

# Influence of Temperature on the Accuracy of Dynamic Bridge Weigh-In-Motion Systems

Ethan MacLeod  
Postdoctoral Fellow  
University of New Brunswick  
Fredericton, New Brunswick  
Ethan.macleod@unb.ca

Kaveh Arjomandi  
Professor  
University of New Brunswick  
Fredericton, New Brunswick

Diego Padilha  
New Brunswick Department of Transportation Infrastructure  
Fredericton, New Brunswick

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## **Abstract**

Increasing traffic loads along with aging bridge degradation are resulting in oversized and overweight vehicles becoming a regular challenge for bridge structures worldwide. It is therefore essential to monitor the movement of heavy trucks on a bridge network for planning and maintenance. This has led to increased development of monitoring solutions to determine the prevalence of overweight loading events and their impact on bridge structures. Bridge Weigh In Motion (BWIM) methods estimate the weights of vehicles at full highway speeds by using an instrumented bridge as a scale. Current operational nonparametric BWIM methods based on the Mosses algorithm require frequent calibration to ensure accuracy due to changes in bridge behaviour from changing operational and environmental conditions. These calibrations currently require isolated vehicles of known weight which can be costly, disrupt traffic flow and are not always practical with busy highway structures. A novel dynamic parametric Bridge Weigh-in-Motion (BWIM) method has recently been developed that utilizes experimentally estimated modal parameters of a two-dimensional bridge structure to simulate its response to a moving load. This research

assesses the method's capability to accurately capture the evolving bridge response under changing environmental conditions by incorporating online modal parameters into the BWIM analysis. The study investigates the impact of temperature changes on estimated modal parameters, analyzes resulting alterations in bridge response characteristics, and evaluates the effect of these variations on BWIM accuracy. Additionally, the proposed automatic dynamic calibration method's effectiveness is evaluated through a full-scale case study involving an arterial highway bridge in New Brunswick, Canada.

## Introduction

With current infrastructure budgets, the number of deficient structures is expected to increase each year (ASCE, 2021), creating a trend that poses a significant challenge as the demand for engineering tools capable of accurately assessing the operational demands on bridge structures intensifies. Factors such as increased traffic loads and bridge degradation contribute to a rising ratio of traffic demand to bridge capacity, resulting in regular challenges from oversized and overweight vehicles. The latter poses a substantial threat to bridge integrity, inducing damage and accelerating degradation, leading to fatigue issues and a shortened service life.

To address this issue, Bridge-Weigh-In-Motion (BWIM) systems have been developed to provide a more practical solution for bridge monitoring. These systems use an instrumented bridge as a scale to estimate vehicle weights at full highway speeds. Traditional BWIM methods are static and based on the early work of Moses<sup>1</sup>. The Moses algorithm estimates the vehicle axle weights by minimizing the difference between the measured bridge response and the predicted bridge response which is calculated using the estimated static influence line of the bridge. The early influence lines employed in the Moses algorithm were purely theoretical and lacked accuracy in predicting the real behaviour of a bridge<sup>2</sup>. The real behaviour of a bridge is not just dependent on the in-situ condition of the structure, but can also be significantly affected by environmental conditions. The influence of environmental factors on the behaviour of bridge structures, particularly the role of temperature, has been extensively explored in numerous investigations<sup>3-6</sup>. Numerous studies consistently highlight temperature as the most significant environmental factor affecting variations in structural vibration properties<sup>7-11</sup>. These investigations reveal a strong negative correlation between frequencies and temperature, emphasizing the dynamic nature of the impact of temperature changes on modal parameters, with variations occurring over diverse periods such as 1 year, 1 week, and 1 day<sup>11</sup>. Notably, modal frequencies have been reported to vary significantly within a single day due to temperature change<sup>10</sup>. The variations in dynamic properties are identified as primarily stemming from changes in the elastic modulus of bridge structures<sup>7,12</sup>.

Given that highway bridge structures are predominantly constructed from concrete and steel, understanding the behaviour of these materials under varying temperatures is crucial. Concrete exhibits an inverse relationship between the modulus of elasticity and temperature<sup>10,13,14</sup>. The elastic modulus of concrete is observed to decrease by 0.25% to 0.65% per degree Celsius increase in temperature from ambient, with the decline remaining consistent across different types of aggregates<sup>12,15</sup>. Conversely, the modulus of elasticity of concrete shows a significant increase with decreasing temperature, following a linear trend<sup>16-18</sup>. Steel, another crucial material in bridge construction, also experiences a decrease in elastic modulus with increasing temperature. However, when considering there is a very small change below 100°C, this effect is not pronounced within the operational range of a bridge<sup>19,20</sup>. Observations under cold temperature conditions, as reported by Levings & Sritharan, reveal no significant change in the elastic modulus of steel, aligning with previous research findings<sup>21</sup>.

The changes in structural behaviour induced by environmental factors have tangible effects on the accuracy of Bridge Weigh-in-Motion (BWIM) systems. Sekiya highlights that the lower ambient

temperature corresponds to a smaller minimum value of the influence line, necessitating the determination of new influence lines when implementing BWIM systems at different temperatures <sup>22</sup>. Failure to account for these changes in influence lines significantly increases errors in Gross Vehicle Weight (GVW) estimation, as emphasized by Sekiya's research. Current assessments of BWIM accuracy, utilizing the COST 323 WIM Accuracy Classification <sup>23</sup>, underscore the need for recalibration due to environmental variability <sup>24</sup>. However, there is a notable absence of specific guidelines on the frequency of recalibrations, with Richardson et al. recommending periodic recalibrations under varied reproducibility conditions <sup>24</sup>. This recalibration process, involving representative test vehicles for different traffic conditions, entails substantial costs and resources.

Recently a new dynamic parametric BWIM method has been developed that utilizes the experimentally estimated modal parameters of the structure to simulate the response of a two-dimensional bridge structure to a moving load. This study evaluates the ability of the method to capture the changing bridge response due to environmental effects through the inclusion of online modal parameters in the BWIM analysis. This would enable the use of an automatic calibration method to reduce the frequency of calibration. The effects of environmental changes on the estimated modal parameters is investigated as well as the resulting changes in the characteristics of the bridge response. Finally, the effect of the environmental variations on BWIM accuracy is assessed and the effectiveness of the proposed automatic dynamic calibration method is evaluated. The research was conducted through the use of a full-scale case study of an arterial highway bridge in the province of New Brunswick, Canada.

## Theory

Recently a dynamic parametric BWIM method has been developed that utilizes the experimentally estimated modal parameters of the bridge structure to simulate its response subjected to moving traffic loads <sup>25</sup>. The estimated modes inherently enable the simulation method to be valid for any generalized structural geometry, boundary conditions and load position, enabling the complex torsional and transverse behaviour of the two-dimensional structure to be captured. The following section briefly outlines the methodology, for more detail, the reader is referred to the full derivation.

In this method, the bridge is modelled using an elastic plate with generalized geometry that is subjected to a series of vehicle axles using classical plate theory. Traditionally for an analytical solution, mode shapes and frequencies must be calculated with the mode shapes consisting of multiple terms of trigonometric and hyperbolic functions where constants can be solved from the boundary conditions of each span. For multiple span plate structures and complex boundary conditions, an analytical solution is cumbersome to develop. Therefore, this method instead uses a formulation that employs the extracted mode shapes  $\hat{\Phi}_n(x, y)$  and natural frequencies  $\hat{\omega}_n$  of the bridge using the modal testing of a bridge where the “ $\hat{\sim}$ ” denotes estimated values. Using the estimated mode shapes from the in-situ condition of a bridge structure allows the solution to account for the bridge geometry, material properties, composite actions, connection effects and boundary conditions as well as the current behaviour of the structure due to environmental effects. This results in the formulation for the n<sup>th</sup> modal equation as:

$$\frac{d^2 q_n(t)}{dt^2} + \hat{\omega}_n^2 q_n(t) = \sum_{s=1}^{na} \frac{-m_s g \hat{\Phi}_n(x_s, y_s)}{\bar{m} K_n} \quad (1)$$

where  $K_n = \int_0^a \int_0^b \hat{\Phi}_n^2(x, y) dx dy$ , with  $na$  being the total number of axles;  $m_s$  is the axle equivalent concentrated mass as the contact point of the  $s^{th}$  vehicle wheel system at located at  $x_s$  and  $y_s$  and  $\bar{m}$  is the mass per unit length of the bridge structure. As most traditional BWIM systems rely on the measured bending strain in the girders, the estimated response of the bridge is modified to represent bending strain at the distance from the neutral axis  $\bar{y}$ :

$$\varepsilon(x, y, t) = \bar{y} \sum_n [\Psi(x, y)(q_n(t))] \quad (2)$$

where the term  $\Psi(x, y)$  is the second partial derivative of the estimated mode shapes. To extract a dynamic influence line for estimating vehicle weights the method must first be calibrated by using a measured response of a known calibration vehicle. The data segment for a measured event is denoted as  $\mathbf{R}$  consisting of the measured strain history for  $g$  girders:

$$\mathbf{R} = \{R_1 \quad R_2 \quad \dots \quad R_g\}^T \quad (3)$$

The estimated response,  $\tilde{\mathbf{R}}$ , can be evaluated from:

$$\tilde{\mathbf{R}} = \mathbf{L}\gamma \quad (4)$$

where  $\mathbf{L} = \{L_1(t) \quad L_2(t) \quad \dots \quad L_g(t)\}^T$  is the estimated response for all girders and the constant  $\gamma = \bar{y} + \epsilon$  is introduced to account for an unknown neutral axis location ( $\bar{y}$ ) and errors  $\epsilon$  due to measurement uncertainties. The calibration coefficient  $\gamma$  is then solved by minimizing the difference between the estimated and measured response while knowing the axle weights of a calibration vehicle. Conversely, for the weighing procedure, the estimated response can be expressed as:

$$\tilde{\mathbf{R}} = \gamma \mathbf{M}\mathbf{W} \quad (5)$$

Where  $\mathbf{M}$  is the dynamic IL of each girder using the calibration coefficient  $\gamma$  and  $\mathbf{W}$  is a vector containing the unknown axle weights. The axle weights can then be solved by minimizing the difference between the estimated and measured response using the least squares method.

As seen in equation (5) the axle weights are linearly proportional to both changes in the dynamic influence line and calibration coefficient. The calibration coefficient is a function of the neutral axis depth and as a function of cross section should remain unchanged during environmental fluctuations. Therefore, once this calibration is completed, the method can produce dynamic influence lines that account for changes in the structure due to environmental conditions since the estimated modal parameters reflect the changes in the structure due to temperature.

## Case study bridge

The effects of temperature changes on the estimated modal parameters and BWIM accuracy is investigated and validated through the Westfield Route 7 overpass (asset W475) bridge located in New Brunswick, Canada. The bridge is a 57 m, three-span bridge constructed in 1986, consisting of six continuous, prestressed, AASHTO Type-III concrete girders as shown in Figure 1. This overpass handles a large volume of heavy truck traffic and permit vehicles and provides insight into the traffic demands along Route 7, a heavy trucking route with mostly through traffic. W475 also represents a typical slab-girder highway bridge type that is widely used in North America, therefore, making it beneficial that the findings could be readily applied to numerous structures. The system installed at W475 is described in detail by MacLeod et. al.<sup>26</sup> with the general accelerometer and strain gauge sensor arrangement as shown in Figure 2.

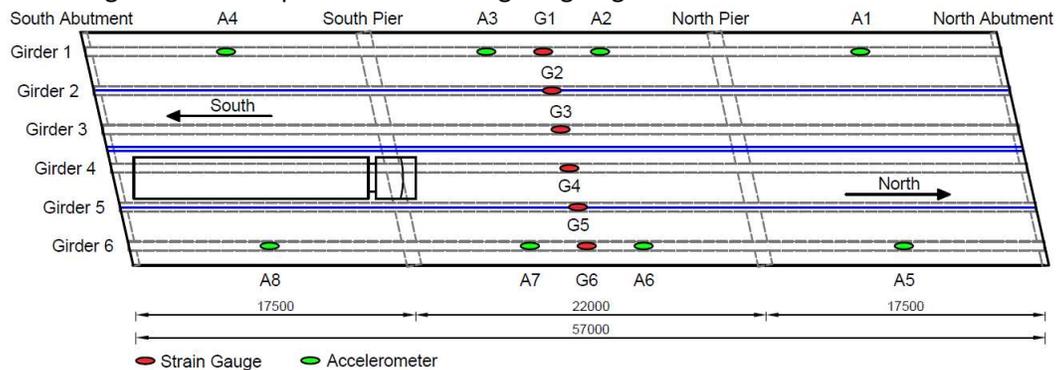
The dynamic BWIM method was validated using a series of field tests on the Westfield case study bridge. The normal traffic was redirected to off/on ramps allowing for a large volume of test runs and vehicle configurations to be tested. Two trucks provided by the New Brunswick Department of Transportation and Infrastructure (NB DTI) were used: A 45 KN 2-axle utility truck and a 185 KN 3-axle plow truck. Additional runs were completed with the 3-axle plow truck towing a loaded 2-axle trailer resulting in a combined GVW of 258 KN. The system was calibrated using runs in the mid-lane position considering all vehicles combined which resulted in a total of 42 runs. This resulted in a mean bias error of -3.2 KN for GVW and a calibration coefficient of 480 mm which is a reasonable location of the neutral axis above the

sensor considering the geometry and dimensions of the girder. The system has been collecting both vehicle loading data and ambient vibration data since August 2020.

Figure 1. Westfield Route 7 overpass (asset W475) elevation.



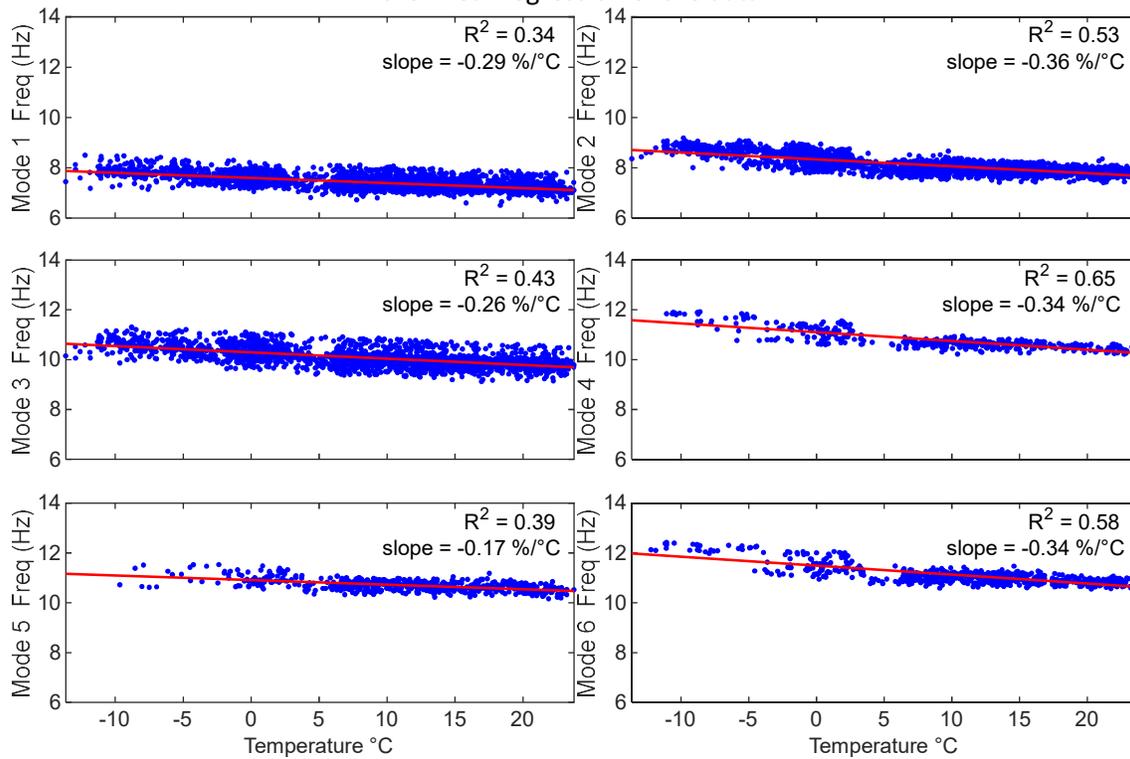
Figure 2. Sensor placement showing weighing sensors and accelerometers.



### Effect of temperature on estimated modal parameters

To investigate the effect of changing environmental conditions on modal parameters Operational Modal Analysis (OMA) was performed hourly for a total of 2903 hours spanning varied seasonal conditions. Modal parameters were estimated for each hour using data-driven SSI using model orders up to 90. The estimated frequencies of the first six modes are plotted as a function of daily temperature measured from a nearby weather station and are shown in Figure 3. A linear regression was performed and the coefficient of determination between temperature and natural frequency was calculated for each mode along with the percentage change of frequency for each degree Celsius. Considering Figure 3 there is a clear relationship between temperature and natural frequency. As the temperature increases, the natural frequency decreases which aligns with the noted trends in the literature. Based on previous research this trend is mostly attributed to a decrease in the modulus of elasticity and the resulting decrease in stiffness. The natural frequencies show an approximate rate of change of  $-0.30 \text{ \%/}^\circ\text{C}$  which over the  $38 \text{ }^\circ\text{C}$  temperature range experienced at the bridge results in an approximate 11% change in natural frequency due to environmental effects over the measuring period.

Figure 3. Natural frequencies of modes 1 to 6 as a function of temperature, while the red line denotes the linear regression of the data.



### Effect of temperature on estimated influence line

Once the effects of temperature on the dynamic behaviour of the structure were established a study was performed to determine the resulting variation in the influence line of the structure. Though the calibration coefficient is a function of cross-sectional geometry and should not be affected by environmental changes, this is only true for a homogeneous material. In the case of reinforced concrete the changes in elastic modulus due to temperature for both the steel and concrete are different with concrete changing significantly and steel remaining relatively unchanged. This can result in changes in modular ratio  $n = E_s/E_c$  where  $E_s$  and  $E_c$  are the elastic modulus for steel and concrete respectively. Changes in the modular ratio affect the equivalent concrete area and subsequent neutral axis location.

To address this effect a study was conducted to determine the sensitivity of the neutral axis location to changes in elastic modulus. An expression was developed for the neutral axis of one of the AASHTO Type 3 prestressed beams from the Westfield overpass and the value of  $E_c$  was then varied while keeping  $E_s$  constant. The change in the neutral axis and corresponding calibration coefficient which is the location of the sensor below the neutral axis as a function of change in  $E_c$  is plotted in Figure 4. Considering the +/- 25% range of change in the value of  $E_c$  expected from the literature results in only a small change in calibration coefficient of +/- 1%. This indicates that the calibration of the proposed method is insensitive to changes in temperature and that the changes in modal parameters can instead be used to capture these effects without the need to recalibrate the system.

To determine the effect the change in modal parameters has on the influence line of the structure the first three modes of the structure shown in Figure 5 were used to simulate the influence line using the

calibration coefficient 480 mm. The hourly modal parameters were used to calculate the influence line for each girder corresponding to a unit load in the center of a lane. The maximum ordinate for each girder is plotted as a function of temperature in Figure 6. A linear regression was performed and the coefficient of determination between temperature and maximum ordinate was calculated for each girder along with the percentage change of the influence line ordinate for each degree Celsius. As the temperature increases, the maximum influence line ordinate increases following a linear trend. This is to be expected considering the decreasing frequency with temperature signifies a decrease in stiffness and thus the deflection of the structure increases. The maximum influence line ordinates show an approximate change of  $-0.80\%/^{\circ}\text{C}$  per girder which over the  $38^{\circ}\text{C}$  temperature range results in approximately 30% change. The influence line ordinates and estimated axle weights are linearly proportionate therefore this change represents a potential 30% error in GVW. Significant errors in GVW estimation are therefore possible if variations in bridge response due to the environment are ignored.

Figure 4. Change in calibration coefficient as a function of change in  $E_c$  and expected range of variation in parameters.

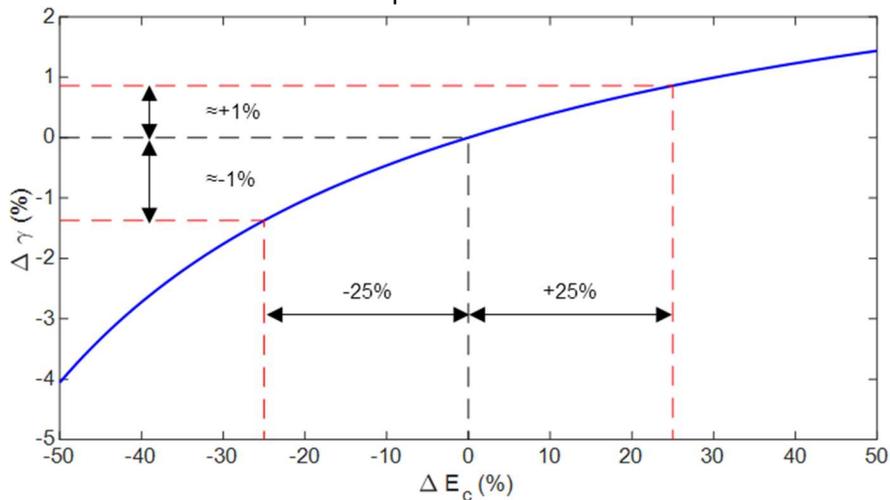


Figure 5: Average estimated mode shapes, natural frequencies and damping ratios of the first three mode shapes. The top subplots illustrate the 3D view and the bottom subplots show the side view.

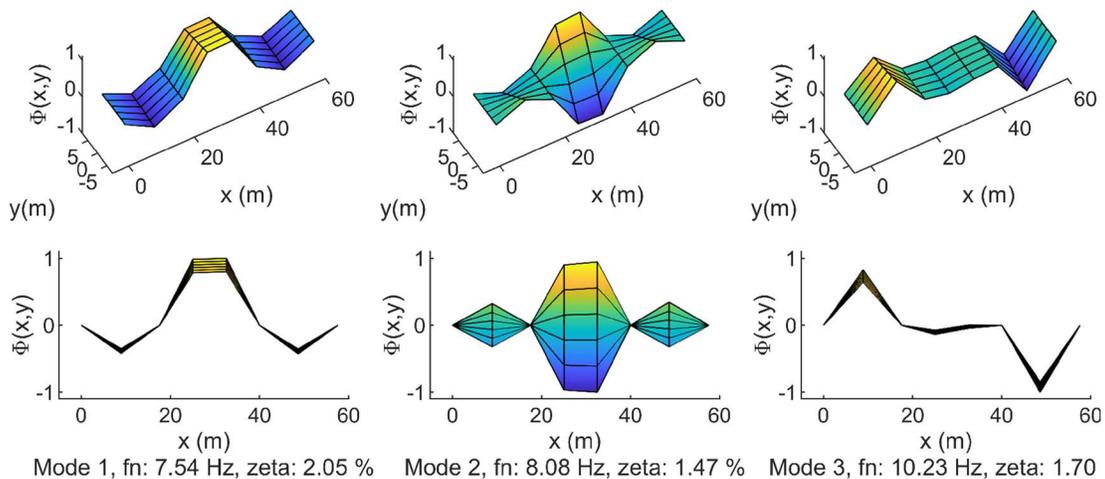
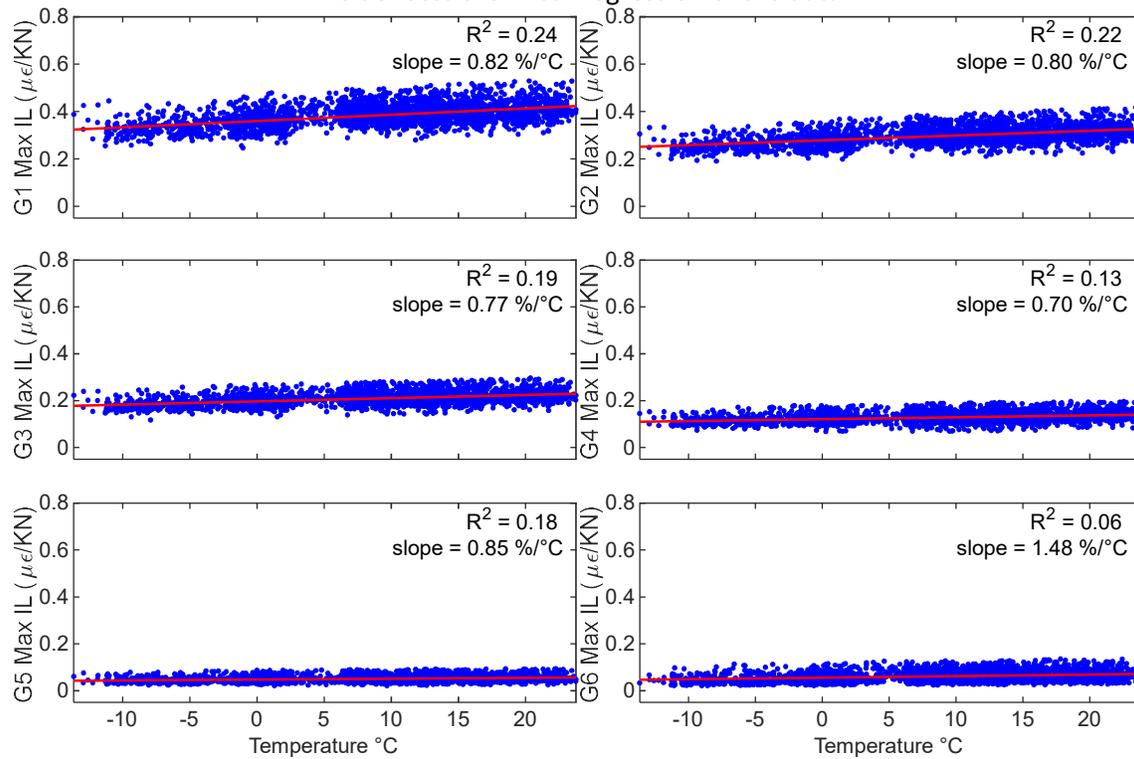


Figure 6. Maximum influence line ordinate of girder 1 to 6 as a function of temperature, while the red line denotes the linear regression of the data.



## Effect of temperature on field-measured bridge response

To validate the numerical study and assess the influence of environmental variability on the structural strain response, field data from 22 days spanning a year were analyzed. Events were precisely identified through timestamped photographs, enabling accurate correlation between recorded strain data and individual vehicle passages. These images facilitated the categorization of events based on axle configurations, allowing truck-type classification while acknowledging inherent variability in Gross Vehicle Weights (GVWs). Strain responses from all girders for each event were aggregated, generating composite strain-time curves, which were then filtered using a low-pass filter with a cutoff frequency of 15 Hz to isolate the dominant vehicle-bridge interaction frequencies. Categories exhibiting tightly clustered strain responses, indicative of consistent loading conditions, were selected for further examination. Two representative vehicle categories were identified and analyzed: a 7-axle log truck (VA-1213) with 46 vehicles travelling South, and an 8-axle tanker truck (VA-1232) with 40 vehicles travelling North. A single travel direction per truck type was selected to minimize variations caused by differing bridge entry conditions. The aggregate strain response of these vehicles and a representative image of each type is shown in Figure 7.

To further mitigate the influence of noise and dynamic vehicle-bridge interactions, strain-time curves were spatially integrated using estimated vehicle velocities, resulting in a metric termed the "Strain Area." Figure 8 presents the relationship between Strain Area and mean daily ambient temperature for the two representative truck categories. Both truck types demonstrate a clear positive linear trend, with Strain Area increasing as the temperature rises, despite expected variability due to weight differences among

vehicles within each category. This observed trend aligns with theoretical expectations derived from calculated changes in influence line ordinates; however, discrepancies in magnitude occur as the theoretical influence line assumes a single unit load on a smooth roadway at the peak response location, whereas the measured response reflects aggregated dynamic effects and inherent variability in vehicle parameters.

Figure 7. Aggregated strain-time responses for selected vehicle categories, VA-1313 and VA-1232, with representative images

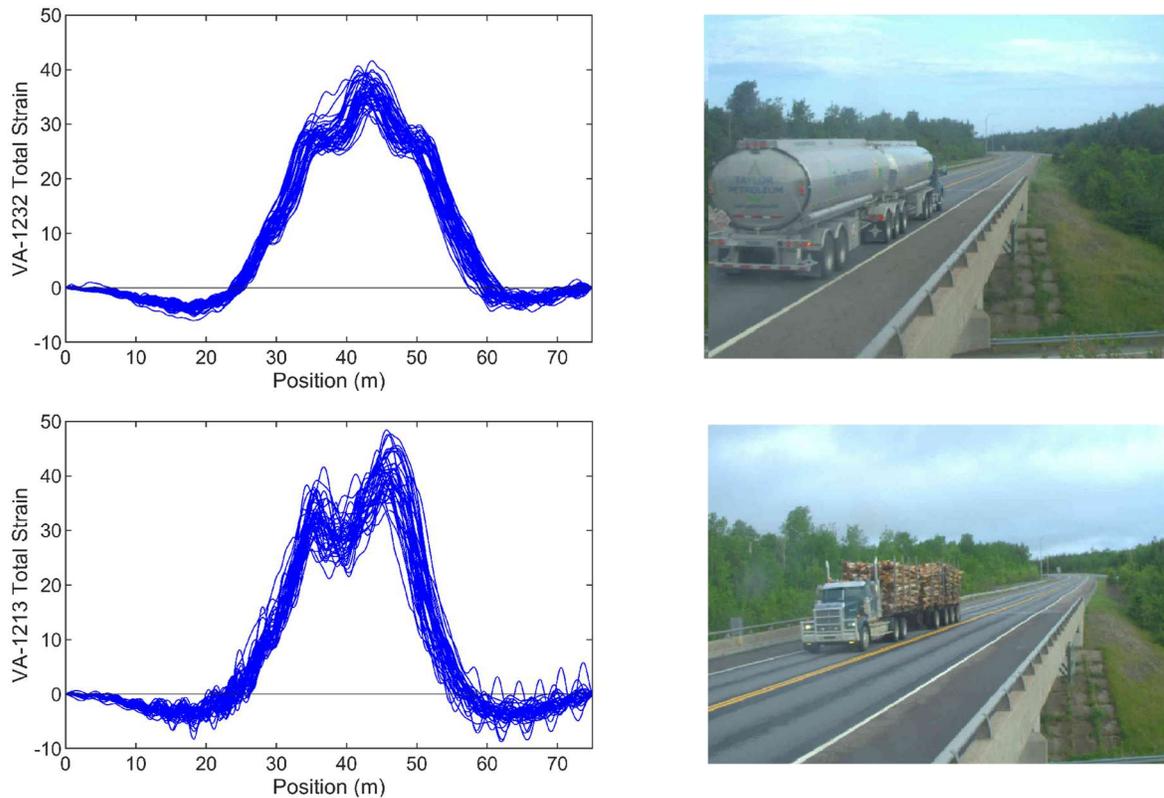
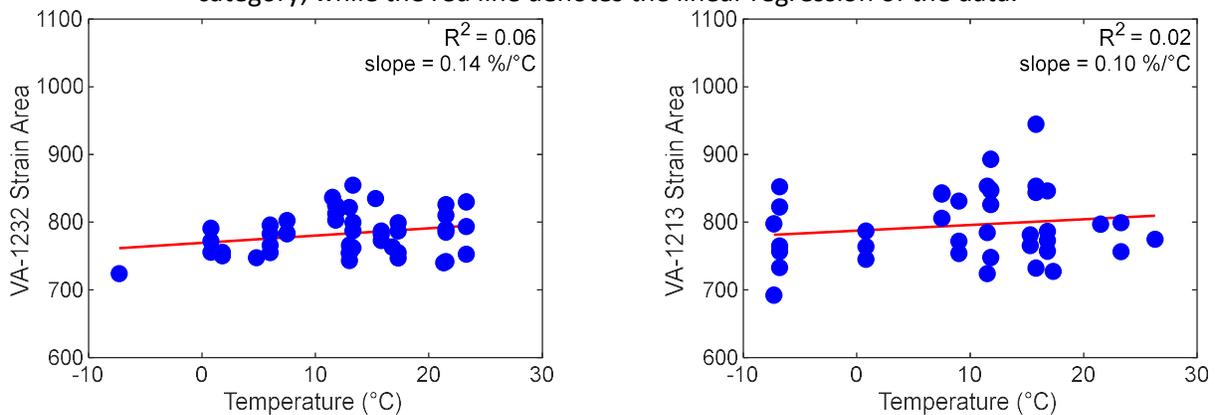


Figure 8. "Relationship between Strain Area and mean daily ambient temperature for each vehicle category, while the red line denotes the linear regression of the data.



## Conclusion

The developed dynamic parametric Bridge Weigh-in-Motion (BWIM) method, which utilizes experimentally estimated modal parameters, has been evaluated for its effectiveness in capturing the changing response of a two-dimensional bridge structure under environmental variations. This study investigated the impact of temperature changes on estimated modal parameters and subsequent alterations in bridge response characteristics. Notably, the temperature range experienced at the bridge resulted in an approximate 11% change in natural frequency over the measuring period. The calibration coefficient of the proposed method demonstrated insensitivity to temperature changes, suggesting that frequent recalibration is unnecessary. Instead, changes in modal parameters effectively captured environmental effects. The study revealed that the temperature variations could introduce a substantial error in GVW estimation if not accounted for. Field data validated the significant influence of temperature on structural strain, highlighting a clear positive correlation with integrated strain responses. This empirical validation aligns with theoretical predictions but highlights increased variability arising from actual vehicle dynamics and loading conditions.

This research highlights the critical influence of environmental factors on bridge response and the consequential impact on GVW estimation accuracy. The inclusion of online modal parameters in the BWIM analysis presents a promising approach for mitigating the need for frequent calibration. By demonstrating the insensitivity of the calibration coefficient to temperature variations and the capacity of modal parameters to capture environmental effects, the proposed method presents a valuable contribution to improving the accuracy and reliability of BWIM systems in real-world conditions.

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