STRUCTURAL ANALYSIS USING BRIDGE WEIGH-IN-MOTION (B-WIM) SYSTEM

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Abstract
The National Department of Transport Infrastructure (DNIT) determines the obligation of a Special Traffic Authorization (AET) for the movement of large loads on Brazilian highways. For infrastructure monitoring there is the Bridge Weigh-In-Motion (B-WIM) system that can highlight the differences in the load capacity analysis that is currently done. Thus, this research proposes the evaluation of a bridge, after instrumentation for 42 days. As a result, for the calculation of the evaluation safety factor through regulations it was 0.94 and for the B-WIM system it was 1.88. It is concluded that in this example, if only the current norms were considered, the AET request would be rejected, which differs from the result obtained by the B-WIM system, where it would be approved. Thus, for the same bridge and same vehicle there would be different results depending on the calculation methodology. The diffusion of the B-WIM technology proves to be effective and safe from the point of view of weighing, traffic control, in addition to the analysis of the resistant capacity of the structures where the installation takes place. In addition, the information obtained by B-WIM can optimize the processes of maintenance and restoration of structures.

Keywords: B-WIM, Structural analysis, Safety factor, Bridges, AET.

1. Introduction

The growing update in vehicle formats and the increase in load capacity, meant that Brazilian highways needed increasingly monitoring. Vehicles with large load capacities can carry divisible or indivisible loads, with a high number of axles and larger dimensions than conventional vehicles. For these vehicles to transit on Brazilian highways, the National Department of Transport Infrastructures (DNIT), determines the obligation of a Special Transit Authorization (AET). During the release of the AET, the DNIT determines the path to be traveled by the loaded vehicle from the origin to the destination, cataloging all the geometry of the road, in addition to the load capacity and dimensions of the bridges and viaducts on the route, so that there is safety.

As for bridges and viaducts, most of the Brazilian structures were built in the 1960s and during the sizing, combinations of axles existing at the time were considered. Loads that exceed the limits considered for design cause fatigue damage to accelerate, which can lead to partial or total failure of the structure. In this line, the bridge support capacity determined in the project tends to decrease or even be null during the life stipulated in the project (Junges, 2017). The evaluation of the resistance capacity and safety factor (rating factor - RF) of the structures are determined by means of regulations and design data. This information, due to the lack of field data, may have resulted in undersized or oversized structures. Another factor to be considered concerns the time difference, since the dimensioned loads no longer correspond to the acting loads.

This increase in transported loads is directly due to the Gross Vehicle Weight (GVW) and estimated and effective weight per axle. Thus, the structures may be receiving loads in excess of those dimensioned in the project, reducing their useful life and causing risks to users, in medium and high intensity. The opposite can also occur, when the cataloging deals with a risk situation, but they present effective resistance and are capable of withstanding the traffic of large loads.

Faced with these issues, Brazil is increasingly investing in methods for monitoring road infrastructure and its components. As for monitoring bridges and viaducts, one of the alternatives is the Bridge Weigh-In-Motion (B-WIM) system. The system was developed by Moses (1979), in the late 1970s, using an algorithm. Through this, it has been used as a way to obtain weighing data and characterization of vehicles, in addition to structural data of bridges and viaducts (Žnidarič et al., 2008). The dynamic weighing system works due to sensors connected under the beams and stringers of the structure. In addition to providing vehicle weight and classification data, they provide additional information that can assist in the structural assessment of bridges (Shinohara, 2019). In general, as the vehicle moves over the structure, the system is able to register the deformation and understand its influence on the weight distribution (Cantero & González, 2017). Through B-WIM, it is possible to assess the safety of the structure and its ability to withstand the levels of loading to which it will be subjected. From the B-WIM it is possible to obtain parameters such as the actual line of influence of the structure and the dynamic amplification factor (DAF) of the vehicles during traffic.

Considering the DNIT's point of view for the release of AETs, it is important to know the structure's resistant capacity so that the route can be traced safely. In this way, accurate knowledge about bridges and viaducts can help the release of AETs that would previously be rejected if only the parameters of the standards were considered, as is currently done. From the instrumentation of the system, the results obtained are compatible with the real ones, discarding the structural undersizing.

The use of the B-WIM system has advantages that favor its use and diffusion, according to Žnidarič & Lavrič (2010) and Žnidarič et al. (2016) who are the pioneering authors in this type of technology. The authors cite as an advantage (i) high precision on uniform surfaces and reasonable accuracy on non-uniform ones; (ii) portability of equipment without reducing precision; (iii) ease of installation of equipment without blocking the road; and (iv) providing structural information on the bridges under analysis.

2. Evaluation of Bridge in Brazil

In Brazil, instrumentation with B-WIM started in 2012, in the state of Santa Catarina, with the installation of sixteen sensors on a reinforced concrete viaduct (ZAG, 2012). Subsequently, three bridges, also in concrete, were instrumented in the state of Goias, using the SiWIM software for analysis of the structure's bearing capacity and traffic monitoring (Junges, 2017). In 2020, the development of Brazilian software for resistant capacity with B-WIM data and focus on analysis of DNIT´s AETs began, with the instrumentation of a concrete viaduct and calibration with trucks with three, five and seven axles. In all installations, the data could be linked with AET release information, providing a safe route for transporting large loads.

The Transport and Logistics Laboratory (LabTrans) of the Federal University of Santa Catarina (UFSC), together with DNIT, has started the development of the Brazilian methodology for inspection and safety assessment of bridges. The aim of the proposal is to verify whether bridges and viaducts are adequate to safely support and resist the levels and effects of prescribed loads, according to the ultimate limit states and the criteria for their satisfaction. Acceptance and validation criteria are still under development, but they are expected to support government in monitoring these structures.

The methodology uses a mixed approach between evaluation by levels and evaluation by partial safety factors. For the determination it is important that the decision and inspection be made for the choice of the bridge to be evaluated and the special inspection carried out. Fundamentally, instrumentation and monitoring are required, such as the installation of sensors and monitoring for a predetermined period. It is also essential for the perfect performance of the system to analyze the safety of the structure, based on the information obtained in the previous phases of structural safety. The instructions used are based on B-WIM techniques.

It is understood that the dissemination of knowledge and technology should be prioritized in the country to guarantee the safety of users during the journey. However, it is important to emphasize that these instruments are expensive and therefore must be carried out in a careful and strategic way. Thus, even if diffusion is occurring slowly, it is essential and must be maintained, as it can be replicated to structures with the same configuration and service condition, even if temporarily.

2.1. Methodology for Structural Assessment

The assessment of the safety of structures can be obtained through the level approach, which occurs theoretically and with complex models. However, this type of evaluation is considered to have significant financial cost and demand time. They should be carried out after initial structural assessments show problems.

The methodology uses a mixed approach between evaluation by levels and evaluation by partial safety factors, being divided into three phases:

- Phase 1: decision and inspection, choosing the structure to be evaluated and carrying out a special inspection.
- Phase 2: instrumentation and monitoring, installation of sensors and monitoring for a predetermined period.
- Phase 3: safety analysis, based on the information obtained in the previous phases of structural safety.

The safety assessment shall verify that the structure is adequate to support and withstand the prescribed levels and effects of loading. Ultimate states and criteria for satisfying the ultimate states of the structure are considered, according to the norm used. This type of evaluation can be carried out, basically, by three approaches: partial safety factor; by levels; mixed.

In the partial factor of safety approach, semi-probabilistic language is used in most normative codes. Its function is to guarantee a safe structure, even though it is not possible to quantify this safety.

As for the approach by levels, this should only be carried out if, after the initial evaluations, the structure presents problems. This determination is made because evaluations in a theoretical way and with complex models are expensive and time-consuming. Thus, they can make the structure unfeasible unnecessarily. Five levels are addressed, with Level 1 being the simplest and Level 5 the most complex, presented as shown in Figure 1.

Figure 1 – Approach levels for evaluating bridges

Another type of approach is carried out by combining factors with assessment by levels. It is considered more efficient, since they are used to optimize the numerical model and obtain important characteristics of the structure. In this approach, the safety level that the bridge presents at that moment is obtained, considering the structure and the incident traffic. The level of safety varies according to the location where the structure is implemented, so those carried out in the same year or with the same methodology can lead to aggregation. In this way, the safety status can be associated with those in a similar situation, expanding the range of assessment and information about the implementation regions.

General principles for structural safety assessment have been developed in various codes (ISO 2394, ISO/CD 13822), in books (Ang & Tang, 1975; Moses & Verma, 1987; Press, et al., 2007), in scientific articles (O'Brien, et al., 2010; Sivakumar & Ibrahim, 2007; Žnidarič et al., 2012), and also in reports (COST 345, 2007; Samaris, 2006; Arches, 2009).

The purpose of assessing the safety of bridges is to verify whether the structure is able to withstand the levels of loading to which it will be subjected. The aim is to identify bridges whose resistance levels are close to their request levels, thus helping in decision-making on the expenditure of resources in intervention actions (maintenance/recovery).

2.2. Safety Factor Calculation (Rating Factor - RF)

For the determination of capacity and load classification of bridges, as-built information was used exclusively for a long time. To obtain more reliable information on imposed traffic load, vibration tests and analysis of real loads can be performed to calibrate finite element models of the structure (AASHTO, 2015).

Another way to keep information about the structure up to date is through inspections. In most countries, this type of close inspection is performed with an interval of typically 2, 3 and 5 years in the United States, China, and Japan, respectively. The condition classification systems used generally do not provide direct information about the remaining load carrying capacity of seriously impaired bridges. Such information is essential for bridge operators to formulate strategies and implement countermeasures such as remediation, reinforcement or enforcement of bridge traffic regulations. Therefore, an in-depth investigation into load-carrying capacity is often required.

Another method of determining the load capacity of structures is given by understanding the performance of permanent and imposed traffic load. Permanent loads are those forces assumed after completion of construction. The imposed traffic loads are attributed to the impacts generated by the traffic on the structure and, therefore, are variable and sometimes seasonally influenced (AASHTO, 2007). The methodology of this article is based on real measurements that feed a numerical model. From this, important structural characteristics are obtained, such as:

- Obtaining the structure's response to the acting load through the construction of the structure's real Influence Line (IL). From the real IL and the load distribution between the stringers (both determined by a B-WIM system), the efforts in each beam can be determined for a truck of known weight. Emphasizing that the IL includes the influence of the stiffness of non-structural elements (such as parapets, slabs and sidewalk concrete), and therefore caution should be exercised in using the real IL.
- Construction and temporal extrapolation of loading caused by traffic, with a 50-year projection.
- Estimation of the real lateral distribution of efforts, with the experimental evaluation of the Dynamic Amplification Factor (DAF).

To obtain these coefficients, it is necessary to perform the B-WIM instrumentation, so that there is data monitoring and reliability. In order for the data obtained to be reliable, it is also necessary to calibrate the system. In this procedure, at each passage of the selected vehicles, the readings of the sensors are obtained.

For validation of the calibration process, at least 10 passes must be performed, with successful measurements, of 3 and 5 axle trucks with known characteristics (weights per axle and their distances). Also during calibration, the impact factor is obtained as a function of vehicle weight, that is, a complex computational response directly determined by the measured deformation signals (measured/static). It is noteworthy that the impact factor is dependent on the coupling of the vehicle to the structure and also on the roughness of the pavement.

The treatment of the collected data is also essential for the information to be accurate. After obtaining this information and other monitoring results, the load RF can be obtained (Zheng et al., 2022). This factor is obtained after load tests and calibration of the structure using the load and resistance factor method, as shown in Equation 1.

$$RF = \frac{\phi \ x \ R_d - \gamma_G \ x \ G_n}{\gamma_Q \ x \ G_Q \ x \ DAF} \tag{1}$$

In which:
- Reduction factor (Φ): obtained by inspecting the structure.
- Section capacity (R_d): obtained by project, inspection or standards.
- Safety factor of permanent load (γ_G): obtained by standards, project or field inspection.
- Permanent load (G_n): obtained by standards, project or field inspection.
- Safety factor of imposed traffic load (γ_Q): obtained by standards, project or field inspection.
- Imposed traffic load (G_Q): obtained from B-WIM monitoring data.
- Dynamic Amplification Factor (DAF): obtained from B-WIM monitoring data.

In addition to the partial safety factors that contemplate requests, in the case of mobile load from traffic, there is a need to consider the dynamic effect of loading through the Dynamic Amplification Factor (DAF). By monitoring the bridge with the B-WIM system, it is possible to obtain the DAF for each vehicle that travels over the structure. The DAF values tend to be inversely proportional to the Gross Vehicle Weight (GVW) of the vehicles, thus, in many studies, the higher the GVW, the lower the dynamic amplification introduced. With monitoring for a sufficient period of time, it is possible to plot a curve that relates GVW and DAF. However, there is still no consensus in the literature on this statement.

3. B-WIM Sensors Instrumentation

An instrumentation procedure was determined for the evaluation of the safety of the structure. This consists of fixing a pre-established number of deformation sensors at the bottom of the structures deck, which are responsible for collecting the signals generated by the passage of vehicles, for calculating the weight of the axles and for determining the classification of the vehicles. The position of fixing the sensors must be defined, a priori, in order to obtain clear, representative signals that characterize the traffic. Three elements were determined for installing the sensors in the structure (Figure 2), namely:

- Underside of stringer (WM): installed in the middle of the span, measuring the bending moment and determining the weight;
- Lateral face of stringer (WC): installed on the support, measuring the shear force and determining the weighing;

- Underside of deck (FAD): installed in the middle of the span and for determining axis deflections.

Figure 2 – Instrumentation position of the B-WIM sensors

After installing the sensors in the structure, the procedures involving the calibration of the B-WIM system to obtain data related to traffic and the structure are started. The calibration process is the most important step during the installation of the monitoring system, as it is during this process that the real Influence Line (IL) of the bridge is obtained, necessary to carry out the correct weighing of the vehicles and to carry out the subsequent evaluation. The calibration uses vehicles with known load and consists of passing over the structure several times and at different speeds. After calibration, the B-WIM system must be in operation for a certain period of time so that there is a characterization of the traffic and efforts that make up that structure.

4. Rating Factor to Release Vehicle Traffic

Based on the RF value, an opinion on its structural safety is given to the structure. In the background, this RF value can also be related to the need for intervention in the structure and its degree of urgency, as shown in Figure 3.

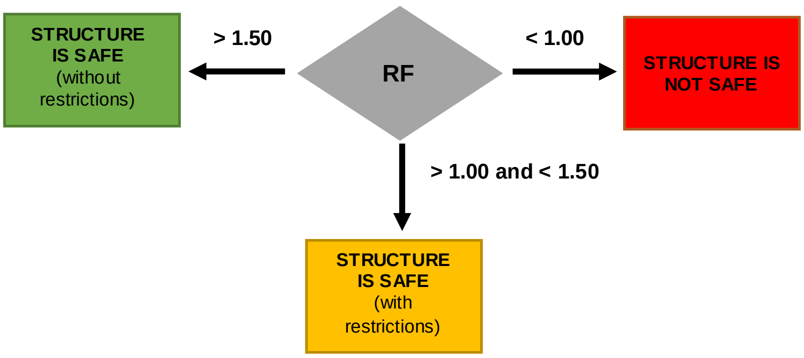


Figure 3 – Correlation attributed to the Rating Factor (RF)

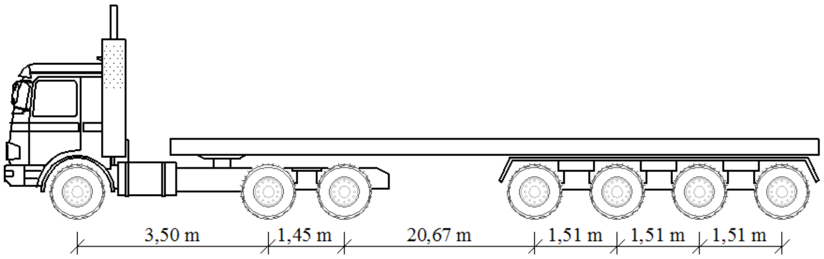
According to the values presented, for structures in which the RF is below 1.0, the decision is that there is inadequate safety in the structure. This notice may lead to secondary actions on the bridge from the point of view of immediate intervention or the need for restoration. This factor is mainly used as a guide for making decisions about interventions in the structure and the degree of urgency. If several structures were under monitoring, based on the indication that one had this value, it would receive priority intervention. In this case, the issuance of AETs by the federal government is not authorized since the structure is not safe.

When values indicative of structure safety range from 1.0 to 1.50 it is considered that the structure presents effective resistance and is compatible with its function and can be used to transport large loads. Even if there is a safety indication, it is important that care is also taken into account, from the point of view of maintenance and restoration. In the case of authorization of AETs, this can be authorized, however, there must be caution and studies regarding decision-making.

As for RF values above 1.0 they indicate that the structure is safe with regard to requests for large loads and, in the case of AET releases, it can be recommended without restrictions. The maintenance period must be maintained as scheduled for the structure to remain stable and safe.

4.1 Example of RF Calculation and the Impacts of using B-WIM

As an example of application, a truck that needs a Special Traffic Authorization (AET) to travel on a highway with high traffic volume in Brazil is checked. The first example considers that the truck will travel over a reinforced concrete bridge that is instrumented with the B-WIM system. From the monitoring of this bridge with the system, information will be obtained such as the real Influence Line (IL), the transverse distribution of loads and the DAF. The truck used has a combined GVW (tare + load) of 69.5 tonne, distributed over 7 axles and presents configuration and loads as shown in Figure 4.



	TRACTION UNIT			SEMI-TRAILER				TOTAL
AXLE	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	
AXLE SPACING (m)	3.50	1.45	20.67	1.51	1.51	1.51		**30.15**
WEIGHT OF THE AXLES (tonne)	7.50	11.00	11.00	10.00	10.00	10.00	10.00	**69.50**

Figure 4 – Vehicle data used in the example

Some considerations were used in the example, the first is that as the truck has a GVW lower than 288 tonne, there is the possibility that another truck is crossing the bridge at the same time. Therefore, for the purposes of releasing the AET, the combined effect of the special vehicle with the type vehicle of NBR 7188 (2013) must be considered. The maximum bending moment is obtained using the real IL when the center of the semi-trailer axles is over the middle of the bridge's central span, that is, at the peak of the IL. Considering that the traction unit has already left the bridge, it can be said that its axes (E1 to E3) do not introduce efforts. For this case, the maximum effort for this 7-axle truck is equal to 862.5 kNm. In turn, the standard vehicle, when positioned in the middle of the central span, introduces a maximum bending moment equal to 1,024.0 kN. In this way, the maximum variable effort G_Q is equal to 1,886.5 kNm (862.5+1,024.0). From these definitions, the combined GVW values are assigned to this truck and the insertion in the DAF equation, the value of 1.13 is reached (Figure 5).

Φ	γ_G	γ_Q	G_n (kNm)	G_Q (kNm)	DAF	R_d (kNm)
0,85	1,2	1,3	1.326,3	1.886,5	1,13	3.273,0

Figure 5 - Combined GVW values (bridge instrumented with B-WIM)

Reinforcing that γG is safety factor of permanent load and γQ is safety factor of imposed traffic load, the application of the parameters involved in the calculation of the RF is shown in Equation 2.

The numbers in Equation 2 are obtained from projects, fields inspection, standards or from B-WIM monitoring data as explained in Equation 1.

$$\text{RF} = \frac{0,85\ x\ 3,273-1.2\ x\ 331.57}{1.3\ x\ 862.13\ x\ 1.13} = 1,88 \quad (2)$$

Considering the values of the example presented and with the monitoring data, the RF value was 1.88. Thus, using the criteria defined for RF, this structure fits as safe, with a value greater than 1.0. In this way, in the case of AET requests for vehicle traffic with this configuration of axles on the bridge, it would be authorized. That is, DNIT can authorize vehicle traffic on this road route using this bridge.

Using the same vehicle, a second example was performed. This time, the results of the behavior of the structure were checked if there was no B-WIM instrumentation and only standardized values were used. In this case, the evaluation can be done using theoretical data for criteria such as IL and DAF. In addition, the coefficients of increase of permanent and imposed efforts are also referenced to the norms of the time of construction of the structure. From these definitions, the combined GVW values are maintained, that is, when inserted into the DAF equation, they result in 1.33. The other resulting values are shown in Figure 6.

Φ	γ_G	γ_Q	G_n (kNm)	G_Q (kNm)	DAF	R_d (kNm)
0,85	1,54	1,5	1.326,3	1.207,5	1,33	3.273,0

Figure 6 - Combined GVW values (bridge with standardized values)

Reinforcing that γG is safety factor of permanent load and γQ is safety factor of imposed traffic load, the application of the parameters involved in the calculation of the RF is presented in Equation 3. The numbers in Equation 3 are obtained from projects, fields inspection, standards or from B-WIM monitoring data as explained in Equation 1.

$$\text{RF} = \frac{0{,}85\ x\ 3{,}273 - 1.54\ x\ 331.57}{1.5\ x\ 1{,}207.5\ x\ 1.33} = 0{,}94 \tag{3}$$

From the results with standards values, the RF value resulted in 0.94. That is, considering the criteria defined for RF, this structure is not safe as it has a value less than 1.0. For these values, AET requests for traffic from vehicles with this axle configuration on the bridge are refused. That is, for the DNIT criteria, the path must be changed because there is no traffic safety in that region.

Thus, it is concluded that a vehicle may or may not be allowed to travel on the bridge depending on the methodology used by Authority. Currently, high safety coefficient values are used, underestimating the capacity of the structure. This is good, as it is in favor of safety, but it refuses the AET and the vehicle's transit on a bridge, forcing it to look for alternative routes, even though the structure is able to support it.

5. Final Considerations

The Brazilian road network operated by DNIT has structures of different configurations and states of conservation. Most of these, as they were built in the 1960s, need to be constantly evaluated in terms of structure in order to maintain their safety conditions. As a way of monitoring these structures and classifying them in terms of structure, this article briefly presents the Brazilian methodology for inspection and safety evaluation of a bridge.

The methodology project is still being developed by LabTrans at UFSC and includes the assessment of bridge safety; the carrying capacity of the critical cross-section; the capacity reduction factor; the effort increase factors; and permanent and imposed traffic load. In addition to the resistant capacity, a result related to its safety is also attributed to the structure based on the RF coefficient. These values can be related to another emerging demand from the Brazilian government, the release of AETs on routes with intense traffic in the road network. The use of the B-WIM system to determine the values of imposed traffic loads on the structure becomes decisive for the Brazilian Methodology. From the values derived from the B-WIM system, one has full functional and structural knowledge of the bridge and also its behavior in vehicle traffic.

To affirm the importance of using the B-WIM system, a reinforced concrete bridge was instrumented with sensors and evaluated with the passage of a seven-axle truck. Initial inspections were carried out on the structure and an example evaluated the difference in the RF result using the B-WIM system and without it, that is, with coefficients derived from regulations at the time of construction of the structure. The RF result was then related to the release of AET for that structure. As a result, using the values of the B-WIM system, the structure presented RF of 1.88 and without the system, of 0.94. A value of 1.88 would confirm the safety of the bridge, its resistant capacity and the release of AET in this stretch. However, the value of 0.94 indicates inadequate safety and the unfeasibility of the AET. That is, from this example it is perceived the need for instrumentation and detailed knowledge about the structures that make up the Brazilian road network. Since, considering the normalized values, the AET would be denied on this route, having to be carried out and sometimes causing greater expenditure of resources for the vehicles that would like to use that route.

The values with B-WIM prove that the structure presents resistance and safety compatible with the requested one, and must release the AET. That is, sometimes the use of standardized coefficients can reject the release of AETs in structures that present resistance and that should be released. This lack of knowledge on the part of the Brazilian government, regarding the real safety capacity of the structures, can increase budgetary expenditures. The developed Brazilian methodology can also help in the identification of structures that need immediate intervention to maintain safety. Thus making the process streamlined and targeted. The procedures presented are still under development by LabTrans/UFSC and seek to increase its network of experiments and tests for mapping the Brazilian road network in an effective and fast way.

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