Some Observations on BWIM Data Collected in Manitoba

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Canadian Journal of Civil Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>cjce-2018-0389.R1</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>04-Feb-2019</td>
</tr>
</tbody>
</table>
| Complete List of Authors: | Algohi, Basheer; University of Manitoba, Civil Engineering  
                           | Khalid, Huma; NED University of Engineering and Technology; University of Manitoba, Civil Engineering  
                           | Bakht, Baidar; SIMTReC  
                           | Mufti, Aftab; University of Manitoba  
                           | Regehr, Jonathan; University of Manitoba, Department of Civil Engineering |
| Keyword:            | BWIM, design load, average daily truck traffic, distribution factors |
| Is the invited manuscript for consideration in a Special Issue? : | Not applicable (regular submission) |
Some Observations on BWIM Data Collected in Manitoba

B. Algoji\textsuperscript{1}, B. Bakht \textsuperscript{1}, H. Khalid\textsuperscript{1}, A. Mufti \textsuperscript{1}, J. Regehr\textsuperscript{2}

\textsuperscript{1}Structural Innovation and Monitoring Technologies Resource Centre (SIMTReC), University of Manitoba, Canada, \textsuperscript{2}NED University of Engineering and Technology, Karachi, Pakistan, \textsuperscript{3}Department of Civil Engineering, University of Manitoba, Canada

Abstract

Three highway bridges in the Canadian province of Manitoba are being monitored continuously not only for their long-term performance but also for bridge weighing-in-motion (BWIM). Data collected for the BWIM study has led to some observations that have far-reaching consequences about the design and evaluation loads for highway bridges. This paper presents the well-known concept of equivalent base length, $B_m$, as a useful tool for comparing trucks with different axle weight and spacing configurations as they influence load effects in all bridges. It is discussed that the statistics of gross vehicle weights (GVWs), $W$, collected over a one-month period is not significantly different from that for the GVW data collected over a longer period. A rational method concludes that the value of $W$ for the CL-W Truck, the design live load specified by the Canadian Highway Bridge Design Code, is 555 kN for Manitoba. The observed truck data in Manitoba presented on the $W - B_m$ space is found to be similar to that collected in the Canadian province of Ontario more than four decades ago. It was also found that the multi-presence factors, accounting for the presence of side-by-side trucks in two-lane bridges, specified in North American bridge design and evaluation codes are somewhat conservative.

Key words: BWIM, design load, average daily truck traffic, distribution factors.

Introduction

Three highway bridges in Manitoba, Canada, have been instrumented for studying their long-term behaviour as well as for bridge weighing-in-motion (BWIM). All three bridges comprise steel girders and composite concrete deck slabs, and include both simply supported and continuous spans. Simply supported spans of two of these bridges, being the Winnipeg Bridge 1 and the Winnipeg Bridge 2 were instrumented for BWIM for obtaining the gross vehicle weights (GVWs) of trucks moving at fairly high speeds, using the technique presented by Bakht (Bakht, B. et al 2013; Helmi, K. et al 2014); these authors have shown that the accuracy of GVW prediction is within the range of 0.9% to 2.8%. Histograms of GVWs collected from these two bridges are being prepared on a monthly basis and presented to bridge owners for the past four or so years.
An example of the GVW histogram for the Winnipeg Bridge 1, collected during the month of June 2016, is presented in Figure 1, in which the mean, standard deviation (SD), and coefficient of variation (COV) of the GVW are shown to be 363 kN, 110 kN and 0.29, respectively.

The probability density functions (PDFs) for the GVWs for the same bridge computed from data for each of 28 months during 2015, 2016 and 2017 are presented in Figure 2, in which it can be seen that the PDFs for the 24 months are very close to each other. It can also be seen that the average values of the mean, SD and COV are 372 kN, 112 kN and 0.30, respectively. Since these values are very close to the respective values for one month, presented in Figure 1, it can be concluded that the statistics of the GVW data collected over a month are representative of those over a longer period, provided of course if the pattern of truck traffic is not affected significantly over the observation period.

The statistics of GVW for the Winnipeg Bridge 2 collected over 13 months is presented, with the monthly values of mean and SD in Figures 3 (a) and (b), respectively. As shown in these figures, the average values of mean and SD for the 13 months are 383 and 110 kN, respectively, giving COV = 0.30. It is striking that the mean, SD and COV values for one bridge obtained over 28 months are very close to those for another bridge obtained over 13 months. This observation not only confirms the validity of the data, but also shows that the vehicle weight data obtained over one month is representative of data obtained over longer periods.

Histograms such as that presented in Figure 1 give an indication of the possible exceedance of weight regulation limits for very heavy trucks, some of which might be very long and possibly travelling under special permits. However, they do not provide information about shorter trucks exceeding the weight regulations of Manitoba; this information could be provided only if the BWIM data includes axle weights and their spacings. A simply supported span of the third bridge, the PTH-23 Bridge in Morris, a small town in Manitoba, was instrumented with additional strain gauges at the two support diaphragms to obtain information about axle weights and spacings; strains from these diaphragms were used to calculate the speeds of the vehicles quite accurately, which in turn were used to calculate the weights of individual axles and groups of closely spaced two- and three-axle groups and their spacings (Algohi et al. 2017); the accuracy of axle weight prediction ranges from -2.9% to 4.0%. The bridge was monitored under a test truck travelling in different transverse positions and at different speeds. Figure 4 shows the cross-section of the bridge and the positions of the test truck travelling in the middle of the marked lanes on the two-lane bridge. The figure also labels lanes and girders.
Axles of trucks come with different weights and spacings, because of which it is not easy to compare different trucks with respect to the maximum load effects they induce in all bridges. In this respect, the concept of the equivalent base length, described in the following, is very useful. Consider a set of \( N \) point loads, shown in Figure 5 along with the notation for their magnitudes and spacings.

By using Eq. 1 given below, the \( N \) point loads with a total weight of \( W \) can be replaced by a uniformly distributed load (UDL) having a total weight \( W \) and an equivalent base length \( B_m \), so that the maximum moments and shears in any simply supported beam due to the UDL are very nearly the same as those due to the point loads (Csagoly and Dorton 1978). The same statement is also true for continuous span beams, but in this case the degree of accuracy is compromised slightly.

\[
B_m = \frac{4}{W} |P_i x_i| - \frac{2(N - 1)}{bN W^2} \left( \sum_{i=1}^{N} (P_i x_i) \right)
\]

[1]

It is noted that Eq. 1, the rationale for which is also provided by Bakht and Mufti 2015, is independent of the span length of the beams.

**Bridge Design Loads vs. Legal Loads in Manitoba**

The Canadian Highway Bridge Design Code (CHBDC), S6-14 (CSA 2014), specifies a flexible design truck CL-W, in which the total weight \( W \) of the truck in kN is decided by the authority having jurisdiction over the bridge, it being noted that the vehicle load regulations in Canada are different in various provinces and territories. Details of the CL-W truck are shown in Figure 6 (a).

As noted in S6.1-14 (CSA 2014), the commentary to the CHBDC, the design live loads of the CHBDC have a direct correspondence with the legal loads on the highways. The task of determining the appropriate level of \( W \) for the CL-W Truck in a particular jurisdiction can be made simple by using the \( W - B_m \) space, as explained in the following. Five trucks of different configurations are selected so that they carry the maximum loads with the smallest axle spacings permitted in the Canadian province of Manitoba; the axle weights and spacings of these trucks are shown in Figure 7, it being noted that in these vehicles, the unusually high weight of 9 t is selected for the steering axle to represent the maximum load permissible in Manitoba on a single axle, and not to suggest that steering axles are so heavy.
The values of \( W \) and \( B_m \) for the five trucks, shown in Figure 7, and their sub-configurations were calculated by using a computer program TRUCK (Mufti et al 2016); these values are plotted in Figure 8, which also shows the corresponding upper-bound curve, designated as the maximum legal load (MLL) line for Manitoba.

Figure 8 also shows \( W - B_m \) points for the CL-625 Truck, the upper-bound curve for which lies above the MLL line in Manitoba. Through an iterative process, it was found that a CL-550 Truck best represents the MLL line in Manitoba. As can be seen in Figure 8, the \( W - B_m \) points for CL-550 Truck closely hug the MLL line. It is thus concluded that the value of \( W \) for Manitoba should be 550 kN. The resulting design truck for Manitoba, in which the axle weights are rounded to the nearest 5 kN, is CL-555, the axle weights for which are shown in Figure 6 (b).

**OBSERVED TRUCK LOADS IN MANITOBA**

Figure 9, presenting the \( W - B_m \) points corresponding to the data collected for single truck events on the PTH-23 Bridge during June 2017, erroneously shows that a large number of trucks with small values of \( B_m \), i.e. short trucks, carry more load than permitted legally. The error in the \( W - B_m \) points for short trucks presented in Figure 9 arose by representing two- and three-axle groups (tandems and tridems, respectively) next to a light steering axle as single point loads. An example of an unrealistically light steering axle with a heavy tandem is shown in Figure 10 (a). The BWIM scheme adopted for the PTH-23 Bridge represents the tandem as a single axle, as shown in Figure 10 (b). The values of \( B_m \) for the actual and assumed vehicles are 5.02 and 1.78 m, respectively. Figure 10 (c) shows analysis performed on errors associated with the assumption. The analysis was done by computing the maximum moments induced due to the assumed single load and that due to two and three closely spaced loads. The ratio between the maximum moments due to single load and multiple load (R) is plotted for different span lengths. It is clear that the error is marginal when the length of the span is more than 10 m. For the bridge under consideration, which has a span length of 22.7 m, the calculated error is less than 0.1%. It can be appreciated that in this case, the representation of the tandem as a single axle moves the \( W - B_m \) point to the left, thus possibly raising it above the MLL line. As will be shown later, the representation of a tandem or a tridem far away from a light single axle as a single point does not affect their presentation on the \( W - B_m \) space significantly.
It was decided to correct the error mentioned above as follows. If a single axle next to a light first axle of a vehicle was calculated to have a weight between 10 and 17 t, it was replaced by two axles with a spacing of 1.2 m. If the calculated weight of a similar single axle was between 17 and 24 t, it was assumed that it was a tridem with the spacing between successive axles being 1.5 m. It was also found that the speed of trucks travelling at speeds lower than 20 km/hr and at speeds higher than 80 km/hr were miscalculated, resulting in respectively larger and smaller values of \( B_m \). Data corresponding to these extreme values of speed were eliminated from consideration. After correction, the \( W - B_m \) points of Figure 9 are reproduced in Figure 11, in which it can be seen that the \( W - B_m \) points lying above the MLL line are now well distributed along the length of \( B_m \), and that these points for longer vehicles are not affected by the correcting procedure, nor is the MOL line. These assumptions are indeed arbitrary but are reasonable in practice.

The design load of the Ontario Highway Bridge Design Code (OHBDC 1979), the forerunner of the CHBDC, was based on truck weight data collected by weighing a large number of trucks on static weighing scales. As shown in Figure 12, the OHBDC design truck corresponded to the MOL line, whereas the MLL line in Ontario was based on the Ontario Bridge Formula (OBF) line (OHBDC Commentary 1983). It is noted that the live load factor for the OHBDC design live loads, corresponding to the MOL line, was 1.4, and for the CHBDC design live load, corresponding to the MLL line, is 1.7. The factored live loads by the two codes are nearly the same, it being noted that the CHBDC design truck for Ontario is the CL-625 Truck. There is a good agreement between the charts presented in Figures 11 and 12, although they represent vehicle weight data collected in two different Canadian jurisdictions more than four decades apart. The Manitoban data, collected in 2017, shows that the MOL line lies almost about 10 t above the MLL line, irrespective of the value of the \( B_m \), or the length of the truck. Similarly, the Ontario data collected about four decades ago shows that the MOL line lies about 100 kN (~10t) above the MLL line, which is shown as the OBF line in Figure 12. This observation confirms the validity of the data presented in Figure 11, which has more detailed information than collected from previous vehicle weight surveys.

**Multi-Presence of Trucks in More than One Lane**

To account for the likelihood of heavy trucks travelling simultaneously in different lanes of a bridge, both the CHBDC and the American Bridge Design Code (AASHTO 2016) specify design loads on a per-lane basis, with the loading in a single lane related to the heaviest truck loads expected to travel on a bridge. For multi-lane loading, the design load per lane is reduced by a modification factor \( m_f \) to account for the
reduced probability of several lanes being loaded simultaneously by the heaviest trucks. For design, the multi-presence factor for two-lane loading is specified by the CHBDC to be 0.90. For the evaluation of the load carrying capacity of existing bridges, the modification factor for two-lane loading for Class A, B and C highways are specified to be 0.90, 0.90 and 0.85, respectively, it being noted that the average number of trucks per lane per day on these highways are >1,000, >250-1,000, and 50-250, respectively (CHBDC 2014). The theoretical basis of these multi-presence factors is provided by Jaeger and Bakht (Jaeger and Bakht 1987; Bakht and Jaeger 1990).

Since it is highly unlikely that trucks of exactly the same weights could be present on a bridge at the same time, the modification factors should be regarded as only tools for design convenience, which provide an estimate for maximum load effects in a bridge due to heavy trucks in more than one of its lanes. Since all the trucks simultaneously present on a bridge are not likely to have exactly the same weight, it is not possible to verify the modification factors by direct observations. It is proposed to verify the CHBDC-specified modification factors indirectly by using data from instrumented bridges. For two-lane loadings, the data collected from the PTH-23 Bridge is presented as an example. According to the truck count by the BWIM system, the bridge lies on a Class B Highway, for which \( m_f \) is specified to be 0.90. The transverse sections of a simply supported span instrumented for BWIM on the PTH-23 Bridge are shown in Figure 13 (a), and the strain gauge locations on the girders are shown in Figure 13 (b). It can be seen that the strain gauges near the bottom of the girders are 150 mm above the top surface of the bottom flanges. The gauge near the bottom of Girder 2 is labelled as ESG 22.

Distribution factors (DFs) for mid-span girder moments in Span No. 2 obtained from calibration tests under a single truck in two different positions are compared in Figure 14 with those given by the semi-continuum method of analysis, which is incorporated in a computer program SECAN (Mufti et al 2016). It is noted that in this and other similar figures, the discrete DFs for girder moments are joined by continuous lines only to facilitate readability. The good correlation between the observed and analytical DFs shown in Figure 14 confirms the validity of the method of analysis.

The program SECAN was used again to analyse girder moments at Section BB of the PTH-23 Bridge under two load cases; in one case, there was a single CL-555 Truck in Lane 1, and in the other load case, there were two side-by-side CL-555 Trucks. The trucks were placed transversely at the middle of the marked lanes, as were the test trucks shown in Figure 4. The longitudinal positions and weights of the axles of CL-555 Truck are shown in Figure 15.
The girder moments for the two cases given by SECAN at Section BB, which lies under the third axle of the design truck are listed in Table 1; this table also gives the ratio of moments, denoted as $R_m$, due to multiple and single trucks for each girder.

Figure 16 (a) presents the histogram of maximum stresses at the location of ESG 22 on Girder G2 of the PTH-23 Bridge over a period of 20 months due to single truck events in Lane 1; these stresses were calculated from observed strains. Similarly, Figure 16 (b) presents the histogram of maximum stresses at the location of ESG 22 on Girder G2 over a period of 20 months due to trucks in the two lanes. It can be seen in these figures that during the observation period, Girder G2 experienced maximum stresses of about 14 and 17 MPa due to single and multiple trucks, respectively. The ratio of maximum stresses due to multiple and single trucks observed over a certain period is denoted as $R_\sigma$. For the two maximum stresses cited above, $R_\sigma = 1.21$.

It is argued that if $R_m$ and $R_\sigma$ have the same value, then the modification factor for multi-presence $m_f = 1.00$. In the other case, $m_f = R_m / R_\sigma$. For the PTH-23 Bridge, the two ratios are not the same, so that for Girder G2, $m_f = 1.21 / 1.67 = 0.72$, which could be rounded up to 0.75; this value is significantly smaller than 0.90 specified by the CHBDC for two-lane loading cases. Since the observed data is used in calculating $R_\sigma$, there is no need to consider either the live load factor or the dynamic magnification of load effects. It is important to note that the value of 0.75 for $m_f$ is applicable to only Girder G2. Before finalizing the value of $m_f$, the same exercise should be conducted for the other three girders of the bridge as well, and largest of four values of the modification factor should adopted as final.

Figure 11 identifies the $W - B_m$ combination of an observed truck on the PTH-23 Bridge that is most likely to induce maximum moments in Span 2; the values of $W$ and $B_m$ for this combination are approximately 67 t (670 kN) and 20.5 m, respectively. In a simply supported span of 21.71 m, the maximum moment due to this UDL $= 670 \times 21.71 / 8 = 1818$ kN.m. From Figure 3, it is found that DF for moments in Girder G2 for the truck in Lane 1 is nearly 0.35, so that the moment received by Girder G2 $= 0.35 \times 1818 = 636$ kN.m. The moment of inertia, $I$, of the composite girder is calculated to be 42,829,728,037 mm$^4$, and the distance of the neutral axis (n.a.) from the bottom of the bottom flange is found to be 1206 mm. Strain gauge ESG 22, shown in Figure 13 (b), is 1056 mm from the n.a., from which it is found that the stress at the location of ESG 22 due to a moment of 636 kN.m is about 17 MPa, which is of the same order of magnitude as the maximum observed stress of 14 MPa that can be seen in Figure 16 (a). The fact that the observed maximum stress is somewhat smaller than the calculated stress can be attributed to three factors: (a) the
simply supported spans of the PTH-23 Bridge were found to have considerable bearing restraint that reduces the tensile stress near the bottom flanges of the girders; (b) the neutral axes of the composite girders have seasonal variations, dropping in hot weather and rising up in cold weather; and (c) the modulus of elasticity of the precast concrete panels might be higher than assumed in calculations. Notwithstanding the small differences between calculated and observed values of the maximum stress due single truck events, it can be appreciated that the observed data is reliable.

Conclusions

The statistics of GWWs obtained from data on one bridge in Manitoba collected over one month were found to be nearly identical to those obtained from data collected on the same bridge over 28 months. Further, these statistics obtained on a heavily traveled bridge were also found to be nearly the same as those on a lightly traveled bridge, also in Manitoba. By representing the maximum truck loads permitted in Manitoba on the \( W - B_m \) space, it is recommended that the CHBDC design live truck CL-W in Manitoba should be CL-555. It has also been shown that irrespective of their lengths, some trucks exceed the vehicle weight regulations of Manitoba by about 10 t. The same observation was made in another Canadian province, Ontario, some four decades ago. The modification factor for two-lane loadings specified by the CHBDC is conservative and can be dropped by further investigations, using the simple but reliable technique presented in the paper.

Acknowledgements

It is acknowledged that the funding for the reported in this paper was provided by Manitoba Infrastructure.

References


Figure legend(s)

- Figure 1: Histogram of GVWs computed from data collected on the Winnipeg Bridge 1 in June 2016
- Figure 2. PDFs for GVWs for 28 months computed from data collected from Winnipeg Bridge 1
- Figure 3: Statistics of GVW observed over 13 months on the Winnipeg Bridge 2; (a) mean, (b) SD
- Figure 4: Cross-section of the PTH-23 Bridge showing two transverse positions of the test truck
- Figure 5: Notation for a series of point loads
- Figure 6: (a) axle loads of the CL-W Truck; (b) axle loads of CL-555 Truck
• Figure 7: Five trucks carrying maximum loads permissible in Manitoba
• Figure 8: MLL line for Manitoba compared with the line representing the CL-625 and CL-550 Trucks
• Figure 9: Uncorrected $W - B_m$ points computed from data collected on the PTH-23 Bridge in June 2017 for single truck events
• Figure 10: Light steering axle with a tandem: (a) actual vehicle, (b) tandem represented as a single axle, (c) error in the assumption
• Figure 11: Corrected $W - B_m$ points computed from data collected on the PTH-23 Bridge in June 2017 for single truck events
• Figure 12: Comparison of OHBDC Truck with MOL and Ontario Bridge Formula line (Commentary to OHBDC 1979)
• Figure 13: Details PTH-23 Bridge: (a) instrumented sections, (b) strain gauges at Section BB
• Figure 14: DFs for observed girder moments in the PTH-23 Bridge
• Figure 15: Axles of CL-555 Truck on Span No. 2 of the PTH-23 Bridge
• Figure 16: Histograms of maximum stresses induced in Girder G2 observed over a period of 20 months: (a) due to all single event trucks in lane 1, (b) stress due to all multiple trucks events
Figure 1: Histogram of GVWs computed from data collected on the Winnipeg Bridge 1 in June 2016

Mean = 383 kN
SD = 110 kN
COV = 0.29

96x64mm (300 x 300 DPI)
Figure 2. PDFs for GVWs for 28 months computed from data collected from Winnipeg Bridge 1

For all 28 months,
Mean = 372 kN
SD = 112 kN
COV=0.30
Figure 3: Statistics of GVW observed over 13 months on the Winnipeg Bridge 2; (a) mean, (b) SD

139x47mm (300 x 300 DPI)
Figure 4: Cross-section of the PTH-23 Bridge showing two transverse positions of the test truck
Figure 5: Notation for a series of point loads

82x47mm (300 x 300 DPI)
Figure 6: (a) axle loads of the CL-W Truck; (b) axle loads of CL-555 Truck
Figure 7: Five trucks carrying maximum loads permissible in Manitoba

115x68mm (300 x 300 DPI)
Figure 8: MLL line for Manitoba compared with the line representing the CL-625 and CL-550 Trucks
Figure 9: Uncorrected W-B_m points computed from data collected on the PTH-23 Bridge in June 2017 for single truck events.
Figure 10: Light steering axle with a tandem: (a) actual vehicle, (b) tandem represented as a single axle, (c) error in the assumption

340x176mm (96 x 96 DPI)
Figure 11: Corrected W-B_m points computed from data collected on the PTH-23 Bridge in June 2017 for single truck events.
Figure 12: Comparison of OHBDC Truck with MOL and Ontario Bridge Formula line (Commentary to OHBDC 1979)

43x46mm (300 x 300 DPI)
Figure 13: Details PTH-23 Bridge: (a) instrumented sections, (b) strain gauges at Section BB
Figure 14: DFs for observed girder moments in the PTH-23 Bridge

72x47mm (300 x 300 DPI)
Figure 15: Axles of CL-555 Truck on Span No. 2 of the PTH-23 Bridge

103x26mm (300 x 300 DPI)
Figure 16: Histograms of maximum stresses induced in Girder G2 observed over a period of 20 months: (a) due to all single event trucks in lane 1, (b) stress due to all multiple trucks events.
Table 1: Moments in girders of the PTH-23 Bridge at Section BB due to CL-555 Truck/s given by SECAN

<table>
<thead>
<tr>
<th>Girder No.</th>
<th>Moments in kN.m due to Two side-by-side design trucks</th>
<th>Moments in kN.m due to Single design truck</th>
<th>Ratio of moments due to multiple and single trucks, $R_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>876</td>
<td>765</td>
<td>1.15</td>
</tr>
<tr>
<td>G2</td>
<td>961</td>
<td>576</td>
<td>1.67</td>
</tr>
<tr>
<td>G3</td>
<td>878</td>
<td>289</td>
<td>3.04</td>
</tr>
<tr>
<td>G4</td>
<td>642</td>
<td>47</td>
<td>13.70</td>
</tr>
</tbody>
</table>