

**CHARACTERIZING IN-SERVICE TRUCK LOADS FOR IMPROVED PAVEMENT AND BRIDGE PERFORMANCE: EXPERIENCES FROM MANITOBA, CANADA**



J.D. REGEHR  
University of  
Manitoba.  
Associate Professor in  
Civil Engineering.



B. ALGOHI  
University of  
Manitoba.  
Centre for Structural  
Innovation and  
Monitoring  
Technologies  
(SIMTReC).



A. MUFTI  
University of  
Manitoba.  
Centre for Structural  
Innovation and  
Monitoring  
Technologies  
(SIMTReC).



A. SHALABY  
University of  
Manitoba. Professor  
in Civil Engineering.

**Abstract**

A comprehensive characterization of in-service truck loads supports emerging design approaches for pavements and bridges. Despite widespread acknowledgement of the value of in-service truck load data, many jurisdictions struggle to adequately collect, interpret, and analyze truck load data and integrate these data into infrastructure design and evaluation practices. This paper documents the applied research efforts undertaken in Manitoba, Canada to address these challenges. Specifically, the paper describes efforts to: (a) estimate system-wide truck traffic volume; (b) assess the quality of various sources of truck weight data (including weigh-in-motion sensors); and (c) develop and apply bridge weigh-in-motion (BWIM) systems. The paper offers several lessons from these experiences. Specifically, the findings reveal the importance of transparently acknowledging and addressing data quality issues while working collaboratively with industry, government, and other researchers to develop meaningful insights.

**Keywords:** Pavement loading, Bridge loading, Load spectra, Weigh-in-motion (WIM), Bridge weigh-in motion (BWIM)

## **1. Introduction**

Emerging methods for the design and evaluation of pavements and bridges have motivated jurisdictions to enhance their ability to produce accurate and timely estimates of in-service truck loads. The adoption of mechanistic-empirical (ME) pavement design procedures requires comprehensive characterization of truck volume and truck axle loads in terms of probability distribution functions or axle load spectra (ALS). Such spectra must be disaggregated by axle group (i.e., single, tandem, tridem) and should ideally reflect the known spatial and temporal variabilities of truck traffic loads (AASHTO, 2008). The truck loading data (along with data about material properties and climatic variables) are used to predict the accumulation of wear over the lifetime of the pavement structure. Analogously, bridge reliability analyses depend on estimates of truck volume, the distribution of axle and gross vehicle weight (GVW), and the potential for multiple vehicles to traverse the structure simultaneously (NCHRP, 2003). Conceptually, the characterization of truck loads as distributions facilitates the adoption of probabilistic approaches for understanding structural resistance (strength) and the safety index ( $\beta$ ). The safety index is the intersection of the truck load (GVW) distribution and the ultimate limit strength (ULS) distribution of a bridge to resist these loads. Together, these distributions enable the designer to quantify the probability of failure.

While infrastructure design and evaluation methods continue to evolve, many jurisdictions struggle to adequately represent truck loads—an essential input to the methods. The collection of in-service truck weight data has traditionally been accomplished through manual roadside surveys or the deployment of weigh-in-motion (WIM) technologies (FHWA, 2016). More recently, on-board mass measurement systems have also begun to provide useable truck weight data (Todts et al., 2013; Di Cristoforo, 2012). However, despite many technological and methodological advances, numerous gaps remain concerning the consistency and quality of truck load data, the effect of uncertainties on design and evaluation methods, and the ability to sufficiently represent natural spatial and temporal variabilities in truck traffic loads.

This paper describes the applied research efforts being undertaken in Manitoba, Canada concerning the estimation and characterization of in-service truck loads. The province manages a 20,000 lane-km network of highways that includes paved and unpaved roads, spring-restricted roads, and winter (ice) roads. Specifically, the objectives of the paper are:

- to document Manitoba's experience with the collection and evaluation of truck volume and truck axle load data for use in the mechanistic-empirical design of pavements;
- to document Manitoba's experience in adapting structural health monitoring expertise to develop, deploy, and calibrate bridge weigh-in-motion (BWIM) technology for evaluating bridge performance; and
- to synthesize these experiences into lessons which could support similar progress elsewhere.

## **2. Truck Loads for Pavement Design**

In Manitoba, the development of truck traffic data inputs for mechanistic-empirical pavement design commenced in 2008. Like many jurisdictions across North America, Manitoba has assessed how best to transition from traditional empirical design methods to emerging mechanistic-empirical approaches. Through several applied research engagements with Manitoba Infrastructure, the University of Manitoba has supported this assessment by

conducting research in two streams: (a) enhancing truck traffic volume estimates; and (b) developing ALS. This section summarizes the research efforts within these two streams.

## **2.1 Estimating Truck Traffic Volume**

Literature regarding the development of truck traffic data inputs for mechanistic-empirical pavement design has focused on the production of ALS. While this work is imperative, there has been relatively little attention given to the need for reliable truck traffic volume estimates (by vehicle class). Truck traffic volume—expressed in annual average daily truck traffic (AADTT) by vehicle class—is a fundamental pavement design input since it effectively acts as a “multiplier” to the representative ALS. Yet, few jurisdictions provide reliable, system-wide information about truck travel on their road network.

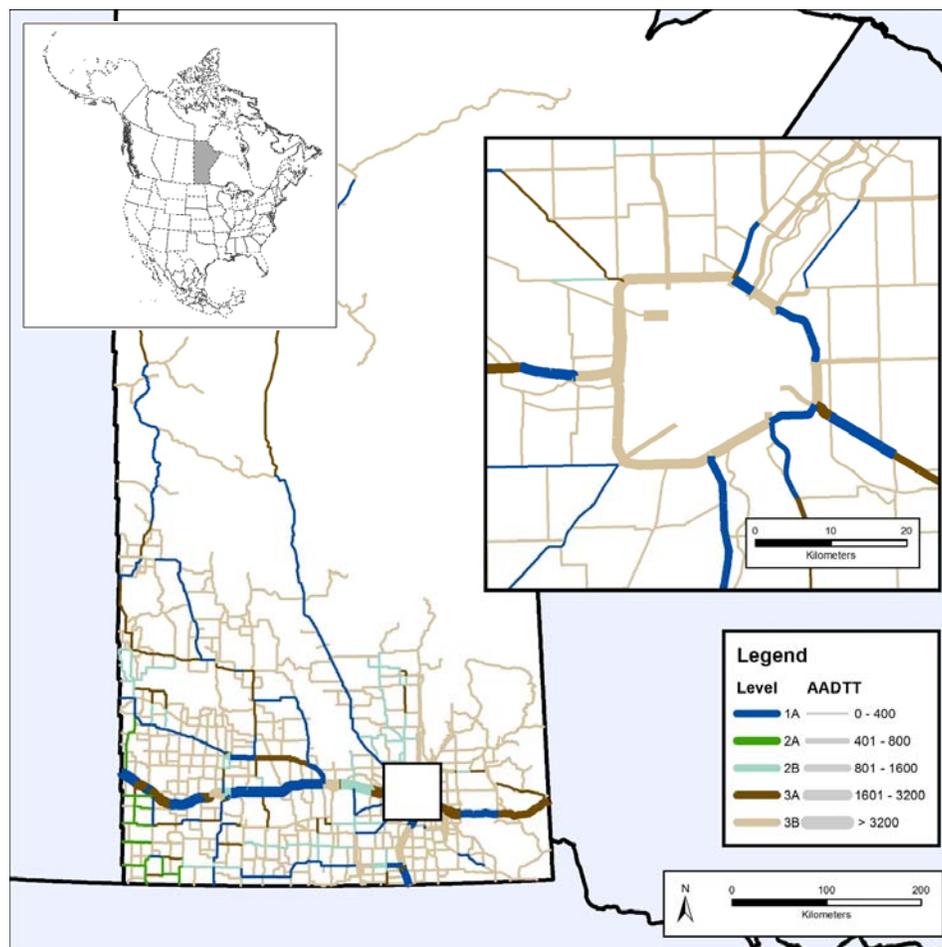
Recognizing this challenge, the development and implementation of a methodology to estimate AADTT by vehicle class anywhere on Manitoba’s network (i.e., system-wide) became an early research focus. Regehr and Reimer (2013) developed this methodology by leveraging one of the key concepts within the *Mechanistic-Empirical Pavement Design Guide* (MEPDG). The MEPDG broadly categorizes data using a three-tier hierarchy. For truck traffic volume data, this hierarchy comprises the following (AASHTO, 2008):

- Level 1 sites—commonly an automatic vehicle classifier (AVC) or weigh-in-motion (WIM) device—provide continuous vehicle classification data for at least one month of the year for 12 consecutive months. (The literature distinguishes between Level 1A and Level 1B sites; however, in Manitoba, Level 1B sites are not applicable. Therefore, the terms ‘Level 1’ and ‘Level 1A’ are used interchangeably.)
- Level 2 sites provide a sample of vehicle classification data. Such samples may have a count duration of 48 hours or more; these qualify as Level 2A sites. Other samples that have a count duration of less than 48 hours (but more than six weekday hours) qualify as Level 2B sites. In Manitoba, both Level 2A and Level 2B counts are available.
- Level 3 sites provide total truck volume data, but not detailed vehicle classification data. In Manitoba, sites for which truck traffic volumes are estimated using the vehicle classification distribution from a nearby site are referred to as Level 3A sites. Level 3B sites are those for which truck traffic volumes are estimated by applying the vehicle classification distribution from the appropriate truck traffic classification group (TTCG).

At Level 1 sites, AADTT is calculated using established formulations and attributed directly to the road segment on which the site is located. To extend the utility of these sites, the methodology develops rules for attributing the AADTT calculated at Level 1 sites to adjacent road segments. At Level 2 sites, an AADTT is estimated by applying monthly, day-of-week, or hourly adjustment factors to the sample data to account for known truck traffic volume periodicities. In Manitoba, researchers developed these factors by first establishing truck traffic pattern groups (TTPGs), which consist of sites with similar temporal truck traffic patterns by vehicle class (Jablonski et al., 2010). A decision algorithm is then used to assign each Level 2 site to one of five TTPGs, based on explanatory variables such as highway functional class, industry activity, and land use. The final step involves attributing the AADTT estimates to the network segments. For Level 3 sites, AADTT estimates are developed by assigning each site to one of six TTCGs. TTCGs comprise Level 1 sites with similar vehicle classification distributions. Each Level 3 site is assigned to a TTCG and the resulting AADTT estimate is attributed to the network segment.

*HVTT15: Characterizing in-service truck loads for improved pavement and bridge performance: Experiences from Manitoba, Canada*

Regehr and Reimer (2013) describe details of this methodology and its results, based on data from 2008. Subsequent unpublished work applied the same methodology using 2013 data. Figure 1 illustrates the resulting system-wide truck traffic flow on Manitoba's highway network. System-wide, in 2013, trucks travelled an estimated 1.0 billion kilometres on Manitoba's highway network. Compared to the previous system-wide estimate developed for 2008, the total distance travelled by trucks on the Manitoba highway network increased by approximately four percent. More specifically, the primary network handled 85 percent of this truck travel even though it represents just over 40 percent of the total provincial network length. Compared to 2008, a greater proportion of truck travel occurred on the primary network than on the secondary network in 2013. Of the 1.0 billion kilometres travelled by trucks on Manitoba's highways, single-trailer truck configurations accounted for 63.5 percent, multiple-trailer truck configurations accounted for 19.3 percent, and single-unit trucks and buses accounted for 17.2 percent.



**Figure 1 – Truck traffic flow on the Manitoba highway network, 2013**

The different colors in the map indicate the quality of the AADTT estimate provided, with Level 1A being the strongest and Level 3B being the weakest. In 2013, 30.1 percent of the total system-wide truck flow was estimated by Level 1 sites, 9.5 percent by Level 2 sites, and 59.7 percent by Level 3 sites. In terms of the extent of the network estimated using these data sources, Level 1 data was used for 11.6 percent of the network, Level 2 data for 8.3 percent, and Level 3 data for 80.2 percent.

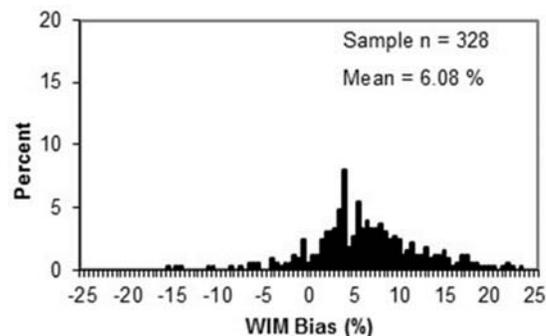
## 2.2 Developing Axle Load Spectra (ALS)

In 2010, Manitoba's initial development of ALS for pavement design relied on data from seven legacy piezo-ceramic WIM sensors situated on the primary highway network. As these sensors reached the end of their life-cycle, there was a need to consider opportunities for enhancing the province's weight data collection capabilities. Wood (2017) investigated the potential to develop ALS from truck axle load data collected at Manitoba's three primary static weigh scales and from a newly installed piezo-quartz sensor. The investigation considered four questions related to data quality:

- How *valid* (precise and accurate) are data produced by the three types of equipment (i.e., piezo-ceramic WIM sensors, piezo-quartz WIM sensors, and static weigh scales)?
- How well do data from these three sources represent the *spatial variability* of truck axle loads?
- How well do data from these three sources represent the *temporal variability* of truck axle loads?
- How *available* are axle load data from these three sources now and how will this availability change in the future?

Wood (2017) conducted several statistical studies to provide answers to these questions. One study involved the completion of two truck pairing surveys. These surveys helped assess the validity of truck axle loads at the new piezo-quartz WIM sensor by enabling statistical comparisons between the loads observed at the WIM and the loads of the same trucks observed at a nearby static weigh scale. During the surveys, researchers recorded truck axle loads at the weigh scale (ground truth data) while simultaneously recording video at the piezo-quartz WIM site. Manual review of the video identified truck pairs (i.e., trucks that were observed at both the WIM and the static weigh scale). The timestamps of the truck observations in the video enabled the extraction of axle loads from the WIM database. The surveys occurred at two weeks and seven months post-calibration, respectively; each survey produced similar results.

To illustrate, Figure 2 shows the pooled results for tandem axles observed during truck pairing surveys. The figure reveals that, on average, the piezo-quartz WIM has six percent positive bias for tandem axle loads. While imperfect, these results supported subsequent decisions to invest in additional piezo-quartz installations in the province. These installations will provide pavement engineers with data that better represent the spatial variability of truck axle loads.

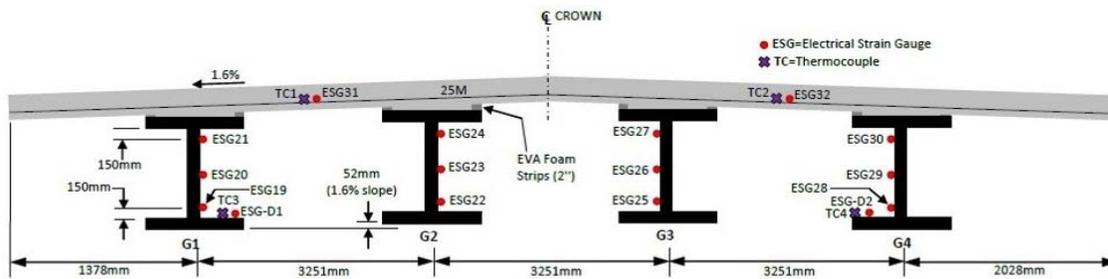


**Figure 2 – Pooled results for tandem axles from the truck-pairing surveys**

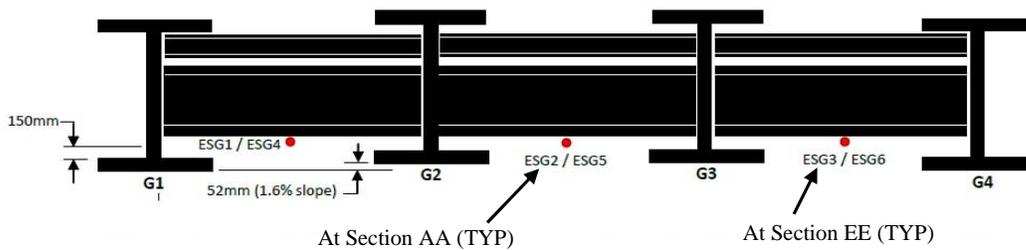
### 3. Truck Loads for Bridge Monitoring and Evaluation

The motivation to collect truck load data for bridge design and evaluation stems from the desire to continuously monitor the responses of bridges to live truck loads and to assess the potential contribution of extreme truck loads (both permitted and non-compliant) to bridge fatigue. Manitoba has instrumented three bridges with bridge weigh-in-motion (BWIM) devices and has collected truck weight data since 2007. Following a brief overview of a BWIM installation, this section provides a summary of Manitoba’s experience with BWIM. Specifically, it describes: (a) the calculation of in-service truck loads using BWIM measurements; and (b) illustrative results of these truck load measurements.

A brief overview of Manitoba’s typical BWIM installation provides context to the discussion in the subsequent sections. A typical BWIM installation in Manitoba’s three instrumented bridges comprises four instrumented sections within a simply-supported span. Sensors at two mid-span sections (BB and FF) are used to determine the truck location, identify truck multi-presence, and calculate truck GVW. Figure 3 shows the mid-span sensor installation at Section BB on Bridge A; sensors are similarly arranged at Section FF. Sensors at the two end-span sections (AA and EE) are used to calculate truck velocities. Figure 4 shows the typical end-span sensor installation on Bridge A. The data acquisition system (DAQ) collects strain values with a sampling rate of 200 Hz to capture the influence line at the instrumented sections resulting from the truck load moving on the instrumented span.



**Figure 3 – BWIM instrumentation on Bridge A at mid-span Section BB**



**Figure 4 – BWIM instrumentation on Bridge A at end-span Sections AA and EE**

#### 3.1 Using BWIM to estimate in-service truck loads

Researchers have developed algorithms to translate bridge responses (i.e., strains) into truck GVWs, accounting for variations in speed, the presence of multiple trucks on the bridge, and the structure of the bridge (Faraz et al., 2017; Bakht and Mufti, 2017; Lydon et al., 2015;

Helmi et al., 2014). Specifically, researchers apply Equation 1 to calculate a truck’s GVW from BWIM system measurements.

$$GVW = \left( \frac{2}{(L - aL)aL} \right) CvA \quad (1)$$

where:

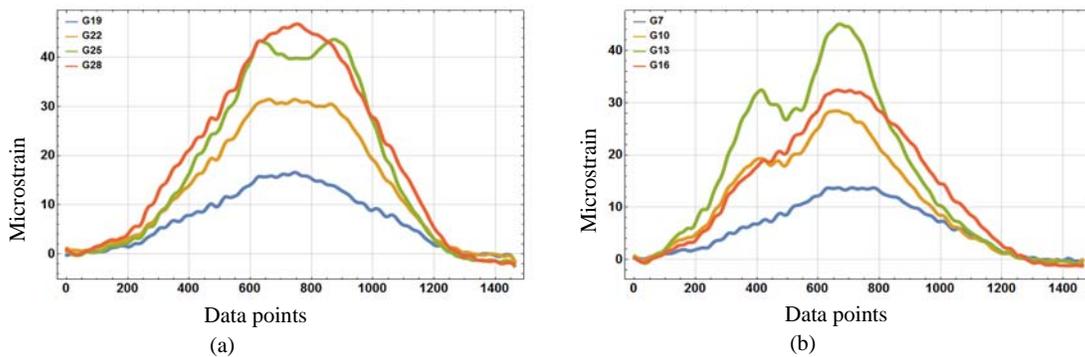
$aL$  : distance to the instrumented section from the support

$C$  : calibration factor found from load test

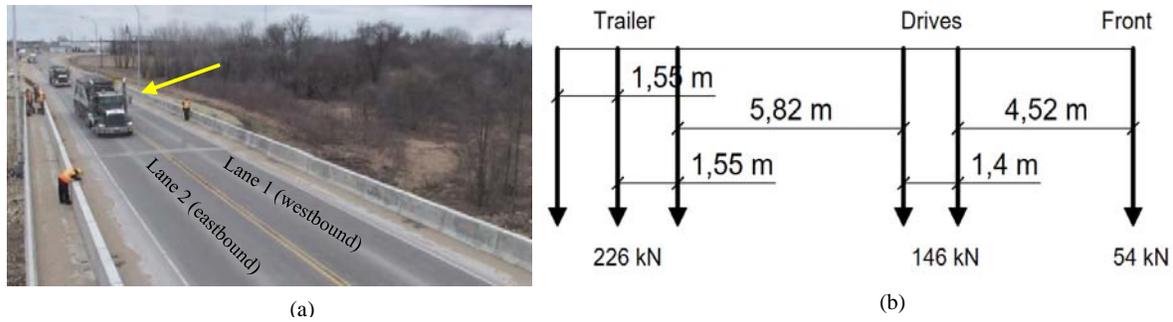
$v$  : velocity of truck event

$A$  : total area under strain signal curve

As indicated, the term  $aL$  is a function of the sensor arrangement on the bridge and the calibration factor,  $C$ , is found from a load test. To determine  $A$ , strain signals from the strain gauges installed at the bottom of the girders are used. To illustrate the calculation, consider the strain signals obtained during a truck load test from Sections BB and FF (Figure 5) and the truck which generated these signals (Figure 6). It is evident from the signals that maximum strain values are induced in the girders directly below the path of the truck (in this case, Lane 2, as shown in Figure 6). Moreover, the location of the truck on the bridge is identified using the distribution of the maximum strains from all the girders. The signals shown in Figure 5 are added together for each section and the area under each section’s curve is used to calculate the GVW using Equation 1. For Bridge A, two GVW values are found, one from Section BB and one from Section FF and the final GVW is the average of the two values.

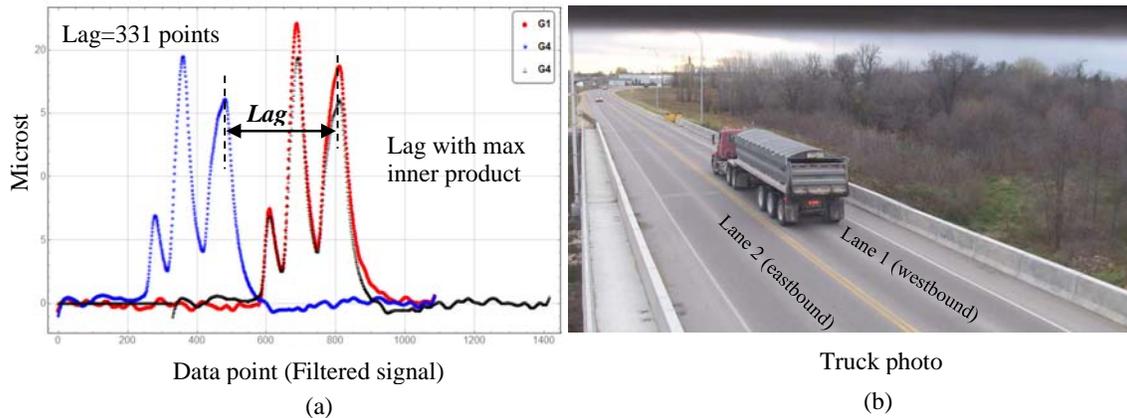


**Figure 5 – Strain signals for strain gauges at the bottom of webs due to a truck event during the load test: (a) Section BB, and (b) Section FF**



**Figure 6 – Truck load test: (a) photo in Lane 2, and (b) axle weights and their spacing**

The velocity of a truck event,  $v$ , is calculated using signals recorded in Sections AA and EE based on the known distance between the two sections (i.e., 22.71 m) and the calculated time lag between observations. The time lag is calculated using cross correlation where the time lag associated with the maximum inner product is found and used to determine the velocity. Figure 7 shows a typical signal recorded by strain gauges G1 and G4 associated with a single truck event. In this truck event, the time lag was 331 points and, with sampling rate of 200 Hz, the time for the truck to travel between the two sections was 1.655 seconds. The velocity of this event is calculated as 49.40 km/h (i.e., 22.71 m divided by 1.655 seconds). This process is applied to find the velocity of all events on the bridge. Once the velocity is calculated, the GVW can be found using Equation 1.

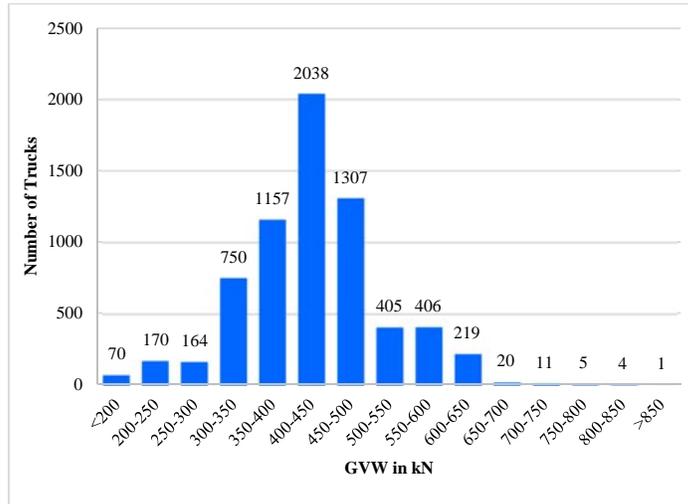


**Figure 7 – Signal of a truck event: (a) signals from G1 and G4 with the signal from G4 shifted to produce the maximum inner product, and (b) photo of the truck**

To enable more detailed analyses, current research has focused on extracting axle group weights and spacings from the bridge response data. The current BWIM algorithm detects the number of axle groups of each truck event. To do so, the system uses the signal recorded by the strain gauges on the cross beams at the ends of the instrumented span. Figure 7 shows a typical signal, recorded by strain gauges G1 in Section AA and G4 in Section EE, associated with a single truck event. It is evident from the figure that there are three peaks associated with three axle groups. A peak detection algorithm is used to determine the number of peak points and, hence, the number of axle groups. The distance between the center of axle groups is determined using the velocity of the truck and the time between axle groups. A recent study by Algothi et al. (2018) used acoustic emission to accurately detect the number of axles; this new method will be incorporated into future work.

### 3.2 Illustrative results of in-service truck loads from a BWIM system

The BWIM systems incorporated in three bridges in Manitoba have provided continuous data for several years, with Bridge A being in-service since 2015. This has generated a large and spatially diverse GVW dataset. Truck load observations are routinely summarized as GVW histograms and reported to the bridge owner. Figure 8a shows a typical GVW histogram generated from Bridge A in October 2016. Moreover, the reports identify potentially overweight truck events; Figure 8b shows an example of such an event.



(a)



<b>Truck number</b>	1
<b>Date</b>	10/22/2016
<b>Time</b>	11:20:51
<b>Direction</b>	Westbound
<b>Speed (km/h)</b>	59.91
<b>GVW (kg)</b>	87,070

(b)

**Figure 8 – (a) Illustrative GVW histogram of truck GVW on Bridge A, October 2016, and (b) example potential overweight truck event on Bridge A**

The three BWIM installations in Manitoba have so far generated reliable results. Algoji et al. (2018) report that the mean, standard, deviation, and coefficient of variation of GVW observations remain consistent over time and between the three bridge locations. While some temporal and spatial variation is expected, overall the consistency in the results appears to validate the GVW data and the underlying algorithm.

### 4. Lessons Learned and Concluding Remarks

The province of Manitoba has supported applied research activities to improve its knowledge of truck traffic loads, which will ultimately enhance the performance of its road infrastructure. Sustained and coordinated research efforts over the past decade have focused on estimating truck traffic volume and developing axle load distributions using both traditional WIM and BWIM systems. The experiences described in this paper point to several transferrable lessons.

The emergence of mechanistic-empirical pavement design methods motivated practitioners and researchers to develop a more sophisticated knowledge base of in-service truck loads. This involved establishing system-wide estimates of truck traffic volume and developing ALS. Key lessons stemming from these efforts follow:

*HVTT15: Characterizing in-service truck loads for improved pavement and bridge performance: Experiences from Manitoba, Canada*

- There is value in leveraging the site-specific truck traffic data available in most jurisdictions to produce system-wide estimates of truck traffic flow. The production of system-wide estimates improves data reliability while transparently accounting for varying levels of uncertainty associated with different data sources. Essentially, a practitioner gains confidence in a site-specific truck volume estimate if it can be assessed within the context of network-wide flow. Moreover, the approach developed in Manitoba helps identify locations within the network that would benefit from improved data collection capabilities.
- An understanding of industry and land use patterns is imperative for developing a reliable and robust truck traffic knowledge base—whether considering truck volumes or loads. Experiences in Manitoba show that this understanding supports the development of pattern groups (both TTPGs and TTCGs), the assignment of sites to these groups, and ongoing decisions about the locations or regions where investment in new monitoring technologies will be most effective in closing remaining data gaps.
- Periodic evaluations of truck traffic patterns—related to both volumes and loads—support a knowledge base that is responsive to the dynamic nature of road freight demand. Certain industries are dynamic, like petroleum developments that have occurred in southwest Manitoba (Reimer and Regehr, 2014). Others, like the agriculture industry, appear to be more stable. Routine evaluations, perhaps every five years, enable these fluctuations to be captured within the data and incorporated into highway planning and design functions.
- The collection of quality truck axle load data is challenging because the concept of “quality” is multidimensional in nature. Quality load data should be valid (accurate and precise), spatially and temporally representative, and readily-available. From Manitoba’s experience, there is a need to balance load data validity (which usually correlates with the costs of the data collection equipment being used) with the ability to meaningfully represent the spatial and temporal variability of in-service truck loads (which may require a more extensive network of data collection equipment).
- While improvements in data quality proceed, the quality of the axle load spectra data available in Manitoba has been found to be appropriate for pavement analysis and design. Manitoba is using the load spectra information together with locally-calibrated performance-based material models to perform pavement designs and in-service performance modeling and to compare the outputs to those produced by traditional design tools.

The following lessons arise from Manitoba’s experiences with bridge monitoring and evaluation:

- Strain and velocity data are fundamental for determining in-service truck GVW. While the area under the strain curve is normally accurate, the velocity calculation is more challenging. Notably, the BWIM system works better for short to medium span lengths (10 to 30 meters). On longer spans, a vehicle’s velocity may change across the length of the span, causing errors in the GVW calculation. To avoid this, the system would need to collect each vehicle’s velocity profile along the span and modifications to the GVW equation would be required. Moreover, if the span is too long, the probability of multi-presence increases. While the BWIM system can easily identify (and discard) multi-truck events, it is more difficult to detect events which include a truck and passenger vehicles. Currently, in these cases, the BWIM system determines the total weight of vehicles passing over the span, including the weight of passenger vehicles.

*HVTT15: Characterizing in-service truck loads for improved pavement and bridge performance: Experiences from Manitoba, Canada*

- Currently it is not possible to calculate axle weights using the BWIM system. BWIM systems fundamentally rely on influence line theory. When a truck passes over a span, all axles interact with each other to generate the strain signal at the instrumented section. A new method is under investigation to find the axle weights. If this proves successful, the BWIM system will provide the granularity of data currently offered by traditional WIM equipment.
- BWIM systems provide valuable information to bridge owners. Gross vehicle load distributions and the identification and validation of potentially overweight truck events offer new data about in-service traffic loads on bridges, which supports fatigue analysis and assessments of long-term bridge health.

Finally, and more broadly, there is evidence that the design and evaluation methods for pavements and bridges have begun to converge in terms of their truck traffic data requirements. As experienced in Manitoba, this convergence offers opportunities for knowledge and data sharing between the traditionally disparate units involved in designing and evaluating pavements and bridges. While opportunities for collaboration exist, there is an ongoing need to better quantify loading uncertainties and to understand the influence that these uncertainties have on infrastructure performance. Such uncertainties may arise because of inherent equipment limitations and because of the spatial and temporal variabilities of in-service truck loads. Practical knowledge about how industrial and seasonal patterns influence truck traffic characteristics and open collaboration between researchers and practitioners support efforts to validate the available data and fill remaining knowledge gaps.

## **5. Acknowledgements**

The authors gratefully acknowledge the financial contributions of Manitoba Infrastructure. The results and conclusions presented are those of the authors and no official endorsement by Manitoba Infrastructure is intended or should be inferred. The financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged.

## **6. References**

- Algoji, B., Huma, K., Bakht, B., Mufti, A., and Regehr, J.D. (2018), “Some Observations on BWIM Data Collected in Manitoba” in Proceedings of the 10th International Conference on Short and Medium Span Bridges, Québec City, Québec.
- Algoji, B., Mufti, A. and Thomson, D.J. (2018), “Detection of Speed and Axle Configuration of Moving Vehicles Using Acoustic Emission,” *Journal of Civil Structural Health Monitoring*, Springer, 1-10, <https://doi.org/10.1007/s13349-018-0281-8>
- American Association of State Highway and Transportation Officials (AASHTO). (2008), *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice*, AASHTO.
- Bakht, B. and Mufti, A. (2017), *Evaluation of One Hundred and One Instrumented Bridges*, Structural Innovation and Monitoring Resource Centre, University of Manitoba.
- Di Cristoforo, R. (2012), “A Non-Intrusive Method for Periodically Recording the Location and Mass of an In-Service Heavy Vehicle Using On-Board Systems” in Proceedings of the 91st Annual Meeting of the Transportation Research Board 91st Annual Meeting, Washington, D.C.
- Faraz, S., Helmi, K., Algoji, B., Bakht, B., and Mufti, A. (2017), “Sources of Errors in Fatigue Assessment of Steel Bridges by Using BWIM,” *Journal of Civil Structural Health Monitoring*, Springer, July, 291-302.

*HVTT15: Characterizing in-service truck loads for improved pavement and bridge performance: Experiences from Manitoba, Canada*

- Federal Highway Administration (FHWA). (2016), Traffic Monitoring Guide, United States Department of Transportation.
- Helmi, K., Bakht, B. and Mufti, A. (2014), “Accurate Measurements of Gross Vehicle Weight through Bridge Weigh-in-Motion, A Case Study,” Journal of Civil Structural Health Monitoring, Springer, April, 195-208.
- Jablonski, B., Regehr, J.D., Kass, S. and Montufar, J. (2010), “Data Mining to Produce Truck Traffic Inputs for Mechanistic-Empirical Pavement Design” in Proceedings of the 8th International Transportation Specialty Conference of the Canadian Society for Civil Engineering, Winnipeg, Manitoba.
- Lydon, M., Taylor, S.E., Robinson, D., Mufti, A., and O’Brien, E.J. (2015), “Recent Developments in Bridge Weigh in Motion (B-WIM),” Journal of Civil Structural Health Monitoring, Springer, May, 69-81.
- National Cooperative Highway Research Program (NCHRP). (2003). Effect of Truck Weight on Bridge Network Costs, Report 495, Transportation Research Board.
- Regehr, J.D. and Reimer, M.J. (2013), “Methodology to Estimate the Distance Traveled by Trucks on Rural Highway Systems,” Journal of Transportation Engineering, Am. Soc. Civ. Engrs, 139, 4, 390-398.
- Reimer, M.J. and Regehr, J.D. (2014), “A Framework for Characterizing Truck Traffic Related to Petroleum Well Development and Production in Unconventional Shale Plays,” Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board, 2339, 112-119.
- Todts, W., Oehry, B., Haas, L., and van Driel, C. (2013), Study on Heavy Vehicle On-Board Weighing, Final Report, Rapp Trans AG.
- Wood, S. (2017), Options for Providing Quality Axle Load Data for Pavement Design, M.Sc. Thesis, University of Manitoba.