Transformation of an Arterial Highway Bridge to an Operational Bridge Weigh in Motion

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Abstract

As highway infrastructure ages and degrades, the ratio of traffic demand to capacity is increasing, making oversized and overweight vehicles a common concern worldwide. Overweight vehicles can cause significant damage to bridge structures, accelerate degradation, shorten the service life, and ultimately lead to a collapse in some instances. This has resulted in a growing interest in the development of technologies and systems that can monitor the frequency and characteristics of overweight loading events and the effect they have on bridge structures. Bridge Weigh in Motion (BWIM) systems use the deformation of a bridge, under live loading, to estimate the characteristics of passing traffic loads. An existing bridge is instrumented with a series of sensors that use the full bridge as a weighing mechanism. The implementation of such a system is discussed through a full-scale case study arterial highway bridge in the province of New Brunswick, Canada. The value of BWIM is examined, operational data is presented, and key findings are discussed.

1 Introduction

According to a survey conducted by Statistics Canada in 2018, more than 10% of bridges in Canada have been assessed to be in poor or very poor condition having an estimated replacement cost of $141B (Canadian Society of Civil Engineers 2016). Similarly, a recent report by the American Society of Civil Engineers (ASCE 2021) showed that approximately 7.5% of bridges in the United States were classified as deficient in 2021. With current infrastructure budgets, the number of deficient structures is expected to increase each year, compounding these deficits further. As a result, there is a growing demand for engineering tools that can accurately assess the operational demands placed on bridge structures. With the increase in traffic loads and bridge degradation, the ratio of traffic demand to bridge capacity is rising, leading to oversized and overweight vehicles becoming a regular challenge for bridge structures. Overweight trucks pose a significant threat to bridges, causing damage and accelerating degradation, which can result in fatigue problems and shortened service life. To address this issue, it is crucial to monitor the movement of heavy trucks on a bridge network for planning and maintenance purposes. As a result, there is currently a heightened interest in the development of real-time remote monitoring systems that can determine the prevalence of overweight loading events and their impact on 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 (Richardson et al. 2014):

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

enforcement but are typically used for the preselection of vehicles to weigh at a static weigh station.

While static and low-speed Weigh-In-Motion (WIM) systems are highly accurate, they may not be an effective means of widescale monitoring due to significant queuing and time delays. In contrast, pavement-based WIM systems have been used for decades to efficiently monitor and record road traffic. These systems work well for general traffic measurement and classification on main highways but are not practical for monitoring traffic compliance on bridges. It can be difficult to predict which bridges a vehicle might encounter after passing a WIM station, given the vast number of bridges within a transportation network. It is not cost-effective to construct WIM stations at every bridge, leaving agencies with limited monitoring options.

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 (Moses 1979). BWIM systems are more economical and durable, as they are not exposed to harsh road conditions or in direct contact with traffic flow. Pavement-based sensors can only record the vehicle response as it momentarily contacts the sensor, resulting in errors in estimating vehicle weight. However, BWIM systems can measure the complete time history of the bridge response, allowing for a more accurate estimation of vehicle weights (Yu et al. 2016).

Although BWIM has the potential to improve vehicle weighing and provide more utility than traditional WIM, it is not yet widely implemented in operational settings. The aim of this paper is to compare the advantages of BWIM with traditional WIM and showcase its implementation by presenting a complete case study conducted on an arterial highway bridge in New Brunswick, Canada. The article presents a comparison between BWIM and WIM, discusses the value of BWIM, describes a case study of BWIM system, and presents operational results using a week-long dataset.

2 Operational BWIM System Description

A prototype hybrid BWIM system was installed at the Westfield Route 7 overpass (asset W475) bridge located in New Brunswick, Canada and results were validated through extensive testing and analysis (MacLeod et al. 2022a; Macleod and Arjomandi 2022; MacLeod and Arjomandi 2023a; b). The bridge is a 57 m long, three-span bridge constructed in 1986, consisting of six continuous, prestressed, AASHTO Type-III concrete girders as shown in Figure 1 and Figure 2. 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. This makes the selected bridge a good test structure for estimating the traffic characteristics of commercial vehicles passing between the cities of Saint John and Fredericton. The monitoring system was designed to perform vibration monitoring and function as a traditional BWIM system. The combination of these functionalities created the potential for hybrid monitoring opportunities. The system needed to be permanent and reliable and was designed to be modular to enable future hardware and software upgrades. This ensured the system would be a useful resource for future research beyond the scope of this work. The instrumentation system installed at W475 is described in detail by MacLeod et. al (MacLeod et al. 2023)

Figure 1: W475 Westfield overpass.

Figure 2: Satellite image of Westfield Route 7 overpass (asset W475) showing orientation and ramps.

The operational system consists of three parts: data collection, data processing, and storage and visualization, as illustrated in Figure 3. The data collection system acquires acceleration data, strain data, and images and is elaborated in detail by Macleod et al. (MacLeod et al. 2022b) The collected data is compressed and stored on servers accessed through Microsoft SharePoint cloud-based services via fixed wireless internet at regular intervals. The data is then transferred to local UNB processing computers, where three levels of analysis are performed: event detection, BWIM analysis, and dashboard analysis. The analysis code is modular, allowing for easy implementation of fixes and features without reprocessing past data. The result from each analysis step is added to SharePoint. The event detection module processes the raw data, including the axle detection signals and weighing signals, to determine when a vehicle loading event occurs and produces a trimmed data segment that corresponds to the time the first axle enters the bridge until the final axle exits the bridge. The resulting local event data segments are then fed into the BWIM analysis module, which performs vehicle identification to determine the gross vehicle weight, number of axles, and axle spacings, as well as key traffic characteristics such as direction and velocity. Images captured with an area scan camera are also matched to each event which aids in the verification of the results. The outputs from the event detection and BWIM analysis are data-rich files that are used for subsequent analysis but are not suitable for use with the Power BI dashboard. Thus, the third level of analysis is conducted to extract and format the data to enable visualization and extract further meaningful analysis for owners. The output of the dashboard analysis is efficient CSV files that can be easily integrated into Power BI and formatted for the desired functionality.

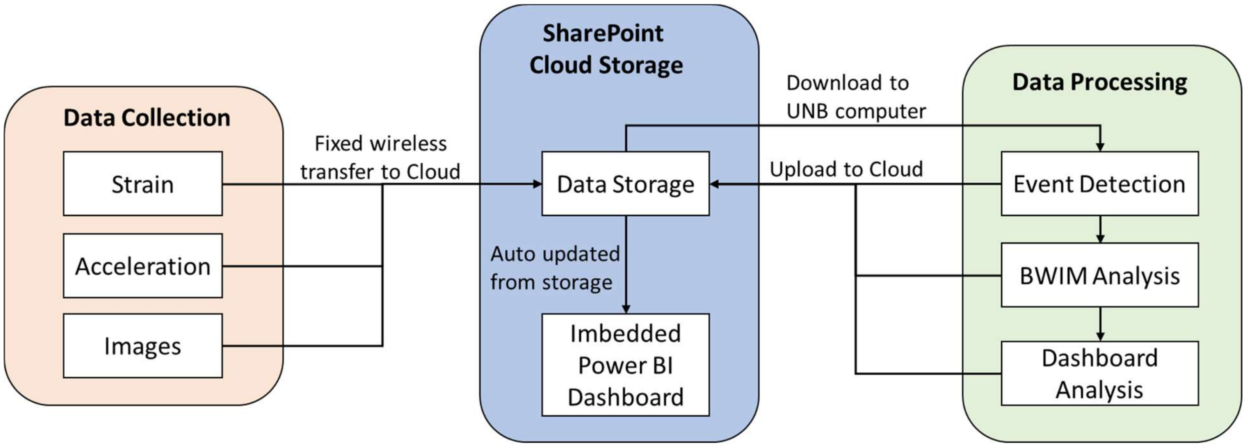
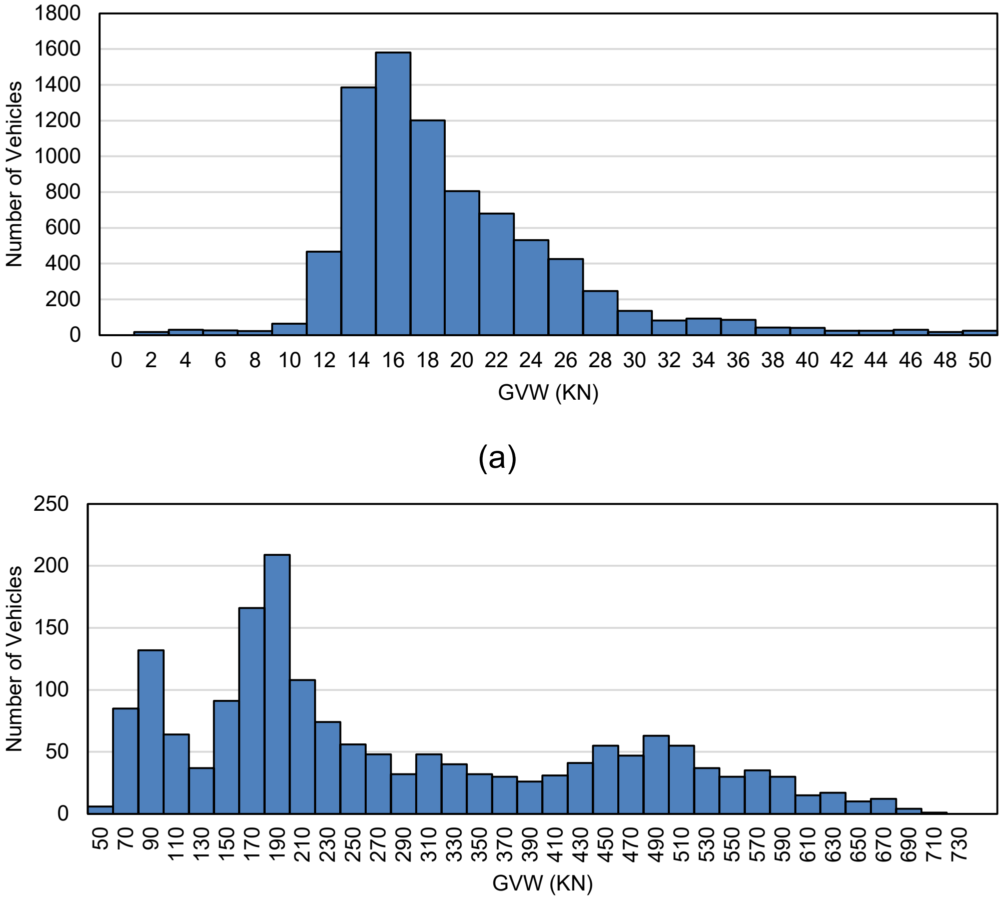


Figure 3: Components of operation BWIM System.

3 Operational Results

To demonstrate the value of the BWIM system, the information from a week-long dataset between July 6th and July 12th, 2021 is presented in this paper. A study was conducted to compare trends for the distribution of GVW, velocity, and travel direction considering both commercial and passenger vehicles. Commercial vehicles are classified as any vehicle with a GVW over 40 KN.

Figure 4 demonstrates the distribution of GVW with a multi-modal distribution. The first peak as seen in Figure 4 (a) is centred between 10 KN and 40 KN and accounts for the expected weight of FHWA Class 2 and Class 3 vehicles, including passenger sedans, sport utility vehicles and mid-size trucks. A second mode in the data can be seen in Figure 4 (b) between 70 KN and 130 KN, which accounts for smaller commercial vehicles and unloaded semi-trucks, followed by two other modes mode of 130-390kN and larger than 390kN, which accounts for loaded semi-trucks. This type of data can inform the bridge owners and operators of the prevalence of heavy truck traffic and can be useful for permit issuing and the design of future structures. It is interesting to note that for the test period, the average commercial weight Southbound towards Saint John is larger than that Northbound towards Fredericton at 271 KN vs. 241 KN, respectively.



(a)

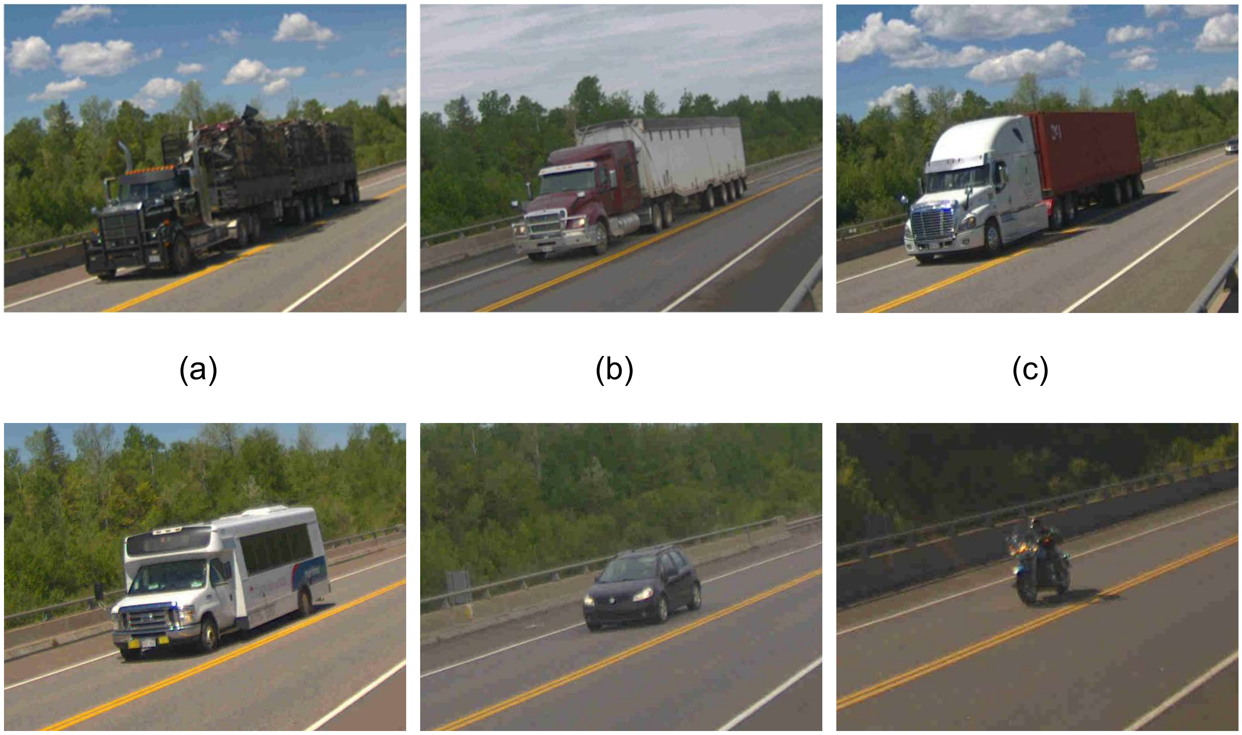
(b)

Figure 4: GVW distribution for (a) passenger and (b) commercial vehicles.

Table 3 summarizes BWIM results for a select set of data with the images of these loading events shown in Figure 5. Traditional WIM would provide data for Class 4, Class 10 and Class 13 vehicles in this example; however, the BWIM system at Westfield has the sensitivity to weigh light passenger vehicles such as Class 2 and even Class 1 (motorcycles). This type of analysis can give valuable insight into the movement of goods and services along highways where BWIM systems are implemented.

Table 1: Selected BWIM results for different vehicle types.

Vehicle Class	GVW (KN)	# Axles	Wheel Base (m)	Velocity (km/hr)
Class 13	617	8	23.3	98
Class 10	671	7	19.2	101
Class 10	498	6	16.0	105
Class 4	47	2	5.5	106
Class 2	14	2	2.6	106
Class 1	3	2	1.6	122



(a) (b) (c)

(d) (e) (f)

Figure 5: Recorded images of vehicle types from Table 3: (a) Class 13 (b) Class 10, 7 axles (c) Class 10, 6 axles (d) Class 4 (e) Class 2 (f) Class 1.

Considering the distribution of velocities in Figure 6, it is evident that there is a significant difference between commercial and passenger vehicles. The mean velocity for commercial vehicles is centred around the posted speed of 100 km/h and there is less variance. This is to be expected from professional truck drivers as well as the speed limitations of a loaded commercial vehicle. Passenger vehicles however display an average velocity of approximately 110 km/h, which is over the posted speed limit, as well as much more variation in the distribution of velocities. The frequency and severity of speeding events could be valuable information for law enforcement officials to help coordinate enforcement activities.

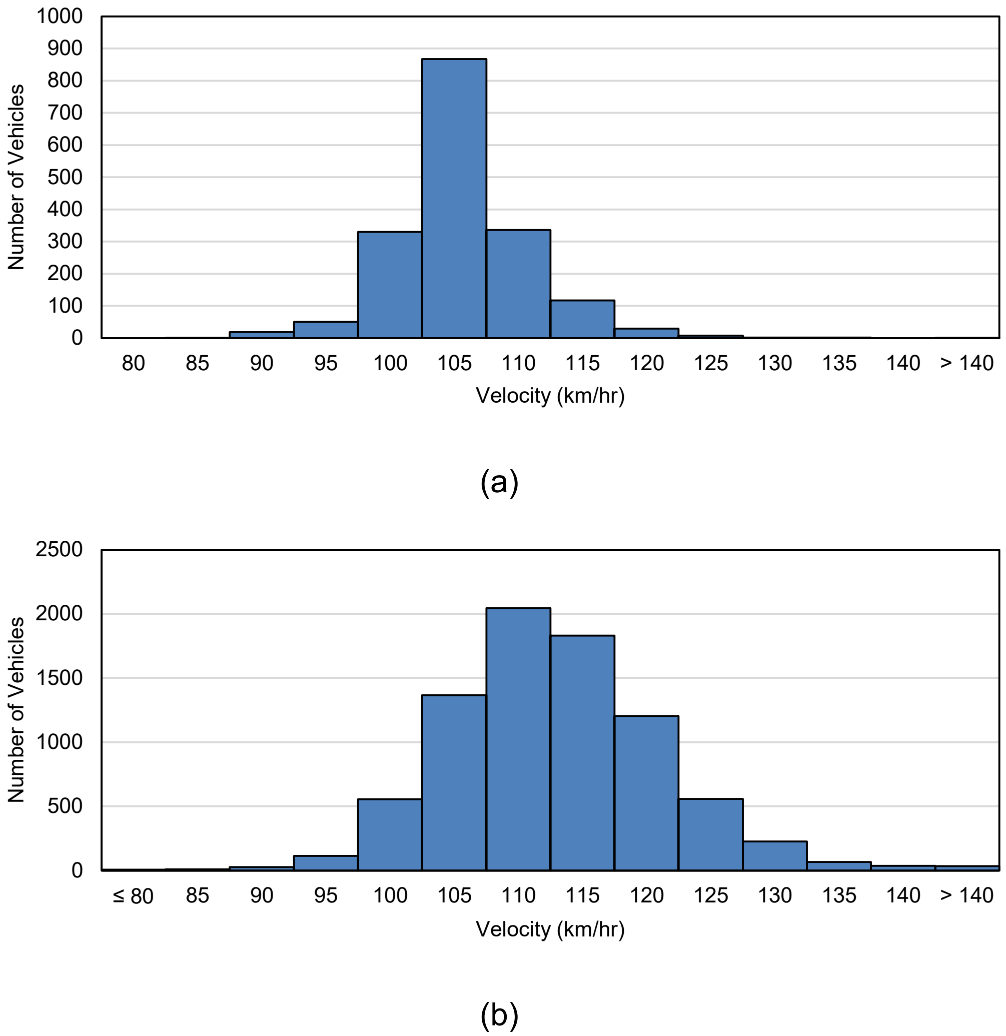


Figure 6: Velocity distribution for (a) commercial and (b) passenger vehicles.

4 BWIM vs WIM

Weigh-in-motion (WIM) technologies include various types of pavement-based sensors (piezoelectric, bending plate, load cell, etc.) that, together with data acquisition and interface systems, provide a product for weighing vehicles uninterrupted, at highway speeds. These systems have some limitations, including technical effectiveness affected by measurement uncertainty from dynamic effects and short contact times (in milliseconds), which can make it difficult to identify and classify vehicles. There are also regulatory effects to consider, such as route changes made by drivers who know the locations of WIM stations to avoid detection (Ryguła et al. 2020). Bridge Weigh-in-Motion (BWIM) systems can provide an alternative product using (mostly) deformation sensors that render a bridge structure effective as a weigh scale where the instrumentation is invisible to drivers.

ASTM (ASTM E1318-09(2017) provides a classification for four types of WIM systems that operate with parameters for vehicle speed, data processing and storage requirements, limits and tolerances for wheel, axle, and axle group tolerances. BWIM systems could potentially be included in this classification and, since any BWIM systems would service the same transportation corridors, it can be assumed to provide a similar controlling effect as pavement-based WIM stations.

In a previous study, Canadian researchers evaluated several types of WIM systems for effectiveness in traffic data collection (Zhang et al. 2007a). The case study provides an economic analysis of pavement rehabilitation costs with respect to the international roughness index (IRI), present serviceability index (PSI), rehabilitation time, present worth cost, and service life based on the percent overload (0% to 30%) from overweight traffic. The authors conclude that the controlling effect of WIM can reduce overload from overweight vehicles, and therefore pavement rehabilitation costs are reduced on the order of 2% to 9%. Continuing with this framework and extending the comparison with the proposed hybrid BWIM system Table 2 demonstrates that, for the same benefit, the hybrid BWIM system can be competitive with pavement-based WIM systems.

Table 2: Feature comparison of WIM vs. BWIM systems (content in orange is reproduced from (Zhang et al. 2007b))

Criteria	**WIM**				**BWIM**
Sensor Type	**Piezoelectric**	**Bending Plates**	**Load Cells**	**Quartz Piezoelectric**	**Ceramic piezoelectric (accel) /foil (strain)**
Cost (per lane)	**Adjusted to 2022 (CAD)**				
equipment & install	$13,000	$28,890	$72,220	$28,890	$33,475
O&M	$7,220	$8,670	$11,550	$14,430	$5,580
Accuracy					
accuracy +/-	15%	10%	6%	10%	5-10%*
confidence level	95%	95%	95%	100%	95%
Sensitivity					
Pavement roughness	high	med	low	high	variable
temperature				no	low
vehicle suspension				low	med*
vehicle speed				low	med*
Expected Life	4 years	6 years	12 years	>15 years (expected)	>12 years (expected)
Reliability	Low	Med	High	Med	Med
Applicability					
traffic data collection	X	X	X	X	X
weight enforcement		X	X	X	X*

*** indicates potential**

For the proposed hybrid BWIM system, the cost reported in Table 2 is the total fixed cost to instrument the case study structure divided by the number of lanes on the bridge. The cost was adjusted from 2020 (when the structure was instrumented) using an annual inflation rate of 5.64% which illustrates the high 11.59% change in Canadian Consumer Price Index (CPI) (Bank of Canada) due to the global pandemic. While the variability of the cost for BWIM systems is dependent on the type of structure, number of girders, and span length, this cost would be representative for a system deployed to a short or medium span, pre-stressed concrete highway bridge carrying two traffic lanes, a design typical to Canadian highway bridges. This includes all critical components for both SHM and BWIM activities. Operational and maintenance costs are estimated based on limited experience over two years and would include calibration of the structure, routine physical inspection, and potentially re-seating of sensors that may have vibrated loose as might be detected by drift in the signal data.

The USD costs for each WIM system have been adjusted to 2022 CAD for comparison using a rate of 2.11% which corresponds to the annual average rate of inflation of the CPI from 2007 to 2022 reflecting pre-pandemic price levels. USD to CAD conversion was taken to 1.0566, the average conversion rate for all months in 2007.

When considering the expected life of BWIM components, values are estimated from literature by manufacturers of the accelerometers (Piezotronics PCB 625B02) and strain gauges (BDI ST350) – the sensors that comprise the hybrid system. The expected life of the BWIM system in Table 1 is based on the sensors only as there are no readily available values for the data acquisition controller. It should be noted that some anecdotal evidence suggests that some sensors could have an expected life of greater than 25 years and the host computer and DAQ controller are thought to have similar estimates for expected life given their environmental conditions and continuous operation under normal conditions.

Since each of the WIM systems has a unique ASTM classification, a more straight-line comparison cannot be made. However, based on the comparison criteria and using cost as a baseline, the BWIM system provides a potentially high-accuracy, highly durable system. A basic present value analysis over a 15-year cycle shown in Table 3, indicates that, compared to the highly accurate load cells, the BWIM system is significantly less expensive even after a full replacement. While this analysis lacks precision based on the underlying assumptions, it, again, illustrates the economic viability of the BWIM system. The underlying assumptions in the PV analysis include (a) cost increases are only affected by inflation; (b) all other direct and indirect costs associated with installation are included (e.g., traffic control, setting up detour lanes, etc.); (c) full replacement of all components at the end of the expected life; (d) a 2.5% discount rate is applied.

From a benefit-cost perspective, the value of the traffic data acquired through all WIM systems for other processes is not available, but it is assumed to provide comparable benefits. While most WIM stations only record commercial truck traffic over a certain weight, BWIM can capture all traffic, making it useful for traffic engineers for transportation planning and asset management. In addition, the proposed hybrid BWIM-SHM system augments the deformation sensors in a traditional BWIM system with vibration sensors which can, with appropriate analysis (including operational modal analysis), provide a more comprehensive set of data that includes information about the structural condition of the bridge influenced by the actual traffic. Traditionally, these data are collected separately, and often manually, as part of an asset management program and the structural condition is often estimated based on empirical values provided in the design codes. As of now, these data are unavailable but further development of the BWIM system would potentially automate real-time load rating and reliability assessments providing even more value than pavement-based WIM stations. These aspects will be part of important follow-on studies in the future.

Table 3: Present Value comparison of WIM vs. BWIM

System	**Totals (per lane at 15 years)**	**Cost Ratio**
WIM- Piezo		
Equipment & install	$ 52,000	
O&M	$ 86,640	
Total	$ 138,640	
Present Value (Total)	**$ 116,672**	**0.88**
WIM- Plates		
Equipment & install	$ 86,670	
O&M	$ 112,710	
Total	$ 199,380	
Present Value (Total)	**$ 168,707**	**1.27**
WIM- Load cell		
Equipment & install	$ 144,440	
O&M	$ 161,700	
Total	$ 306,140	
Present Value (Total)	**$ 260,336**	**1.96**
WIM- Quartz		
Equipment & install	$ 28,890	
O&M	$ 216,450	
Total	$ 245,340	
Present Value (Total)	**$ 207,553**	**1.56**
BWIM		
Equipment & install	$ 66,950	
O&M (incl. calibration)	$ 89,280	
Total	$ 256,230	
Present Value (Total)	**$ 133,034**	**1.00**

5 Conclusion

This paper highlights the value that BWIM systems can offer in the development of an intelligent transportation network. A comparison of the benefits of BWIM to traditional pavement-based WIM systems is presented to illustrate economic feasibility and highlight potential competitiveness. A full-scale case study of a BWIM system implemented on an arterial highway bridge in New Brunswick, Canada is discussed, and the results showcase capabilities for determining axle configurations and GVW. This paper serves to emphasize the potential of BWIM to capture all types of traffic and provide data for transportation planning and asset management. Overall, the study presents a valuable comparison between traditional WIM and BWIM, highlighting the potential benefits and operational results of implementing the latter.

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