BRIDGE WEIGH IN MOTION FOR SIMULTANEOUS MULTIPLE VEHICLES

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INTRODUCTION

Intelligent Traffic Systems (ITS) and Structural Health Monitoring (SHM) have the potential to save highway infrastructure managers millions in traffic control and maintenance operations, respectively. However, implementation of these systems individually by industry has been slow. The integration of the two systems is more attractive to practitioners because it brings improved value. That is, on one hand, ITS can make SHM estimates more accurate by providing load information. On the other hand, SHM can complement ITS data to help assess the impact of traffic on bridge condition. By fusing system information, fewer sensors may be required overall. Thus, an integrated, cost-effective monitoring system can be beneficial for the transportation agencies to first, detect overloaded vehicles without disrupting traffic, and second, regularly monitor the bridge integrity without imposing much additional cost.

As part of this study, we identified the use of Nothing on Road Bridge Weigh in Motion (NOR-BWIM) as a promising candidate for integration with bridge SHM, due to commonalities in both instrumentation (strain gages) and extracted information (influence lines). However, one of the pressing challenges to integration is the estimation of influence lines during cases of multiple vehicles simultaneously on a bridge. This is particularly important for long span bridges in the aim to avoid lane closures. This study describes two phases of work: (1) the development of a novel methodology for multiple presence NOR-BWIM and (2) its integration within an SHM methodology, forming the basis for a dual purpose (traffic and infrastructure) monitoring system.

METHODOLOGY

Multiple presence NOR BWIM technique

The proposed approach works by extracting the localized strain response associated with a truck passage, as this response is largely independent of the surrounding traffic (Figure 1). This is done by fitting a curve to the non-localized portion of the response, which is sensitive to the combined weight on a bridge. The non-localized portion is removed by subtracting the fitted curve from the original strain response. Then, the modified strain response is fed into the standard Maximum Likelihood Estimation (MLE) BWIM procedure. This procedure uses a set of prerequisites (axle spacing, vehicle speed) to extract to calibrate a modified influence line (MP-IL, not shown) using trucks of known weight. The calibrated MP-IL can then be implemented to obtain weight estimates of each unknown vehicle, independently of other vehicles on the bridge.

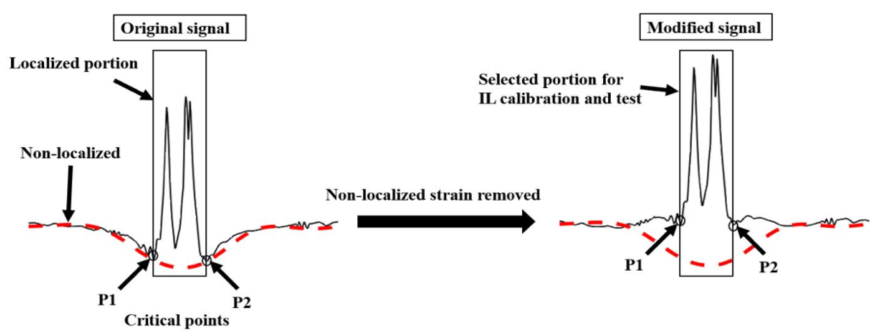

Figure 1. Visual illustration of strain decomposition for multiple presence events.
(Left: Full strain response due to a single truck passage with fit to the non-localized stress response;
Right: Response with non-localized strain removed.)

Integration of Multiple Presence BWIM into SHM procedure

Influence lines (IL) can also be used for bridge integrity monitoring applications. If the stiffness of an indeterminate bridge changes due to damage, the IL of the bridge will change due to internal force redistribution. Thus, the IL is a connecting element to convert the SHM and BWIM systems to a single, multi-functional system. The central idea is to perform both with a single set of strain gauges. In this study, we have simulated a novel, integrated SHM+BWIM procedure, taking advantage of the MP-IL produced by the multiple presence NOR BWIM technique.

The integrated procedure has two main steps: (1) calibration on the intact bridge, and (2) integrity monitoring. For the first step, reference trucks of known weight and axle spacing should move through the intact bridge several times and the strain-time responses should be obtained. This procedure would be practically identical to the calibration step in BWIM, and so does not impose any additional cost. A reference IL is obtained from averaging multiple passages for a single truck. In the integrity monitoring stage, a "damage indicator" (DI) is computed as the mean-square-error (MSE) of the reference IL and a new IL at the monitoring stage (for the same reference truck). The DI critical threshold is the upper 95% confidence bound of the DIs calculated using the ILs extracted from the intact bridge.

DATA SUMMARY

The data for this study were obtained from the calibrated finite element model (FEM) of three approach spans of the Varina-Enon bridge (VEB) in Richmond, VA, shown in Figure 2. The spans are post-tensioned, concrete-box-girders, 45.7 meters in length, and support three lanes of traffic. The model properties (topping thickness, elastic modulus, bearing stiffness) were calibrated based on two traffic load tests done on the actual bridge. The data used to test the methodology involved running various traffic patterns of multiple simultaneous trucks on the bridge (e.g., side-by-side, close following, and zig-zag patterns). The strain data from these loading cases were recorded at locations shown in Figure 3. A previous study showed that this transverse position was the most sensitive to traffic loading, showing the clearest peaks for each axle crossing.

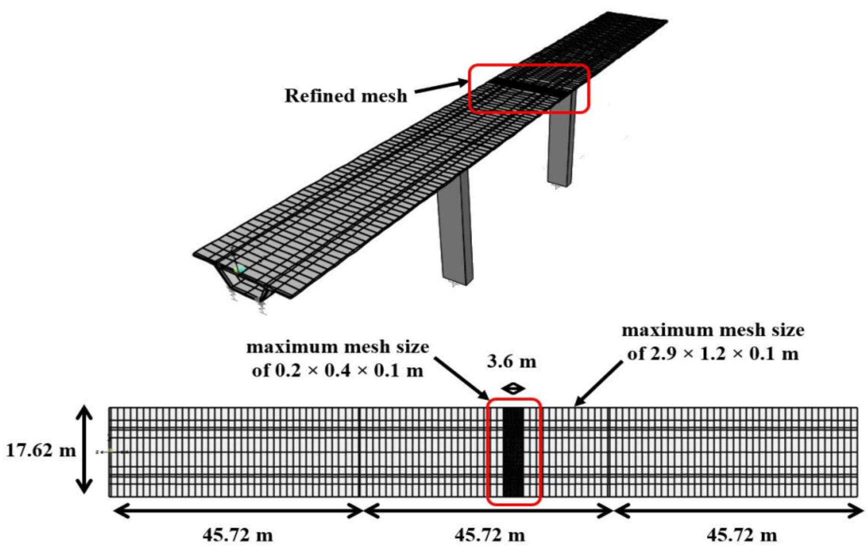

Figure 2. Varina Enon finite element model.

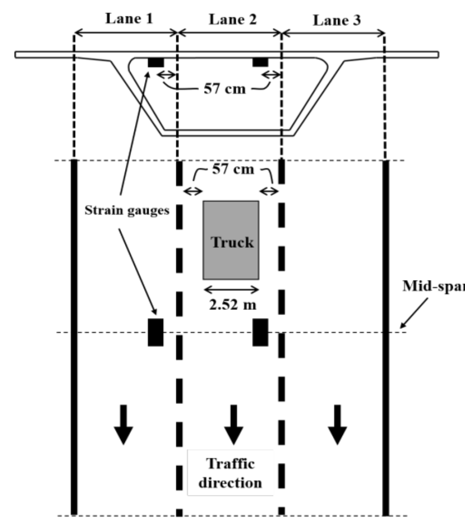

Figure 3. Sensor positions.

EVALUATION RESULTS

Multiple presence NOR BWIM results

Table 1 compares the results of the proposed multiple presence NOR BWIM technique to the standard MLE BWIM for single vehicle crossings. Even though the technique is intended for multiple simultaneous vehicles, this helps to evaluate how much information is being lost through the strain decomposition approach. The results show that gross vehicle weight (GVW) error improves by about 2% with the new technique. On the other hand, axle weight estimates decrease in accuracy by 3-4%. This is reasonable, given that some information is discarded to remove the influence of nearby traffic.

Table 1. Comparison of multiple presence technique with standard BWIM.

Technique	Lane	GVW Avg. Error (%)	Axle Weight Avg. Error (%)
Standard BWIM	1	4.1	4.8
Standard BWIM	2	4.8	6.5
Multi Presence BWIM	1	2.2	7.4
Multi Presence BWIM	2	2.4	10.6

The second study performed was an evaluation of the technique's ability to isolate truck weights in multiple vehicle patterns. In this case, of course, standard BWIM could not be used. Table 2 shows the results from testing six different traffic combinations of 3-axle and 5-axle trucks. The accuracies for both are fairly similar, and as expected, slightly higher than for the single truck case (Table 1).

Table 2. Comparison of multiple presence technique with standard BWIM.

Technique	Truck Type	GVW Avg. Error (%)	Axle Weight Avg. Error (%)
Multi Presence BWIM	3-axle	5.0	11.5
Multi Presence BWIM	5-axle	3.2	11.0

Integration of Multiple Presence BWIM into SHM results

In the calibration step of the multiple presence BWIM simulation, three reference trucks (3-axle, 4-axle, and 5-axle) were used to extract a reference MP-IL. Each reference truck passed through the bridge nine times with additional traffic present and variation in noise and transverse position, with the reference MP-IL being the average of these nine runs for each truck. Then, the DIs and, accordingly, the DI thresholds were computed for each truck. To test the sensitivity of the MP-ILs to damage, 11 different damage scenarios were tested, each corresponding to the removal of an element (0.2 x 0.4 x 0.1 m) in the top flange of the box girder bridge. Each damage scenario was tested by simulating the passage of one of the reference trucks as well as an additional truck of unknown weight simultaneously. The obtained MP-ILs were compared to the reference MP-IL to obtain the DI for each damage scenario. It was shown that DIs for certain damage scenarios were sensitive to only some of the reference trucks, as shown in Figure 4.

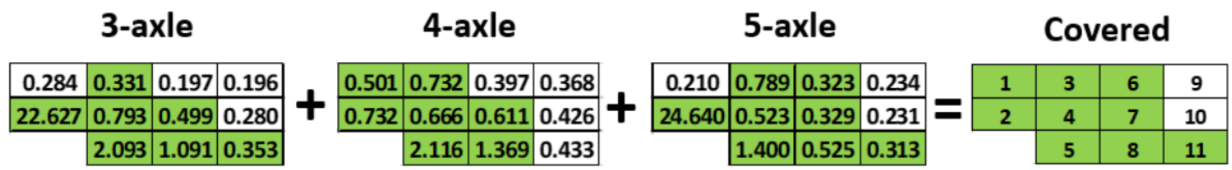

Figure 4. Damage scenarios detected by various reference trucks (3-, 4-, 5-axles) in multiple presence traffic.
(Each cell represents the DI for the removal of a 0.2 x 0.4 x 0.1 m element relative to the sensor position. Green cells represent a true positive result. “Covered” cells are those that were detected by at least one truck.)

CONCLUSION AND IMPLEMENTATION

The study led to the following conclusions about the integration of NOR-BWIM systems with an IL-based SHM approach:

- Extracting only the localized strain response to traffic can retain important information for WIM when compared to single truck standard BWIM. Although single truck loading cases are still preferable in terms of accuracy, this concept can be used to perform WIM even in multiple truck presence cases.
- Out of 15 trucks tested in 6 different *multiple-truck* scenarios, 9 GVW errors were less than 5%, 5 errors were between 5% and 10%, and only 1 GVW error was greater than 10%. Additionally, out of 53 axle weight estimations, 44 cases had an error less than 20% and only 9 cases had an error greater than 20%. These results are comparable with expensive pavement-based WIM systems and traditional BWIM technologies.
- When performing IL-based SHM, it is important to consider variations in the IL estimation due to transverse position and reference truck configuration (number of axles and axle weights distribution). The former can be addressed through statistical analysis of the damage index variation for various runs on an intact bridge. The latter can be addressed by creating different reference ILs for each reference truck.
- Furthermore, having a variety of different reference truck configurations was shown to be beneficial in damage detection, as some damage scenarios were only detected by a certain truck while missing others, and vice-versa.

For future work, it is recommended that these techniques be extended to real structures to address practical limitations to implementation.

For More Information

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