A New Model for Dynamic Amplification Factor from B-WIM Data in Indonesia

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Abstract

In recent years, Indonesia has rapidly developed Bridge Weigh-In-Motion (B-WIM) systems for measuring vehicle loads, now having at least ten permanent stations. These systems collect data on the dynamic loads vehicles acts on bridges, which differ from static loads. Dynamic loads can increase the impact of a vehicle's weight on a bridge, known as dynamic load amplification, which must be considered in bridge design for safety. The Dynamic Amplification Factor (DAF) is used in design to adjust for these effects. This study evaluates the DAF using data from ten B-WIM systems in Indonesia. By analyzing the bridge's response to vehicles with strain sensors, the study found a consistent pattern: heavier vehicles have lower DAF values. A new DAF model based on gross vehicle weight was proposed, which proved more accurate and efficient than current standards. This model can improve bridge design by providing lower, more precise DAF values, better reflecting the actual dynamic behavior of bridges under varying vehicle loads.

Keywords: bridge design code, dynamic amplification factor (DAF), Bridge Weigh-in-Motion (B-WIM), gross vehicle weight (GVW), heavy vehicle.

1 Introduction

Bridge design requires meticulous consideration of various load conditions to ensure safety and durability throughout its designated service life. Among these, dynamic loads caused by moving vehicles play a crucial role, as they differ significantly from static loads. Dynamic loads amplify the static weight of vehicles acting on a bridge, a phenomenon referred to as dynamic load amplification (1). If not accurately accounted for, these amplified loads can compromise the structural performance of bridges, particularly under conditions of high traffic or heavy vehicle loads. Therefore, addressing dynamic load amplification is an essential aspect of bridge design.

To accommodate the effects of dynamic load amplification, the Dynamic Amplification Factor (DAF) is introduced in bridge design as a multiplier for the standard live load (2). In Indonesia, the SNI 1725:2016 standard specifies DAF values ranging from 30% to 40% of the static vehicle load, depending on bridge span length (3). However, these values are based on consensus and references to international standards, such as the AASHTO LRFD Bridge Design Specifications (4), Bridge Management System (5), and Canadian Highway Bridge Design Code (6), rather than localized data. As a result, current DAF provisions may not fully reflect the actual dynamic behavior of bridges in Indonesia under varying vehicle loads.

In recent years, Indonesia has rapidly adopted Bridge Weigh-In-Motion (B-WIM) technology to measure vehicle loads dynamically while the vehicles moving (7), with at least ten permanent B-WIM stations currently in operation (8). These systems provide valuable data on the dynamic responses of bridges under real traffic conditions, offering an opportunity to develop a more accurate and efficient DAF model based on Indonesia's context. This study utilize data from four B-WIM systems across Indonesia to analyze the relationship between DAF and vehicle gross weight (GVW).

The primary objective of this research is to propose a new DAF model based on GVW, which provides lower and more precise values compared to existing standards, while maintaining safety and structural performance. By refining DAF calculations through actual measurements, this study aims to improve bridge design efficiency and contribute to the update of SNI 1725:2016 DAF provision, aligning it more closely with local traffic and infrastructure conditions.

2 Dynamic Amplification Factor

Dynamic loads occur when vehicles traverse a bridge, introducing additional forces beyond their static weight due to factors such as vehicle speed, bridge surface conditions, and vehicle-bridge interaction. This phenomenon, known as dynamic load amplification, can significantly impact the internal forces and stresses within a bridge structure. The Dynamic Amplification Factor (DAF) is used in bridge design to account for these effects by amplifying the standard live load. Studies have shown that dynamic amplification is influenced by multiple factors, including vehicle gross weight (GVW), bridge span length, surface roughness, and the interaction between vehicle frequency and bridge natural frequency (9). Failure to accurately incorporate these effects into design calculations can lead to underestimation of loads and potential structural vulnerabilities.

2.1 Existing Standards for Dynamic Amplification Factor

In Indonesia, SNI 1725:2016 serves as the primary standard for bridge loading and specifies DAF values ranging from 30% to 40%, depending on the bridge span length. These values are derived from international standards, such as the Canadian Highway Bridge Design Code (CSA 2012), which similarly accounts for dynamic effects based on empirical and theoretical considerations. However, the SNI provisions are based on generalized assumptions and limited localized data, leading to potentially conservative values that may not reflect the actual dynamic behavior of bridges in Indonesia. The Canadian standards, for instance, consider factors such as vehicle-bridge resonance, road surface irregularities, and span length, but their application to Indonesia’s specific bridge and traffic conditions remains limited.

2.2 Role of Bridge Weigh-In-Motion (B-WIM) Technology

Bridge Weigh-In-Motion (B-WIM) technology has emerged as a critical tool for understanding dynamic loads on bridges. As shown in Figure 1 for site ID001, B-WIM systems utilize strain transducer sensors installed on the bridge structure to capture the strain response generated by passing vehicles, allowing for the calculation of both static and dynamic loads.

Figure 1. B-WIM Strain transducer sensors (Site ID001)

Previous studies have demonstrated the effectiveness of B-WIM in capturing real-time data, allowing for a more accurate calculation of DAF. For instance, research in Europe and North America has utilized B-WIM data to develop localized DAF models that account for regional traffic and bridge conditions (10). However, similar efforts in

Indonesia remain limited, despite the increasing adoption of B-WIM systems in the country.

3 Methodology

This study utilized data from four Bridge Weigh-In-Motion (B-WIM) systems located at strategic bridges in Indonesia to evaluate the Dynamic Amplification Factor (DAF). The selected locations represent diverse traffic conditions and bridge settings across both national and toll road networks. The sites include Jembatan Pawiro Baru (ID001) on the Central Java North Coast national road, Jembatan Lubuk Serasa (ID002) on the South Sumatra East Coast national road, Jembatan Kaligawe (ID004) on the Semarang Toll Road, and Jembatan Surabaya (ID006) on the Surabaya-Gempol Toll Road. Data were collected over a continuous seven-day period, from October 17, 2024, to October 23, 2024. Each B-WIM system measured the structural response of the bridge to passing vehicles, capturing dynamic and static loads using strain transducer sensors installed on the bridge girders.

The Dynamic Amplification Factor was calculated as the ratio of the dynamic response of the bridge, including vehicle-induced vibrations, to the static response. Strain data collected by the sensors were processed using the Moses algorithm to separate the dynamic and static load components (11). This allowed for the calculation of the DAF for each passing vehicle, alongside corresponding gross vehicle weight (GVW) and vehicle speed. To analyze the influence of GVW on DAF, vehicles were categorized into two groups: light vehicles with a GVW less than 25 tons and heavy vehicles with a GVW of 25 tons or greater. This classification helped to identify the varying effects of dynamic load amplification across different vehicle types.

Using the processed data, a new DAF model was developed based on the relationship between GVW and DAF. The model employed a bilinear approach, utilizing separate equations for light and heavy vehicles to reflect the observed behavioral transition at the 25-ton GVW threshold. The model was further analyzed and compared with the provisions in SNI 1725:2016, which currently specify DAF values ranging from 1.3 to 1.4. The comparison demonstrated that the proposed model provides a more accurate and efficient representation of actual bridge behavior under dynamic loading conditions. In addition, validation of the proposed model was conducted using statistical methods to ensure reliability in practical bridge design applications.

4 Results and Discussions

The measurement results of Dynamic Amplification Factor (DAF) from four B-WIM sites are summarized in Table 1, with the relationships between DAF and Gross Vehicle Weight (GVW) displayed in Figure 2, and DAF versus vehicle speed shown in Figure 3. The data highlights significant variations in DAF behavior across the sites, reflecting the influence of traffic and structural conditions at each location.

Table 1. DAF Result Statistics

Parameter	**Site ID number**			
	ID001	**I002**	**ID004**	**ID006**
Mean	1.18	1.25	1.16	1.14
Variance	0.01	0.03	0.02	0.01
Std.Deviation	0.11	0.18	0.15	0.10
Coef. Of Variation	0.09	0.14	0.13	0.09
Percentile				
Min	1.02	1.00	0.05	1.00
5%	1.05	1.05	1.01	1.01
10%	1.07	1.07	1.03	1.02
25% (Q1)	1.10	1.12	1.07	1.06
50%	1.15	1.19	1.12	1.13
75% (Q3)	1.23	1.34	1.22	1.19
90%	1.34	1.54	1.32	1.27
95%	1.38	1.59	1.40	1.31
Max	1.69	1.89	1.79	1.68
Nominal	*1.35*	*1.51*	*1.38*	*1.30*

Table 1 presents the key statistical parameters for DAF across the four sites. ID002 (Jembatan Lubuk Serasa) has the highest mean DAF at 1.25, followed by ID001 (Jembatan Pawiro Baru) at 1.18, ID004 (Jembatan Kaligawe) at 1.16, and ID006 (Jembatan Surabaya) at 1.14. This pattern suggests that ID002 experiences greater dynamic effects, potentially due to higher variability in vehicle weights or structural conditions. Variance and standard deviation values also follow a similar trend, with ID002 has the largest variability (variance of 0.03

and standard deviation of 0.18), while ID006 shows the least variability (variance of 0.01 and standard deviation of 0.10).

The coefficient of variation (CoV) provides information about the relative variability of DAF values compared to the mean. Both ID001 and ID006 have the smallest CoVs at 0.09, indicating more consistent DAF behavior, while ID002 (CoV = 0.14) and ID004 (CoV = 0.13) show higher variability. The range of DAF values, as indicated by the minimum, maximum, and percentile distributions, further supports these observations. ID002 has the widest range of DAF values, with a minimum of 1.00 and a maximum of 1.89, whereas ID006 displays the narrowest range, from 1.00 to 1.68.

The nominal DAF, calculated as the mean plus 1.5 times the standard deviation, reflects the upper limit of DAF values for 90-95% of cases and serves as a reference for design considerations. ID002 has the highest nominal DAF at 1.51, followed by ID004 at 1.38, ID001 at 1.35, and ID006 at 1.30. These values align with the observed variability and mean trends at each site.

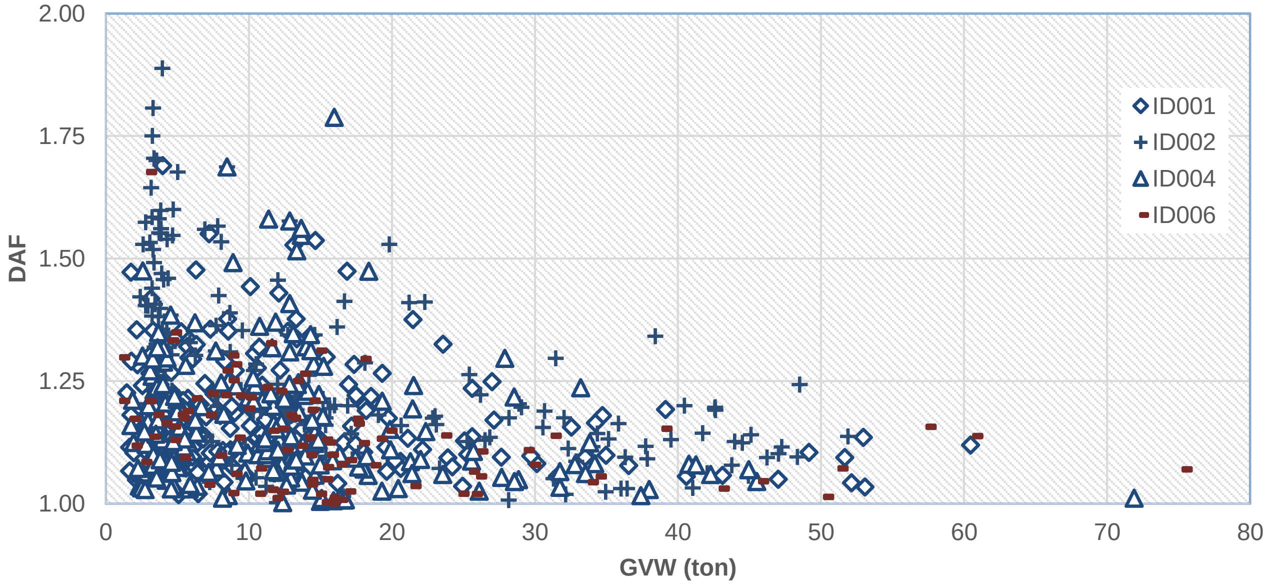

Figure 2. DAF vs GVW for B-WIM ID001, ID002, ID004, and ID006

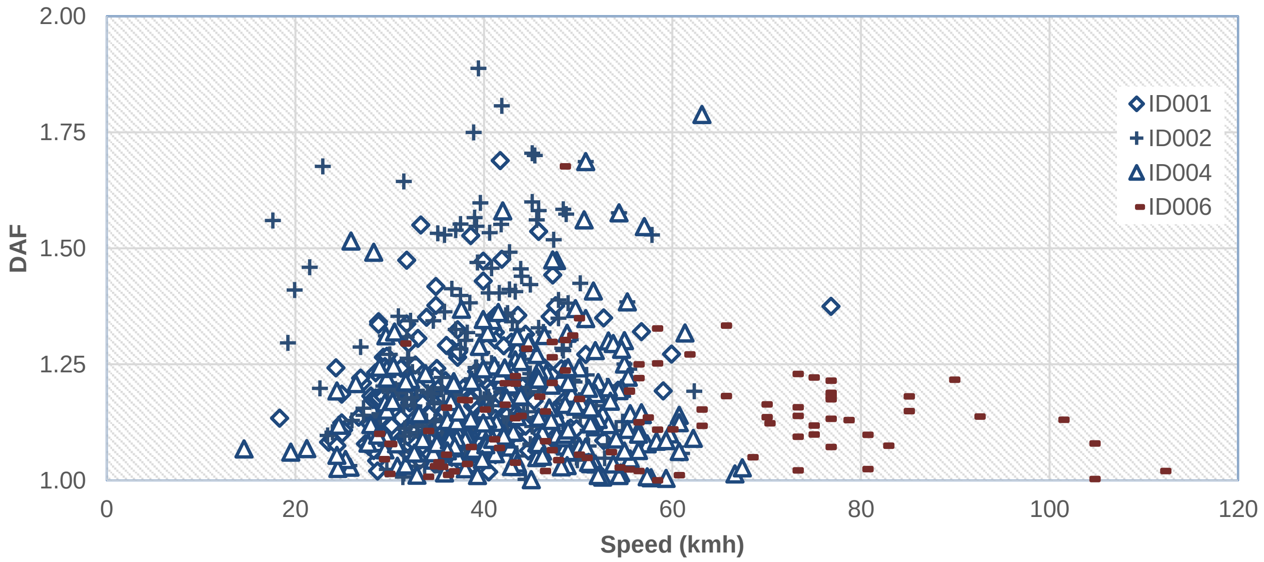

Figure 3. DAF vs Speed for B-WIM ID001, ID002, ID004, and ID006

The data in Table 1, Figure 2, and Figure 3 provide valuable information about the dynamic behavior of vehicles on bridges. The relationship between DAF and GVW in Figure 2 demonstrates a general trend where heavier vehicles exhibit lower DAF values, as observed across all sites. This is consistent with the principle that lighter vehicles experience greater dynamic amplification due to their higher sensitivity to road surface irregularities and bridge vibrations. For example, ID002, which shows the highest mean DAF, likely experiences more frequent light vehicle traffic or amplified conditions from its structural and environmental factors.

Conversely, Figure 3 illustrates the relationship between DAF and vehicle speed. The data reveal no strong correlation between DAF and speed across the sites, as DAF values remain scattered regardless of vehicle velocity. This suggests that factors such as GVW and structural dynamics of the bridge play a more dominant role in influencing DAF than speed alone.

The variability in DAF across the sites reflects site-specific conditions, including traffic composition, road surface quality, and bridge structural characteristics. ID002's high variability and upper nominal DAF indicate that this site may have more challenging dynamic conditions, such as greater surface roughness or traffic-induced pseudo-resonance. On the other hand, ID006's lower variability and nominal DAF suggest more stable dynamic behavior, potentially due to smoother road conditions or less variability in vehicle types.

The nominal DAF values calculated for each site offer a practical benchmark for design considerations. For instance, the nominal DAF values at all sites are generally lower than the 1.40 value specified in SNI 1725:2016 for short-to-medium-span bridges. This indicates that using site-specific DAF values based on actual measurements could lead to more efficient and accurate bridge design, reducing over-conservatism while maintaining safety.

The relationship between Gross Vehicle Weight (GVW) and Dynamic Amplification Factor (DAF) observed from the data indicates a clear trend: larger GVW results in lower DArbnbF, while smaller GVW corresponds to higher DAF values. This behavior aligns with the principle that lighter vehicles are more sensitive to dynamic effects, such as surface roughness and structural vibrations, leading to higher amplification. In contrast, heavier vehicles tend to dampen these effects due to their larger mass, resulting in lower amplification factors. This trend is evident across all sites, as seen in Figure 2, which plots DAF against GVW.

To improve the existing SNI 1725:2016 provisions, this study proposes a new DAF model that accounts for site-specific conditions and traffic characteristics. The proposed model consolidates data from all four B-WIM sites to provide a comprehensive representation of DAF behavior. The data were categorized into light vehicles (GVW < 25 tons) and heavy vehicles (GVW ≥ 25 tons), with 25 tons used as the threshold to separate the two groups. Statistical analysis shows that heavy vehicles (GVW ≥ 25 tons) result in an average DAF of 1.11 with a standard deviation of 0.06843, while light vehicles (GVW < 25 tons) produce a higher mean DAF of 1.20 with a standard deviation of 0.15429. Using the formula for nominal DAF (mean + 1.5 × standard deviation), the nominal DAF values were calculated as 1.21 for heavy vehicles and 1.43 for light vehicles. While the mean values for both groups are relatively close, the higher standard deviation for light vehicles results in a significantly higher nominal DAF, reflecting the greater variability in their dynamic amplification.

The nominal DAF values calculated for each group also have a 90-95% probability of not being exceeded by the population, ensuring that the proposed model maintains safety while reducing over-conservatism. The higher nominal DAF for light vehicles accounts for their larger variability, while the nominal DAF for heavy vehicles reflects their more consistent behavior. These findings highlight the importance of separating vehicle categories in modeling DAF, as the dynamic effects differ significantly between light and heavy vehicles.

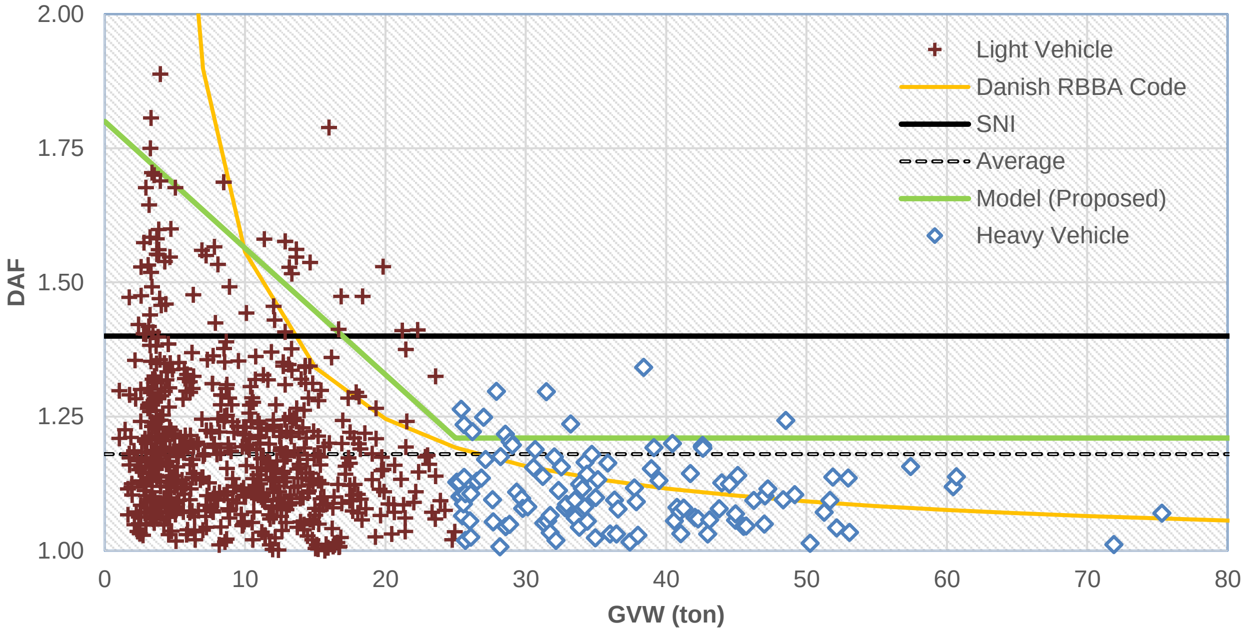

Figure 4. DAF vs GVW Proposed Model

To accurately represent the relationship between DAF and GVW, a new bilinear model is proposed, with separate equations for light and heavy vehicles. For light vehicles (GVW < 25 tons), the proposed equation is:

$$DAF = 1.8 - \frac{GVW}{42.37}$$

For heavy vehicles (GVW ≥ 25 tons), the DAF is modeled as a constant:

$$DAF = 1.21$$

This bilinear model, shown in Figure 4, is compared alongside the DAF provisions in SNI 1725:2016 and the RBBA Danish code (12). The proposed model demonstrates a closer fit to the actual measured DAF values, capturing the variability and trends observed in the data. The light vehicle equation reflects the gradual decrease in DAF with increasing GVW, while the constant DAF for heavy vehicles aligns with their more consistent dynamic behavior.

The proposed model provides a more accurate and efficient approach to DAF estimation compared to the SNI 1725:2016 provisions, which use generalized values that do not account for GVW variability. By incorporating the actual relationship between GVW and DAF, the proposed model better reflects the real dynamic behavior of bridges under varying vehicle loads, as supported by the measurement data.

5 Conclusions

This study highlights the critical role of Dynamic Amplification Factor (DAF) in bridge design to account for the dynamic loads induced by vehicles, which differ significantly from static loads. Using data collected from four Bridge Weigh-In-Motion (B-WIM) systems in Indonesia, the analysis revealed a clear relationship between Gross Vehicle Weight (GVW) and DAF: lighter vehicles (GVW < 25 tons) exhibit higher DAF values due to greater sensitivity to dynamic effects, while heavier vehicles (GVW ⩾ 25 tons) consistently show lower DAF values. These findings align with the broader trends observed in dynamic load amplification and emphasize the importance of accurately incorporating these effects into bridge design standards.

A new DAF model was proposed in this study, based on a bilinear relationship that separates light and heavy vehicles, using a 25-ton GVW threshold. For light vehicles, the DAF decreases linearly with increasing GVW, while for heavy vehicles, it remains constant at a nominal value of 1.21. This model better reflects the actual dynamic behavior of bridges under varying traffic loads, as validated by the statistical analysis of the B-WIM data. The nominal DAF values calculated for light (1.43) and heavy vehicles (1.21) provide 90-95% probability of not being exceeded, ensuring safety while reducing over-conservatism compared to existing standards.

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