Real Condition Experiment on a new Bridge Weigh-in-Motion Solution for the Traffic Assessment on Road Bridges

François-Baptiste Cartiaux, Véronique Le Corvec, Jorge Semiao

OSMOS Group SA, Paris, France

Bernard Jacob, Franziska Schmidt

Université Gustave Eiffel, Champs-sur-Marne, France

Alexandre Brouste

Laboratoire Manceau de Mathématiques, Le Mans Université, Le Mans, France

Alain Ehrlacher

Cabinet Ehrlacher, Grisy-Suisnes, France

Contact: cartiaux@osmos-group.com

Abstract

Weigh-in-Motion is currently the only way to precisely assess and monitor traffic loads on road bridges from real measurements. This assessment helps to detect potential overweight vehicles and to optimize the maintenance operations on the bridge thanks to an accurate knowledge of its real load conditions.

An experiment, performed on a precast prestressed concrete beam girders bridge overcrossing a highway in France, is described. The Weigh-in-Motion (WIM) system uses the bridge deck as a large scale, part of the weighing device, and measures strain in critical parts of the structure.

The system is able to get significantly accurate estimations of the gross weight of the vehicles on most types of bridges, including long span box girders, large composite decks or the multiple precast prestressed concrete beams considered in the study. However, the axle load estimation is still much less accurate and not presented here.

The experiment started in February 2019 and is still going on, also proving the robustness of the solution for an operation over long durations, as a permanent part of the bridge management through its whole lifecycle. Thus, the WIM sensors used are relevant for the Structural Health Monitoring of the bridge deck as well.

Keywords: weigh-in-motion (WIM); road bridge; structural health monitoring; traffic load; strain measurement; optical strand.

1 Introduction

Infrastructure managers and operators, road authorities, traffic regulators and other stakeholders need detailed and extensive data about traffic loads and density, especially on heavy commercial vehicles (HCVs), for various purposes of traffic monitoring. The most important challenges are: to ensure a fair competition between transport modes and companies [1], to improve road and truck safety [2], to assess impacts on and mitigate damages to infrastructure [3, 4, 5], to survey logistic chains and provide economic indicators on freight transport [6], and even to optimize truck design, or their parts [7]. For all these objectives, enforcement of overloaded HCVs is a major challenge [8]. Weigh- in-motion (WIM) is the perfect tool to collect and provide traffic load data, and much more on vehicle size, spacing, speed, etc.

WIM data provide fruitful information for road infrastructure management, e.g. inspections, maintenance and repair. They allow planning these operations in advance, providing warning when the traffic aggressiveness reaches some threshold, and minimizing the impact on structure and traffic. Extensive WIM data were used to develop or calibrate bridge loading codes, e.g. the Ontario bridge code in the late 70s, or the Eurocode 1991-2 in the late 80s and in the 2000s [9, 10]. Assessment of fatigue of steel and composite bridges under moving loads also mainly uses WIM data [11].

WIM systems can be classified, based either on the operation mode or on the technology as:

- High-speed WIM (HS-WIM) vs low-speed WIM (LS-WIM),
- Road sensors, instrumented bridge (B-WIM) and in vehicle - on-board (OB-WIM).

LS-WIM is done mainly outside the traffic flow, on dedicated and controlled area, at speed below 10-15 km/h (no dynamic effect) on smooth and flat surfaces, and generally for legal purposes, enforcement, or trade. Therefore, the accuracy of these systems is generally assessed using the OIML R-134 recommendation [12]. HS-WIM consists of weighing the vehicles at current speed in the traffic flow, on existing roads and motorways. Because the measurements are affected by the vehicle-infrastructure dynamic interaction, a statistical accuracy assessment is done, e.g. using the COST323 specification [13]. However, there are now some countries or attempts using HS-WIM for direct enforcement [14, 15]. LS-WIM systems mainly use load cell plates, while road sensor HS-WIM systems use load-cell or bending plates, or various strip sensors, piezo-quartz, piezo-ceramic, piezo-polymer, fiber optics or strain gauges.

B-WIM is a HS-WIM solution, in which an instrumented bridge is used as a scale to infer the weights and dimensions of the trucks crossing it. Therefore, the bridge is equipped with strain sensors, gauges, fiber optics or optical strands (by OSMOS). An inverse problem of identification is resolved by fitting the computed strains in diverse sub-structures of the bridge, derived from the influence lines or surfaces and the axle or wheel loads and spacing (which are the unknown variable), on the measured strains. The calibration of the system (algorithm) is done with test trucks by adjusting the influence lines.

Depending on the type and state of the bridge, the accuracy of a B-WIM system varies between the classes D+(20) and A(5) with respect to the COST323. The advantages of a B-WIM are: no or very low intrusive system, may be safely installed or removed without traffic cut with an access underneath the bridge deck, difficult to avoid it by the drivers, low exposure to vandalism or traffic loads. However, B-WIM requires the right bridge at the right location, a good level of expertise for the installation and calibration, and it is not easy to get a type approval for metrological and legal applications, while the bridge is part of the instrument. However, such systems provide information on both the traffic loads and the bridge response and are very relevant tools to assess and monitor bridge behaviour under traffic loads.

2 The OSMOS B-WIM Solution

OSMOS first proposed its B-WIM solution called WIM+D® in 2018. This solution takes advantage of the accuracy of the Optical Strand, a long basis strain sensor, which uses a proprietary technology to get strain measurements at a high sampling rate from the analysis of light attenuation in a fiber optic device [16].

Compared to previous B-WIM techniques, the novelty of the OSMOS WIM+D solution is to radically separate the estimation of Gross Vehicle Weight or Mass (GVW, GVM) and axle load.

GVW is obtained from sensors which measure global effects on main structural elements, e.g. main girders, where it is easier to smooth vibration effects and to get accurate influence lines. Meanwhile, the minimum number of sensors required for this estimation, whatever the transverse location of the vehicle, corresponds the number of main girders, usually 2 or 4 only, mostly less than 10 for a 2-lane deck.

The speed of the vehicle is derived from the time gap between measurements from sensors located on two successive spans.

The axle transverse locations and weights are obtained from additional sensors sensitive to local effects, e.g. measuring slab floor bending. Only one axle weight sensor is required for each traffic lane, which leads typically to two sensors on usual road bridges. The axle spacing is retrieved from peak identification in post processed signals, with inputs from several sensors. The axle weights are computed by distributing the previously estimated GVW on each axle identified by the sensors, with ratios deduced from the relative amplitudes of the axle's local effects.

The raw data are sent to the OSMOS cloud every 30 seconds. The WIM+D algorithm performs the data analysis on the cloud and releases comprehensive "Run Data Sheets" for every single truck run over the bridge, on a web interface named "Safe WIM+D", within a 1 min average delay (Figure 1, 2 and 3).

Time :	2021/01/30 at 13:29:08 UTC
Maximum Strain (mm/m) :	0.0334
Gross Weight (tons) :	38.8
Number of Axles :	5
Length (m) :	9.04
Speed (km/h) :	75.7
Direction :	N–S

Figure 1. Typical results on a Run Data Sheet

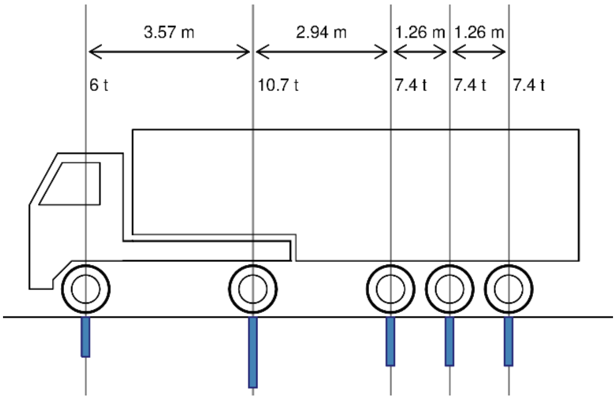
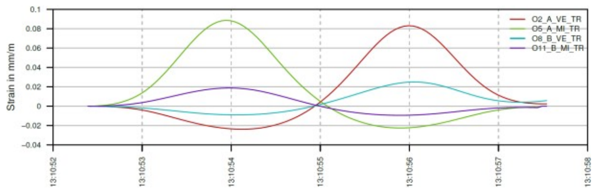


Figure 2. Truck Configuration as displayed on the Run Data Sheet



The advantages of the WIM+D® solution are: (1) the low number of required sensors, which increases the portability of the system and reduces acquisition and installation costs (only 6 sensors on a typical composite deck bridge with two main girders and two spans), (2) the availability of all raw strain data on a web cloud for further Structural Health Monitoring analysis, including vibration or fatigue assessment, and (3) its adaptability to a wide range of different bridge types, at least for the gross weight estimation.

3 The Auzouer Experiment

3.1 Asset and System Description

The Auzouer bridge is an overpass located in central France near Tours, overcrossing the motorway A10 operated by Vinci Autoroutes. It supports a two lanes road, used by abnormal load HGVs. It has two main spans of 14.5 m over the motorway lanes, and two shorter side spans.

The bridge deck, made of a reinforced concrete slab, is supported by ten parallel precast prestressed concrete beams. The challenge, for such a bridge configuration with multiple main girders, is to choose the minimum number of weighing sensors to install, thus of beam to instrument.

The experiment started in February 2019 with the installation of an OSMOS monitoring system including 10 optical strands and 2 tri-axial accelerometers (not used for WIM). The optical strands are set as follows:

- Four sensors on the web of four main beams on main span 1, at mid-span,
- Two sensors on the web of two main beams on main span 2, at mid-span,
- Four sensors on the bottom face of the slab on main span 1, at mid-span (figure 4).

Figure 4. Optical strands on main span 1

The first set of four sensors is used for gross weight estimation, along with the second set of two sensors, used for the speed estimation.

The last set of four sensors is used to detect the axles, derived from local slab bending. This methodology is reliable if at least the left or right wheels of the truck induce a significant local bending of the slab over at least one of the four sensors (among nine) mounted under the slab.

3.2 Load Test

The performance assessment of the WIM+D® system on the Auzouer bridge uses the results of a load test performed on November 7, 2019.

Three reference (test) trucks with known weights and dimensions, measured in static, were used to calibrate the system. A rigid 2-axle truck, a rigid 4-axle truck, and a short 5-axle semi-trailer (Figure 5) were rented, by a construction company located nearby the bridge. They have been fully loaded, respectively at 19.2 tons, 31.8 tons and 43.9 tons (GVM). The static weighing was done in the morning before the tests and in the evening after the tests, to check that the loads did not vary along the day.

Figure 5. Two trucks (out of three) that have been used for the load test

The test trucks were driven several times over the bridge, and the structural response has been recorded for each run. The runs addressed various situations:

- One test truck crossing the bridge alone, vs the presence of 2 test trucks at the same time on the bridge,
- Several speeds, from very slow speed (quasi-static, 10 km/h) to maximum allowed speed (80 km/h),
- Various lateral truck positions on thebridge deck, either centred in each lane onthe bridge, and out of a lane.

3.3 System Performance

Among 49 test runs, some of them have been discarded as they correspond to unusual traffic situations, such as runs at very low speed (under 10km/h, with a stop of the truck on the bridge), or while two trucks were very close each other. A total of 33 runs remains, 6 of them used for the calibration and 27 for the accuracy assessment of the B-WIM system. The calibration runs are chosen to cover various situations: one run for each lane, one run centred, at least two different trucks in both directions. The calibration yields four coefficients, one for each sensor used for the GVW estimation.

The relative errors on GVW for the 27 truck runs, are computed with respect to the static weights measured on approved scales (Figure 6). The 5% and 95% quantiles of the negative and positive errors are -5.3% and +4.7 % respectively. The standard deviation is 3.9%.

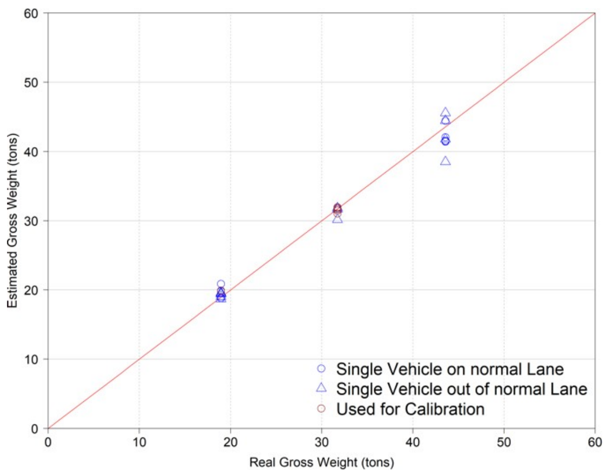


Figure 6. Comparison of the real and estimated weight for different load cases

According to COST323, the B-WIM system is in the C(15) accuracy class for GVW, very close to the class B(10) – the tolerance at the required confidence level is below 11%.

For axle loads and spacing, the updated version of the WIM+D® system developed by OSMOS was significantly improved, compared to the first 2018 version. The former system was unable to properly identify axles on this type of bridge. The current maximal error of axle spacing measurement is below 0.25 m, smaller than a tyre imprint length, and the standard deviation is 0.14 m.

The axle load is computed by the distribution of the GVW over the identified axles. Due to the complexity of influence lines, related to the geometry of the bridge, the estimated axle load may present error up to 35%. Advanced analysis methods are under study to improve the accuracy of this estimation.

This type of bridge justifies keeping on the effort on axle load estimation. However, a previous study carried out with the WIM+D® system on a composite bridge deck with two main girders gave more accurate results on axle loads, with a maximal error of 15% for axles above 10 tons and a standard deviation of 7.5% [17].

3.4 Statistical Results

Based on the recorded measurements of the optical strands and the calibration parameters, the identification of trucks is automatically performed, and traffic data are directly released to the client via the web interface WIM+D® of the OSMOS Safe website.

The dynamic detection level is set to record all trucks above 40 tons, but some lighter trucks are also recorded. A statistical analysis of the recorded trucks over the year 2020 is performed (Figure 7).

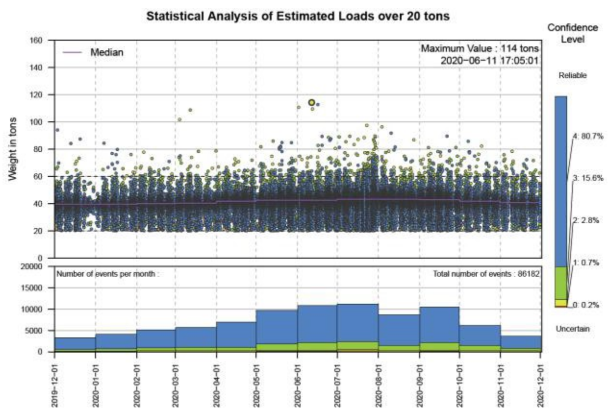


Figure 7. Statistical analysis of the identified trucks over one year.

About 86,000 trucks were recorded over the year (Figure 8). The most frequent truck silhouette is a 5-axle truck T2S3 (2-axe tractor with a semi-trailer and tridem axle), which is coherent with the usual traffic pattern on French roads.

The traffic evolves over the year: the traffic flow doubles in Summer compared to Winter. These data are useful for the asset manager to monitor the traffic on the bridge, to plan the maintenance schedule, and to perform fatigue analysis.

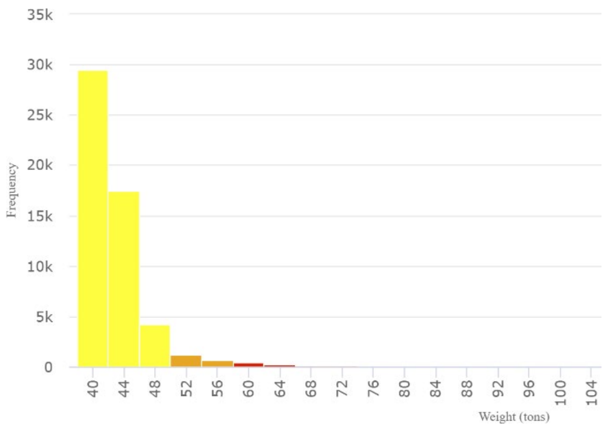


Figure 8. Weight distribution of the identified trucks over one year, as displayed in real-time on the web interface.

The comprehensive data also allow to identify abnormal loads crossing the bridge. These abnormal loads are compared with those declared in the released authorisations. On the Auzouer bridge, 6 crossings over 100 tons (GVW) have been identified in 2020 and the measured truck configuration by the WIM-D+ appears realistic.

4 Conclusions

This article presents the B-WIM system developed by OSMOS and its application on the Auzouer bridge, a precast prestressed concrete beam girders bridge. This bridge configuration implies complex load influence line, for which OSMOS had to improve its B-WIM system.

With a limited number of sensors (4 sensors for the gross weight and 4 for the axle location and load estimation), the system can estimate the GVW of trucks with a standard deviation of 3.9 %. The identification of the axle location has been significantly improved and a better evaluation of the axle load is currently under study.

It appeared that the transverse location of the trucks on the bridge is highly scattered: a significant part of the runs did not induce any local bending of the slab where the axle detection sensors are mounted. Thus, two additional sensors were set up on the bottom surface of the slab in December 2020. The results presented in this paper do not consider this improvement. An additional test is scheduled in 2021 to qualify the performance of the improved system.

By performing an accurate measurement of the traffic load in real time, the OSMOS B-WIM system is an efficient system for infrastructures managers to assess current traffic loads and optimize maintenance schedule.

Acknowledgements

The authors wish to thank Cofiroute and Mr Nicolas Bardou for the support in using the Auzouer bridge as a practical case study, which made this real condition experiment possible.

References

[1] Dolcemascolo V., Hornych P., Jacob B., Schmidt F., Klein E. Heavy Vehicle Traffic and Overload Monitoring in France and Applications. *Proceedings of the XXVth World Road Congress, Road and Mobility creating new Value from Transport*, Seoul, Nov. 2-6, 201.

[2] Jacob B., Feypell de la Beaumelle V. Improving truck safety: Potential of weigh-in-motion technology. *IATSS Research*, 34, 2010, 9–15.

[3] Schmidt F., Jacob B. Experimentation of a bridge WIM system in France and applications to bridge monitoring and overload screening. *Proceedings of the International Conference on Weigh-In-Motion ICWIM6*, Eds. B. Jacob et al., Jun 2012, 52-59

[4] Schmidt F., Glaeser K.-P., Hornych P., Piau J.-M., Jacob B. Impacts from Truck Traffic on Road Infrastructure. *PIARC, Routes/Roads 358*, 2013, 74-83.

[5] Papagiannakis A.-T., Jackson N.-C. Traffic Data Collection Requirements for Reliability in Pavement Design. *Journal of Transportation Engineering,* 2006, 237-243, 132, 3.

[6] Eurostat, Road freight transport by vehicle characteristics,

https://ec.europa.eu/eurostat/statistics-explained/index.php/Road_freight_transport_by_vehicle_characteristics#Road_freight_transport_by_axle_configuration, accessed 12/01/2021.

[7] Schmidt F., Jacob B., Domprobst F. Investigation of Truck Weights and Dimensions Using WIM Data. *Transportation Research Procedia, Volume 14*, 2016, 811-819.

[8] Dolcemascolo V., Jacob B., Klein E. French policy to prevent overloading. *Proceedings of the International Conference on Weigh-in-Motion ICWIM8*, Eds. B. Jacob & F. Schmidt, May 2019, 15-23.

[9] Flint A., Jacob B. Extreme Traffic Loads on Road Bridges and Target Values of their Effects for Code Calibration. *Proceedings of IABSE Colloquium Basis of Design and Actions on Structures*, Copenhaguen 1996, 469-477.

[10] Jacob B., Kretz T. Calibration of bridge fatigue loads under real traffic conditions. *Proceedings of the IABSE Colloquium: Basis of Design and Actions on Structures*, Copenhagen, 1996, 479-487.

[11] Jacob B., Arroyo-Contreras G.-M., Schmidt F., Assessment in Fatigue of an orthotropic Steel Deck Bridge under Traffic Loads and Impact of abnormal Loads – Case of the Normandy Bridge, *Proceedings of the TRB Annual Meeting*, Washington, 2019.

[12] OIML (2006). *Automatic Instruments for weighing Road Vehicles in Motion and Axle Load measuring*. Part 1: Metrological and technical requirements – Tests. R 134-1.

[13] COST323. *European Specification on Weigh-in-Motion of Road Vehicles*. EUCOCOST /323/8/99, LCPC, Paris, August 1999, 66 pp.

[14] Cottineau L.-M., Jacob B., Hornych P., Schmidt F., Klein E. Direct enforcement of overload by WIM. *Proceedings of the International Conference on Weigh-In-Motion ICWIM7*, November 2016, 281-290.

[15] Antofie A., Boreux J., Corbaye D., Geroudet B., Liautaud F. Approach of the Wallonian Legal Metrology (Belgium) for Weigh-In-Motion (WIM) free-flow direct Enforcement. *Proceedings of the International Conference on Weigh-in-Motion ICWIM8*, Eds. B. Jacob & F. Schmidt, May 2019, 147-154.

[16] Cartiaux F.-B., Pelletier P., Semiao J. Traffic and Temperature Effects Monitoring on Bridges by Optical Strand Strain Sensors. *Proceedings of the Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures SMAR2019*, Potsdam, August 2019.

[17] Cartiaux F.-B., Koutsonika S., Andrikopoulos G., Pelletier P. Bridge Monitoring & Assessment via OSMOS Optical Strands. *Proceedings of the Fourth Joint International Symposium on Deformation Monitoring JISDM2019*, Athens, May 2019.