Innovative Strain Based Bridge Weigh-In-Motion System for Truss Bridges

Ethan MacLeod MSCE, Research Assistant, University of New Brunswick

Kaveh Arjomandi Ph.D., P. Eng., Associate Professor, University of New Brunswick

Tracy MacDonald P. Eng., Bridge Engineer, New Brunswick Department of Transportation and Infrastructure

Josiah Matthews P. Eng., Bridge Engineer, New Brunswick Department of Transportation and Infrastructure

Paper prepared for presentation at the Structures Session

of the 2019 TAC-ITS Canada Joint Conference, Halifax, NS

Acknowledgments

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the New Brunswick Department of Transportation and Infrastructure (NBDTI) for supporting this research.

Abstract

Efficient management of bridge structures requires a thorough understanding of the traffic using a bridge. In this paper an innovative static strain-based remote Bridge-Weigh-In-Motion (BWIM) system is deployed on a truss bridge in rural New Brunswick, Canada. The analysis methods are briefly outlined, and the system is successfully validated with a truck of known weight resulting in an average error of 7% in gross vehicle weight estimation. It is shown how the BWIM system can be used in estimating the dynamic amplification factors use in the analysis and design of bridges.

Introduction

Oversize and overweight vehicles have become a common concern worldwide as the demand to structural capacity ratio is continuously increasing due to changes in traffic and aging of bridge structures. Overweight trucks can cause serious damage to bridges and accelerate the degradation, causing fatigue problems and shortening service life. The province of New Brunswick, located in Atlantic Canada, is home to 770,000 residents and more than 3000 bridges. The large number of bridges per capita combined with a high ratio of heavy commercial vehicle traffic and a small number of commercial vehicle enforcement officers, makes overweight loading a significant concern for the New Brunswick Department of Transportation and Infrastructure (NBDTI). There is a growing desire for the development of real-time remote monitoring programs to monitor the frequency of over weight loading events and the effect they have on the bridge structures.

Pavement based weighing systems have been in use for decades to enforce overloaded road traffic. The systems can be divided into three categories:

1. Static – very accurate measurements but require vehicle be stationary on scales. Typical at roadside weigh stations.
2. Low speed Weigh In Motion (WIM) – still reasonably accurate and adequate for enforcement but require vehicles be traveling at speeds between 5-15 km/h
3. High speed WIM – vehicles can maintain highway speed with the sensors typically imbedded into the highway surface. These systems are not accurate enough for enforcement but are typically used for preselection of which vehicles to weigh at the weigh station.

Though highly accurate, static and low speed WIM systems can be an ineffective form of enforcement as they cause significant queuing and time delays. Pavement based WIM systems can more efficiently monitor traffic and have been in use for decades to monitor and record road traffic. Pavement based systems work well for general measurement and classification of routine traffic traveling down main highways but are impractical for monitoring compliance of traffic passing over bridges. This due to the large number of bridges in a transportation network and once a vehicle passes a WIM station there is no way to know which bridges it may pass over. Agencies have not had a cost-effective mechanism to monitor these structures of concern as

WIM stations are very costly and it would be impractical to construct a station at every bridge of concern.

This has resulted in the development of Bridge-Weigh-In-Motion (BWIM) systems to provide a more practical solution for bridge monitoring. BWIM methods estimate weights of vehicles at full highway speeds by using an instrumented bridge as a scale (Richardson et al. 2014). BWIM systems are more economical and are also more durable as they are not exposed to harsh road conditions such as snow and de-icing products as well as not being in direct contact with the traffic flow. Pavement based sensors can only record a few milliseconds of the vehicle response due to the limited time the wheels are in contact with the sensors. Therefore, they are not sufficient to record a complete cycle of force oscillation which results in errors in estimating the vehicle weight. BWIM systems however, measure the complete time history of the bridge response enabling more accurate estimation of the vehicle weights (Yu et al. 2016). In BWIM systems, axle detection techniques are used to estimate vehicle velocity, axle spacing and axle position in the lane. This information can be incorporated into weight estimation techniques which fall into two main categories of static and dynamic algorithms (Yu et al. 2016).

Static algorithms estimate the vehicle weights based on methods which use static influence lines to compare the measured response of a bridge to the theoretical value. A number of methods have been developed for modifying the influence lines to better match the measured data (McNulty and O'Brien 2003, Caprani et al. 2006). The transverse position of the vehicle within a lane can significantly affect the accuracy of the influence lines. The use of two-dimensional influence line surfaces can help reduce this error (Quilligan 2002). However, these methods can have significant errors introduced from the dynamic response of the bridge as only the static influence line is considered.

Dynamic algorithms obtain the time histories of axle forces from a vehicle passing over the bridge. These methods known as Moving Force Identification (MFI) can be very accurate in theory as the complete dynamic effects of the vehicle can be identified and removed from the response to calculate the static axle weights (Yu et al. 2016). Since the 1990s a number of methods have been proposed such as the Interpretive Method (IM) (O'Connor and Chan 1988), the Time Domain Method (TDM) (Law et al. 1997) and the Frequency-Time Domain Method (FTDM) (Law et al. 1999). Deployment and calibration of these methods are computationally expensive compared to their static counterparts making them inefficient to be employed for automated online monitoring. Most of these methods also still employ very simplified structural models which provide good analytical results for simple systems but do not accurately represent the complexity of an actual bridge.

The main source of inaccuracy from BWIM systems is due to dynamic-vehicle bridge interaction which is a very active field of study of its own. Much of the research being conducted on vehicle-bridge interaction is in the context of determining Dynamic Amplification Factors (DAF). DAF can be defined as "an increase in design traffic load resulting from the interaction of moving vehicles and the bridge structure and is described in terms of the static equivalent of the dynamic and vibratory effects" (Chan and O'Connor 1990). DAF is commonly expressed as:

$$DAF = \frac{E_{dyn}}{E_{stat}} \quad (1)$$

Where E_{dyn} is the maximum total load effect experienced by the bridge for a loading situation and E_{stat} is the maximum static load for the same event. There has been significant progress in recent years in accurately modeling dynamic vehicle bridge interaction, ranging from simple closed form models (Lin and Weng 2004) to highly complex Finite Element (FE) models (Li et al. 2006). Researchers have also investigated other factors that can affect the dynamic behavior of the bridge besides model of choice for analysis. The effects of road surface condition on the dynamic effects of vehicle bridge interaction was found to have the most significant effect on the DAF of a bridge (Paeglite and Smirnovs 2015). Deng and Phares conducted an extensive investigation for the Iowa Department of Transportation and found that DAF increases with speed by performing field testing on a one concrete slab, two steel girder and two prestressed concrete bridges (Deng and Phares 2016). O'Brien et. al. proposed a statistical method for determining the DAF of a bridge which uses characteristics of the expected traffic source (O'brien et al. 2006). Similarly, Caprani et. al. presented a probabilistic method based on the most critical predicted static loading on the bridge. Using this model it was possible to determine the correlation between critical static loading and DAF (Caprani et al. 2006)

In this paper, a strain-based remote monitoring system is utilized to record high resolution real-time strain data to estimate Gross Vehicle Weight (GVW) using static BWIM techniques. Field validation of the sensor and monitoring system was conducted in partnership with NBDTI at the North Thoroughfare Bridge on Rte. 690, a rural single lane bridge 40 km east of Fredericton NB. The analysis procedure is briefly outlined and the BWIM system is validated using a NBDTI plow truck of a known weight and axle spacing at 10 km/h to 60 km/h, at 10 km/h increments, with four passes per increment. DAF values are calculated and compared against current design values.

North Thoroughfare bridge

The bridge is a 39m long Baltimore through truss built in 1922 shown in Figure 1 and is located 40 km east of Fredericton NB seen in Figure 2. The north bridge is one of two bridges shown in Figure 3 and was selected as it was simply supported whereas the south bridge is a swing bridge with a central pier. This bridge is currently the only restricted portion of Rte. 690 with a posted speed limit of 30 km/h and a maximum axle weight of 6 ton and a GVW of 10 ton resulting in a lengthy detour to bypass the structure. Due to these restrictions, and the large amount of traffic on the road to access summer cottages and communities on Grand Lake, this bridge is suspected to experience overloaded vehicle traffic.

Figure 1: North Thoroughfare Bridge

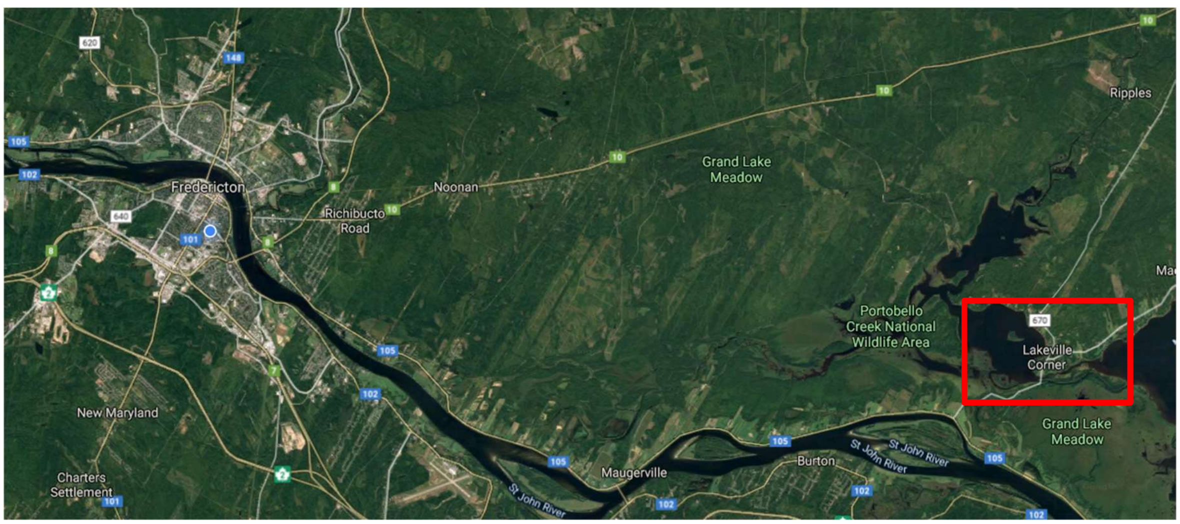

Figure 2: North Thoroughfare Bridge location 40 km east of Fredericton NB

Figure 3: Ariel view of North and South Thoroughfare Bridges

BWIM Instrumentation

The BWIM system is comprised of four main components: axle response measurement, global response measurement, traffic camera and data communication shown in Figure 4. The system is triggered to begin sampling at 100 Hz by a vehicle entering the bridge using a Banner QT50RAF radar motion detector (Fig 5.a) mounted to each approach of the bridge. This event also triggers a MOBOTIX AllroundDual M16 infrared capable camera (Fig 5.b) to take a picture of the vehicle for verification purposes. The axle detection response is measured using BDI ST350 strain gauges (Fig 5.c) installed on both the upstream and downstream midspan vertical hangers. As these are theoretically zero force members unless the applied load is in proximity, the strain response is dominated with peaks which correspond to the passing axles. At the same time the global response of the bridge is measured by BDI ST350 strain gauges (Fig 5.d) on the upstream and downstream bottom chords at midspan in order to measure an influence line for the entire loading event. The data is recorded by a Campbell Scientific CR1000X data logger installed in a water proof enclosure along with reserve batteries, a GSM router and antennae (Fig 5.e) that is mounted to the downstream wingwall. Strain data and temperature are also recorded every 5 minutes to monitor the long-term effects and trends of the bridge response. All data is automatically uploaded to a UNB server every 1 hour. Figure 6 shows a sample of the measured strain and temperature data over 100 seconds.

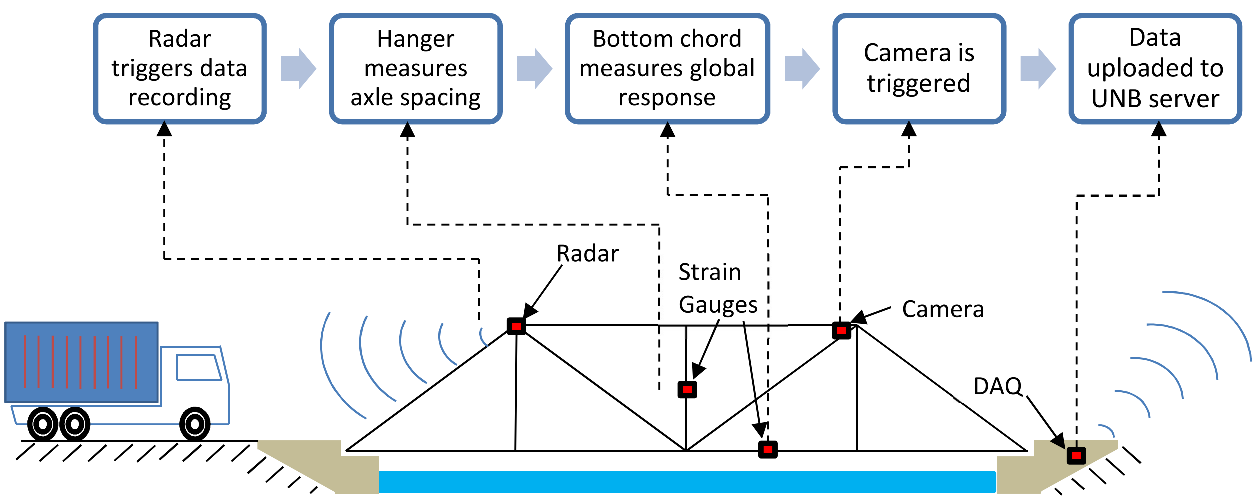

Figure 4: BWIM System diagram

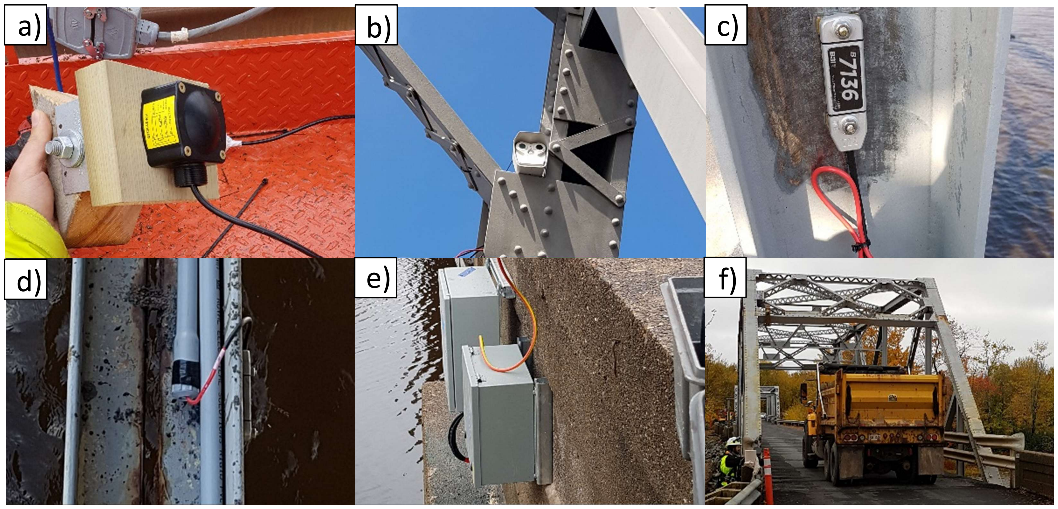

Figure 5: a) Banner radar motion detector on custom mounting block, b) MOBOTIX camera, c) BDI ST350 strain gauge installed to vertical hanger, d) BDI ST350 strain gauge installed to bottom chord, e) data logger enclosure and power converter unit, f) standard plow truck

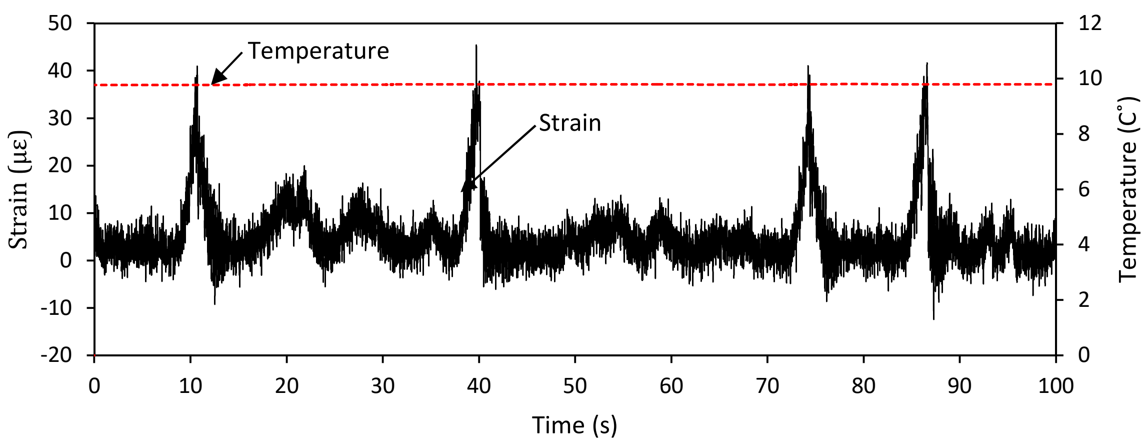

Figure 6: Sample strain data for the upstream bottom chord and temperature measurement

BWIM Analysis

The proposed BWIM analysis method consists of four phases: signal processing, static model updating, axle detection, and GVW estimation. Before the strain data can be analyzed, individual loading events are identified and isolated. Next the strain from the upstream and downstream sensors are averaged to account for vehicle lane position. To remove the oscillating dynamic component from the signal, a convolution is performed between the signal $f(t-u)$ at time lag u and a half sine wave $g(u) = \sin(t/2T)$ of increasing period T shown in Equation 2:

$$h(t) = \int_{-\infty}^{\infty} f(t-u)g(u)du \quad (2)$$

where $h(t)$ is the estimated static signal. The resulting static strain from this smoothing can be seen in Figure 7 and was validated using measurements from a static load test of the bridge.

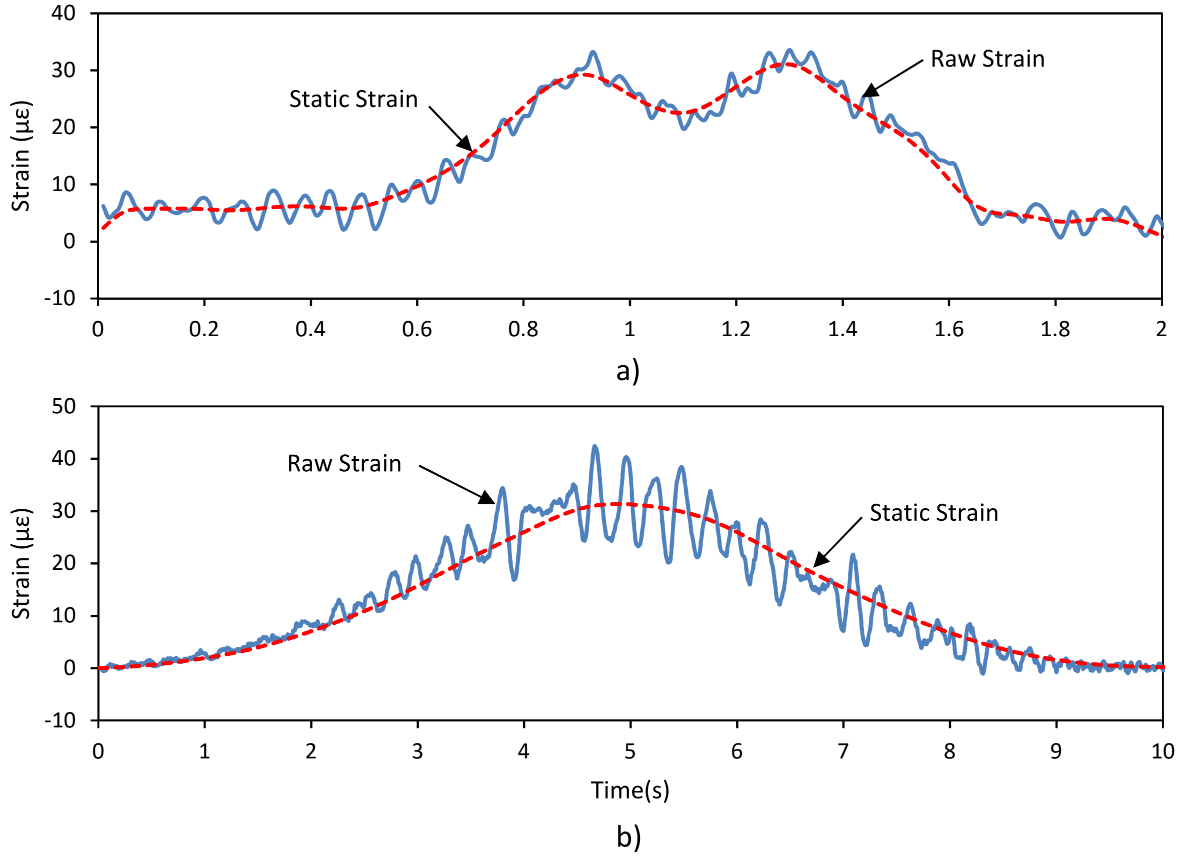

Figure 7: Raw and static strain a) axle detection b) GVW estimation

Using the peak dynamic strain from each trial and the measured static strain from a static loading event the DAF for each vehicle speed was calculated and is presented in Figure 8. From this figure it is evident here is no clear correlation between increasing vehicle speed and increasing DAF values as the max average value occurs at 30 km/h. The max recorded values was 1.6 measured at a vehicle speed of 30 km/h which is significantly larger than the highest recommended design value of 1.4 from the Canadian Highway Bridge Design Code (CSA Group 2014). Using the proposed BWIM method DAF can easily be calculated for each loading event from the measured peak strain and estimated static strain. This would enable the statistical analysis of values and create a greater insight into the performance of the structure in operating conditions and how the performance changes over time.

The theoretical influence line of the bridge for a loading event was calculated using a 2D finite element model developed in Matlab based on structural drawings for the bridge provided by NBDTI. For the model to accurately reflect the in-situ conditions and account for simplifications in the 2D model, finite element model updating was performed. The stiffness (EA), of the truss members were updated to minimize the difference between measured and theoretical influence lines for the loading event of passing the standard test truck. As can be seen in Figure 9, a close agreement between measured and theoretical strain was achieved using this process.

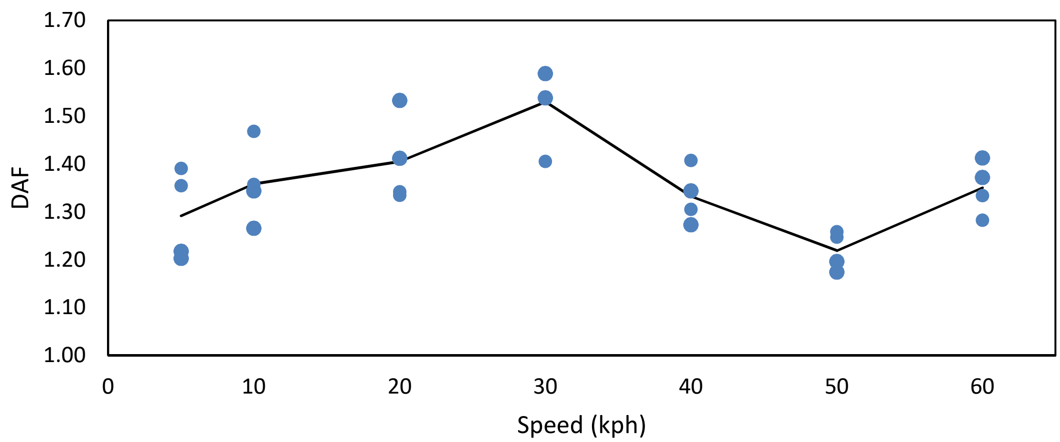

Figure 8: Average calculated DAF factor at the various vehicle test speeds

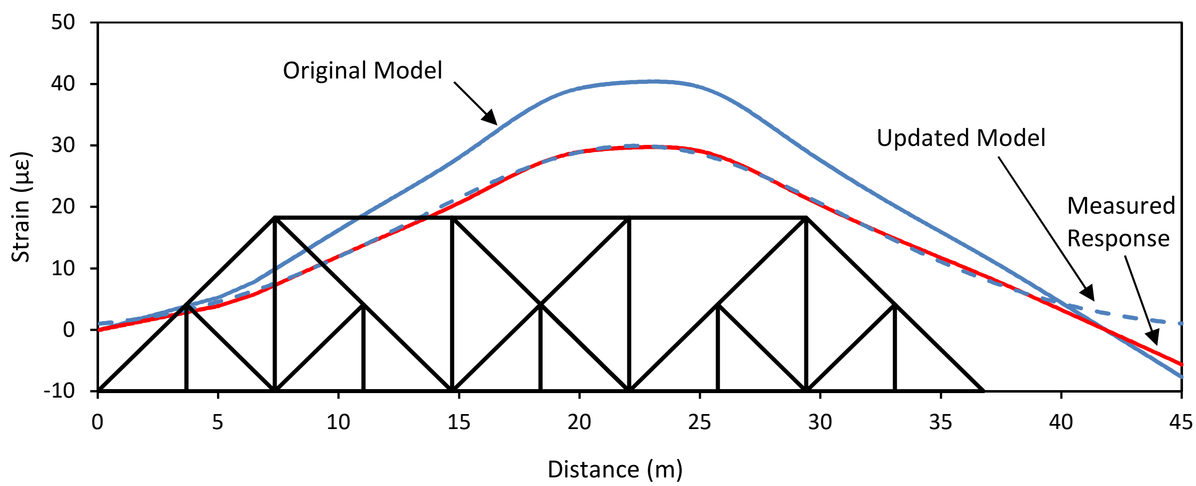

Figure 9: Bottom chord influence lines

Once the model is updated and the signals are smoothed, the axle group spacings are determined using the distance between the peaks in the hanger average strain response. The vehicle speed is estimated using the time between the entrance and exit triggers, assuming constant velocity once the vehicle is on the bridge. This axle group spacing is then used in the finite element model to calculate axle group loads by minimizing the difference between the theoretical values and the measured static influence lines. These axle loads are then summed to determine an estimate for the GVW.

Results

Using the data from the 24 trial passes of the NBDTI test truck, model updating, axle group spacing estimation, and GVW estimation were performed. After performing model updating on all trials the average member stiffness increased by 44%. This difference is mainly due to the difference between 2D and 3D behavior as in the real structure the stringers contribute to carrying axial loads. The increase in estimated member stiffnesses was then used to calculate the percentage of stringer area that was mobilized to carry tension, found on average to be 32%, and is summarized in Figure 10.

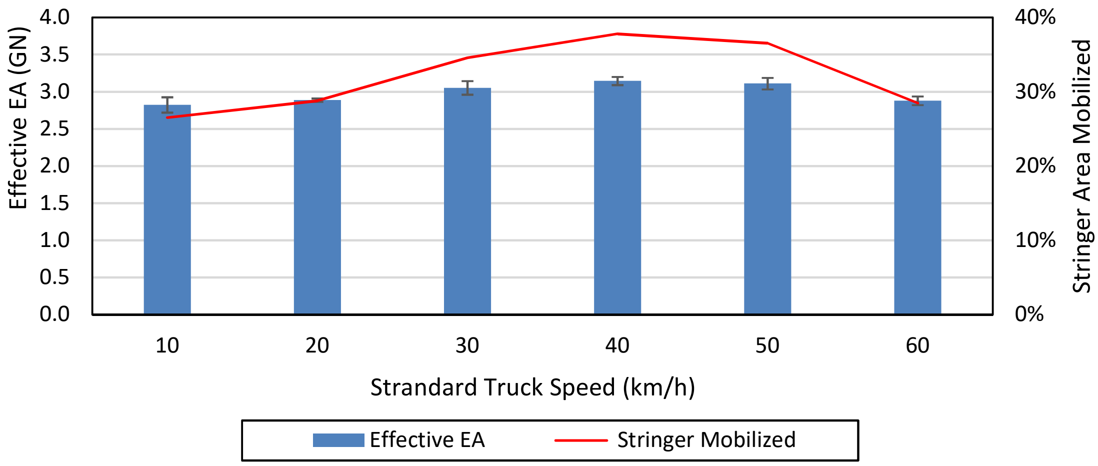

Figure 10: Model Updating Results (Error bars show standard deviation)

Using the proposed method for axle group spacing estimation resulted in an average value of 5.5 m with standard deviation of 0.5 m, these results are summarized in Figure 11. This results in an average error of 4% from the true value of 5.7 m which is less than the contact patch of a tire on the road surface and thus deemed acceptable.

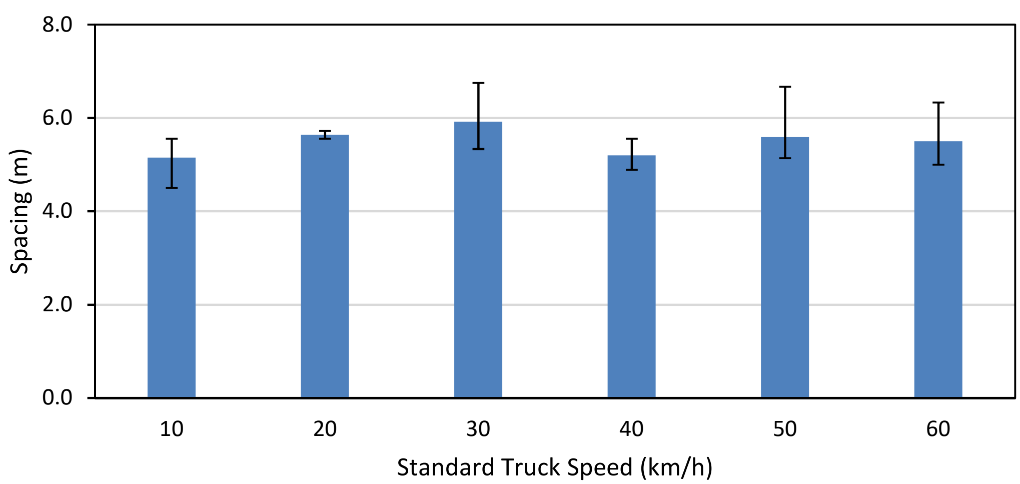

Figure 11: Estimated axle group spacing (Error bars show standard deviation)

An average GVW estimate of 13700 kg with a standard deviation of 800 kg was achieved using the proposed static BWIM method with the results summarized in Figure 12. The true GVW of the truck measured by portable scales from the New Brunswick Department of Justice and Public Safety, Commercial Vehicle Enforcement, was 14800 kg. This results in an average error of 7% in GVW measurements. Comparison of the average percent error between different vehicle speeds show that the error is significantly higher for the trials performed at 30, 40, and 50 km/h.

Analyzing the strain time histories and DAF values of Figure 4, it was found that these vehicle speeds produced the largest dynamic effects.

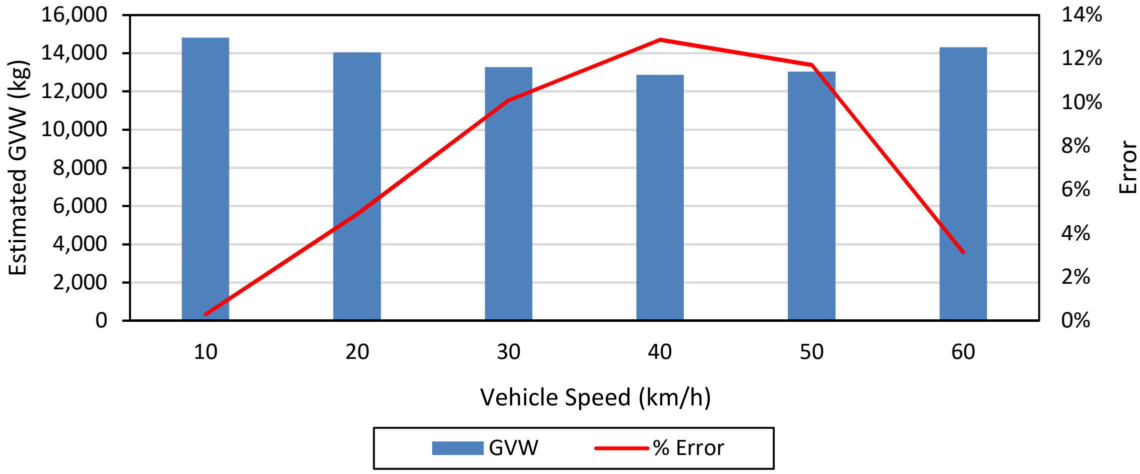

Figure 12: Estimated GVW for each vehicle speed and average percent error.

Conclusions

This paper outlines the deployment of a static BWIM system on a medium span truss bridge for accurate estimation of the GVW of vehicles with various speeds. The system was successfully validated with a truck of known weight resulting in an average error of 7% in gross vehicle weight estimation. The DAF values were calculated and found to be significantly higher than the current suggested design values. This demonstrates that a remote strain based BWIM system can be a viable and cost-effective dual-purpose solution for bridge traffic monitoring and long-term condition monitoring.

Reference

Caprani, C.C., Rattigan, P.H., Gonzalez, A., O'Brien, E.J., González, A., and OBrien, E.J. 2006. Determination of characteristic bridge DAF using dynamic finite element analysis of critical static loading scenarios. Bridge and Infrastructure Research in Ireland, 21–28.

Chan, T.H.T., and O'Connor, C. 1990. Vehicle Model for Highway Bridge Impact. Journal of Structural Engineering, 116(7): 1772–1793.

CSA Group. 2014. S6-14 Canadian Highway Bridge Design Code. CSA Group.

Deng, Y., and Phares, B.M. 2016. Investigation of the Effect of Speed on the Dynamic Impact Factor for Bridges with Different Entrance Conditions.

Law, S.S., Chan, T.H.T., and Zeng, Q.H. 1997. Moving Force Identification: A Time Domain Method. Journal of Sound and Vibration, 201(1): 1–22.

Law, S.S., Chan, T.H.T., and Zeng, Q.H. 1999. Moving Force Identification—A Frequency and Time Domains Analysis. Journal of Dynamic Systems, Measurement, and Control, 121(3): 394–401. ASME.

Li, H., Kwasniewski, L., Malachowski, J., and Wekezer, J. 2006. Development of Finite Element Models of Heavy Vehicles Development of Finite Element Models of Heavy Vehicles. 9th International Symposium on Heavy Vehicle Weights and Dimensions, State College, Pennsylvania.

Lin, J., and Weng, C. 2004. Evaluation of dynamic vehicle load on bridge decks. Journal of the Chinese Institute of Engineers, 27(5): 695–705.

McNulty, P., and O'Brien, E.J. 2003. Testing of Bridge Weigh-In-Motion System in a Sub-Arctic Climate. Journal of Testing and Evaluation, 31(6): 11686.

O'brien, E., González, A., Caprani, C., Li, Y., and Harris, N. 2006. Bridge Dynamics and Loading. Bridge and Infrasturcture Research in Ireland,: 347–358.

O'Connor, C., and Chan, T.H.T. 1988. Dynamic Wheel Loads From Bridge Strains. Journal of Structural Engineering, 114(8): 1703–1723.

Paeglite, I., and Smirnovs, J. 2015. Dynamic effects caused by the bridge-vehicle interaction. 5th International Conference Civil Engineering`15 Proceedings Structural Engineering. Guangzhou, China.

Quilligan, M. 2002. Development and Testing of a 2-Dimensional Multi-Vehicle Bridge-WIM Algorithm. Third International Conference on Weigh-in-Motion (ICWIM3). Orlando, Florida.

Richardson, J., Jones, S., Brown, A., O', E., Brien, N.A., and Hajializadeh, D. 2014. On the use of bridge weigh-in-motion for overweight truck enforcement. International Journal of Heavy Vehicle Systems, 21(2): 83.

Yu, Y., Cai, C.S., and Deng, L. 2016. State-of-the-art review on bridge weigh-in-motion technology. Advances in Structural Engineering, 19(9): 1514–1530.