability of existing bridges against the traffic loads.

That is one of the goals of the WIM systems installed all around the world on highways and motorways. The methodology and some tools for fatigue assessment are briefly reported here, and an application to forecast the possible consequences of an increase of the truck gross weight limit in France from 40 to 44 tons is presented.

# 2. Millau viaduct instrumentation

## *2.1. Millau viaduct*

The Millau viaduct is a 2,460 m cable stayed multiple span bridge, completed in 2004 over the Tarn valley in Aveyron, south of France (Figure 1).

Figure 1: Viaduct of Millau.

It carries the motorway A75 (Clermont-Ferrand to Béziers and Montpellier), one the of main north-south road corridor in France. The viaduct has 8 spans, 6 of them of 340 m in length, and 7 pylons, the tallest one, P2, being 343 m above the Tarn river (245 m pier and 87 m pylon).

The deck is a steel box orthotropic deck, 32 m in width and 4.20 m in height, which carries 2 lanes and an emergency lane in each direction. The average daily traffic is app. 12,000 veh. incl. 12 to 15% of trucks (i.e. 1500 trucks/day).

## *2.2. Millau viaduct instrumentation for B-WIM*

The WIM data collection the on Millau viaduct is motivated by two main applications:

a detailed knowledge of the traffic patterns and traffic loads on the bridge is needed to assess the fatigue damage along the service life, and to check that the guaranteed 120 year lifetime will be safely ensured;

the French Department of Transport and the Regional DOT are in charge of overload enforcement on the national road and motorway network to ensure traffic and infrastructure safety and a fair competition between transport modes and transport companies.

Therefore a nation-wide network of WIM systems is now developed to perform continuous checks of truck loads, and to screen the overloads during the control periods (Stanczyk & Klein, 2012). Near the viaduct of Millau, a static enforcement area equipped with weighing scales in both directions is installed near the toll gate, 4 km north of the viaduct. A B-WIM system on the bridge could be an efficient tool to screen the overloads in the south-north direction, prior to the static weighing.

In 2009 the LCPC and CEVM agreed to organize a B-WIM test on the viaduct of Millau, jointly with another field test organized by SETRA and Eiffage Group for a French project (Orthoplus) on steel orthotropic deck reinforcement using ultra high performance fibre reinforced concrete (UHPFC), see (Pouget, 2011). The instrumented section was located in the first span, close to the north end of the viaduct, under the slow lane (#1) in the south-north direction. The trapezoidal stiffeners 2 to 13 were instrumented by extensometers, which covered the lane 1 and part of the lane 2 and the emergency lane, at mid-span between two cross beams (Figure 2).

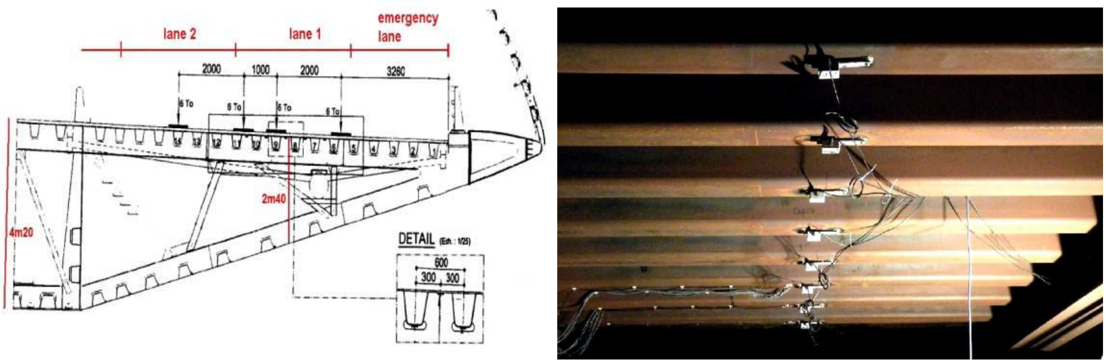


Figure 2: Millau viaduct. On the left: scheme of the box-girder.On the right: picture of the extensometers that have been glued to the bottom of the longitudinal stiffeners at mid-span of the first span.

Four more extensometers were installed on the stiffeners 4 to 7, 4 m upstream, as part of the FAD B-WIM system. The measuring location was chosen upstream of the expansion join where the traffic speed is rather constant (the truck speed limit is 80 km/h on the viaduct) in order to avoid dynamic effects which could affect the WIM system. The SiWIM was installed inside the box, well protected against rain and wind.

# 3. B-WIM Experimentation

## *3.1. Test plan and organization*

During the test, two rented trucks, a rigid 3-axle (C3) and an articulated 5-axle (T2S3, 2-axle tractor and semi-trailer with a tridem axle), were used to calibrate the SiWIM. They made repeated runs, crossing the viaduct at different speeds (60 and 80 km/h) and transverse locations (the right wheel along the emergency lane mark, 0.3 m away and 0.7 m away, i.e. the truck centred in the lane 1).

## *3.2. Collected data*

During this test, 52 trucks from the traffic flow were weighed by the SiWIM and stopped for static weighing, over a period of 4.5 hours. Among them 45 were properly identified on each system with an ID number. 2 of them were not correctly weighed by the SiWIM, one having a tridem axle instead of a tandem, and the other a tandem instead of a tridem. Finally the studied sample size was 43, which correspond to 95.6% of accepted vehicles. The numbers and proportions of each trucks were: four 2-axle rigid (9.3%), two 4-axle articulated (4.65%) and 37 5-axle articulated (86%).

# 4. Results of B-WIM

## *4.1. Results and assessment of the SiWIM algorithm*

According to the COST323 European specifications of WIM (Jacob et al. 2002), the relative errors $e_r$ were calculated for each axle load, and gross vehicle weight of the 43 vehicles (Equation 1).

(1)

where $W_d$ and $W_s$ are the in motion loads measured by the SiWIM and the static loads. Four sub-populations were considered:

i. gross vehicle weight,

ii. single axles,

iii. axle group (i.e. tandem and tridem), and

iv. axles of a group, and the statistics of the relative errors are given in Table 1.

| | Number | Mean | Standard deviation | Class |
|---|---|---|---|---|
| Gross weight | 43 | -3.24% | 5.76% | C(15) |
| Single axle | 86 | 1.09% | 11.18% | D+(20) |
| Group of axles | 39 | -8.01% | 5.32% | C(15) |
| Axle of group | 115 | -7.93% | 9.46% | C(15) |

Table 1: Accuracy of this B-WIM at the viaduct of Millau.

According to the test conditions of the COST323 specifications, which are here full reproducibility (R2), i.e. trucks from the traffic flow, and environmental repeatability (EI), i.e. a short test period within the same season, the tolerance intervals for the required confidence levels, [-$\delta_{min}$, $\delta_{min}$], are calculated for each criterion as specified in the COST323 specifications. The associated exact classes of accuracy $\delta_c$ are derived, and both values $\delta_{min}$ and $\delta_c$ are plotted in (Figure 3). The final accuracy class of any criterion, given in the last column of Table 1, is obtained by rounding up $\delta_c$ to the closest value 5, 7, 10, 15, 20, 25 or 30, which correspond to the standard classes.

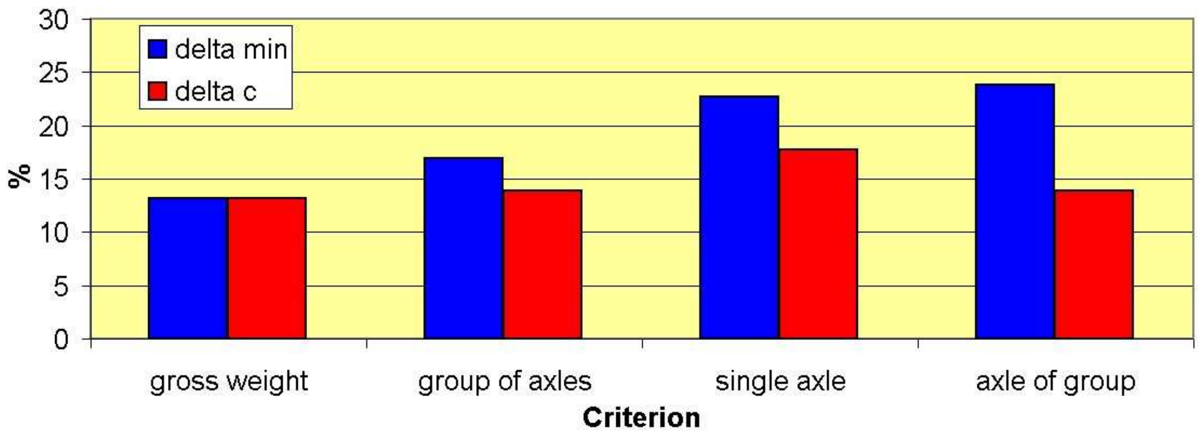


Figure 3: Classes of accuracy of this B-WIM test at the viaduct of Millau.

For all criteria but the single axles which are in the class D+(20), the system is in the class C(15). This accuracy is comparable to that of common road sensor WIM systems. However, the axles of a group are under-weighed by 8%, while the single axles are over-weighed by 1% and are rather scattered with a standard deviation of the relative errors larger than 11%. This is likely due to some lack of the SiWIM algorithm for such type of bridge, which uses a 1-D model, i.e. the longitudinal influence lines of the stiffener bending moments, not accurate enough to account for the variations of the lateral wheel location and of the tire types, single or twin wheel and regular.

More precisely, the current SiWIM algorithm uses a weighted average of the measured strains on all the instrumented longitudinal stiffeners to calculate the loads and weights. The coefficients of the weighted average are adjusted in the calibration process. The single axles are either front axles with single standard tires or drive axles with twin tires. Thus, the front axles have a much narrower lateral imprint (≈0.25 m in width) than the drive axles (≈0.70 m in width), which may explain the high scattering of the errors. The difference between the mean bias of the single axles and axles of a group, which mainly consist of wide single tires (≈0.35 m in width), is less obvious. It may be a cumulative effect of the longitudinal and transverse wheel load distribution. Most of the groups of axles are tridem with a wheelbase of 2 x 1.3 = 2.6 m, on which the total load is applied in the same short span. Thus, the maximum stiffener bending strain is less than for a single axle of the same load, which may explain the rather large negative bias.

# 5. WIM data and calculation tools for bridge assessment in fatigue

The data obtained through B-WIM experiments can be used twice: first, in order to obtain information about the traffic crossing the bridge (number of trucks, distribution of GVWs, dimensions of trucks ...) and also in order to obtain information about the structural behaviour of the bridge. Indeed, B-WIM makes it possible to assess empirically real influence lines of the bridges (Ieng, S.-S. And al., submitted).

Here, we present a king of study that can be done with these two types of information, measured traffic data and measured influence lines, in the case of application of new regulations in size and dimensions of trucks.

To do that, we use a representative French WIM data and influence lines of typical French bridges.

## *5.1. WIM data*

Traffic data and loads are collected in France for bridge engineering by WIM systems since the early 1980's. However, with the recent development of a national WIM network for overload screening and enforcement (Marchadour & Jacob 2008), more reliable and accurate data are collected continuously on the main highways and motorways. The traffic data used in this study were collected on two adjacent traffic lanes of the French motorway A9 near Montpellier in South France, over a month in June 2009. Figure 4 shows the gross vehicle weight distributions on the slow lane over one and two weeks.

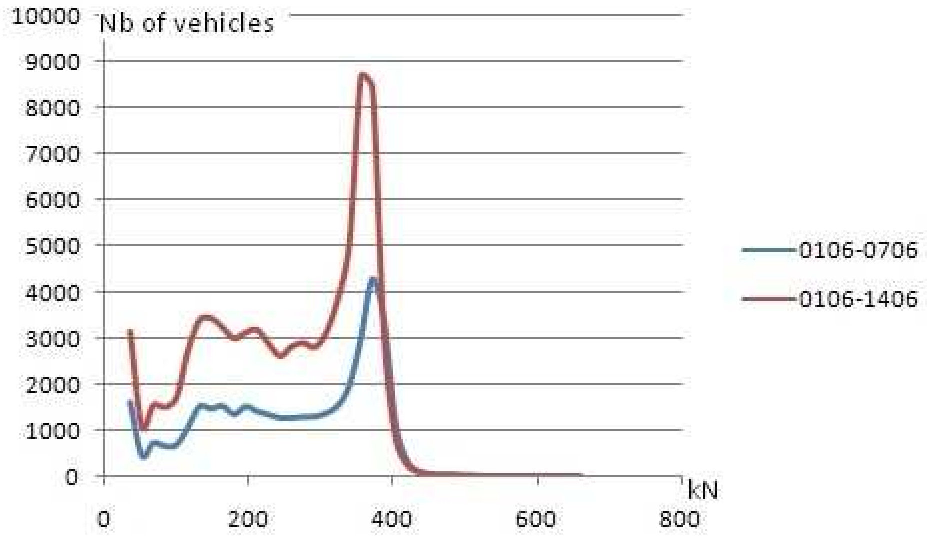


Figure 4: Distribution of GVW of the WIM data used in the study presented here: the blue line is the distribution for the first week of June 2006, the blue one is the distribution for the first two weeks.

Axle loads and spacing, speed and time of passage in 1/100 s are also recorded for each truck in both lanes. The accuracy of these data are at least in class C(15), but mostly in class B(10) of the European specifications of WIM (Jacob et al. 2002), i.e. app. 95% of the gross weights are within ±10% and of axle loads within ±15% of the static values taken as the reference.

## *5.2. Influence lines*

The effects of traffic on a bridge are usually calculated by applying traffic loads, either measured by WIM systems or simulated by software, on influence lines or surfaces. For local effects sensitive to the wheel transverse location, WIM data shall contain this information and an accurate influence surface, i.e. a two-dimensional calculation, must be used. For most of the global or semi-global and longitudinal effects, such as bending moments at mid-span or on pier, shear forces or pier reactions and for bridges whose transversal behaviour is simple, one or a set of parallel longitudinal influence lines (one per traffic lane) are sufficient, and the traffic data lane by lane are used. That is the case in the study presented here.

The influence lines or surfaces are obtained numerically, through 1-D bridge model or 2-D finite elements calculations, or on site through experimentation (by strain measurement on a bridge under a known truck). In this later case, several parameters are taken into account, such as the stiffness of the pavement surface, sidewalks and safety barriers, which are neglected in the numerical method. So through the B-WIM algorithm a correct characterisation of the bridge through its real influence surface can be obtained. But here, we will not present the results for this Millau viaduct because of the importance of the transversal position of the vehicles. We will explain the assessment for two simple cases of composite bridges.

The effects considered in this study are, for two bridges:

- The bending moment stress at mid-span of a simple supported 40 m span bridge, near Auxerre. This is a composite bridge with two main steel girders and a concrete deck.
- The bending moment stress at mid-spans and on piers of the Libourne 4-span bridge (respectively 48, 60, 60 and 48 meters-long). This is also a 2-steel girder composite bridge.

The influence lines are given in MPa/MN in Figure 5.

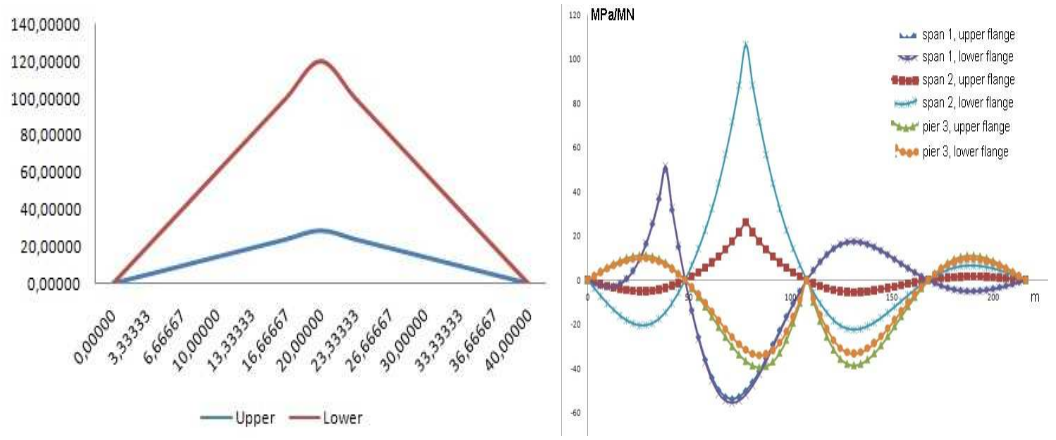


Figure 5: Influence lines that have been used in this study. On the left: influence line of the bending moment stress at mid-span of a simple supported 40 m span bridge, near Auxerre. On the right: influence line of the bending moment stress at mid-spans and on piers of the Libourne 4-span bridge.

The dominant effects are in the lower flange at mid-span and in the upper flange on pier. These influence lines are those calculated for a load applied along a steel girder. To obtain the influence surface, they have to be combined with the transverse influence line, given by Courbon's coefficient.

## 5.3. Traffic data adaptation

The WIM data presented in section 5.1 contain two adjacent lanes in the same direction, i.e. one slow lane and one fast (passing) lane. Auxerre bridge supports 3 traffic lanes (each 3.50m in width), including 2 slow lanes (one in each direction) and one fast passing lane. Libourne bridge has 2 slow lanes (one in each direction).

Thus, the recorded data are adapted to fit to the bridge operation conditions. The natural data of the slow lane are applied on one slow lane of each bridge, and the data of the fast lane on the fast lane of Auxerre. The slow lanes in the other direction are filled with the slow lane data shifted by 10 minutes, which simulate a traffic correlated (same peak and low hours) but with independent trucks.

### *5.4. CASTOR and POLLUX software*

The POLLUX software, developed by the LCPC, is a new and extended version of the former CASTOR software (Eymard & Jacob 1989). It uses WIM data and load effect or stress influence lines of any bridge, and calculates the effects of the whole traffic on this bridge.

Different modules of POLLUX perform successive tasks:

- Traffic data cleaner: the traffic data files, provided by WIM systems, are first checked and cleaned if necessary. If some anomalies are detected, the involved vehicles are deleted. For example, vehicles with a length below 1.5 m or over 25 m, or with only one axle or more than 8 axles, are eliminated. If the gap between two successive vehicles is greater than 90 minutes, the system is assumed to have failed and the time period is deleted. All these limits are defined by the user.
- CASTOR, which became a sub-routine of POLLUX, calculates the effects of the traffic loads. For each effect (set of influence lines for each traffic lane), the time history of the effect is calculated with a constant time step, chosen by the user with respect to the influence line shape.
- The sub-routine “Extrap” calculates the damage and lifetime in fatigue, for a detail submitted to the stress history resulting of the traffic loads applied to a stress influence line, as explained in section 6.1.

## 6. Fatigue assessment depending on the weight limit

### *6.1. Fatigue assessment method*

This section describes the method used by CASTOR and POLLUX to calculate bridge lifetime in fatigue. The fatigue damage *D* of a detail is assessed using Miner’s rule (Equation 2).

— (2)

where $n_i$ is the number of cycles in the class $\Delta\sigma_i$ of the stress rain-flow histogram; $N_i$ is the number of cycles at failure corresponding to $\Delta\sigma_i$ in the S-N (Wöhler) two slope curve defined by (Equation 3).

(3)

in the Eurocode 1993 Part 1-9 (CEN EN 1993-1-9, 2005), $\Delta\sigma_L$ corresponds to $N_L = 10^8$ cycles, so $\Delta\sigma_L = 0.55\,\Delta\sigma_D$ . The conventional lifetime (in years) of the detail is $1/TD$, where $T$ is the length of the time period which corresponds to the rain-flow histogram.

## 6.2. Weight limits in the current French legislation and future plans

In France, and in Europe for international transport, the standard gross vehicle weight limit is 40 tons. Some countries allow higher weights, such as 44 tons in the UK for 6-axle articulated trucks. In France, there are a couple of derogations which allow 44 tons for 5-axle articulated trucks if: (i) 40 ft containers are transported in a multi-modal journey, (ii) the freight comes from or goes to a maritime or inland harbor, where it is carried by ship, (iii) some specified agricultural goods are transported during specific seasons. Moreover, log trucks are allowed up to 48 tons on 5 axles and 57 tons on 6 axles by decree.

In 2008, the French parliament voted a law called “Grenelle de l’environnement” to reduce the CO2 emissions and the fossil energy consumption. An article stated that road transport regulation shall be adapted for that. In February 2009, the parliament asked to the government to study the positive and negative impacts of increasing the gross weight limit to 44 tons. The main criteria to consider were road safety, CO2 emission and energy consumption, traffic congestion, and infrastructure (bridges and pavement...) lifetime and maintenance.

## 6.3. Weight limits in the current French legislation and future plans

For bridges, the first task was to compare the effects of a single 44 t truck to those of a 40 t truck. Because the axle load limit would not be increased, only medium span (15 to 40 m) bridges could be affected, or 10 m continuous span bridge for bending moment on pier. Shorter spans could not support a whole truck at once. Longer spans are not so much sensitive to a single truck. For medium span bridges, the load effects would be increased by less than 10%, which is not too much critical for the extreme loads and load effects on healthy bridges. However, the impact of multiple presences (truck crossing or overtaking) of 44 t trucks, or the effect on the fatigue lifetime was to be investigated more in depth.

Therefore, it is necessary to make some assumption on how the whole traffic would change with new regulations and to assess the effects of this whole new traffic, see (O'Brien and al., 2012) for an Irish example. The very simple and crude assumptions done here are: (i) the gross weight of every heavy vehicle lying between 36 and 44 tons would be increased by 10%, the additional weight being uniformly distributed on all axes; (ii) all the other vehicles would have the same load as before (volume limitation or not enough freight to carry).

With these assumptions, a micro-simulation generated a "modified" traffic file named "44 t" derived from the natural traffic record of the WIM system on the A9 motorway, named "40 t". Both traffics were used with the influence lines introduced in the section 5.2, to obtain the effects and their histograms.

## *6.4. Fatigue damage*

To assess the fatigue damage and detail lifetime, the rain-flow histograms are used, with the S-N curves and the Miners' law (section 6.1). Figure 6 gives the rain-flow histograms of the bending moment stresses in the lower flange at mid-span for both traffics (40 tons and 44 tons) on Auxerre bridge. An increase of 10% of the peak abscissa (18 to 20 MPa) is visible when the 44 ton trucks are introduced. Reversely, the distribution shows a drop at 18 MPa in this case, because truck gross weights between 36 and 40 tons were increased by 10%, and thus, there are no more trucks in this weight interval.

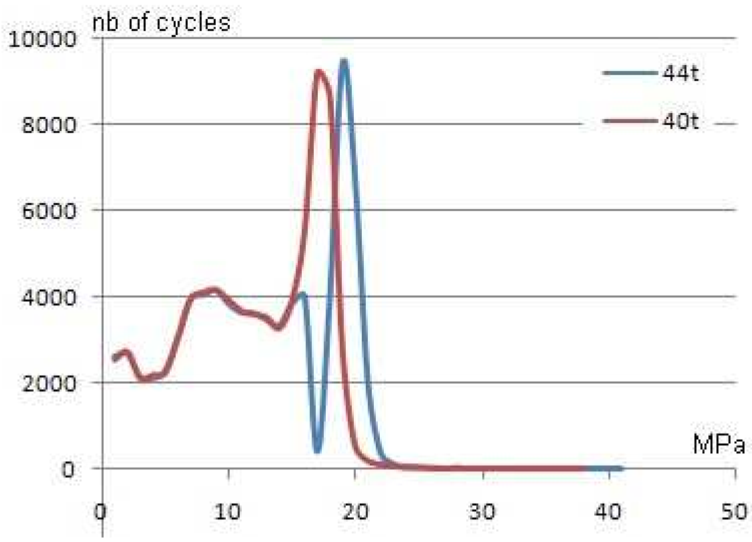


Figure 6: rain-flow histograms of the bending moment stresses in the lower flange at mid-span for both traffics (40 tons and 44 tons) on Auxerre bridge.

Then the fatigue damage is calculated for the S-N curves 56, 63 and 71 MPa (Table 5). The detail is classified in class 71 but the flange is 70 mm in thick, and therefore a reduction factor of: $\sqrt[4]{25/70} = 0.77$ leads to the class 56.

The annual damage is obtained by multiplying the weekly damage by 50. The conventional lifetime is the inverse of the annual damage. The lifetimes for Auxerre bridge are given in Table 2 for both traffics. The values are very short, but the traffic of the A9 motorway, one of the busiest in France, is much more severe than the local traffic around Auxerre. The most important finding is the reduction of the lifetime by almost 20% when the 44 ton trucks are introduced. That gives an estimation of the effect of such a change in the regulation for bridges.

| | Lifetime in years | |
|---|---|---|
| Fatigue class | Limit of 40t | Limit of 44t |
| Class 56 | 10.1 | 8.5 |
| Class 63 | 14.3 | 12.0 |
| Class 71 | 20.1 | 16.9 |

Table 2: Auxerre bridge lifetime for A9 traffic, 40 or 44 t gross weight limit.

Similar results are given for Libourne bridge, and more precisely for the weld of the vertical stiffener on the girder lower flange at mid-span of the first span.

These calculations show a decrease of the lifetime by app. 20% with the 44 ton trucks, as with Auxerre bridge.

# 7. Conclusions and perspectives

## *7.1. B-WIM system*

The B-WIM experimentation on Millau viaduct was the first large scale test of the SiWIM, a marketed B-WIM system developed by Cestel, on a steel orthotropic deck bridge. Ten years after the first tests of a prototype B-WIM system on such type of bridges, carried out on another orthotropic steel deck bridge, the results are very consistent. But some research works were undertaken to develop a 2-D model fully adapted to this type of bridge, in order to improve the SiWIM accuracy.

## *7.2. Bridge assessment in fatigue*

Assessment or re-assessment of existing bridges under traffic loads require an accurate knowledge of the load patterns. WIM data are very useful for these applications, either to give an account of the current traffic loads or to forecast the potential impact of future loads.

This assessment also requires an accurate knowledge of the bridge, in particular its present health condition. This cannot be obtained through calculations like finite elements. But through the B-WIM algorithm, we have access to this real influence line (or influence surface). Adapted assessment can then be performed. The implications of new size and weight regulations for trucks can be assessed.

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