The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 13.3
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.13.3


# Performance of a damage sensitive parameter obtained from different response-based bridge weigh-in-motion

**D. Paul and K. Roy**

**Department of Civil and Environmental Engineering,**
**IIT Patna, India**

## Abstract

The importance of bridge health monitoring (BHM) has increased considerably and has become an essential component in monitoring transportation network. Visual inspection is mostly used to monitor the structural health of bridges. However, it has some downsides such as variability in the judgment of individual inspecting personnel, the necessity of physical presence at the bridge location, inaccessibility at remote areas, and many more. Several BHM methods are available, however, there is no solution for any type of bridge and damage condition. This leaves greater scope for new technologies to be adopted for BHM. The bridge weigh-in-motion (B-WIM) is gaining much attention as a promising alternative approach to BHM. B-WIM system captures bridge response due to vehicles traversing over it and estimates the vehicle weights. The main advantages of the B-WIM system are durability, portability, and easy installation. In addition to the weight estimation, it provides other structural information and also overcomes the limitations of pavement-based weigh-in-motion (P-WIM) systems. A few damage sensitive parameters (DSPs) have recently been developed in the last decade using the B-WIM system. However, the performance of a DSP computed utilizing multiple response time histories from a single bridge under identical circumstances is seldom studied. In this paper, a 3D finite element (FE) bridge model of a real bridge is analyzed and acceleration, strain, and displacement response time histories are captured in every quarter location of the bridge length within the span. These response time histories are then fed to the B-WIM algorithm to estimate gross vehicle weights (GVW) and DSP values are

determined and compared for performance evaluation. Finally, conclusions are drawn from this comparative study with an attempt to highlight the future aspects.

**Keywords:** bridge health monitoring, bridge weigh-in-motion, damage sensitive parameter, strain, acceleration, displacement.

# 1 Introduction

A bridge is an important structure for transportation that connects two points separated by different obstacles. Bridge continuously carries vehicle loads which lead to fatigue and significantly shortens service life [1]. Beside this, an increase in traffic volume, vehicle overloading, exposure to harsh weather and natural aging degrade bridges over time [2]. Therefore, it is required to assess the condition of bridges at a regular interval.

The most common practice for monitoring bridges is by visual inspection which has some mentionable limitations due to variability of judgment, inaccessibility in remote locations, and requirement of physical presence [3]. Vibration-based BHM methods are one of the earliest approaches which use natural frequency and modal parameters. However, no single solution is available which can be used for any type of bridge and circumstance as mentioned by Cantero and González [4]. Therefore, there is a scope for new technologies for BHM [5]. In recent years, B-WIM technology has attracted researchers as it has the potential to become a promising alternative to available BHM methods [6]. B-WIM system is one of the dynamic WIM systems, which use sensors mounted at the bottom of the bridge to capture bridge responses and estimate axle weights (AW) and GVW while vehicles traverse over it [7]. The use of a bridge as a weighing station was first presented by Moses in the late 70s [8]. Later, different independent research works are carried out to improve B-WIM algorithms [9–11]. B-WIM is capable of providing additional information such as vehicle speed, axle spacing, recurrence of vehicles, traffic volume and also overcomes the limitations of traditional WIM systems [12].

From the literature, it is found that the application of B-WIM system for BHM is seldom studied until fatigue damage analysis by Wang et al. [13], and a few DSPs using different response-based B-WIM systems were reported in a few literature [2, 4, 14–16]. Researchers have used bridge responses in terms of strain, stress, acceleration, etc. at different locations and rotation at supports in B-WIM algorithm and presented damage detection capability. However, the performance of a DSP derived using different response time histories for a single bridge and circumstances is not been investigated yet. In this paper, a 3D FE model of a real bridge is analyzed to evaluate the performance of DSP values determined from longitudinal strain, vertical acceleration, and vertical displacement-based B-WIM.

# 2 Methods

A B-WIM system first calibrates the bridge influence line (BIL) by running a vehicle of known axle spacing and weight at different velocities. The captured bridge response due to unknown vehicles is then processed with calibrated BIL using methods such as least square to estimate the GVW. The fundamental equation of B-WIM is [17]:

$$R_k = \sum_{i=1}^{N} A_i I_{k-C_i} \tag{1a}$$

$$C_i = \frac{D_i f}{v} \tag{1b}$$

where, $I_{i,k-Ci}$ is BIL co-ordinate at ($k$ – $Ci$) position of $i^{\text{th}}$ axle, $A_i$ is the weight of $i^{\text{th}}$ axle, $C_i$ is the number of scans corresponding to $D_i$, $D_i$ is the distance of $i^{\text{th}}$ axle from 1st axle, $f$ is the sampling frequency, $N$ is the number of axles, and $v$ is the velocity of vehicle. When damage occurs, whether locally or globally, the response of the bridge due to vehicular load will change, resulting in a change in the BIL. As a result, B-WIM system will estimate a different GVW, which becomes the basic fundamental of B-WIM based BHM. Following the study by Cantero and González [4], the DSP can be calculated as:

$$E_{BWIM} = \frac{W_g - W_{gt}}{W_{gt}} \times 100 \tag{2}$$

where, $W_g$ and $W_{gt}$ are the estimated GVW after damage and the actual GVW, respectively.

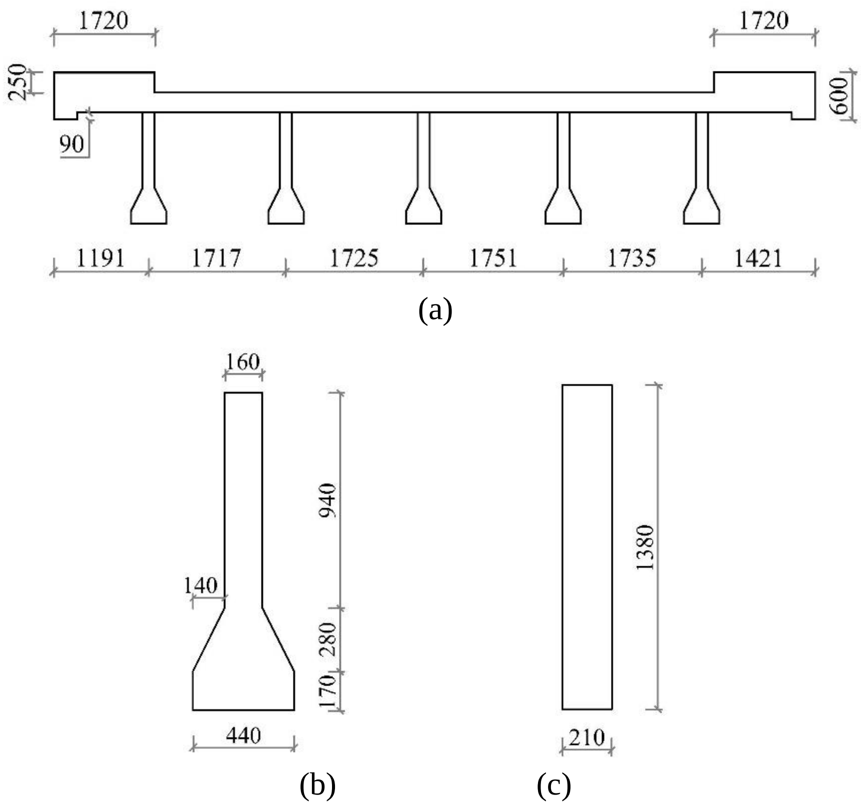



Figure 1: Cross-sections of: (a) bridge, (b) beam, and (c) diaphragm (mm).

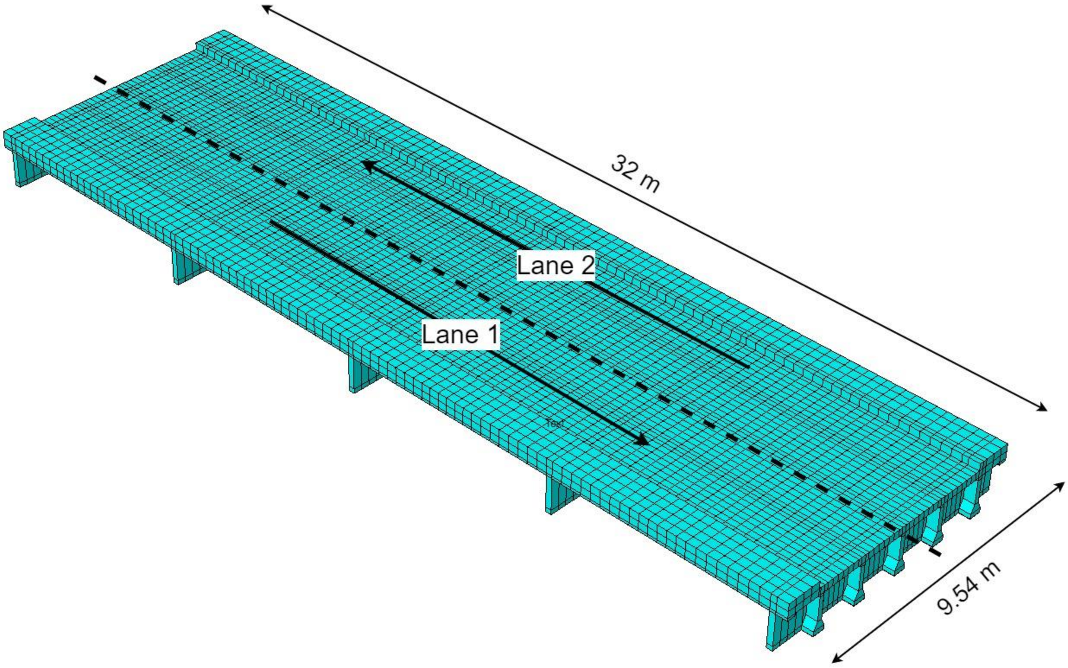



Figure 2: 3D FE model of the bridge

A 3D FE model of a real bridge [18] with cross-sections given in Figure 1, is developed in Abaqus as shown in Figure 2, to investigate the performance of the DSP. Under the same boundary and damage conditions, the DSP values are computed using three different response time histories. The bridge is 9.54 m wide and simply supported over 32 m span. Young's modulus and Poisson's ratio of concrete are taken as 48000 MPa and 0.15 respectively with 3% damping. A 2-axle vehicle is adopted from the article by Zhang et al. [19] as shown in Figure 3. The vehicle traverse through lane-1 following the center line and responses are captured at every quarter location of the middle beam under lane-1 within the span. As employed by Cantero and González [4], global damage is induced in the model in three stages by lowering the material's Young's modulus by 10% in each step up to 30%. GVW of the vehicle is also varied by reducing 10% of the AWs up to 30%. The results obtained are presented in the following section.

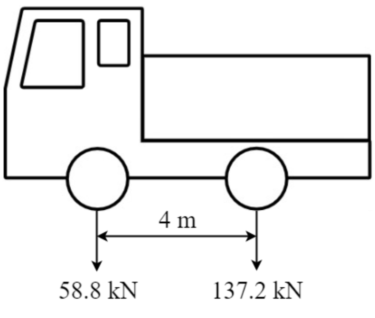



Figure 3: Vehicle configuration.

# 3 Results

To validate the FE model, eigen value analysis is performed and modal frequencies are presented in Table 1. Obtained values are then compared with the experimental values are found in agreement with an experimental study on the real bridge conducted by Brady et al. [18].

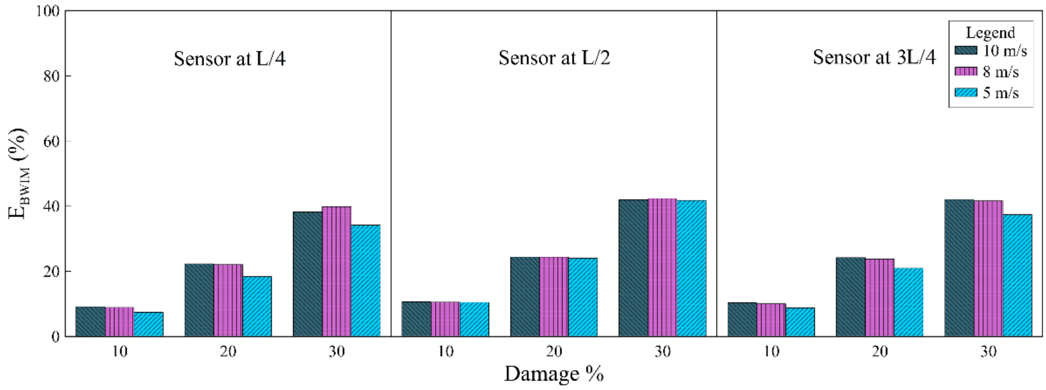
| Mode no. | Frequency (Hz) | | % Error |
|---|---|---|---|
| | Experiment [18] | FE Model (present study) | |
| 1 | 3.58 | 3.503 | -2.15 |
| 2 | 4.6 | 4.669 | 1.51 |
| 3 | 12 | 12.304 | 2.53 |
| 4 | 13.02 | 13.053 | 0.25 |

Table 1: Modal frequencies.

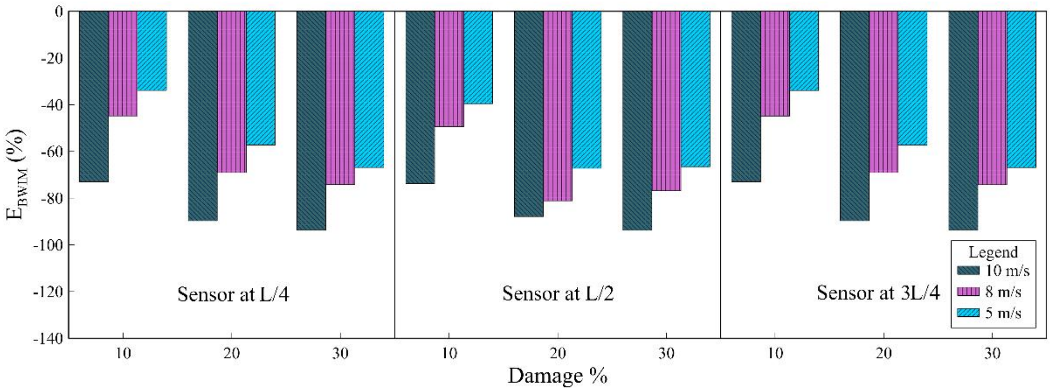
Following the frequency analysis, different response time histories produced by vehicular loads are recorded for healthy bridge conditions and processed to calibrate BIL. Damage is then incorporated in the bridge model as described in the preceding section and response time histories are captured. These responses are then fed into B-WIM algorithm to estimate the GVWs. Subsequently, the DSP values are determined using Equation (2). Figure 4(a) shows DSP values obtained using longitudinal strain response time histories. It is seen that strain data provides positive DSP and increases as damage percentage increases. Positive DSP indicates that the estimated GVW is higher than the true GVW. It is also observed that DSP values vary with the velocity of vehicle from sensors located at L/4 and 3L/4.

DSP values determined from vertical acceleration time histories are plotted in Figure 4(b). It is observed that acceleration response time histories provide negative values, which indicates that acceleration-based B-WIM estimates less GVW than true GVW. As damage increases, it provides lesser GVW and with a decrease in velocity, DSP values increase. In this case, the DSP values vary with the velocity of vehicle and show higher GVW when vehicle runs with a lower velocity. This may be due to the bridge not having as much time to vibrate at a larger amplitude when a vehicle passes at a faster speed.

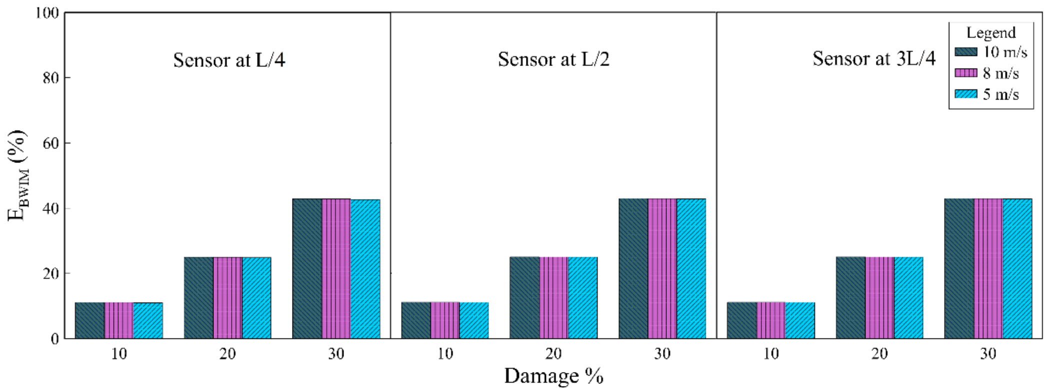
Similarly, DSP values are determined using vertical displacement time histories as shown in Figure 4(c). Displacement data also provides positive DSP values. It is observed that the DSP values do not vary much with vehicle velocity and are consistent for all the sensor locations.




(a)




(b)




(c)

Figure 4: Damage sensitive parameter values determined using response time histories based on: (a) strain, (b) acceleration, and (c) displacement.

## 4 Conclusions and Contributions

This paper investigates the performance of a DSP using B-WIM system utilizing longitudinal strain, vertical acceleration, and vertical displacement response time histories with varying damage percentage, GVW, and velocity of the vehicle for a single 3D bridge model under the same boundary conditions. The basic fundamental concept of B-WIM system is used to get the GVWs and DSP values are determined from every response captured. Based on the findings, the following conclusions can be drawn:

1) In terms of estimation of GVW, acceleration response time history provides much less GVW than actual GVW. On the contrary, both strain and displacement response time history provide higher GVW than true GVW when damage occurs.

2) DSP values determined using acceleration time history decrease as the percentage of damage increases. In contrast, DSP values obtained from strain and displacement response time histories increase with an increase in damage percentage.

3) Variation of DSP values with respect to vehicle velocity is higher for acceleration response time history. For strain response time history, variation is much less. However, DSP values are almost the same for displacement response time history.

4) DSP values determined from displacement response time history are almost linear in pattern with respect to the degree of damage and consistent irrespective of the sensor location.

Further study is needed in this area which can contribute to the development of damage quantification using B-WIM-based BHM.

## References


[1] K. Wardhana, F.C. Hadipriono, "Analysis of recent bridge failures in the united states", Journal of Performance of Constructed Facilities, 17(3), 144-150, 2003. doi:10. 1061/(asce)0887-3828(2003)17:3(144)

[2] Z.-W. Chen, S. Zhu, Y.-L. Xu, Q. Li, Q.-L. Cai, "Damage detection in long suspension bridges using stress influence lines", Journal of Bridge Engineering, 20(3), 05014013, 2015. doi:10.1061/(asce)be.1943-5592.0000681

[3] E.J. O'Brien, P.C. Fitzgerald, A. Malekjafarian, E. Sevillano, “Bridge damage detection using vehicle axle-force information”, Engineering Structures, 153, 71-80, 2017. doi:10.1016/j.engstruct.2017.10.012

[4] D. Cantero, A. González, “Bridge damage detection using weigh-in-motion technology”, Journal of Bridge Engineering, 20(5), 04014078, 2015. doi:10.1061/(asce)be.1943-5592.0000674

[5] D. Cantero, R. Karoumi, A. González, “The virtual axle concept for detection of localised damage using bridge weigh-in-motion data”, Engineering Structures, 89, 26-36, 2015. doi:10.1016/j.engstruct.2015.02.001

[6] S. Alamandala, R.L.N. Sai Prasad, R.K. Pancharathi, V.D.R. Pavan, P. Kishore, “Study on bridge weigh in motion (BWIM) system for measuring the vehicle parameters based on strain measurement using FBG sensors”, Optical Fiber Technology, 61, 102440, 2021. doi:10.1016/j.yofte.2020.102440

[7] H.V. Loo, A. Žnidarič, “Guide for Users of Weigh-In-Motion: An Introduction to Weigh-in-Motion”, International Society for Weigh-in-Motion, 2019.
[8] F. Moses, “Weigh-in-motion system using instrumented bridges”, Transportation Engineering Journal of ASCE, 105(3), 233-249, 1979. doi:10.1061/tpejan.0000783
[9] M. Lydon, S.E. Taylor, D. Robinson, A. Mufti, E.J. O'Brien, “Recent developments in bridge weigh in motion (b-WIM)”, Journal of Civil Structural Health Monitoring, 6(1), 69-81, 2016. doi:10.1007/s13349-015-0119-6
[10] Y. Yu, C.S. Cai, L. Deng, “State-of-the-art review on bridge weigh-in-motion technology”, Advances in Structural Engineering, 19(9), 1514-1530, 2016. doi:10.1177/1369433216655922
[11] M. Sujon, F. Dai, “Application of weigh-in-motion technologies for pavement and bridge response monitoring: State-of-the-art review”, Automation in Construction, 130, 103844, 2021. doi:10.1016/j.autcon.2021.103844.
[12] S. Kim, J. Lee, M.-S. Park, B.-W. Jo, “Vehicle signal analysis using artificial neural networks for a bridge weigh-in-motion system”, Sensors, 9(10), 7943-7956, 2009. doi:10.3390/s91007943
[13] T.-L. Wang, C. Liu, D. Huang, M. Shahawy, “Truck loading and fatigue damage analysis for girder bridges based on weigh-in-motion data”, Journal of Bridge Engineering, 10(1), 12-20, 2005. doi:10.1061/(asce)1084-0702(2005)10:1(12)
[14] I. González, R. Karoumi, “BWIM aided damage detection in bridges using machine learning”, Journal of Civil Structural Health Monitoring, 5(5), 715-725, 2015. doi:10.1007/s13349-015-0137-4
[15] D. McCrum, E.J. O'Brien, M. Khan, “Bridge health monitoring using an acceleration-based bridge weigh-in-motion system”, V. Pakrashi, J. Keenahan, (Editors), “Proceedings of Civil Engineering Research in Ireland 2018 (CERI 2018)”, CERAI, Dublin, Ireland, 84-87, 2018.
[16] E.J. O'Brien, J.M.W. Brownjohn, D. Hester, F. Huseynov, M. Casero, “Identifying damage on a bridge using rotation-based bridge weigh-in-motion”, Journal of Civil Structural Health Monitoring, 11(1), 175-188, 2021. doi:10.1007/s13349-020-00445-w
[17] X. Zheng, D.-H. Yang, T.-H. Yi, H.-N. Li, “Development of bridge influence line identification methods based on direct measurement data: A comprehensive review and comparison”, Engineering Structures, 198, 109539, 2019. doi:10.1016/j.engstruct.2019.109539
[18] S.P. Brady, E.J. O'Brien, A. Žnidarič, “Effect of vehicle velocity on the dynamic amplification of a vehicle crossing a simply supported bridge”, Journal of Bridge Engineering, 11(2), 241-249, 2006. doi:10.1061/(asce)1084-0702(2006)11:2(241)
[19] J. Zhang, H. Peng, C.S. Cai, “Field study of overload behavior of an existing reinforced concrete bridge under simulated vehicle loads”, Journal of Bridge Engineering, 16(2), 226-237, 2011. doi:10.1061/(asce)be.1943-5592.0000140