Statistical Analysis of Extreme Live Load Effects on Indonesian Bridges

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ABSTRACT: This study investigates the live load effects on simply supported beam bridges by considering important factors such as vehicle weight, speed, axle spacing, and following distance. The analysis utilizes data from the Pawiro Baru Bridge weigh-in-motion (B-WIM) system, located in the Northcoast of Central Java National Road, Indonesia. The site of the B-WIM system is characterized by high numbers of heavy vehicles and high traffic volume. Data collected over one year is employed to analyze the live load characteristics and assess their impact on bridge structures. Finite element models are developed for four types of simply supported beam bridges with spans ranging from 25 to 40 meters, and moving load analysis is conducted to simulate traffic loading conditions. By employing statistical methods of extremes, the maximum value distribution of live load for a bridge's projected 75-year lifetime is determined. The results indicate that the mean value of the live load for the simply supported beam bridges, based on B-WIM measurements of actual traffic flow, is lower than the nominal design live load specified by the SNI 1725 2016 Bridge Loading code. However, the standard deviations and distribution data obtained from the study offer valuable insights for the reliability-based evaluation of standard-designed simply supported beam bridges in Indonesia. This research contributes to enhancing the understanding of live load effects on Indonesian bridges, particularly in the context of simply supported beam bridges. By incorporating B-WIM measurements and statistics of extremes, accurate assessments of live load characteristics are made possible.

1. INTRODUCTION

Indonesia, as a developing country, relies heavily on road transportation infrastructure, with bridges playing a crucial role in maintaining regional connectivity and supporting economic activity. However, the persistent problem of overloaded trucks has caused significant damage to these structures, compromising their safety and service life (Deng & Yan, 2018). The challenge is further exacerbated by the limited availability and effectiveness of static weighing stations, which restrict the collection of reliable vehicle load data and allow overloading to continue unchecked. To address this issue, Indonesia began implementing Weigh-in-Motion (WIM) systems in 2017, including Bridge Weigh-in-Motion (B-WIM), as depicted in Fig. 1, which utilizes existing bridges or culverts as weighing platforms (Nugraha, Sidi, et al., 2023).

Fig. 1 B-WIM instrumentation on the Pawiro Baru Bridge (Nugraha, Sidi, et al., 2023)

The B-WIM system estimates vehicle weights by analyzing their effects on bridge structures through the use of embedded sensors and data-processing algorithms (Nugraha, Riyono, et al., 2023). Unlike traditional methods, B-WIM enables continuous, non-intrusive, and real-time traffic load monitoring, making it an efficient tool for infrastructure management (Žnidarič & Kalin, 2020).

This study utilizes one year of B-WIM data collected from a high-traffic bridge site to analyze the characteristics of live traffic loads. Simply supported beam bridges represent the most common bridge type in Indonesia, accounting for around 57% of the bridge population (Nugraha, Sidi, et al., 2023). Understanding the live load effects on these bridges is essential for ensuring their safety and long-term performance. This study addresses that need by applying extreme value statistical methods to estimate the distribution of maximum live loads over a 75-year design life. The resulting mean live load effects are then compared to the nominal design loads outlined in the SNI 1725:2016 Bridge Loading Code to assess the adequacy of current design standards (Badan Standardisasi Nasional, 2016).

2. MATERIAL AND METHODS

The data used in this study was collected from the Bridge Weigh-In-Motion (B-WIM) system installed at Site ID-001 on the Pawiro Baru Bridge in Central Java, Indonesia. The B-WIM system employs existing bridge structures as virtual scales by using sensors and algorithms to estimate vehicle weights based on the structural response of the bridge as vehicles pass over it. This method allows for continuous, non-intrusive collection of traffic load data without the need for conventional static weigh stations.

For this study, one month of traffic data was recorded from October 1 to October 31, 2018. The dataset includes key parameters such as gross vehicle weight (GVW), axle loads, axle spacing, axle distances, and vehicle speed. An example record is shown in Fig. 2 which presents a six-axle truck with a GVW of 59.72 tons traveling at a speed of 32.91 km/h, along with detailed axle configurations.

Fig. 2 Example of a six-axle truck measurement results from B-WIM

To evaluate the live load effects on Indonesian bridges, four types of simply supported Bina Marga PCI Girder Standard Bridges were selected for analysis (summarized in Table 1). These bridges represent common span configurations used nationwide. Finite Element Models (FEM) of the selected bridges were developed to simulate structural responses under traffic loading. Each model incorporated B-WIM traffic data and used moving load analysis to replicate real-world vehicle effects.

Finite Element Modeling (FEM) was used to simulate the structural response of the selected bridges under actual traffic loads. Fig. 3 illustrates the FEM model developed for a 30-meter span Bina Marga PCI Girder Standard Bridge, which served as a representative structure for traffic load analysis (Direktorat Jenderal Bina Marga, 2008). The model included deck, girder, and support components, and it was calibrated using relevant bridge specifications to reflect realistic structural behavior.

Table 1 Summary for Bina Marga PCI Girder Standard Sample Bridge

No	Bridge Span (m)	Bridge Width (m)	No of Girder	Girder Spacing (mm)	Girder Dimension HxB (mm)		Deck thickness (mm)
1	25	9	9	1750	1600	650	270
2	30				1700	700	200
3	35				2100	700	200
4	40				2300	700	200

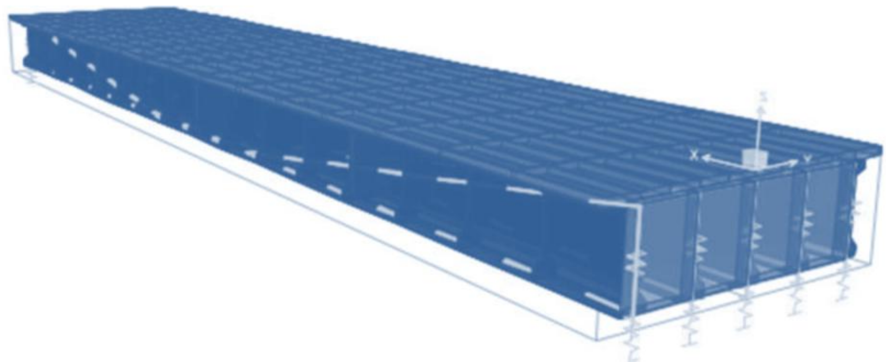

Fig. 3 FEM Model of 30-meter Bina Marga PCI Girder Standard Bridge

Traffic loading simulations were conducted on the FEM using the B-WIM data collected over the month. For example, as shown in Fig. 4, the heaviest vehicle sequence recorded on October 27, 2018, over a 30-meter span was used to simulate its impact on the bridge model. This process was repeated for all daily traffic data recorded during the monitoring period.

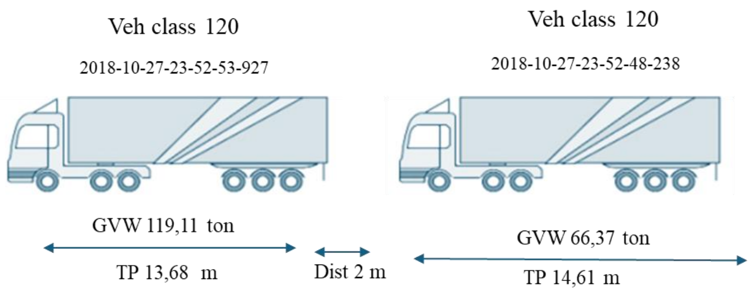

Fig. 4 FEM Model of 30-meter Bina Marga PCI Girder Standard Bridge

The simulation outputs focused on extracting the maximum bending moment in the girders for each day. These daily maximum bending moments, obtained from FEM analysis under B-WIM-measured loading, were compiled into a dataset for statistical analysis. Extreme value statistical methods were used to analyze the data and determine the 75-year return period loading effects. Gumbel theory, specifically designed to model the distribution of extreme values, was employed to predict the probability of maximum load occurrences (Gumbel, 1958). This approach is particularly useful in structural engineering for estimating the return levels of extreme events, such as the maximum load effects on bridges over a long period. Its ability to extrapolate beyond observed data and handle real-world measurements, like those from the B-WIM system, ensures reliable predictions (Xu et al., 2021). The results were then compared with the SNI 1725:2016 bridge loading code to evaluate the adequacy of the current design standards and identify any potential areas for improvement.

3. RESULTS AND DISCUSSION

The data analysis process involved a comprehensive examination of the B-WIM measurements collected over the month of October 2018. Key metrics analyzed included vehicle weight, speed, axle spacing, and following distance. These parameters were critical in understanding the impact of different types of vehicles on the structural integrity of the bridges. The collected data provided the foundation for subsequent finite element modeling and statistical analysis.

FEM simulations were conducted for four PCI girder bridge spans: 25 meters, 30 meters, 35 meters, and 40 meters. The results indicated that the longer the bridge span, the greater the daily maximum girder bending moment resulting from B-WIM vehicle loading. Additionally, the simulations showed that heavier vehicle load sequences led to higher daily maximum bending moments in the girders. Table 2 presents a comparison of statistics of simulated bending moments across the various spans data, that shows the daily value of vehicle load is a random variable, requiring statistical analysis for a more comprehensive understanding.

Table 2 Statistics of daily maximum girder bending moments data from FEM structural analysis due to B-WIM vehicle loading

No	**Date**	**Span length**			
		25 m	**30 m**	**35 m**	**40 m**
1	Mean	333.62	447.80	742.17	698.79
2	Standard Deviation	21.75	40.16	40.77	47.82
3	Minimum	299.99	377.12	655.83	599.55
4	25% Percentile	318.16	426.50	712.23	664.07
5	50% Percentile	328.34	440.36	743.78	698.50
6	75% Percentile	350.01	464.80	769.52	737.10
7	Maximum	376.61	599.36	845.03	799.25

The statistical analysis of extreme value data was performed using Gumbel theory to fit the observed data. This analysis enabled the calculation of the 75-year return period loading effects. For instance, Fig.5 illustrates the Cumulative Distribution Function (CDF) of the 75-year maximum bending moment for a 30-meter PCI girder. The data, plotted as a black line, was fitted to the Gumbel extreme distribution (black striped line) and then projected using extreme value theory for the 75-year maximum distribution (blue striped lines on the right). From this CDF, the mean value of the 75-year maximum bending moment for the 30-meter PCI girder was calculated to be 845.07 ton.m.

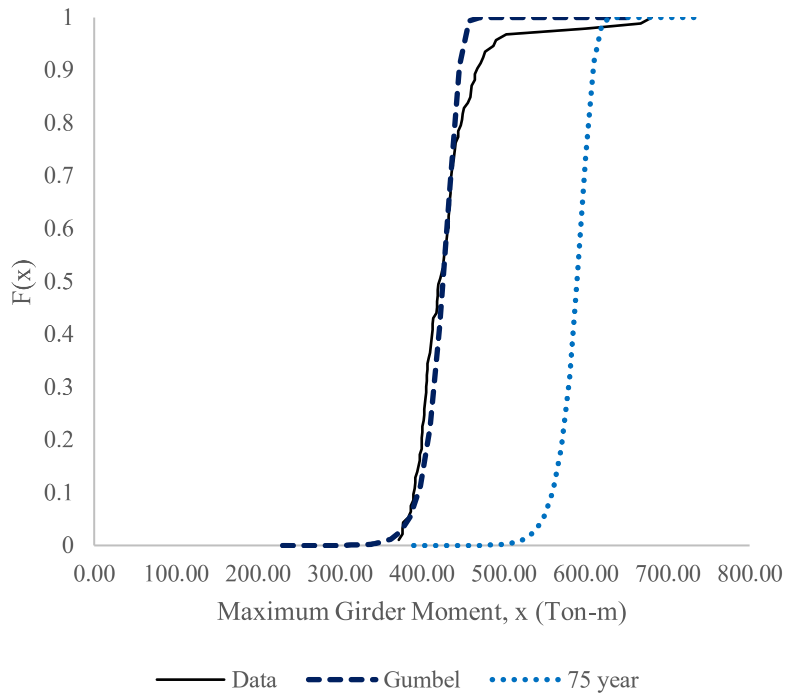

Fig. 5 CDF of 75-year maximum for 30 m PCI Girder bending moment

The evaluation of bending moments against the SNI 1725:2016 design standards revealed discrepancies between the calculated 75-year maximum moments and the SNI standards. Table 3 shows the comparison for different bridge spans. For a 25-meter span, the 75-year maximum bending moment was 498.34 ton.m compared to the SNI standard of 424.54 ton.m, resulting in a ratio of 117%. The highest ratio was observed for the 30-meter span at 142%, with the ratios decreasing for longer spans: 137% for 35 meters and 108% for 40 meters. These findings suggest that the current SNI 1725:2016 standards may not adequately account for the extreme loads that bridges could experience over their lifetime.

Table 3 Comparison of PCI girder bending moments from 75-year maximum and SNI 1725 2016

Bridge Span	Mmax 75 year (ton-m)	Mmax SNI 1725 2016 (ton-m)	Ratio
25	498.34	424.54	117%
30	845.07	593.12	142%
35	1083.76	789.59	137%
40	1094.50	1013.95	108%

5. CONCLUSIONS

This research provides valuable insights into the live load effects on PCI girder bridges in Indonesia, utilizing real-time data from B-WIM measurements and advanced finite element modeling techniques. The findings underscore significant discrepancies between the current SNI 1725:2016 design standards and the actual extreme loads that bridges might experience over their lifetime. Specifically, the study revealed that the 75-year maximum bending moments for PCI girder bridges often exceed the maximum bending moments due to design load set by the SNI standards, particularly for shorter spans.

The major conclusions drawn from this research highlight the necessity for revising the SNI 1725:2016 standards to better account for extreme loading conditions, ensuring the structural safety and longevity of bridges. This study demonstrates the critical role of accurate, real-time data and FEM modeling in understanding and mitigating the impacts of heavy vehicle loads on bridge infrastructure. Future research should focus on further refining these methods and expanding the analysis to include more bridge types and conditions, ensuring robust infrastructure that can withstand future demands.

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