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DATA-DRIVEN BRIDGE ANALYSIS USING TRAFFIC LOAD MEASUREMENTS

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Abstract

Effective bridge management relies on accurate status information to balance maintenance costs, risks, and performance. Structural safety, a key indicator, depends on detailed knowledge of traffic loads and structural resistance. Advanced assessment is especially valuable for ageing bridges nearing the end of their service life, as understanding loading and performance helps determine whether major or minor interventions are needed. Traditional analytical methods alone struggle to demonstrate the safety of these bridges, so combining structural and material testing with traffic load monitoring can help prevent unnecessary strengthening or replacement. The paper shows how to apply bridge weigh-in-motion technology to measure critical freight traffic parameters for optimising bridge safety assessment: axle loads and spacings of all heavy goods vehicles on the loading side, and influence lines, girder distribution, and dynamic amplification due to the traffic loads on the bridge performance side. Their actual, not assumed, values significantly improve structural modelling and reduce uncertainties and risks associated with the load effects used in safety assessments, thereby supporting more optimal decision-making and the efficient use of infrastructure maintenance funds. Finally, an example demonstrates how finite element model updating can benefit from bridge weigh-in-motion measurement results.

Keywords: bridge assessment, traffic loading, dynamic loading, measurements, weigh-in-motion, WIM

1 Introduction

Over 50% of European bridges are over 50 years old [1] and are thus approaching the end of their design lifetime. They were constructed at a time when trucks were considerably smaller and lighter, and therefore, traffic loading on pavements and bridges was considered considerably lower than it is today. Furthermore, as bridges deteriorate, their capacity to sustain traffic loads declines. Finally, to improve the efficiency of freight transport and introduce modern, greener vehicles inevitably means we will see even heavier vehicles on our existing infrastructure. This is less of a problem for international haulage because motorways on the main corridors are typically newer and designed to carry higher loads. The situation may quickly become critical on regional and municipal roads, where bridges are older, less well-maintained, and often neglected. Figure 1 displays the general evolution of freight transport in the European Union. Apart from short periods around the economic crisis of 2010 and the COVID-19 pandemic in 2020, the freight traffic in Europe has steadily grown [2]. The highest average annual growth is observed for sea (+1.0%) and road cargo (+0.6%), while rail cargo decreased by almost 2% annually and air cargo by 1%. Despite strategic goals to increase rail transport in Europe, its share of freight transport fell from 28.9% in 2000 to only 21.9% in 2023.

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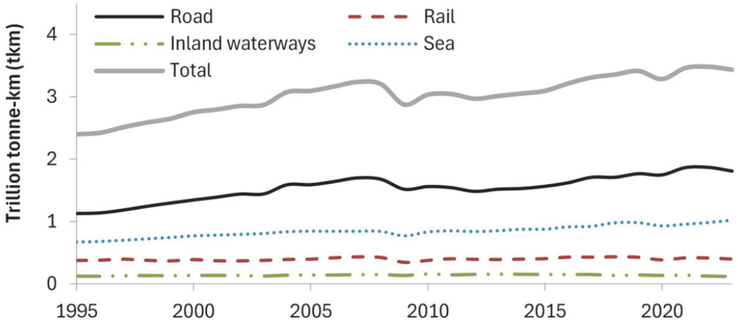

Figure 1 Development of the 4 most important freight traffic modes in the EU

2 Measurements of traffic loading

To understand and to properly consider heavy vehicle loads in various applications, they must be measured. The most common devices for collecting traffic flow data are traffic counters. Counting technologies range from manual recording to the installation of rubber tubes, inductive loops, and modern optical and laser devices. Traffic counters are indispensable for collecting traffic flow data, but they do not provide evidence of the actual axle loads of heavy vehicles. To know the actual axle loads (ALs) and gross vehicle weights (GVW) of the heavy vehicles, they need to be weighed. This can be done statically, in-motion or with on-board weighing systems (figure 2). On-board weighing refers to sensors that are built into the vehicles [3], but they are not widely used in Europe and are not relevant to this paper.

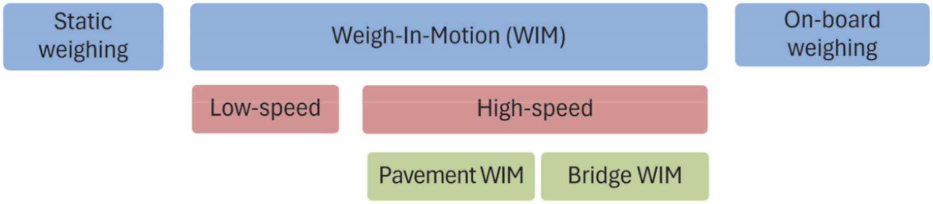

Figure 2 Division of weighing systems

2.1 Static weighing and low-speed weigh-in-motion

Static weighing is the most accurate and, in most countries, the only legally accepted method for imposing fines. Devices used include weighbridges, axle and wheel weighers. Weighbridges weigh the entire vehicle and are mainly installed permanently at industrial sites. Their use in Europe is limited due to cost and space. Axle and wheel weighers are more common in Europe. They are less accurate than weighbridges but provide axle-load data for enforcement. Portable wheel scales offer flexibility, and levelling mats help reduce load redistribution. Certification and calibration are required. Low-speed Weigh-in-Motion (LS-WIM) systems use dedicated lanes that limit vehicle speed over sensors and prohibit acceleration or braking. They are accurate (with up to 1% error for most measurements) and, in some countries, are used for the direct enforcement of overloaded vehicles.

2.2 High-speed weigh-in-motion

A high-speed WIM system, often called just a WIM system, measures the dynamic ALs of the vehicles passing at highway speed under uncontrolled conditions and calculates the best possible approximation of their static axle weights [4]. WIM systems deliver at least ALs, axle group loads, GVW, number of axles, vehicle length, axle spacings, speed, and vehicle type or class [5]. The supporting structures, either a pavement or a bridge, serve as the physical framework for a WIM sensor to convert the axle loads of passing vehicles into an electrical signal [6]. The most common sensing technologies today are piezo-quartz materials, strain gauges and fibre optics [7]. With respect to the supporting infrastructure, we distinguish pavement and bridge WIM systems.

A typical pavement WIM installation consists of inductive loops that measure vehicle velocity and detect vehicle type and length, and various weighing sensors. They are divided into two major groups: plate sensors and strip sensors. Plate sensors exceed the tyre footprint and capture the entire axle load (figure 3, left). Similar sensors are used for static and low-speed axle-load measurements. Plate sensors can provide very accurate axle loads. However, their installation cannot be done while traffic is present and may require a 2-day roadblock. Strip sensors are narrower than the tyre footprint. To determine the total axle load (AL), the collected signals are integrated over time. Piezo quartz technology is currently the leading choice, providing highly accurate and stable AL measurements, though it is more expensive than piezoelectric, piezopolymer, or strain-gauge options. Compared to plate sensors, strip sensors cause less pavement damage and work effectively on smooth roads. However, installing and maintaining them requires closing the road, which can be challenging in heavy traffic. Their accuracy drops as pavement quality declines, particularly with flexible pavements. As a result, WIM systems should be placed on the smoothest available road sections and recalibrated frequently to ensure their precision.

Figure 3 Wheels over a plate and a strip WIM sensor

2.3 Bridge WIM

The bridge WIM or B-WIM was introduced 20 years after the first pavement WIM system [8] and was not widely used in the early years. They became common only in Australia, where instrumentation was applied to culverts rather than bridges [9, 10]. In the early 1990s, B-WIM prototypes were developed independently in Slovenia, Ireland, Japan [11] and Canada. They were extensively studied in the EU action COST 323 "Weigh-in-Motion of Road Vehicles" [4] and 4th Framework Programme (FP) project WAVE [12], resulting in the SiWIM® system [13, 14].

This has been further improved within the 7th FP projects TRIMM [15] and Bridgemon [16]. Today, B-WIM research is regaining worldwide attention [17-21]. Industrial B-WIM systems transform the existing bridges or culverts into hidden weighing scales [14]. Measured strains on the main longitudinal members provide response records of the structure under the moving vehicles. Today, the traditional axle detectors on the bridge deck have been largely replaced by free-of-axle detector (FAD) setups, which capture axle information from additional strain sensors beneath the bridge (figure 4). Measurements during the entire bridge crossing provide redundant data, facilitating the evaluation of axle loads. B-WIM is particularly appropriate for:

- short-term measurements, lasting up to several weeks, collect essential traffic data; unlike pavement WIM, this equipment can be easily moved between sites
- measurements on sites where cutting grooves into the pavement to install sensors is not allowed or is not feasible due to the dense traffic
- bridge assessments, by providing strain levels, actual influence lines, dynamic behaviour of the bridge and load distribution between structural members.

Recently, the precision of B-WIM results has been improved using a low-cost computer vision (CV) extension for existing B-WIM installations that verifies strain-inferred axle configurations using traffic camera images and flags GVW estimates as reliable or unreliable. A study has shown that a commercially available B-WIM system has improved the reliability of GVW estimates from 96.7 to 99.89% [22], effectively excluding nearly all erroneous measurements. This has great potential for using B-WIM not only to collect data for statistical purposes but also in fields that require very high accuracy, such as weight enforcement.

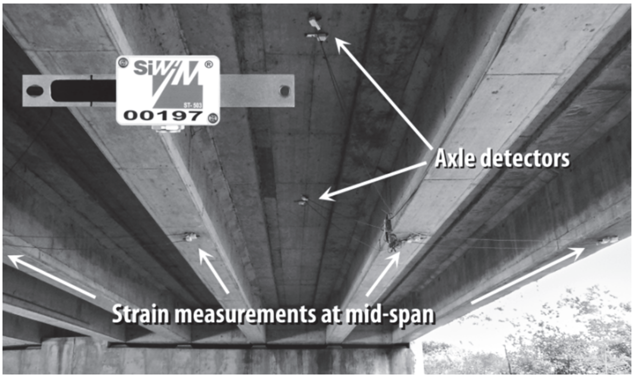

Figure 4 Typical B-WIM instrumentation [23]

3 B-WIM and Bridge assessment

Assessing the existing structural safety of bridges for increased traffic, or when bridges have deteriorated, and their carrying capacity has been reduced, is often challenging due to insufficient data. Old bridges typically have no drawings, or it is unclear how they were designed and built. Still, as bridges are designed conservatively, with hidden reserves in resistance, they are likely safe, despite being damaged and carrying higher traffic loads. The bridge safety assessment goal is to prove that a structure has adequate capacity to resist specific loading levels/effects, i.e., the assessment should demonstrate that the probability of failure is less than the values in the codes [24-26] or specifications. Efficient assessment gradually incorporates more detailed information, including material testing, measurements of loads and bridge performance under those loads. The research projects SAMARIS [27] and ARCHES [28] proposed using B-WIM systems for this purpose.

3.1 Site-specific traffic load modelling

A reliable WIM data source used for traffic load modelling on bridges should contain at least 100.000 heavy goods vehicle records [29]. Furthermore, individual vehicle timestamps must be recorded to at least 1/100 of a second to enable simulation of loading events involving several vehicles on the bridge. Not all WIM systems provide such information.

3.2 Calculation of static load effects

Static load effects on the bridge due to traffic, Q_s, are calculated by combining axle loads of the measured vehicles with the influence lines:

$$Q_S = \sum_{i=1}^{N} AL_i I\left(x_i\right) \tag{1}$$

where AL_i is the weight of the axle i, N is the number of axles of the vehicle and $I(x_i)$ is the value of the bending or shear influence line due to the axle i at location x [8, 13, 30, 31]. The shape of the influence lines depends on the bridge span and its boundary conditions (presence, age and quality of bearings and expansion joints) and should be measured, not modelled [32].

3.3 Simulation of extreme load effects

Traffic loads in the bridge assessment are typically presented as the maximum expected load effects (moments and shear forces) at critical sections of the bridge. Normal or extreme value Gumbel, Fréchet or Weibull distributions are used to fit the tail of load effect distributions and extrapolate data to the ultimate expected values [33, 34]. Alternatively, detailed simulations are applied to forecast the extreme load effects [35].

The statistical convolution method is an efficient tool to analyse traffic loading on shorter bridges. It assumes that the maximum load effect results from one heavy vehicle in each of the two traffic lanes [29, 32, 36, 37]. Its application has been tested on bridges shorter than 40 meters, including over 90% of European bridges [1]. The load effects in each lane create two independent probability mass functions, f_x and f_y, which are convoluted to obtain the probability mass function f_z of load effects generated by pairs of vehicles from both lanes:

$$f_Z\left(z\right) = \sum_{k=-\infty}^{\infty} f_X\left(k\right) f_Y\left(z-k\right) \tag{2}$$

The cumulative probability density function $F_z(z)$ is calculated, and the extreme value theory is applied to extrapolate the distribution and obtain the expected maximum load effect Q_{max} in a selected period z, typically 25 years for a limited and 75 years for a normal lifetime [38]:

$$Q_{max}\left(z\right) = \left(F_Z\left(z\right)\right)^{N_T} \tag{3}$$

N_T is the number of meeting events of two heavy vehicles in the selected period, extracted from B-WIM data. Typically, 250 working days per year are considered.

3.4 Soft load testing

The concept of soft load testing (SLT) was first proposed in the SAMARIS project [27]. Its goal is like that of traditional diagnostic load tests: to update the bridge analytical model based on measured structural performance. Using B-WIM systems avoids the need for costly pre-weighed vehicles to load the bridge, required during traditional load tests. The bridge is also left open during the measurements, which reduces traffic delays and detours. Finally, there is no risk of damaging the old, deteriorated structure due to the lower load levels.

SLT supports analyses at serviceability limit states, not ultimate limit states. It can answer common questions, such as whether the bridge is safe under the current traffic load or whether it should be posted or closed. SLT primarily means measuring and calibrating the actual influence lines, which on older single-span bridges differ substantially from the theoretical ones, due to constrained support rotations and insufficient knowledge of the construction details. Further structural model improvements are due to the measured girder distribution factor (GDF) and dynamic amplification factors (DAF). These parameters are computed from thousands of measured loading events. The validity of bridge assessment is generally short-term, up to a few years, and so should be the analysis based on SLT. Finally, it should be used by experienced bridge engineers who know how the bridge might behave under heavier loading.

3.4.1 Bridge dynamic response and B-WIM measurements

Bridges are excited by vehicles rolling over uneven pavement. Potholes and settlements on the approaches amplify the dynamic response by pushing vehicles upward as they reach the bridge. The degree of vibration depends on the vehicle type, speed, mass, and suspension characteristics, and varies substantially from one vehicle to another. Advanced finite element modelling can account for bridge-vehicle interaction and provide reasonably accurate estimates of realistic dynamic responses [39, 40], but the procedure is time-consuming and difficult to calibrate. The B-WIM systems measure flexural strains of a bridge. Consequently, the SAMARIS project [27] suggested a procedure to automatically calculate the dynamic amplification due to all vehicle loading events, using a common dynamic amplification factor (DAF) definition [14, 40, 41]:

$$DAF = \frac{\varepsilon_T}{\varepsilon_S} \tag{4}$$

where the total load effect of the fast-moving vehicles from free-flowing traffic is typically larger than the one obtained from a static analysis. In B-WIM, equals the maximum measured strain amplitude, and the maximum approximated value of the estimated static response. If the axle loads are measured correctly, the static response of a random vehicle equals the sum of its axle contributions, the dashed lines in figure 5. These are calculated by multiplying the influence line by the axle loads, as shown by the dotted lines in figure 5. Misidentified axles and ill-conditioned B-WIM equations, common on bridges with longer influence lines, cause erroneous axle loads [14] and DAF values. The ARCHES project [42] addressed this by separating static and dynamic response components using characteristic frequencies: signals were transformed into the frequency domain [43], low-pass filtered at a set cut-off, and retransformed to the time domain [44], yielding a static response for DAF calculation. However, selecting filtering parameters required expertise. To reduce subjectivity, the latest method processes each loading event twice – first to set filtering parameters, then to calculate DAFs [41].

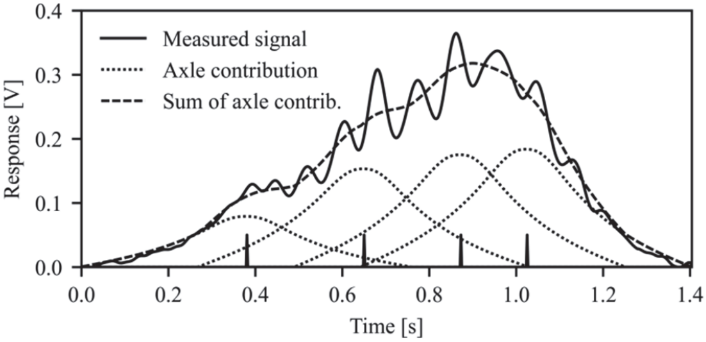

Figure 5 An example of B-WIM results during the passage of a 4-axle truck [41]

3.4.2 Evolution of DAF values with loading

Theoretical studies [39, 40], research projects [27, 42] and measurements [41] demonstrate the decreasing dynamic amplification with increasing static loading. In other words, extreme events involving several heavy trucks meeting on a bridge trigger far lower dynamic amplification than lighter single-vehicle crossings. An example of DAF measurements is given in the case study description. Without B-WIM evaluated DAFs, the ARCHES project recommended using DAF = 1.15 for bridges with two or more traffic lanes. This is more conservative than typical measurement results but still lower than what is considered in design codes. An extensive test was performed to verify the hypothesis that the DAF decreases with increasing loading [41]. The results from 17 B-WIM datasets from Slovenia and the USA align with theoretical studies and previous research: the high DAF values were observed for lighter vehicles and were associated with resonance effects. The method proved to be robust and reliable.
Figure 6 aggregated results for the three groups of roads: Slovenian (SI) state roads and motorways, and US highways. The abscissa in GVW percentiles allows combining the datasets with different GVW distributions. Each represents the mean DAF value in a GVW interval. For example, the ordinates at 0% give the mean of all DAF values, at 95% of the heaviest 5% of the loading events, etc. Added are the linear regression curves, which ideally describe the decreasing DAF trends. It must be stressed that despite the apparent trends, the dynamic behaviour of bridges is site-specific. For example, on two structurally almost identical multi-span bridges, 2.2 times higher was measured on the one with vehicles hitting a bad expansion joint before the measured span. For the 17 considered datasets, the values ranged from 1.01 to 1.11. For this reason, it is difficult to recommend a general reduction of DAF for bridge assessment below 1.15. However, if B-WIM results are available, DAF analysis will reveal substantial additional reserves for the analysed bridge, which can play a decisive role in the duration and cost of the selected remedial measures.

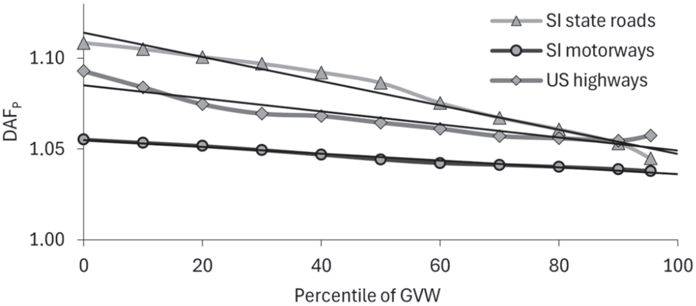

Figure 6 DAF$_p$ as a function of GVW percentile for three groups of bridges

4 Case study

The benefits of using a B-WIM system for optimised bridge assessment are demonstrated using data from a typical simply supported overpass in the USA, with six steel girders, steel hinges at the supports, a reinforced concrete deck, and cross-trusses at mid-span and at the span quarters (figure 7). Its theoretical span was 27 meters. The superstructure was 8.5 m wide and carried two lanes of traffic and a shoulder. Six transducers near the mid-span of each of the six girders measured strain under loading, and four additional ones on the slab between the girders detected axles (figure 8, left). The pavement on the approach to the bridge was extremely rough, with severe potholes and asphalt ravelling (figure 8, right).

Figure 7 Side view and steel hinge at supports

Figure 8 Axle detection sensor and damaged pavement at the bridge approach

4.1 Experimental influence line

Effective weighing and bridge assessment requires using the actual instead of the theoretical influence lines (IL) [13]. Figure 9 compares the theoretical IL of the span at the measurement point, the measured influence line generated by the B-WIM system from responses of all fully loaded 3- and 4-axle rigid trucks and 5-axle tractor-trailers, and the IL from the calibrated finite-element model. In the model, support springs were adjusted to match the measured performance of the bridge. Furthermore, the tip of the influence line was rounded because of the superstructure's depth. Figure 9 confirms that even a bridge with steel hinges does not perform as predicted, with maximum bending moments reaching only 78% of the theoretical values. On older bridges lacking bearings or expansion joints, or where these components are damaged or underperforming, actual mid-span bending moments may be less than half of theoretical values. Using a calibrated structural model, the true influence lines at critical points can then be determined [12].

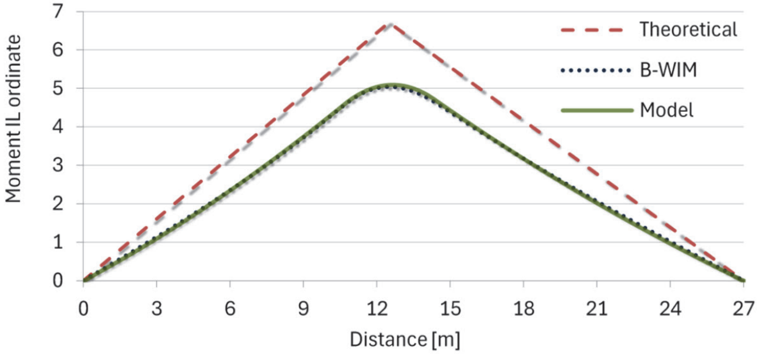

Figure 9 Theoretical, measured and modelled bending moment influence lines

4.2 Site-specific traffic load modelling

Traffic load modelling starts with multiplying the load effects calculated from the B-WIM axle loads by the corresponding influence lines. Figure 10 shows the bending moment histograms for the driving and fast lanes of the case-study bridge, equation (1). Using equation (3), their convolved probability curves are extrapolated to 1, 10, 25, and 75 years in figure 11. If needed, the procedure is repeated for the shear forces, hogging moments, or load effects at any other structural location. The characteristic values are read from the diagram at different probabilities, depending on the selected return period. This example considers the 1000-year return period, which roughly corresponds to the ordinate values at the 95th percentile [29]. The bending moments recalculated using the modelled IL, resulted in a 22.4% reduction (table 1). Although these savings are far from those of older bridges, the benefits are clear and should be accounted for when assessing the structural safety of existing bridges. The shear forces increased by 1% when the theoretical influence lines were replaced with the measured ones.

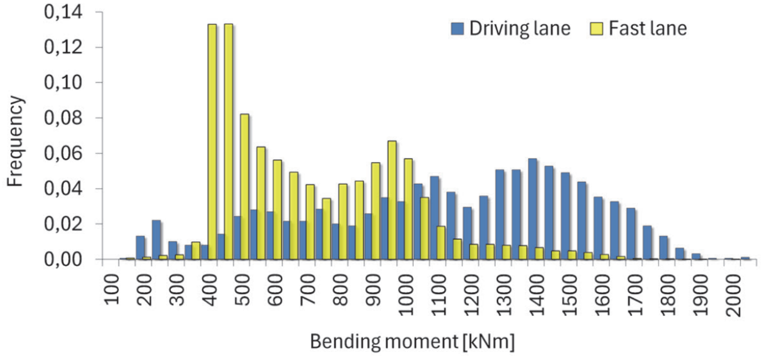

Figure 10 Distribution of bending moments on the test bridge

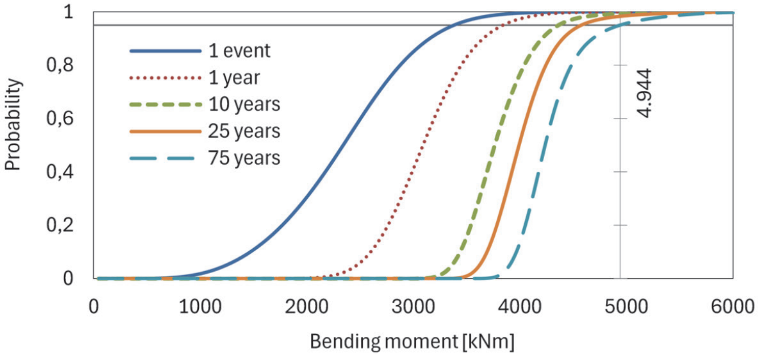

Figure 11 Extrapolated bending moments calculated with the theoretical IL

Table 1 Reduction of bending moments, in kNm, with measured influence lines

Period	1 event	1 year	10 yrs	25 yrs	75 yrs
Mean moments calibrated IL [kNm]	2, 622	3, 002	3, 382	3, 572	3, 838
Mean moments theoretical IL [kNm]	3, 408	3, 840	4, 368	4, 608	4, 944
Proportion of theoretical value	0.769	0.782	0.774	0.775	0.776

4.3 Measured load distribution

The SiWIM® system calculates the statistical parameters of the traffic load distribution between the strain transducers on each girder, corresponding to the girder distribution factor (GDF) or the lane distribution factor (LDF). Maximum strains of a few thousand bridge responses under vehicle runs are processed to obtain measured values of these parameters. Figure 12 displays the mean GDF values for the case-study girders. Sensors close to the supports would provide GDF values for shear forces and hogging moments above the supports.

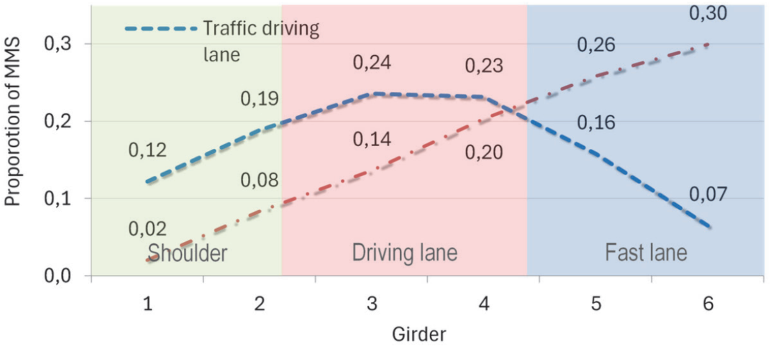

Figure 12 Girder distribution factors for traffic in driving and fast lanes

4.4 Dynamic amplification factor

Despite recording fewer loading events than recommended [29], the DAF distribution corresponded with the anticipated Gumbel-shaped distribution (figure 13). Furthermore, the case-study bridge was highly responsive, with its first natural frequency at 3.1 Hz, close to the frequency of heavy-vehicle bounces. Figure 14 presents these vehicles as high-value DAF points in the GVW range of 200-400 kN. Consequently, the average value of DAF was 1.14, compared to around 1.05 for typical 'quitter' bridges. The 95th percentile of DAF exceeded 1.30, again well above the values observed on quieter bridges. Nevertheless, as with all other measured bridges, the DAF values for the heaviest loading events and the maximum induced strains converged to 1.

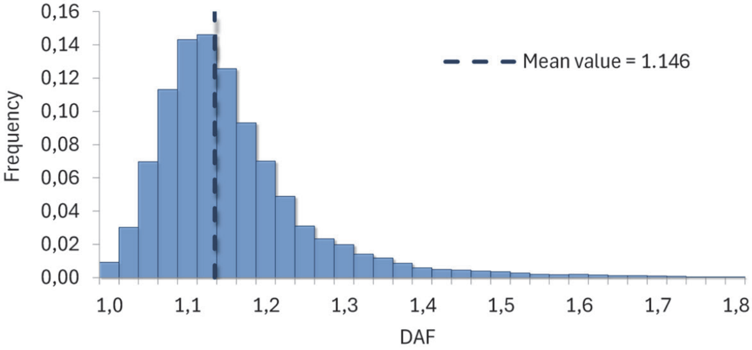

Figure 13 Distribution of measured DAF values on the case study bridge

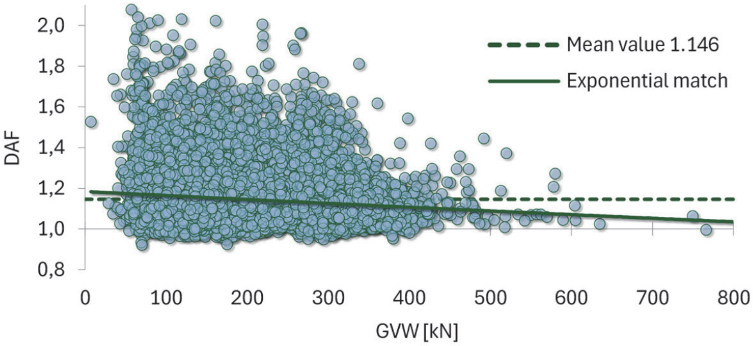

Figure 14 Measured DAF values as a function of GVW

5 B-WIM and model updating

Lately, B-WIM results have been successfully used for FEMU – Finite Element Model Updating [45]. A case study bridge near Ljubljana served as a B-WIM and structural health monitoring (SHM) living laboratory for developing and testing new technologies, sensors, and methodologies. Results from this bridge demonstrated that measured strain ILs, a by-product of B-WIM measurements, offer new opportunities for leveraging B-WIM results in FEMU and SHM applications. Strain ILs have been shown to enhance conventional acceleration and mode shape (MAC) based FEMU results, particularly when assessing bridges under traffic loads.

This finding was validated through an independent comparison of measured vertical mid-span displacements during calibration vehicle crossings, showing strong agreement between the measured results and the strain IL-based updated model. Four independent FEMU studies were performed: frequency-based, MAC-based, frequency-and-MAC-based, and strain-IL-based. Three Young's modulus adjustment factors were updated: for the main girders 1 and 2 (MG1, MG2), and other elements. Combining frequency and MAC-based methods proved more effective than using either alone, producing narrower adjustment ranges. This combined approach yielded moderate increases in stiffness for MG1 (25%) and MG2 (20%), while the strain IL-based method showed larger increases (35% and 50%, respectively). For other elements, the combined method indicated a 10% reduction, whereas the strain IL-based approach suggested a 35% increase in Young's modulus. The independent comparison of measured and modelled vertical mid-span displacements demonstrated that the strain IL-based FEMU model described bridge performance under traffic loading much better than any other model. The authors concluded that care is needed when using FEMU based solely on modal parameters, as misinterpretation can lead to errors. Including strain ILs enhances model accuracy and agreement with measured bridge performance, expanding B-WIM's role in FEMU and SHM.

6 Conclusion

Over the last few decades, B-WIM systems have evolved into important players in the WIM market, serving as traffic data collectors and tools to support optimised bridge assessment and monitoring. Their main advantages are portability, the potential for accurate weighing results, and the ability to install the system without axle detectors, which substantially reduces traffic congestion. Bridge engineers use load tests to validate the structural models. As performing a traditional load test is expensive and requires traffic closures, soft load testing was proposed as a cost-efficient alternative. With the same objective of optimising the structural model based on measured bridge performance under traffic loads, it uses a B-WIM system to collect bridge response information from running traffic rather than from pre-weighed vehicles. B-WIM systems provide axle loads and configurations of all vehicles, which we use to calculate reliable site-specific load models that are far less conservative than those in the design codes. B-WIM systems also measure bridge responses under traffic to calculate the realistic values of the three key performance indicators: influence lines, girder distribution factors, and dynamic amplification factors. If measured, all three reduce the calculated load effects and allow the partial safety factors (β indices) in structural analyses to be reduced. Finally, B-WIM results have been shown to efficiently update finite-element structural models to match the actual performance of bridges.

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