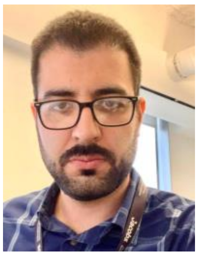
TOWARDS A MORE PRACTICAL BRIDGE MONITORING SYSTEM USING A NOVEL BRIDGE-WEIGH-IN-MOTION FOR MULTIPLE-VEHICLE EVENTS



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Abstract

This study integrates Bridge-Weigh-in-Motion (BWIM) and structural health monitoring (SHM) systems to address multiple-vehicle events on bridges. Phase one introduces a novel BWIM approach for enhanced detection in complex multiple-truck traffic cases. Simulations on an experimentally verified long-span bridge model demonstrate precise axle weight and gross vehicle weight (GVW) estimations. Phase two integrates SHM with the novel BWIM using a multiple-presence dual-purpose (MPDP) approach, leveraging existing sensors. MPDP detects damage scenarios in single and multiple-truck events, even with changing positions. The combined BWIM-SHM system offers practical bridge integrity monitoring, providing accurate weight estimations with mean absolute errors (MAE) of 4.5% for GVW and 11.3% for axle weight.

Keywords: Dual-purpose procedure, Multiple-truck presence, Structural health monitoring, Bridge-weigh-in-motion, Transverse position

1. Introduction

Integrating intelligent transportation systems (ITS) and structural health monitoring (SHM) systems achieves two objectives: detecting overloaded vehicles without traffic disruption and monitoring bridge integrity at low cost. Previous studies lack practical techniques for handling multiple vehicles and overlook critical factors such as noise and transverse positions, leading to false alarms even for intact bridges. To address these shortcomings, this study proposes a novel approach called multiple-presence dual-purpose (MPDP) structural health monitoring (SHM). The study is organized into two phases, each addressing a specific aspect of integration. Phase One focuses on the development of a novel bridge-weigh-in-motion (BWIM) approach for accurate weight estimation, specifically tackling the challenges associated with multiple trucks being present on the bridge. The proposed approach eliminates the non-localized portion of strain responses and utilizes a single strain gauge per lane, providing a cost-effective solution for weight estimation. Furthermore, the approach enables successful decomposition of strain responses even when calibration trucks are surrounded by unwanted vehicles, eliminating the need for lane closures during influence line (IL) calibration. In Phase Two, the study explores the integration of the developed BWIM with SHM systems by repurposing the existing BWIM instrumentation for SHM tasks. This approach focuses on changes in ILs compared to their reference values extracted from intact bridges, effectively detecting damage. Crucially, the MPDP method remains effective even when other vehicles are present on the bridge simultaneously. Additionally, the MPDP technique considers challenging factors such as environmental noise and transverse positions, providing a more realistic and robust SHM approach. The subsequent sections provide methodology, model validation, procedure, results, and main conclusions for each phase.

2. Methodology

In this study, first, a novel BWIM approach is proposed to handle multiple-truck cases with arbitrary traffic patterns, consisting of multiple trucks and light-weight vehicles involved (Moghadam et al., 2022). When the bridge is subjected to a truck load that is right on top of the sensors, the strain response under the truck tires consists of two components that should be superposed together: 1) the strain of the entire bridge span (acting as a beam) due to the internal moments which appears as slowly changing compression in the top slab and 2) additional strain due to stress concentration on the top plate/slab bending (plate behavior) which appears as sharp peaks in tension corresponding to axle crossings. These two strain portions are called localized and non-localized strains. In this study, the proposed approach first properly decomposes the strain responses associated with each truck in multiple-truck strain responses. To do this, a curve should be fitted to the non-localized portion of the response and subtracted from the original strain response. Then, the strain response associated with each truck will be extracted and fed into the standard BWIM methods (Carraro et al., 2019). The MPDP procedure (Moghadam et al., 2023) consists of two main steps. In the first step, called "calibration" on the intact bridge, strain-time responses are obtained as SHM trucks pass through the intact bridge multiple times. This accounts for variations in transverse position and environmental noise and ILs are extracted for single and multiple truck cases, and a reference IL is obtained using maximum likelihood estimation. The Damage Indicator (DI) is computed as the mean-square-error (MSE) between the reference IL and the IL at the monitoring stage. Damage is identified when the DI exceeds the upper 95% confidence bound calculated from calibration runs. The second step, called "Integrity Monitoring", involves the same trucks with identical configurations and weights to obtain strain responses at the monitoring stage. The DI is calculated as the MSE between the new IL and the reference ILs.

3. Numerical Model and Experimental Verification

The Varina-Enon bridge (VEB), a long-span, cable-stayed, post-tensioned, concrete-box-girder bridge located in Virginia, was used in this study. This bridge has a total length of 1426.5 m with twenty-eight spans. The top slab consists of three lanes and two shoulders, with a width of approximately 17.62 m. The concrete box has a trapezoidal shape and a total height of around 3.66 m, with varying slab depths. To validate the bridge model, two strain measurement points were selected on the VEB in span 6 (45.72 m), located 18.3 m from Pier 7. Two large truck crossing events, representing experimental tests conducted in 2020, were considered. The first event involved a special permit vehicle crossing the second travel lane, while the second event was a superload test with two lowboy trucks and two dump trucks crossing the bridge simultaneously. A finite element (FE) model was simulated, and a time-history analysis was performed to obtain strain-time responses under traversing trucks. The FE model's accuracy was validated by comparing it to experimental strain-time measurements taken at similar locations during the large events. The FE model successfully captured the strain responses, showing good agreement in terms of shape, magnitude, and localized strains under axle weights.

4. Procedure

In phase one, the developed BWIM approach was evaluated under various multiple-truck scenarios, including two cases with trucks arranged in a single row, two cases with zigzag truck configurations, one case with a mix of trucks and light-weight vehicles, and one case with side-by-side trucks. Measurements were taken at three consecutive points in 57 cm from the pavement markings in each lane, with a sampling rate of 100 Hz, using known weights and configurations of 3-axle and 5-axle trucks. In phase two, simulations were conducted using similar measurement points and sampling rate to calibrate the system on the intact bridge. Strain gauges were placed in a specific region of interest (ROI) representing areas prone to cracking and maximum deflections. Damage scenarios were simulated by removing elements from the ROI to assess the system's ability to detect and locate structural damage. Three SHM trucks with different weights and axle configurations were used. The study considered variability in transverse truck positions and noise effects. Thresholds for damage detection were computed, ensuring the system's reliability in real-world scenarios. Single and multiple-truck events were analyzed for each damage scenario using different trucks, comparing the resulting DI values to the thresholds, with DI values exceeding the thresholds indicating the occurrence of damage with 95% confidence.

5. Results

Phase one indicates that the proposed BWIM approach is capable of accurately estimating axle and gross vehicle weights in real-world scenarios, as used in six different traffic patterns. The MSEs for gross vehicle weight (GVW) and axle weight estimations were 4.50% and 11.3%, respectively. The performance of the approach varied based on factors such as truck type, lane position, and traffic pattern. In phase two, it was observed that for single-truck events, any of the SHM trucks could effectively detect damage in the ROI. However, the evaluation of multiple-truck events showed that certain damage scenarios were covered by all trucks, while others were only detected by specific truck types or not covered at all. Thus, incorporating different truck types improved accuracy. Overall, the MPDP procedure proved effective for both single-truck and multiple-truck events for this case study and damage scenarios.

6. Conclusions

This study presents a comprehensive integration of BWIM and SHM systems to address challenges in multiple-vehicle events on bridges. In phase one, a novel BWIM approach is introduced, enhancing the detection of multiple-vehicle cases, even in complex traffic scenarios. The second phase of the study proposes a multiple-presence dual-purpose (MPDP) SHM approach that effectively detects damage scenarios in both single and multiple-truck events, even when transverse positions change. The combined BWIM-SHM system offers practical bridge integrity monitoring, delivering accurate weight estimations with MSEs of 4.5% for gross vehicle weight (GVW) and 11.3% for axle weight estimations.

7. References

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