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Live Load Factors for Military Traffic in Bridge Evaluation

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Abstract

Military vehicles are sometimes required to transit bridges owned and operated by civilian bridge authorities. Using available data regarding the gross vehicle weight and associated axle loads of military traffic, live load factors, calibrated to the Canadian Highway Bridge Design Code, are proposed for bridge design and evaluation. This paper recommends live load factors for three categories military vehicles: (1) Wheeled-Transport vehicles; (2) Wheeled-Fighting vehicles; and (3) Tracked-Fighting vehicles. The values are derived for interior girders of simply supported slab-on-girder bridges subjected to a single lane of traffic loading and are believed to be generally applicable for other structural elements and bridge types. Inherent differences between fighting vehicles, which are heavily armoured, and transport vehicles, which although armoured have high payloads, suggest that highway bridges should be evaluated separately for military fighting vehicles and military transport vehicles using distinct live load factors.

Keywords: Bridge Evaluation, Code Calibration, Military Vehicles.

Introduction

Military vehicles are often required to transit civilian bridges during the course of various types of road moves such as: routine movements of equipment; military training exercises; and, domestic and international operations. At such times, civilian bridge owners will be approached by the Canadian Armed Forces to determine if the military vehicles can cross safely. Military Engineers from the Canadian Armed Forces may also be required to evaluate the capacity of bridges themselves. In either case, the evaluation is likely to follow the Canadian Highway Bridge Design Code (i.e. CAN/CSA S6-19), but this standard does not recommend live load factors for military traffic. The Canadian Armed Forces manual that specifies procedures for evaluation of nonstandard fixed bridges was last official published in 1990 with an unpublished update in 2007. The manuals mostly rely on allowable stress methods of evaluation. If load and resistance factors of evaluation are used “the load and load combination factors, as well as resistance factors, will be taken from civilian bridge design codes with all necessary adjustments” (DND 2007). As such, this paper draws upon available research regarding Gross Vehicle Weight (GVW) and axle loads of military vehicles as well as their dynamic load effects and lateral live load distribution on bridges to quantify live load factors for different traffic volumes and target reliability indices.

The objective of this paper is to compare observed statistical parameters for dynamic load effects and lateral live load distribution, that are specific to military traffic, to those for non-military traffic used to calibrate CAN/CSA S6-19. This is necessary to investigate whether the code-specified Dynamic Load Allowance (DLA) and Simplified Methods for Lateral Load Distribution are appropriate for military traffic. Moreover, live load factors for non-military traffic may be inappropriate for military traffic which is more uniform than normal Non-Permit traffic

and likely less uniform than permit traffic. Specific load factors for military traffic, that are suitable to rate civilian bridges for use by military vehicles, will be investigated.

1. Static Load on Simply Supported Spans

To determine the static load of military vehicles on simply supported spans, the probabilistic definitions for GVW and axle/track loads as described by MacDonald, et al. (2017) for the AHSVS-PLS, LAV III-ISC, and Leopard 2A4M Tank are used. These vehicles, shown in Fig. 1, are representative of three categories of military vehicles: (1) the AHSVS-PLS is representative of Wheeled-Transport vehicles; (2) the LAV III-ISC is representative of Wheeled-Fighting vehicles; and, (3) the Leopard 2A4M Tank is representative of Tracked-Fighting vehicles. The statistical GVW parameters of these vehicles for event and annual maxima for traffic volumes of 100, 1,000, and 10,000 vehicles per year from MacDonald, et al. (2017) are summarized in Table 1. The bias coefficient is the ratio of mean to nominal values, while the Coefficient of Variation (CoV) is the standard deviation divided by the mean. The nominal GVW, referred to as the combat weight, is the sum of the curb weight and nominal payload. The curb weight is the weight of the fuelled vehicle and, if applicable, additional armour including mine protection. The nominal payload weight consists of cargo, crew, ammunition, communications equipment, consumables, secondary weapons, crew personal equipment, and mission-specific equipment. The combat weight refers to the maximum allowed weight under normal operating conditions. CSA (2019b) provides values of bias coefficient and CoV of vehicle loads for normal and permit traffic. For permit traffic these statistical parameters directly relate to the maximum annual vehicle load bias coefficient and CoV for GVW specified by Kennedy et al. (1992). The GVW bias coefficient and CoV in Table 1 are similar to static load bias coefficient and CoV quantified in Table 2 for longer spans, where single axle load statistics do not govern, which is

expected (e.g., Kennedy et al. 1992). As the maximum vehicle GVW for traffic volumes over 100 are all described by Gumbel distributions, the distribution parameters for other annual traffic volumes can be determined using the log-shift principle. A comparison with statistical parameters for non-military traffic loads in CSA (2019b) indicates that for the evaluation of bridges:

- AHSVS-PLS at annual traffic volumes less than 3000 vehicles/year (bias = 1.22, CoV = 0.06) could be safely considered similar to Normal Traffic (Alternative Loading) (bias = 1.35, CoV = 0.035). The effect of the lower bias coefficient for AHSVS-PLS loading is counteracted by its higher CoV, making AHSVS-PLS and Normal Traffic (Alternative Loading) essentially equivalent;
- LAVIII-ISC at annual traffic volumes less than 100,000 vehicles/year (bias = 1.24, CoV = 0.01) could be safely considered similar to Permit Annual (PA) Traffic (bias = 1.25, CoV = 0.017) because the bias coefficient and CoV for LAVIII-ISC are both less than for PA Traffic; and
- Leopard 2A4M Tank at nearly any annual traffic volume, given its extremely low event CoV (at annual traffic rate of 1,000,000, bias = 1.05 and CoV = 0.001), could be safely considered similar to Permit Bulk (PB) Traffic (bias = 1.06, CoV = 0.0094) because the bias coefficient and CoV for the tank loading are both less than for PB Traffic. This aligns well with CSA (2019b) which states that some “non-cargo types of vehicles, ..., often meet the requirements to be considered as PB vehicles. Such vehicles typically have fixed configurations, a specified vehicle weight that includes all items carried by the vehicle and that does not carry any significant cargo.”

Using the relationship between GVW and axle loads (or roadwheel load for tracked vehicles), again from MacDonald et al. (2017), vehicles of each type were randomly generated.

Then maximum shear forces and bending moments on simply supported spans between 1 and 100 m were computed, neglecting dynamic effects, for the different vehicle types. Spans up to 100 m were investigated to clearly discern where individual axle loads ceased to dominate load effect bias and CoV and became governed by GVW.

2.1 AHSVS-PLS (Wheeled-Transport)

Fig. 2 shows that Gumbel distributions fitted the data for both the front- and rear-wheel axle groups of the AHSVS-PLS vehicle. The data imply the need for two distinct Gumbel distributions: for cumulative probabilities less than 0.95, the maximum vehicle axle load is governed by Axles 1 and 2; and, for greater cumulative probabilities, it is governed by Axles 3 and 4. Fig. 2, shows essentially identical probability density functions for the maximum axle load on the vehicle as that for Axles 1 & 2 for loads less than 86 kN, and essentially identical probability density functions for Axles 3 & 4 for loads greater than 88 kN. This illustrates the transition on short spans, from the front axles governing the load effect (for most cases) to the rear axles governing the load effect (for the extreme load cases).

For increasing span lengths, due to the additional axles present and their spacing becoming increasingly small compared to the span length, the sample cumulative distribution functions for shear or moment can be described by a single Gumbel distribution. This occurred at span lengths of approximately 16 m for shear and 20 m for moment.

The nominal shear and moment are as produced by a vehicle of the nominal combat weight. At shorter spans, where different axles can govern the maximum event shear or moment, the extreme value distribution corresponding to each annual traffic volume, n , was defined using

the most severe load effect due to the same number of randomly generated vehicles. The generation of n vehicles and associated shear and moment on different spans was simulated one thousand times, the greatest load effects from each simulation was used to determine the bias coefficient and CoV for traffic volumes up to $n = 1,000$. Since the extreme value distribution for $n = 1,000$ can be idealized using a single Gumbel distribution, the distribution parameters for greater annual traffic volumes can be determined using the log-shift principle. The bias coefficient and CoV of both the static shear and moment are both greater for shorter span lengths. The event CoV for the AHSVS-PLS is reduced for shorter span lengths because the critical force effect is due to a single tandem axle (the larger of the front and rear axles). So the event CoV corresponds to the CoV of that axle, which for most cases is the front tandem axle with a low CoV (see Fig. 2). On the other hand, extreme value distributions of the critical force effects for traffic volumes greater than 100 vehicles are mainly defined by the rear axles, which have a higher CoV.

Table 2 summarizes the bias coefficient and CoV for the static load effects on simply supported spans up to 100 m for different traffic volumes. The statistical parameters for the AHSVS-PLS are essentially constant at span lengths greater than 16 m for shear and 20 m for moment. Increases in traffic volume cause large increases of the mean force effect of the extreme annual distribution, with a comparatively small decrease in CoV. The bias coefficient is normalized using the nominal shear and moment that would be produced by the vehicle at its combat weight.

2.2 LAV III-ISC (Wheeled-Fighting)

Following similar procedures, the bias coefficient and CoV for shear and moment due to the LAV III-ISC for various simply supported span lengths were determined. The nominal shear and moment are as produced by the LAV III-ISC at its nominal combat weight. For span lengths greater than 15 m for both shear and moment, the parameters are constant.

Table 2 shows the statistical parameters that define static moment and shear due to the LAV III-ISC vehicle on simply supported spans. Distinct parameters are provided for short spans, less than 15 m; and for longer spans. The span length defining the boundary between short and long spans is shorter than that for the AHSVS-PLS, because the distance between the front and rear axles of the LAV III-ISC is about half of that for the AHSVS-PLS. Increases in traffic volume again increase on mean force effect of the extreme annual distribution, with comparatively small decreases in CoV. A smaller proportion of the LAV III-ISC is payload (i.e. variable load), so the increase in mean force effect is smaller than that for the AHSVS-PLS for the same increase in traffic volume.

2.3 Leopard 2A4M Tank (Tracked-Fighting)

As noted by Wong (2010), tracked vehicles have peaks of pressure where roadwheels are located along the track. Following NATO Allied Engineering Publication (AEP)-3.12.1.5 (NATO 2017) formerly Standardisation Agreement (STANAG) 2021, tracked vehicles are evaluated as having a Uniformly Distributed Load (UDL) over the contact area of the tracks. Given this, when evaluating bridges following AEP-3.12.1.5, there would likely be a consistent difference between the evaluated load and the actual static load of a tracked vehicle.

For the Leopard 2A4M tank, data were not available for the fully loaded roadwheel loads. To estimate the fully loaded values, the payload and fuel loads were distributed over the 4 rear roadwheels because a large portion of the fuel and payload is located at the rear of the vehicle. Given the configuration of the Leopard 2A4M, this is intended to concentrate the additional load due to fuel and payload to 4 rear roadwheels to ensure a conservative estimate of the bias in shear when nominal load is analyzed as a UDL. Table 3 shows the combined load applied by successive pairs of roadwheels as an absolute load and a percentage of the total vehicle weight, where road wheel loads are higher near the center of the vehicle. It was assumed that ratio of roadwheel load to total vehicle weight is maintained for all weights of the Leopard 2A4M tank.

Using the procedures previously described, the bias coefficients and CoV values for shear and moment on simply supported spans were quantified. The bias coefficient for shear is greater for spans shorter than 10 m due to the difference between the nominal UDL and the simulated roadwheel loads which has a slight concentration of load. If only a simulated UDL is considered, the bias coefficient for shear would be constant for all spans.

Table 2 presents the statistical parameters for the static shear and moment caused by the Leopard 2A4M tank, taking the worst case of roadwheel loads or the UDL idealization. The nominal shear and moment correspond to those caused by the Leopard 2A4M at its nominal combat weight if idealized as a UDL. Due to the different bias coefficients for shear at spans less than 10 m, two categories of span are considered for shear in Table 2. The coefficients of variation for the event and the extreme annual distributions are very small, which can be attributed to the relatively small total payload compared to the total vehicle weight.

2. Dynamic Load Allowance

The DLA is “an equivalent static load that is expressed as a fraction of the traffic load and is considered to be equivalent to the dynamic and vibratory effects of the interaction of the moving vehicle and the bridge, including the vehicle response to irregularity in the riding surface” (CSA 2019a). Lenner (2014) noted that a “...review of literature does not provide a single value for [Dynamic Load Allowance] that can be used for military vehicles in general terms”, but rather “varies from country to country or even agency to agency due to different assumptions and test outcomes”. References recommending DLA or similar factors are “mainly concerned with [the] deterministic value of the [DLA] and no regard is given to the stochastic properties” (Lenner 2014).

A review of the literature for observed dynamic effects of military vehicles is summarized in Table 4. Trimble, Cousins and Seda-Sanabria (2003) and Everitt (2019) report experimental dynamic effects in bending of fixed bridges. Trimble, Cousins and Seda-Sanabria (2003) studies two concrete T-beam bridges: Franklin County, and Patrick County (herein referred to as “Franklin” and “Patrick” respectively). Everitt (2019) investigates a continuous two-span steel girder bridge with composite concrete deck. In Table 4: the AHSVS-PLS would be similar to the M1075 PLS and HL VW; the Leopard 2A4M tank would be similar to the M1-A1 and Leopard 2A6M; and, the LAV III-ISC would be similar to the Bison, and the E-LAV.

The observed dynamic load effects from the literature are compared to the statistical parameters for DLA in CSA (2014) which are also shown Table 4. Statistical parameters for “Short spans” are for spans up to 10 m, for all other conditions “Other span” - 1 lane loaded are used (CSA 2014). The provisions of CSA (2019a) would assign DLA values of 0.25 to the

Concrete T-Beam (Patrick) with a span of 14.6 m and the 2-span continuous steel girder with composite concrete deck (Everitt 2019), with spans of 29.6 m and 32.9 m, and 0.3 to the other bridges.

Table 4 indicates that the DLA specified in CSA (2014; 2019a; 2019b) is conservative compared to that observed for the Franklin Bridge and the bridge described by Everitt (2019). Conversely, it is unconservative for the Patrick Bridge. For the fixed bridges, the maximum dynamic increment observed during multiple crossings was reported. The overall mean dynamic load increment on fixed bridges for wheeled vehicles, when considering all cases, yields a bias coefficient between 0.28 and 0.33 with respect to the mean DLA given in CSA(2014) (e.g. mean dynamic increment from testing divided by the mean DLA given in CSA (2014) which can be derived by multiplying the code specified bias coefficient for DLA by the specified DLA, i.e., $0.05/0.18 = 0.28$ and $0.05/0.15 = 0.33$), with a similar standard deviation, 0.14 versus 0.12 (CSA 2014).

The observed statistical parameters shown in Table 4 show the following general trends:

- (1) The maximum observed DLAs for fixed non-standard bridges are consistently within one standard deviation of those given in CSA (2014) except for Patrick Bridge.
- (2) For vehicles crossing a particular bridge, tracked vehicles have consistently lower and less variable maximum observed dynamic load increments compared to wheeled transport vehicles (e.g. Everitt (2019): Leopard 2 vs. HLVW Low-bed; Kosmatka (2011): M1-A1 vs. HET; Robinson and Kosmatka (2011): M113 vs. M1075 PLS).

(3) Deployable bridges experience greater DLAs than fixed bridges, likely due to rougher approaches that substantially increase the observed dynamic load increment (Everitt 2019), as well as, greater flexibility and overall geometry with abrupt changes in running surface grade.

It is clearly not appropriate to designate a single DLA for all possible combinations of military vehicles and bridge types. Only Tracked-Fighting vehicles have observed statistical parameters for dynamic loading that are enveloped by the values recommended in CSA (2019a; 2014) for both fixed bridges and deployable/mobile bridging. Given the general trend that deployable bridges require a greater DLA than fixed bridges, it would be conservative to apply the statistical parameters for DLA given in CSA (2014; 2019b) to military Tracked-Fighting vehicles or Wheeled-Fighting vehicles on fixed bridges. In considering Wheeled-Transport vehicles further data collection may be necessary as observations from Trimble, Cousins and Seda-Sanabria (2003) for Patrick Bridge yielded a mean dynamic increment nearly two standard deviations higher than the DLA statistical parameters given in CSA (2014).

Further research into the dynamic amplification caused by military vehicles is required. In lieu of better information, the bias coefficient and CoV specified by CSA (2014; 2019b) will be assumed to apply to all military vehicles. This is primarily based on the observed dynamic effects reported by Everitt (2019) where the maximum observed dynamic increment for Wheeled-Transport, Wheeled-Fighting, and Tracked-Fighting vehicles were very close to the mean DLA given by CSA (2014) of 0.15.

3. Lateral Load Distribution

There is again limited available literature on the lateral live load distribution for military vehicles on bridges. Based on the available literature, the single lane military vehicle lateral

distribution for moment to an interior girder of slab-on-girder bridges (e.g., steel girder, prestressed concrete, and concrete T-beam) will be presented.

Kim, Tanovic and Wight (2010) examined the lateral load distribution of NATO Military Load Classification (MLC) wheeled design trucks on a 36 m, simple-span, steel I-girder bridge. Using a calibrated three-dimensional Finite-Element Analysis (FEA), the lateral load distributions of these trucks were examined and compared to AASHTO (2007) Load Distribution Factors (LDF). The LDF for moment is defined as follows (Kim et al. 2010):

$$[3] \quad \text{LDF} = \frac{M_{ref}}{M_{l_0}}$$

where, M_{ref} is the moment per girder and M_{l_0} is the moment per design lane.

Pinero (2001) derived load distribution formulas similar to those specified in AASHTO (1996; 2007; 2012) that are specific to different types of wheeled and tracked military vehicles used by the US military. These are expected to be more accurate for military traffic compared to the CSA (2019a) simplified methods. Harmonic decomposition was used to find the maximum live load effects on a simply supported multi-girder slab-on-girder system. Three bridge types were investigated: steel girder, pre-stressed concrete, and concrete T-beam. Using the LDF determined for specific vehicle and bridge combinations, nonlinear regression analysis was applied to develop proposed load distribution formulas.

CSA (2019a) approaches lateral load distribution somewhat differently than AASHTO (2012), so the LDF's reported by others were converted to amplification factors that are consistent with the CSA procedures. For AASHTO (2012) the LDF is multiplied by single lane traffic load to find the moment for each girder. CSA (2019a) is similar where the equivalent of

the LDF is the product of the truck load fraction, F_T , and skew factor F_S , which is then multiplied by the longitudinal moment of a single lane of CL-W loading. The design moment per girder, M_L , is therefore (CSA; 2019a):

$$[4] \quad M_L = F_T F_S M_T$$

This paper considers only cases where the skew factor, F_S , is 1.0 (e.g. non-skewed bridges). As such, the CSA (2019a) amplification factor, F_T , is equivalent to the LDF for this dataset. Conveniently, the bias coefficients and CoVs of the LDF and the F_T would be identical.

A comparison was conducted between the load distribution formulas from Pinero (2001), AASHTO (2012), and CSA (2019a), for Class A & B Highways. Where there is no skew in the bridge alignment, the LDF from AASHTO (2012) and Pinero (2001) is directly comparable to truck load fraction, F_T , from CSA (2019a). Pinero (2001) proposes “52 new formulas for different types of [US military] vehicles, different types of [girder] bridges, bending moment and shear force values, interior and exterior girders, and for single and multiple lane loading cases”. In AASHTO (2012), the distribution of live load moment to interior girders, for one design lane loaded on a slab-on-girder bridge is given by:

$$[5] \quad LDF = 0.06 + \left(\frac{S}{14}\right)^{0.4} \left(\frac{S}{L}\right)^{0.3} \left(\frac{K_g}{12Lt_s^3}\right)^{0.1}$$

where, S is the girder spacing (ft), L is the span (ft), t_s is the depth of concrete slab (inches), and K_g is the longitudinal stiffness parameters (in⁴). Parameter K_g is computed as:

$$[6] \quad K_g = \frac{E_B}{E_D} (I + A e_g^2)$$

where, E_B is the modulus of elasticity of the girder, E_D is the modulus of elasticity of the deck, I is the moment of inertia of the girder, A is the area of the girder, and e_g is the eccentricity distance between the centers of gravity of the girder and deck. Simplified values of $\left(\frac{K_g}{12L t_s^3}\right)^{0.1}$ are also given for certain types of bridges specified in AASHTO (2012). For the cases under investigation, the derivation of LDFs in AASHTO (2012) has remained unchanged to AASHTO (1996) which is referenced by Pinero (2001).

To make a comparison between lateral load distribution, four bridges were considered: (1) the 36 m, simple-span, steel I-girder at 2.44 m center-to-center spacing with 205 mm thick slab bridge described in Kim, Tanovic and Wight (2010); (2) a 37 m, simple-span, prestress concrete CPCI girder at 2.4 m center-to-center spacing with 350 mm thick slab described by Morrison Hershfield Ltd. (2012); and (3) the two reinforced concrete T-beam bridges (Franklin Bridge and Patrick Bridge) described by Trimble, Cousins and Seda-Sanabria (2003) respectively with spans of 12 m and 15.6 m, deck slabs 203 mm and 191 mm thick, and beams spaced at 2.13 m and 2.45 m. The various distribution factors proposed by Pinero (2001) do not differ greatly from each other and are generally bounded by CSA (2019a), as a conservative upper bound, and AASHTO (2012), as a slightly unconservative lower bound. Table 5 presents a comparison between the lateral load distribution amplification factors from CSA (2019a), AASHTO (2012) and Pinero (2001) for the four bridges identified. The distribution factor formula from Pinero (2001) for a PLS vehicle on a steel girder bridge may be in error, and the associated values are shown in bold font and highlighted in grey in Table 5. The only other

instances where the distribution factor proposed by Pinero exceeds that computed using the provisions of CSA (2019a) are for the concrete T-beam bridges, but the discrepancies are much less, only 4% and 2%. Thus, the lateral load distribution for military vehicles is likely in most cases to be less severe than for civilian vehicles, which may be due to the typically wider wheelbase of military vehicles.

Pinero (2001) conducted harmonic analysis to determine the governing LDF on 137 beam bridges. The M1075-PLS is similar to the Canadian AHSVS-PLS, and the ABRAMS M1-A1 is similar to the Canadian Leopard 2A4M tank. Table 6 summarizes Pinero's (2001) assessment of the accuracy of his proposed formulas in the context of his harmonic results. The bias coefficients and CoVs shown are based on the ratio of harmonic analysis result to the result obtained from his proposed formula. With the assumption of Log-Normal distribution for the ratios in Table 6, using the given mean and CoV, 10,000 data points were randomly generated. Table 7 shows statistical parameters computed from the reciprocals of these generated data points that are applicable to the present study.

The statistical parameters in CSA (2019b) for the "Simplified" lateral load distribution category are a bias coefficient of 0.93 and CoV of 0.12. Compared to the bias coefficient and CoV for the equations proposed by Pinero (2001), some important observations can be made. With the exception of two cases for the M1075-PLS, Pinero's CoV values in Table 7 do not exceed 0.12. For all but these two cases presented in Table 5, Pinero's bias coefficients are never greater than 93% of the CSA (2019a) value. Given that Pinero's harmonic analysis shows his proposed equations have a bias coefficient close to 1.00, it can be inferred that the bias coefficient for lateral load distribution for military vehicles as computed using the "Simplified Method" in CSA (2019a) will be less than 0.93, which conveniently, is the bias coefficient

reported in CSA (2019b) for this lateral distribution category. Furthermore, the lateral load distribution factors derived from CSA (2019a) can be applied conservatively for military vehicular loads for the circumstances investigated.

4. Overall Live Load Effects

Overall live load coefficients were determined with the bias coefficient of the live load effect, δ_{L_1} , as CSA (2019a):

$$[9] \quad \delta_{L_1} = \delta_L \delta_A \left(\frac{1 + \delta_{DLA} DLA}{1 + DLA} \right)$$

where, δ_L , δ_A , and δ_{DLA} are the bias coefficients for nominal live load, analysis (based on lateral live load distribution), and DLA respectively. The CoV for the live load effect, V_{L_1} , is (Kennedy et al. 1992):

$$[10] \quad V_{L_1} = \sqrt{V_A^2 + V_L^2 + \left(\frac{\delta_{DLA} DLA}{1 + \delta_{DLA} DLA} \right)^2 V_{DLA}^2}$$

where V_A , V_L , and V_{DLA} are the CoV for A , L , and DLA respectively.

Accounting for the dynamic load allowance and transverse live load analysis, the annual maximum load effects bias coefficients and CoVs for short and other spans are presented in Table 8. These statistical parameters apply to moment due to a single lane of traffic on interior girders of slab-on-girder type bridges. The statistical parameters for the static live load of

military vehicles are taken from Table 2. The statistical parameters are considered for DLA, taken as $DLA = 0.25$ for all cases, with statistical parameters corresponding to those given in CSA (2019b), $\delta_{DLA} = 0.60$ and $V_{DLA} = 0.80$, for the all vehicle categories. Lateral load distribution amplification factors are as specified in CSA (2019a). The statistical parameters for CSA (2019a) are for the “Simplified” lateral distribution category with, $\delta_A = 0.93$ and $V_A = 0.12$.

5. Partial Load Factors

Partial load factors for military bridge evaluation and design can be derived approximately using:

$$[11] \quad \alpha_{L_1} = \delta_{L_1} e^{(\beta \alpha^* V_{L_1})}$$

where α_{L_1} is the partial live load factor, α^* is a separation factor of 0.70, β is the annual target reliability index, δ_{L_1} is the bias coefficient of the live load effect, and V_{L_1} is the CoV for the live load effect. This equation has historically been widely used to compute load factors although its limitations have been noted (e.g. Bartlett 2008).

Table 9 shows the live load factors for a range of target reliability indices for the AHSVS-PLS, LAV III-ISC, and Leopard 2A4M vehicles for different annual traffic volumes. These values are obtained using Eq. [11] with the statistical parameters of Table 8.

6.1 Statistical Load Parameters for Other Unsurveyed Vehicle Populations

The statistical parameters, and the associated load factors, derived herein for the live load of three specific military vehicles. Statistical parameters to define the loads of other military vehicles can be estimated using the payload weight fraction, which is simply the ratio of the maximum nominal payload weight to total vehicle weight (MacDonald 2017). The payload weight fraction is typically less than 0.25 for fighting vehicles, which are heavily armoured, and typically greater than 0.35 for transport vehicles which, although armored, have high payloads. The payload weight is variable compared to the empty vehicle weight, so vehicles with low payload weight fractions have markedly less variable live loads. MacDonald (2017) therefore recommends using the statistical parameters of payload for the AHSVS-PLS vehicles for other Wheeled-Transport (W-T) vehicles, LAV III-ISC payload parameters for Wheeled-Fighting (W-F) vehicles, and the statistical parameters for the Leopard 2A4M Tank for other Tracked-Fighting (T-F) vehicles. For longer spans, the statistical parameters for the vehicle load are approximately the same as those for the vehicle weight (Kennedy et al. 1992). Given this, partial load factors can be derived using Equation [11] for vehicles of different payload weight fractions. Fighting vehicles would be defined “as those with payload weight fractions less than 25% and Transport vehicles as those with payload weight fractions greater than 35%” (MacDonald 2017).

6.2 Load Factors by Military Vehicle Category

Fig. 3 shows the partial load factors calculated for each vehicle listed in MacDonald (2017) and summarized in Table 10. Payload weight fractions for each classification were then used to

compute vehicle static load bias coefficients and CoVs using equations proposed by MacDonald (2017). The bias coefficient of the vehicle weight, δ_V , is calculated as:

$$[12] \quad \delta_V = \gamma(\delta_P - 1) + 1$$

where, γ is the payload weight fraction, and δ_P is the bias coefficient of the payload weight. The CoV of the vehicle weight, V_V , is:

$$[13] \quad V_V = \frac{V_P \delta_P \gamma}{\gamma(\delta_P - 1) + 1}$$

where, V_P is the CoV of the payload.

Statistical parameters for dynamic load effect and lateral load distribution are as specified in Section 5. The partial load factors shown were calculated using Equation [11], it was found that the partial load factors for Fighting Vehicles (Wheeled Armoured Personnel Carriers (APCs), Tracked APCs and Tanks) closely align. Given this, it is possible to simplify presentation in Fig. 3 by assigning a trend line for all fighting vehicles and a second trend line for all military transport vehicles. This simplified approach could be used to assign partial load factors based on the vehicle payload weight fraction, γ , as shown in Fig. 3. An annual traffic volume of 1,000 vehicles is considered because it is likely an upper bound: Military vehicles do not make up a large portion of typical traffic, and domestic military operations are typically of limited duration and intensity. Specific circumstances may require the use of other traffic volumes for evaluation.

Based on available information using the average values of γ in Table 10, partial load factors are proposed for Wheeled-Transport, Wheeled-Fighting, and Tracked-Fighting vehicles in Table

11. Given the lack of axle load data for all vehicles, load factors for short spans are the same as those for the AHSVS-PLS, LAV III-ISC, and Leopard 2A4M Tank. For other spans, the load factors are derived based on the average payload weight fraction for the military vehicle category: these are similar to the AHSVS-PLS, LAV III-ISC, and Leopard 2A4M but differ slightly as the γ for these three vehicles differ slightly from the average for the military vehicle category they are associated with. These factors are specifically derived for interior girders subjected to bending and are believed to be more broadly applicable for evaluation as described by CSA (2019a). Wheeled-Transport at annual traffic rates over 1,000 have relatively high load factors when compared to Wheeled-Fighting and Tracked-Fighting vehicles.

6. Summary and Conclusions

This paper has investigated statistical parameters for the load effects of military vehicles on highway bridges to recommend military traffic load factors for the evaluation of bridges following the Canadian Highway Bridge Design Code (CSA 2019a). The statistical parameters of the static load of three representative military vehicles (AHSVS-PLS, LAVIII-ISC, and Leopard 2A4M Tank) were investigated for different annual traffic volumes. Literature on the dynamic load increment and lateral load distribution of military vehicles was reviewed for compatibility with CSA (2019a). Using the overall probabilistic live load effects for static load, lateral load distribution, and DLA, load factors were derived for the three vehicles investigated. Load factors were also derived for other unsurveyed military vehicle populations based on their payload weight fraction.

The following conclusions are drawn:

- (1) Statistical parameters for the static live load of military vehicles are similar to that given by CSA (2019b) for permit traffic as defined in CSA (2019a). The AHSVS-PLS (Wheeled-Transport) is comparable to Normal Traffic (Alternative Loading). The LAVIII-ISC (Wheeled-Fighting) is comparable to PA Traffic. The Leopard 2A4M Tank (Tracked-Fighting) is comparable to PB Traffic.
- (2) Literature on the dynamic load increment of military vehicles indicates that the DLA prescribed by CSA (2019a) is typically conservative for military Tracked- and Wheeled-Fighting vehicles, with maximum observed dynamic load increment from tests rarely exceeding the mean DLA from CSA (2014; 2019b), and is likely acceptable for military Wheeled-Transport vehicles. CSA (2019a) simplified methods for lateral load distribution could be used conservatively, with existing literature calibrating load distribution factors specific for military traffic yielding a truck load fraction in nearly all cases less than 90% that given by CSA (2019a).
- (3) The payload weight fraction, the ratio of the payload weight to total vehicle weight, is markedly different for fighting vehicles, which are heavily armoured, and transport vehicles, which although armoured have high payloads. The payload weight is variable compared to the empty vehicle weight so live load factors for military vehicles should be derived on the basis of payload weight fraction. Highway bridges should therefore be evaluated separately for military fighting vehicles and military transport vehicles, using distinct live load factors.

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Fig. 1. (a) AHSVS-PLS (image courtesy of Neil Peacock); (b) LAV III-ISC (image courtesy of Neil Peacock); (c) Leopard 2A4M (DND photo by Master Corporal David McVeigh)

Fig. 2. Probability density of AHSVS-PLS axle loads (a) overall; (b) inset detail; (c) cumulative distribution on Gumbel probability paper.

Fig. 3. Load factor for maximum annual load effects for 1,000 vehicles per year based on payload weight fraction

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Table 1. Summary of statistical parameters for military vehicle GVW given in
MacDonald, et. al. (2017)

Vehicle	Curb/Combat Weight	Statistical parameters	Event (Distribution Type)	Maximum Annual (All Gumbel Distribution)		
				100	1000	10 000
AHSVS-PLS	22,900 kg /	Bias	0.764 (Gumbel)	1.029	1.162	1.294
	39,000 kg	CoV	0.096 (Gumbel)	0.072	0.064	0.057
LAV III-ISC	16,744 kg /	Bias	1.082 (Log-Normal)	1.170	1.197	1.220
	20,000 kg	CoV	0.030 (Log-Normal)	0.013	0.011	0.010
Leopard 2A4M	59,184 kg /	Bias	1.021 (Weibull)	1.039	1.042	1.044
	61,214 kg	CoV	0.008 (Weibull)	0.002	0.001	0.001

Table 2. Static load bias coefficient and CoV, for simply supported spans

Vehicle	Force Effect	Parameter	Span Range	Event	Annual Traffic Volume		
					100	1,000	10,000
AHSVS-PLS	Shear	Bias	< 16 m	0.816	1.057	1.261	1.502
		Bias	> 16 m	0.764	1.030	1.164	1.305
		CoV	< 16 m	0.096	0.116	0.103	0.089
		CoV	> 16 m	0.096	0.072	0.063	0.059
	Moment	Bias	< 20 m	0.816	1.057	1.281	1.533
		Bias	> 20 m	0.765	1.031	1.165	1.308
		CoV	< 20 m	0.096	0.117	0.103	0.092
		CoV	> 20 m	0.096	0.072	0.063	0.060
LAVIII-ISC	Shear	Bias	< 15 m	1.232	1.380	1.423	1.459
		Bias	> 15 m	1.085	1.167	1.191	1.210
		CoV	< 15 m	0.049	0.018	0.014	0.014
		CoV	> 15 m	0.030	0.012	0.010	0.010
	Moment	Bias	< 15 m	1.228	1.380	1.423	1.458
		Bias	> 15 m	1.085	1.168	1.191	1.211
		CoV	< 15 m	0.049	0.019	0.014	0.013
		CoV	> 15 m	0.030	0.012	0.010	0.010
Leopard 2A4M	Shear	Bias	< 10 m	1.215	1.237	1.241	1.245
		Bias	> 10 m	1.020	1.039	1.042	1.045
		CoV	0-100 m	0.011	0.002	0.001	0.001
	Moment	Bias	0-100 m	1.020	1.039	1.042	1.045
		CoV	0-100 m	0.011	0.002	0.001	0.001

Table 3. Fully laden Leopard 2A4M road wheel load

Road Wheel Pair	1 st	2 nd	3 rd	4 th	5 th	6 th	7 th	SUM
Roadwheel Load (kN)	81.4	88.9	88.0	92.0	91.2	82.9	75.9	600.3
Percent of Total Weight (%)	13.6	14.8	14.7	15.3	15.2	13.8	12.6	100.0

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Table 4. Summary of experimental dynamic effects for military vehicles on various bridges

Reference	Type	Span (m)	Vehicle Name	Vehicle Category	# of Trials	Observed Dynamic Effects			DLA CSA (2014) ^{a, b, c}	
						Max	Mean	Std. Dev.	Mean	Std. Dev.
Fixed Non-Standard										
Trimble, Cousins and Seda-Sanabria (2003)	Concrete T-Beam (Franklin)	12	M1075 PLS	Wheeled Tpt.	4	0.15	0.10	0.03	0.18	0.14
	Concrete T-Beam (Patrick)	15.6	M1075 PLS	Wheeled Tpt.	4	0.46	0.39	0.06	0.15	0.12
Everitt (2019)	Steel Girder (4) with Composite Concrete Deck, 2-Span Cont.	29.6 and 32.9	Cougar	Wheeled Fighting	10	0.13	-0.01	0.08	0.15	0.12
			HLVW Low-Bed	Wheeled Tpt.	10	0.19	-0.01	0.07	0.15	0.12
			E-LAV	Wheeled Fighting	10	0.19	0.01	0.10	0.15	0.12
			Leopard 2	Tracked Fighting	10	0.14	0.01	0.04	0.15	0.12
Deployable / Mobile Bridging										
Kosmatka (2011)	Carbon / Epoxy	11.9	M1-A1	Tracked Fighting	15	0.26	0.23	0.03	0.18	0.14
			HET	Wheeled Tpt.	15	0.69	0.62	0.09	0.18	0.14
Robinson and Kosmatka (2011)	Low Profile FRP Composite	4.7	M113	Tracked Fighting	11	0.12	0.02	0.06	0.20	0.12
			M1075 PLS	Wheeled Tpt.	9	0.71	0.49	0.19	0.20	0.12
Landherr (2008)	FRP Box Beam	10	Bison	Wheeled Fighting	6	0.28	0.13	0.07	0.20	0.12
			HLVW	Wheeled Tpt.	1	0.27	0.27	N/A	0.20	0.12

^a Short Spans: ($\delta_{DLA} = 0.67$; $V_{DLA} = 0.6$); and Other Spans: ($\delta_{DLA} = 0.60$; $V_{DLA} = 0.60$).

^b Mean DLA is the product of the bias coefficient for DLA and the nominal value from CSA (2019a)

^c Std. Dev. Is the product of the CoV for DLA and the mean value computed per note b.

Table 5. Lateral load distribution factors

Bridge Classification from Pinero (2001)		All Beam Bridges (Steel Girder)	All Beam Bridges (Pre- Stressed)	Steel Girder	Concrete T-Beam (Franklin)	Concrete T-Beam (Patrick)	Pre-Stressed Concrete	
Sources		Kim, Tanovic and Wight (2010)	Morrison Hershfield Ltd. (2012)	Kim, Tanovic and Wight (2010)	Trimble, Cousins and Seda-Sanabria (2003)		Morrison Hershfield Ltd. (2012)	
CSA (2019a) Highway Class A&B, (F_m)		0.57	0.56	0.57	0.53	0.60	0.56	
AASHTO LRFD Bridge (2012), (F_m $= LDF \cdot N$)		0.41	0.40	0.42	0.53	0.54	0.44	
Experimental Results		Avg – 0.27 Max – 0.29 (FEA)	-	Avg – 0.27 Max – 0.29 (FEA)	0.37 (measured on site)	0.63 (measured on site)	-	
Pinero (2001)	All	Amplification Factor	0.47	0.41	0.44	0.42	0.47	0.45
	Military Vehicles	Fraction of CSA (2019a)	0.83	0.73	0.77	0.79	0.79	0.82
		Fraction of AASHTO	1.14	1.02	1.03	0.79	0.87	1.03
	M1075 PLS	Amplification Factor	0.51	0.45	0.83	0.56	0.61	0.47
		Fraction of CSA (2019a)	0.89	0.81	1.47	1.04	1.02	0.84
		Fraction of AASHTO	1.22	1.13	1.97	1.04	1.13	1.06
	M113	Amplification Factor	0.46	0.42	0.42	0.41	0.45	0.46
		Fraction of CSA (2019a)	0.82	0.75	0.73	0.77	0.76	0.83
		Fraction of AASHTO	1.12	1.04	0.98	0.76	0.84	1.04
	ABRAMS M1-A1	Amplification Factor	0.50	0.45	0.44	0.45	0.53	0.47
Fraction of CSA (2019a)		0.88	0.81	0.78	0.84	0.88	0.85	
Fraction of AASHTO		1.21	1.12	1.04	0.83	0.98	1.07	

Table 6. Accuracy of proposed load distribution factors for interior girder bending moments (Pinero, 2001)

Bridge Type	Coefficient	Vehicle Type			
		M1075-PLS	M113	ABRAMS M1-A1	All Vehicles
All Beam	Mean	1.05	1.007	1.01	1.015
	CoV	0.159	0.069	0.098	0.119
Steel Girder	Mean	0.999	1.003	1.001	1.018
	CoV	0.078	0.042	0.059	0.066
Pre-Stressed Concrete	Mean	1.023	1.019	1.008	1.006
	CoV	0.115	0.091	0.102	0.12
Concrete T-Beam	Mean	1.021	1.015	1.073	0.997
	CoV	0.170	0.074	0.119	0.111

Table 7. Bias coefficient and CoV of load distribution factors from Pinero (2001)

Bridge Type	Coefficient	Vehicle Type				Lateral Load Distribution CSA (2019a and 2019b)
		M1075-PLS	M113	ABRAMS M1-A1	All Vehicles	
All Beam	Bias	0.98	1.00	1.00	1.00	0.93
	CoV	0.16	0.10	0.07	0.12	0.12
Steel Girder	Bias	1.01	1.00	1.00	0.99	-
	CoV	0.08	0.06	0.04	0.07	-
Pre-Stressed Concrete	Bias	0.99	1.00	1.00	1.01	-
	CoV	0.12	0.10	0.10	0.12	-
Concrete T-Beam	Bias	1.01	0.95	0.99	1.02	-
	CoV	0.17	0.12	0.07	0.11	-

Table 8. Live load effects, moment

	Vehicle	Parameter	Event	Annual Traffic Volume		
				100	1,000	10,000
Short Spans	AHSVS-PLS	Bias	0.698	0.904	1.096	1.312
		CoV	0.186	0.197	0.189	0.184
	LAV III-ISC	Bias	1.051	1.181	1.218	1.247
		CoV	0.166	0.160	0.160	0.160
	Leopard 2A4M tank	Bias	0.873	0.889	0.892	0.894
		CoV	0.159	0.159	0.159	0.159
Other Spans	AHSVS-PLS	Bias	0.655	0.882	0.997	1.119
		CoV	0.186	0.175	0.171	0.170
	LAV III-ISC	Bias	0.928	0.998	1.019	1.035
		CoV	0.162	0.159	0.159	0.159
	Leopard 2A4M tank	Bias	0.873	0.889	0.892	0.894
		CoV	0.159	0.159	0.159	0.159

Table 9. Load factors for reference military vehicles for different annual traffic volumes for annual target reliability indices

	Vehicle	Traffic Volume	$\beta =$								
			2.00	2.25	2.50	2.75	3.00	3.25	3.5	3.75	4.00
Short Spans	AHSVS-PLS	100	1.19	1.23	1.28	1.32	1.37	1.42	1.47	1.52	1.57
		1,000	1.43	1.48	1.53	1.58	1.63	1.69	1.74	1.80	1.86
		10,000	1.70	1.75	1.81	1.87	1.93	1.99	2.06	2.12	2.19
	LAV III-ISC	100	1.48	1.52	1.56	1.61	1.65	1.70	1.75	1.80	1.85
		1,000	1.52	1.57	1.61	1.66	1.70	1.75	1.80	1.85	1.90
		10,000	1.56	1.60	1.65	1.70	1.74	1.79	1.84	1.90	1.95
	Leopard 2A4M tank	All Traffic Rates	1.12	1.15	1.18	1.22	1.25	1.28	1.32	1.36	1.40
	Vehicle	Traffic Volume	$\beta =$								
			2.00	2.25	2.50	2.75	3.00	3.25	3.5	3.75	4.00
Other Spans	AHSVS-PLS	100	1.13	1.16	1.20	1.23	1.27	1.31	1.35	1.39	1.44
		1,000	1.27	1.30	1.34	1.39	1.43	1.47	1.52	1.56	1.61
		10,000	1.42	1.46	1.51	1.55	1.60	1.65	1.70	1.75	1.80
	LAV III-ISC	100	1.25	1.28	1.32	1.36	1.40	1.44	1.48	1.52	1.56
		1,000	1.27	1.31	1.35	1.38	1.42	1.46	1.51	1.55	1.59
		10,000	1.29	1.33	1.37	1.41	1.45	1.49	1.53	1.57	1.62
	Leopard 2A4M tank	All Traffic Rates	1.12	1.15	1.18	1.22	1.25	1.28	1.32	1.36	1.40

Table 10. Summary of payload weight fraction for Canadian Armed Forces vehicles
(MacDonald, 2017)

Vehicle Type	Associated Military Vehicle Category	Number of Different Vehicle Configurations Investigated	Payload Weight Fraction		
			Max	Min	Mean
Tank	T-F	9	0.12	0.02	0.04
Armoured Personnel Carrier	T-F	9	0.21	0.06	0.13
	W-F				
Transport	W-T	6	0.60	0.38	0.47
Overall	T-F	24	0.60	0.02	0.18
	W-F				
	W-T				

Table 11. Load factors for military traffic based on annual target reliability indices for annual traffic volumes of 100, 1,000, and 10,000

Wheeled-Transport (W-T) Vehicles	Short Spans (< 20 m)									
	$\beta =$	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
	100	1.19	1.23	1.28	1.32	1.37	1.42	1.47	1.52	1.57
	1,000	1.43	1.48	1.53	1.58	1.63	1.69	1.74	1.80	1.86
	10,000	1.70	1.75	1.81	1.87	1.93	1.99	2.06	2.12	2.19
	Other Spans (>20 m)									
	$\beta =$	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
	100	1.14	1.17	1.21	1.25	1.29	1.33	1.37	1.41	1.46
	1,000	1.29	1.33	1.38	1.42	1.46	1.51	1.55	1.60	1.65
	10,000	1.44	1.48	1.53	1.57	1.62	1.67	1.72	1.77	1.82
Wheeled-Fighting (W-F) Vehicles	Short Spans (< 15 m)									
	$\beta =$	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
	100	1.48	1.52	1.56	1.61	1.65	1.70	1.75	1.80	1.85
	1,000	1.52	1.57	1.61	1.66	1.70	1.75	1.80	1.85	1.90
	10,000	1.56	1.60	1.65	1.70	1.74	1.79	1.84	1.90	1.95
	Other Spans (>15 m)									
	$\beta =$	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
	100	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.53
	1,000	1.24	1.28	1.31	1.35	1.39	1.43	1.47	1.51	1.56
	10,000	1.26	1.29	1.33	1.37	1.40	1.44	1.49	1.53	1.57
Tracked-Fighting (T-F) Vehicles	All Spans									
	$\beta =$	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
	All Traffic Volumes	1.13	1.16	1.19	1.22	1.26	1.29	1.33	1.37	1.41

Fig. 1. (a) AHSVS-PLS (image courtesy of Neil Peacock); (b) LAV III-ISC (image courtesy of Neil Peacock); (c) Leopard 2A4M (DND photo by Master Corporal David McVeigh)

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Fig. 3. Load factor for maximum annual load effects for 1,000 vehicles per year based on payload weight fraction