ASSESSMENT OF EXISTING ROAD BRIDGES BASED ON ACTUAL TRAFFIC DATA

Diego Lorenzo Allaix [1,2], Ana Sánchez Rodríguez [3], Paola Daró [4]
[1] TNO, the Netherlands
[2] Gent University, Belgium
[3] University of Vigo, Spain
[4] Sacertis Ingegneria S.r.l., Italy

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ABSTRACT: The safety assessment of existing bridges is a relevant topic for the management of the transport infrastructure system of the EU countries due to the increase of traffic loads and aging of the structures. Among the actions applied to bridges, traffic loads are in general the most significant variable action to be considered when the assessing existing structures. Usually, engineers perform the safety assessment by using the traffic load models given in the design codes for new structures. This approach might lead to unnecessary conservativism in the assessment because the design load models do not represent the specific loading conditions of the bridge under investigation. In addition, the residual service life of existing structures is generally shorter than the 50 or 100 years period assumed in the design standards for new structures.

This paper presents the vision and preliminary results of the Horizon CSA IM-SAFE project about the use of monitoring of traffic loads and conditions for assessing the structural safety of existing bridges. Current monitoring technologies, methods for assessing traffic loads models and approaches to the safety assessment supported by traffic load data are presented. Furthermore, the needs for standardisation to enable the safety assessment based on the actual traffic loads at the probabilistic and semi-probabilistic levels are discussed.

INTRODUCTION

The reliability assessment of highway bridges is a relevant topic in the management of the roadway system of the EU, since a large part of the goods transport travels by road. Several studies showed a noticeable increment of the goods travel in the past few decades and an increasing trend is expected also in the future. The reliability assessment of road bridges requires probabilistic models for the actions effects and structural resistances and robust numerical methods able to estimate the probability of failure with respect to the relevant limit state conditions. Within the actions applied to the bridges, the traffic load is, in general, the most significant variable action to be considered when the ultimate limit states are under investigation. Consequently, the traffic load models play an important role in the design of new bridges but also in the reliability assessment of existing structures. The design load models of the actual structural codes are believed to be conservative for several reasons. First, they have to be calibrated in such way the design load effects cover all the possible traffic scenarios that could take place during the design lifetime of the bridge. Second, the load models have to be used for bridges of different types, static schemes and span lengths. Finally, the load model should include an estimation of the uncertainty deriving from several sources, i.e. limited size of the collected data, variability of the traffic load in time and space. Besides, an existing structure may not satisfy the safety requirements of the actual design codes due to deterioration and damage processes occurred during time or because the design rules at the time of construction are considered inadequate nowadays. Several intervening scenarios could be drawn, including the strengthening, replacement of the structure and restrictions to the freight transport. It is reasonable to think that these scenarios could be very costly and, in some circumstances unnecessary, if the structural assessment is performed using the design load models of the today's design codes. Consequently, a better knowledge of the real loads applied to the bridge and of the structural resistances is desirable to check the reliability of the structure.

It is clear that the heavy traffic is decisive in the actualisation of traffic load models for existing bridges. The modelling of this traffic component is a complex task due to its inherent uncertainty and variability in time and space. As stated before, an increasing trend has been observed in Europe during the last decades in the freight transport both in terms of traffic volume and vehicular loads. Besides the economic reasons of this trend, the technical improvements in the design and construction of the trucks and the regulation of the local governments of the European countries allowed heavier transports on the roadways and bridges. Moreover, the trucks are frequently overloaded and the legal limits concerning the axle loads and the gross weight are often exceeded.

ULTIMATE LIMIT STATE ASSESSMENT OF EXISTING BRIDGES

The safety assessment of existing bridges can be performed at different levels that are differentiated in terms of the procedures for reliability verification and data used for this purpose. With regard to the procedures for reliability verification, the full probabilistic method and the partial factor method differ in terms of the quantity considered in the verification. The full probabilistic method is based on the comparison between the probability of failure of the structure or element with respect to the chosen limit state condition and the maximum acceptable failure probability. The probability of failure is assessed based on probabilistic models of the governing random variables describing material resistances, geometrical uncertainties, actions and model uncertainties. The partial factor method, which is very often used in practice, relies on a set of partial factors and characteristic values of material properties and actions, which are given in the corresponding Eurocodes, or can be estimated from structure specific information. Structural safety is checked by comparing the design values of the governing load effects with the design values of the corresponding resistances.
In the following, the focus is on the semi-probabilistic approach to the assessment of the design values of the load effects induced by traffic loads in road bridges. Three levels are proposed, which are characterised by a decreasing conservativism of the assessment and, at the same time, by an increasing demand of structure-specific information regarding the traffic loads and their effects in bridges [1]. Structural safety can be evaluated starting from the lowest level. If it is not possible to demonstrate that the structure meets the reliability requirements, the assessment might be performed at the next level.

Level 1 - Partial Factors and Load Reduction Factors for Existing Infrastructure
The semi-probabilistic safety assessment using the Eurocodes is based on the partial factor method and the load models of EN 1991-2. With regard to the global analysis of the bridge, adjustment factors to the load model LM1 are given in the standard for the uniformly distributed load on the notional lanes, the tandem axles and the uniformly distributed load applied to the remaining areas. The values of the adjustment factors are Nationally Determined Parameters (NDP) and they depend on the expected traffic and route class. EN 1991-2 recommends a maximum reduction of 20% of the intensity of the tandem axles on the first notional lane and values of the adjustment factor equal to or larger than 1 for the uniformly distributed load on all notional lanes except the first one. As an example, the Dutch National Annex to EN1991-2 [2] gives for the adjustment factors α_{Q1} and α_{q1} for the first lane value between 0.74 and 1 as a function of the yearly number of heavy vehicles per lane (between 200 and more than 2 millions) and the length of the influence line.
Two additional traffic load reduction factors are introduced in the Dutch context. The first one is related to the reference period. The intensities of the traffic loads in EN1991-2 are based on a reference period of 100 years. When assessing existing structures, the remaining lifetime is often shorter than 100 years. Therefore a reduction factor is introduced as:

$$\Psi = \left[\frac{\ln(n_a \cdot t)}{\ln(n_a \cdot T)}\right]^{0.45} \qquad (1)$$

where n_a is the number of heavy trucks, t is the reference period used for the assessment ant T = 100 years is the reference period used in EN 1991-2.
The second reduction factor is related to the trends of the traffic loads. Axle loads and traffic intensities are expected to increase in time. For the purpose of the safety assessment, the effects of such trends on the governing load effects in bridges are of relevance. Based on analyses of these effects, a reduction factor α_{trend} has been determined as a function of the influence length and reference period.
The Swiss standard SIA 269/1 [3] provides in a similar way values of the adjustment factors as a function of the bridge type and span length. The reduction factors were based on a study [4] aiming to define the design values of traffic load effects in bridges from the modelling of traffic loads based on

WIM data. In that study an assumption is made for the evolution of the trends of traffic loads for a period of 15-20 years. Reduction factors for the tandem load in the range 0.3-0.5 and 0.5-0.6 are given in [3] for the first two notional lanes and in the range 0.5-0.6 for the uniformly distributed load on all notional lanes and the remaining area.

Level 2 - Design value method of load effects based on analyses of Weigh-In-Motion (WIM) data
If the safety estimated based on the current standards is not sufficient, Annex C to EN 1990:2002 [5] provides through the design value method the possibility of improving the accuracy of the assessment by estimating the design load effect based on simulations of WIM data. The design value method is based on the following definition of the design value of the load effects E_d [6, 7]:

$$P(E > E_d) = \Phi(\alpha_E \beta) \tag{2}$$

where:
- $\Phi(\cdot)$ is the cumulative distribution function of the standard normal random variable
- α_E = -0.7 is the sensitivity factor for dominant load variables
- β is the target reliability level

For ULS verifications, the random variable E models the extreme traffic load effects for the reference period of interest, which might be chosen shorter than the design lifetime of 100 years as stated above. The distribution of the extreme traffic load effects should consider all the relevant uncertainties, including the traffic loads, traffic composition and intensity, future trends over the chosen reference period and the uncertainty of the structural models used to assess the traffic load effects. This approach can be based on WIM datasets representative of the traffic loads acting on the bridge. However, since WIM measurements are accurate when the speed is sufficiently high (e.g 60 km/h), specific assumptions might be needed for particular traffic conditions (e.g. full stop condition for long influence lines). While in Level 1, traffic loads may be reduced based on the expected number of heavy trucks per lane and the reference period, the application of the design value method enables consideration of the current traffic composition and traffic flow (convoys of vehicles, etc.) that have an impact on the critical load events [8].

Level 3 - Design values of load effects Based on Measurements
An additional level of sophistication consists of replacing the use of WIM data, traffic flow models and structural models with direct measurements of the traffic load effects. The design value of the traffic load effects is determined by applying Eq.(2). In terms of reduction of conservativism with respect to Level 2, this approach does not need any probabilistic modelling of the uncertainties of the load effect model and other factors such as the dynamic amplification factor. However, the measurement uncertainty should be taken into account.

ASSESSMENT OF BRIDGE-SPECIFIC TRAFFIC LOAD MODELS

In the following, the focus is on the Level 2 "Design value method of load effects based on analyses of Weigh-In-Motion (WIM) data" approach. The definition of bridge-specific traffic load models requires:

- technologies measuring traffic loads
- methodologies for simulating traffic load effects in bridges
- methodologies for assessing the design values of the traffic loads and the adjustment factors to EN 1991-2

Technologies
A WIM system implements the process of weighing a moving road vehicle by first measuring the dynamic (varying with time), vertically-downward component of the tire force from each wheel on the vehicle as the vehicle passes on a smooth road surface over specially-designed sensors. The most important physical quantities measured by WIM sensors are:

- weight of the vehicles (estimation)

- axle group loads, axle loads, wheel loads of the passing vehicles
- tire impact forces
- strain forces
- velocity of the vehicles

WIM systems consist of:

- WIM sensors embedded in the roadway surface or placed under/on the bridge deck for detection of the exceeded weight, classification of the vehicles. Typically used sensors are: bending plates, load cells, quartz piezo sensors, polymer piezo sensors, and strain gauge strip sensors.
- Electronics which are needed for the control of the system functions and to provide vehicles records,
- Infrastructure such as junction boxes, directional bore, cabinet, poles, conduit needed to connect parts of the system,
- Support devices, mainly power supply which can be A/C, solar or wind needed to run the system,
- Software and hardware to process, analyze, format, and report the data collected during the measurements,
- Communication devices including a cellular modem or telephone jacks.

There are three main types of WIM systems depending on the application and technology:

- High-Speed Weight-in-Motion systems – the weighing is carried out in the open traffic lanes at normal speed and under free-flow conditions. The measurements are affected by the vehicle dynamics that depend on a combination of the geometry of the road, the driving behavior of the driver, and the reaction of the vehicle suspension on the influences mentioned previously. More and less accurate systems are also available.
- Low-Speed Weight-in-Motion systems - the weighing takes place in a dedicated controlled area, mostly outside the main traffic lane, on a flat and smooth platform (generally made of concrete) that is longer than 30 m. In the weighing area, the velocity and transverse movement of the passing vehicles are controlled to eliminate the dynamic effects of the vehicle
- Bridge Weight-in-Motion systems - a dynamic weighing system where the sensors are attached to the soffit (bottom side of beams or deck) of a bridge, viaduct, or culvert. The sensors typically measure strains due to the bending of the bridge caused by the passing vehicles. In addition to the same vehicle information as provided by the pavement WIM systems, the B-WIM systems can also collect valuable data about structure behaviour that can be used for safety assessment of the bridge

High-speed Weight-in-Motion systems are the most used in Europe to measure traffic loads on highways.
The measurement accuracy is a varying parameter, depending on the type of system used, type of structure for which the system is applied, decisions regarding the choice of the conditions, as well as the type of sensors used and their configuration. The accuracy of the system of weighing the trucks traveling on the highway is stated in probabilistic terms as follows: in at least 95% of the cases, the relative deviation between the measured and the static loads is not larger than a given percentage that characterizes the class of the WIM system [9]. This statement can be formulated as follows:

$$P\big(L_{static}(1-\delta) \leq L_{measured} \leq L_{static}(1+\delta)\big) \geq 95\% \quad (3)$$

where:

- $L_{measured}$ is the measured axle load
- L_{static} is the measured axle load
- level δ is half of the width of the confidence interval centred on L_{static} at the confidence level 95%

It is questionable if the accuracy of the measurements has implications on the assessment of traffic loads effects. Recently, an investigation of the influence of the aforementioned accuracy of the WIM data on the prediction of extreme load effects has been exploited [10]. The conclusion of the investigation was that the accuracy of the WIM data plays an important role only for short span lengths,
where the axle load governs the prediction of the extreme load effects. On the contrary, as the span length increases, the importance of the vehicular load increases with respect to the axle load. The inaccuracy of the measured data has not a significant influence on the predicted extreme load effects in this case.

Simulation of traffic load effects
The first step in the assessment by probabilistic approach of the extreme traffic load effects induced in a bridge is the simulation of traffic load effects. When defining the simulation strategy, the representativeness of the available WIM database with respect to the loading conditions for the bridge under investigation is evaluated. The simulation of the traffic load effects can be directly based on the available WIM dataset if the WIM station is close to the bridge and the measurement period is sufficiently long to include also the month-to-month variability of traffic.
The general scheme illustrated in Figure 1 has been used in most of the research work on traffic load effects in bridges.

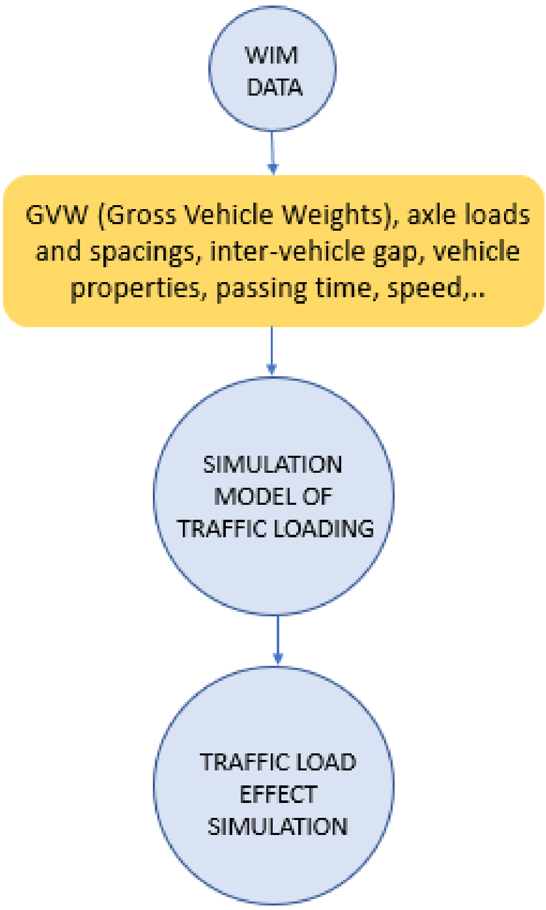

Figure 1 - General scheme.

As the first step of the procedure, the measured WIM data must be cleaned, as WIM systems may have some measurements errors and are thus sensitive to environmental conditions such as the variation of temperature, which can cause the subsequent process to produce distorted results.In the simulation model**,** key random traffic variables are identified and fitted to probability distribution models. These parameters refer to vehicle properties (e.g. the gross, vehicle weight, axle loads) or to the traffic flow (e.g. number of vehicles in a convoy, intervehicle gap, daily or weekly traffic intensities). Then, , artificial WIM data and loading scenarios are generated by the Monte Carlo method. The traffic load effect simulation makes use of influence lines or influence fields for the governing load effects need to be defined based on static scheme and type of bridge. In case of influence fields, it is necessary to account for the configuration of the roadway on the bridge deck and the amount of heavy trucks on the various traffic lanes.

Approach to the assessment of bridge-specific design values of traffic load effects and adjustment factors to EN 1991-2

Once the traffic load effects have been simulated, the distribution of the extreme traffic load effects for the reference period of interest is assessed. This distribution should also account for the uncertainties of the load effect model, the dynamic interaction between the vehicles and the bridge and the future trends in traffic loads. Therefore, extreme value distributions are fitted to the results of the simulations and probabilistic models are defined based on available literature and previous traffic analyses. The design value of the traffic load effects can be determined by means of Eq. (2) with due consideration of the target reliability index. The adjustment factors to LM1 of EN 1991-2 can be determined from the comparison of the obtained design values of the traffic load effects and the corresponding values obtained from the application of EN 1991-2 [14-15].

CONCLUSIONS

Monitoring of actions can be used to determine the assessment value of the loads, according to the approach presented in CEN/TS 17440:2020. In case of traffic loads on bridges, a different approach may be considered to update the design load models LM1 of EN 1991-2 “Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges”. In this approach the adjustment factors multiplying the characteristic values of the loads given in the standards based are reassessed based on the infrastructure- or structure-specific loading conditions.

The following recommendations are given for the evaluation of bridge-specific adjustment factors:

- The assessment of the adjustment factors to the LM1 should account for the uncertainty of the axle loads and the effects of traffic on the bridge, considering also the actual composition of traffic, the traffic conditions and the relative frequency of load events on the bridge.
- A dataset of measured traffic loads representative of the actual loading conditions should be the basis of the analysis. The measurement period should be chosen to include random variations (e.g. month-to-month variations) and to avoid systematic variations (e.g. reduction of traffic intensities due to maintenance and / or interventions). The measurement location and the number of measured lanes should be chosen such that the measurements are representative of the loading conditions on the bridge.
- The required accuracy of the load measurements should be defined based on the objective of the safety assessment, investigated failure modes, static scheme and length of the bridge. In case of data gathered at WIM stations, the accuracy may be defined in terms of the accuracy classes provided in [9].
- Traffic load effects should be evaluated by using representative structural models of the bridge accounting also for bridge-vehicles dynamic interaction. Also the uncertainties of the structural models should be evaluated.
- The estimation of the future trends in traffic loads and traffic load effects should be based on long-term information on traffic intensities and loads.

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REFERENCES

1. Maljaars, J., Steenbergen, R., Abspoel, L., Kolstein, H. (2012). Safety Assessment of Existing Highway Bridges and Viaducts. *Structural Engineering International, 1/2012*, 112-120.
2. NEN (2019). NEN-EN 1991-2+C1/NB. National Annex to NEN-EN 1991-2+C1: Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges
3. SIA (2011). SIA 269/1:2011. Existing structures – Actions.
4. EPFL-ICOM (2006). Evaluation de ponts routiers existants avec un modèle de charge de trafic actualisé.
5. CEN (2002). EN 1990:2002. Eurocode - Basis of structural design.
6. *fib* (2016). Bulletin 80 - Partial factor methods for existing concrete structures.
7. La Gasse, L.C., Steenbergen, R.D.J.M. & Allaix, D.L. (2019). Traffic load model for road bridges in the urban road network, Heron, 64.
8. Caprani, C.C., O'Brien, E.J. & McLachla, G.J. (2008). Characteristic traffic load effects from a mixture of loading events on short to medium span bridges. Structural Safety, 30, 394–404.
9. COST 323 (1997). Collection and Analysis of Requirements as regards weighing Vehicles in Motion, Liubjana.
10. O'Connor, A.; O'Brien, E.J. (2005). Traffic load modeling and factors influencing the accuracy of predicted extremes. Canadian Journal of Civil Engineering, 32, 270-278.
11. Crespo-Minguillón, Casas, J.R.. (1997) A comprehensive traffic load model for bridge safety checking. *Structural Safety, 19(4)*, 339-359.
12. Zhou, X.Y., Schmidt, F., Toutlemonde F. & Jacob, B. (2013). Applying Weigh-in-motion traffic data to reliability based assessment of bridge structures. ICOSSAR2013, 11th International Conference on Structural Safety & Reliability.
13. Sedlacek, G., Merzenich, G., Paschen, M., Bruls, A., Sanpaolesi, L., Croce, P., Calgaro, J.A., M. Pratt, M., Jacob, B., Leendertz M., de Boer, Vrouwenvelder, A. & Hanswille, G. (2008). Background document to EN 1991- Part 2 - Traffic loads for road bridges – and consequences for the design. JRC Scientific and Technical Report.
14. Bailey, S.F., Bez, R. (1999). Site specific probability distribution of extreme traffic action effects. *Probabilistic Engineering Mechanics, 14*, 19-26.
15. Brühwiler, E., Lebet, J.P. (2010). Updating of traffic loads on existing bridges. Joint IABSE-fib Conference, Cavtat, Dubrovnik-Neretva County, May 3-5, 2010, p.1177-1184.