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Assessing Accuracy of Bridge Weigh-in-Motion on Least Favorable Bridge Type: Voided Slab Bridge Case Study

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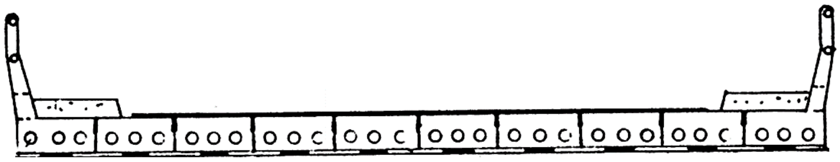
Abstract. The Bridge Weigh-in-Motion (B-WIM) system is a non-destructive means of gathering traffic loading information, using an existing bridge as a weighing scale to determine the weights of vehicles passing over it. This system can be applied to almost any type of bridge, provided that the distance between the two furthest points affecting the measurement, known as the influence line, is less than about 40 m. In this study, the B-WIM method was tested on a least favorable type of bridge, namely a single-span voided concrete slab bridge, located in a heavy industrial truck traffic area between Cikande and Rangkasbitung, Indonesia. The accuracy of the B-WIM system was evaluated using the calibration procedure regulated in European COST 323, which categorizes the accuracy class of a WIM measurement. The results showed that the average deviation for the gross vehicle weight of vehicles passing over the bridge was less than 10%. Thus, it was concluded that the B-WIM system can provide accurate measurements of vehicle weight, with accuracy class B(10). This study provides valuable information for transportation authorities and bridge engineers, particularly in areas where the ideal type of bridge for B-WIM measurements is not available. It also highlights the importance of regularly monitoring and evaluating the accuracy of B-WIM systems to ensure reliable data for transportation planning and infrastructure design.

Keywords: *Bridge Weigh-In-Motion (B-WIM); voided slab bridge; dynamic amplification factor (DAF); accuracy class; calibration procedure.*

1 Introduction

Bridge weigh-in-motion (B-WIM) systems have revolutionized the way traffic loading information is gathered. Instead of traditional destructive means of weighing vehicles, B-WIM systems use existing bridges or culverts as weighing scales to determine the weight of vehicles passing over them [1]. The B-WIM concept can be applied to almost any type of bridge, as long as the distance between the two furthest points that affect the measurement, known as the influence line, is less than 40 m [2]. The types of structure used range from short culverts to beam-and-slab and orthotropic deck bridges. In Indonesia, B-WIM is used to measure vehicles passing through bridges based on specific selection criteria [3]. However, the ideal bridge type may not always be available in road sections that require traffic load measurements. For example, in the national road section between Cikande and Rangkasbitung, only three bridges are available within the span length criteria, consisting of a voided slab bridge and two truss bridges. However, truss bridges are not suitable for B-WIM measurements due to their bridge reaction being mainly distributed on steel trusses as axial force, and not bending moment force like girder or culvert bridges [4]. Similarly, the connection between individual voided slabs in a voided slab bridge is weak laterally, making it the least favorable option for B-WIM [5].



a. Cross-section

b. Bottom view

Figure 1 Ciliweut-Nameng 3 Bridge

Given that the only option available for B-WIM in the national road section between Cikande and Rangkasbitung is the Ciliweut-Nameng 3 Bridge, which is a single span voided concrete slab bridge, consisting of 9 individual voided slabs with a total width of 7.1 m and span length of 8.5 m, a B-WIM one-year measurement was conducted to determine overloading vehicles in this heavily industrialized truck traffic area. This bridge, as depicted in Figure 1, is the least favorable type for B-WIM due to its weak lateral connection between individual voided slabs. However, it was interesting to test the accuracy of the B-WIM method using this type of bridge.

To determine the accuracy of the B-WIM system, a calibration procedure was carried out according to the European COST 323 regulation [6]. This regulation categorizes the accuracy class of a WIM measurement. In this study, the average percentage difference between the statically known vehicle data, such as gross vehicle weight, single axle weight, axle group weight, vehicle speed, and distance between axle, with the B-WIM measurement data was calculated for a minimum of 10 passes over the bridge.

This paper investigates the accuracy of B-WIM when using a voided slab bridge for traffic load measurement. The voided slab is the least favorable type of bridge for B-WIM due to its weak connection laterally between individual voided slab. However, in some cases, this type of bridge may be the only option for traffic load measurement. Therefore, this study aims to evaluate the accuracy of the B-WIM system using a voided slab bridge and to calculate the dynamic amplification factor due to heavy vehicle traffic in the area. By exploring the behavior of the voided slab bridge under heavy loading, this study will contribute to a better understanding of the use of B-WIM on this type of bridge and provide insights into the structural response of the bridge.

2 Voided slab bridge as the least favorable type of bridge for B-WIM

Voided slab bridges have been widely used in various road networks, particularly in low and medium volume roads, as they offer numerous advantages over conventional solid slab bridges, such as lower weight, material saving, and better performance in seismic regions. Voided slabs' primary purpose is to reduce the volume of the concrete and, as a result, the slab's self-weight. If properly designed, it can lower the self-weight of the slab by up to 35% for the same section and span when compared to a solid slab [5]. However, their design and structural behavior under loading are considerably more complex than those of conventional solid slab bridges. One of the issues related to voided slab bridges is their behavior under dynamic loading, particularly under heavy vehicle traffic [7].

B-WIM is an emerging technology that provides a non-destructive means of gathering traffic loading information by using an existing bridge as a weighing scale to determine the weights of vehicles passing over [6]. However, the accuracy of the B-WIM system is heavily influenced by the bridge type, and not all bridge types are suitable for B-WIM measurements. In particular, voided slab bridges are considered the least favorable type of bridge for B-WIM measurement due to their weak connection laterally between individual voided slabs, which could affect the accuracy of the measurement.

Various studies have been conducted to evaluate the accuracy of B-WIM measurements using different types of bridges, which are categorized as favorable in COST323, such as PCI girder bridge, steel composite girder, box culvert bridge, and reinforced concrete girder bridge [8]. These studies have shown that the accuracy class of B-WIM measurements for these types of bridges can range from A(5) to B+(7) [1]. However, the accuracy is heavily influenced by the bridge surface and the condition of the bridge approach pavement. Despite the promising results, there is limited research on the accuracy of B-WIM measurements using the least favorable type of bridge, the voided slab bridge. Their use can still be justified in certain situations, particularly when no other bridge types are available. Hence, this study aims to evaluate the accuracy of B-WIM measurements on a voided slab bridge. Additionally, this study aims to explore the dynamic amplification factor of the bridge due to heavy vehicle traffic to understand the behavior of the voided slab bridge under heavy loading.

3 Methodology

3.1 Evaluation of B-WIM measurement accuracy using calibration procedure

This study employed a quantitative research design to evaluate the accuracy of Bridge-Weigh In Motion (B-WIM) measurements on voided slab bridges. The evaluation of B-WIM measurement accuracy is a critical step to ensure the reliability and validity of the measurement. The calibration procedure used to evaluate the B-WIM measurement accuracy is described in the COST 323, which categorizes the accuracy classes of a WIM measurement. After installation, a WIM system must undergo initial calibration using a pre-weighed vehicle or truck, as shown in Fig. 2, that has been weighed using static weighing scales. The data measured using static scales include GVW, single axle load, one of the group axle loads, and axle group load, along with inter-axle distance. The pre-weighed truck then passes over each line of the WIM systems a minimum of 10 times [6]. The average percentage difference between the static data and the WIM measurement data for those 10 measurements is then calculated and compared to the tolerances of the accuracy classes as depicted in Table 1 from COST 323.

This calibration procedure is crucial in determining the accuracy class of the B-WIM measurement and ensuring the reliability and validity of the WIM system.

Table 1 Tolerances of the accuracy classes (δ in %)

Criteria (type of measurement)	**Domain of use**	**Accuracy Classes: Confidence interval width δ (%)**						
		A (5)	**B+ (7)**	**B (10)**	**C (15)**	**D+ (20)**	**D (25)**	**E**
1. Gross weight	Gross weight > 3,5 t	5	7	10	15	20	25	>25
Axle load:	Axle load > 1 t							
2. group of axles		7	10	13	18	23	28	>28
3. single axle		8	11	15	20	25	30	>30
4. axle of a group		10	14	20	25	30	35	>35
Speed	V>30 km/h	2	3	4	6	8	10	>10
Inter-axle distance		2	3	4	6	8	10	>10

Figure 2 Pre-weighed truck for calibration

The calibration procedure was carried out using a preweighed 3-axle truck with a 1-2 axle configuration, weighing 39.52 tons with axle distances of 4.4 m and 1.3 m between the first and second axles and between the second and third axles, respectively. The truck was weighed using portable static scales, and its individual axle distance was measured using a measurement tape.

3.2 Dynamic amplification factor and its calculation

The Dynamic Amplification Factor (DAF) is commonly used to account for the dynamic component of bridge traffic loading. It is the ratio between the dynamic and static load effects on a bridge [9]. To account for such effects, a common practice is to apply a DAF as follows: R Dynamic = (1 + DAF) × R Static. In which R Dynamic is the dynamic response of the bridge, R Static is the static response of the bridge, and DAF is the dynamic amplification factor [10].

A new method of obtaining DAF experimentally, using bridge weigh-in-motion (B-WIM) measurements, has been developed. Different bridge sites have been used to evaluate DAF with this proposed method. The results agree with numerical simulations and experiments performed in the ARCHES project: dynamic amplification decreases as static loading increases [11]. The reason is that extreme loading events, which include several heavy trucks with many axles, induce far smaller dynamic amplification than lighter individual vehicles [12].

4 Results and Discussion

4.1 B-WIM on voided slab bridge accuracy

The results of the study revealed several important findings regarding the accuracy of B-WIM measurements on voided slab bridges and the DAF associated with heavy loading conditions. Firstly, the B-WIM measurements on the voided slab bridges demonstrated a relatively acceptable accuracy level for GVW measurements. The average percentage difference between the B-WIM measurements and the static weighing measurements for the GVW fell within the acceptable range for the B(10) accuracy class defined in the COST 323 guidelines. This indicates that the B-WIM system on the voided slab bridges effectively captured and measured the total weight of the passing vehicles.

Table 2 Calibration statistic results (δ in %)

Parameters	Lane 1			Lane 2		
	GVW	Group	Single	GVW	Group	Single
N		14			16	
Mean	0.00	1.70	-8.75	0.00	-0.65	3.36
St Dev	3.30	4.39	8.40	3.04	3.81	11.84
Delta δ Crit.	9.61	10.34	25.14	8.79	8.13	30.10
Delta δ Class	10	15	30	10	10	35
Class	B(10)	C(15)	E(30)	B(10)	B(10)	E(35)

The calibration results for the B-WIM system on the voided slab bridge are presented in Table 2. In the first lane of the bridge leading to Rangkasbitung, the preweighed truck passed over the bridge 14 times for calibration purposes. The results showed that the GVW measurement had a delta of 9.61% with a standard deviation of 3.30, meeting the accuracy class requirement of B(10) according to the COST 323 guidelines. However, the accuracy for group axle load measurements and single axle load measurements was lower. The delta result for group axle load measurement was 10.34% with a standard deviation of 4.39, meeting the accuracy class requirement of C(15) according to COST 323. On the other hand, the delta result for single axle load measurement was 25.14% with a standard deviation of 8.40, meeting the accuracy class requirement of E(30) according to COST 323.

In the second lane of the bridge, which goes to Cikande, the calibration procedure was also conducted and the results are shown in Table 2. The preweighed truck passed over the bridge 16 times for calibration purposes. The results indicated that the GVW measurement had a delta of 8.79 with a standard deviation of 3.04, meeting the accuracy class requirement of B(10) according to COST 323. Notably, the delta results for group axle measurements in this lane showed better accuracy, with a delta of 8.13 and a standard deviation of 3.81, meeting the accuracy class requirement of B(10) according to COST 323. However, the single axle measurements exhibited a lower accuracy class, with a delta of 30.10 and a standard deviation of 11.84, only meeting the accuracy class requirement of E(15) according to COST 323.

The results of the study indicate that the Bridge-Weigh In Motion (B-WIM) system installed on the voided slab bridges effectively captured and measured the total weight of passing vehicles. However, when focusing on the accuracy of B-WIM measurements for individual axle loads, the findings revealed a lower level of precision compared to the Gross Vehicle Weight (GVW) measurements. The percentage difference for group axle loads and single axle loads exceeded the tolerances specified for higher accuracy classes, such as C(15) and E(30) respectively, according to the COST 323 guidelines. These results suggest that the B-WIM system on the voided slab bridges may encounter difficulties in accurately capturing axle-specific weight information. One potential explanation for this discrepancy could be the placement of the axle detection sensors below the voided slab, which might not directly sense the axle response due to the presence of a void between the upper slab of the bridge and the lower flange of the voided slab. This leads to a greater level of uncertainty in the measurement of single axle load compared to GVW.

In contrast, other favored B-WIM system bridge types, such as girder bridges or culverts, install the axle detection sensor on the bottom surface of the slab, which is directly influenced by contact of the vehicle. Therefore, the accuracy of B-WIM system in measuring single axle load on the voided slab bridge is lower compared to other favored bridge types. Further research could explore alternative sensor placement methods or modifications to the voided slab design to improve the accuracy of B-WIM system in measuring single axle load on this type of bridge.

4.2 DAF measurement from B-WIM on voided slab bridge

The DAF analysis provided insights into the behavior of the voided slab bridges under heavy loading conditions. using The average DAF value of 1.27 with a standard deviation of 0.24, indicating higher variation and a higher value on lighter vehicles as shown in Fig.3. Conversely, heavier vehicles produced a lower average DAF with lower variation, which is in line with the Danish Code RBBD [13] and highlight the importance of considering dynamic effects in bridge design and maintenance practices.

Compared to other bridge types, the DAF results for the voided slab were generally higher, indicating a significant dynamic effect on the bridge. This could potentially affect B-WIM measurement accuracy, which was calculated using static weighing as references. It is crucial to acknowledge that dynamic effects can play a crucial role in bridge response, amplifying the loading acted upon the bridge. Therefore, it is essential to consider the dynamic effects in B-WIM measurement accuracy assessment to ensure reliable data collection and analysis.

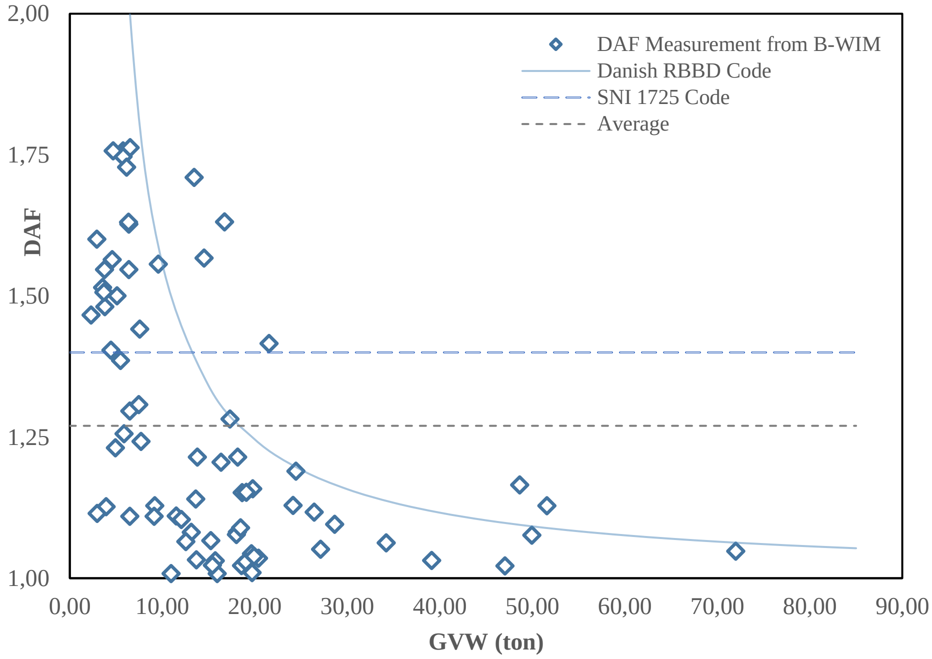


Figure 3 DAF measurements based on B-WIM data on voided slab bridge

The results of this study emphasize the satisfactory accuracy of B-WIM measurements for the total weight of vehicles on voided slab bridges. However, caution should be exercised when using B-WIM systems on voided slab bridges to measure individual axle loads, as the accuracy may be compromised. The analysis of the dynamic amplification factor underscores the significance of accounting for dynamic effects in the behavior of voided slab bridges under heavy loading conditions. Future research should focus on further improving the accuracy of axle load measurements and exploring potential modifications to the B-WIM system placement on voided slab bridges. These findings contribute to enhancing the understanding and application of B-WIM technology for voided slab bridges in the field of bridge engineering.

5 Conclusion

This research aimed to evaluate the measurement accuracy of B-WIM system installed on a voided slab bridge and to determine the dynamic amplification factor (DAF) using B-WIM measurements. The study used a calibration procedure that involved a pre-weighed truck that passed over the B-WIM system a minimum of 10 times. The study found that the accuracy of B-WIM measurements varied depending on the type of measurement taken. GVW measurements were found to be more accurate than single axle load measurements. The calibration procedure using a pre-weighed truck and repeated measurements show that the system meets the B(10) accuracy class for GVW and group axle load, while single axle load measurement has a lower accuracy class of E(30) and E(15) for the first and second lane, respectively. The study also found that the DAF for the voided slab bridge was higher compared to other bridge types.

The study concludes that the B-WIM system can be used to measure overloading vehicles on a voided slab bridge to certain extent of accuracy class B(10) for GVW measurement, despite it being considered the least favorable bridge type. However, the dynamic amplification factor (DAF) calculated using the B-WIM system showed higher values for the voided slab bridge compared to other bridge types, which may affect the accuracy of the B-WIM measurements as they are calibrated using static weighing as a reference. Therefore, it is recommended that future research investigates the effect of dynamic loading on B-WIM measurements and how to incorporate it into the calibration procedure to improve the accuracy of the measurements. Additionally, future research could explore the use of other B-WIM system configurations or sensors to improve the accuracy of single axle load measurements in voided slab bridges.

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