AiMT

Advances in Military Technology
Vol. 12, No. 1 (**2017**), pp. 129-145
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01178

Probabilistic Gross Vehicle Weights and Associated Axle Loads for Military Vehicles in Bridge Evaluation and Code Calibration

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The manuscript was received on 15 February 2017 and was accepted after revision for publication on 22 June 2017.

Abstract:

Military vehicles frequently use civilian bridges. The loading effects of military vehicles, both wheeled and tracked, are specific and different than those of civilian vehicles in normal traffic. Calibration to determine appropriate load factors for military loading of civilian bridges has not been fully performed and the corresponding levels of safety have not been quantified. This is partially due to the lack of probabilistic information of the gross vehicle weights and corresponding axle loads of military vehicles while operating in real-world conditions. This paper quantifies probabilistically the gross vehicle weight and axle loads for three military vehicles in use by NATO, each of which is representative of: military transport vehicles; armoured personnel carriers; and main battle tanks. A general means are proposed to quantify the probabilistic gross vehicle weight of military vehicles on the basis of maximum nominal payload as a proportion of the total nominal vehicle weight. Based on observed probabilistic gross vehicle weight of military vehicles, it is recommended to differentiate between military transport and military fighting vehicles as different categories of vehicles in bridge evaluation.

Keywords:

highway bridge design, highway bridge evaluation, military vehicle, gross vehicle weight, military engineering

1. Introduction

Military vehicles frequently use civilian bridges in domestic, peacekeeping, stabilization and combat theatres of operation. The load effects of military vehicles, both wheeled and tracked, are unique and likely different than those of civilian vehicles in

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normal traffic. The probabilistic quantification of military vehicle bridge loading has not been fully performed. Calibration to determine appropriate load factors for military loading of bridges therefore cannot be undertaken and the corresponding reliability is unknown. This lack of calibration prevents the proper implementation of Limit States methods (e.g., Canadian Standards Association [1]) in military bridge design and evaluation. The objective of the research reported in this paper is to quantify probabilistically the gross vehicle weight and axle load of military vehicles and so partly address the shortfall of information needed for this calibration.

Three vehicles were investigated: the Armoured Heavy Support Vehicle System – Palletized Loading System (AHSVS-PLS); the Light Armour Vehicle III – Infantry Section Carrier (LAV III-ISC); and the Leopard 2A4M tank. They were selected because they represent three distinct loading categories: they have either transport or fighting functions and are either wheeled or tracked. This paper quantifies probabilistically the Gross Vehicle Weight (GVW), defined as the sum of the curb weight and payload. The curb weight is the weight of the fuelled vehicle and, if uparmoured (which relates to vehicles that have optional armour kits to achieve different levels of protection), additional armour including mine protection. The payload weight consists of cargo, crew, ammunition, communications equipment, consumables (i.e. extra fuel, water, food, etc.), secondary weapons, crew's personal equipment and mission-specific equipment. The nominal weight of the vehicle is the published combat weight, the sum of the nominal curb weight and nominal payload weight.

2. Estimation of Gross Vehicle Weight

2.1. AHSVS-PLS (Wheeled-Transport)

Fig. 1 shows the AHSVS-PLS, a Palletized Loading System (PLS) variant of the militarized Mercedes-Benz Actros truck that fulfils various heavy logistics functions as a military transport vehicle. Fig. 2 shows the idealized axle loads in kg for the curb "weight" (above) and combat "weight" (below). The AHSVS-PLS facilitates loading / unloading of 6.1 m (20 ft) long intermodal shipping containers, its primary payload, without the need of an external lift by using its PLS.

The weights of intermodal shipping containers flown by the Canadian Armed Forces from Kandahar Afghanistan between 2006 and 2012 are assumed to be representative of intermodal shipping containers transported by the AHSVS-PLS. A query of the Department of National Defence (DND) National Material Distribution System (NMDS) for 6.1 m intermodal containers yielded 3 723 unique intermodal containers [2]. The mean mass of these containers is 6 880 kg with a Coefficient of Variation (CoV), defined as the standard deviation divided by the mean, of 0.415. Using Weibull plotting positions sample data was fitted to Exponential (shifted), Normal, Log-Normal, Gumbel, Weibull, and Rayleigh (shifted) distributions. Linear regression of the transformed data was used to determine the best-fit slope and y-axis intercepts values, from which the parameters defining each distribution were computed. The fitted Log-Normal and Gumbel distributions were in closest agreement with the data.

The two corresponding root-mean-square errors are 0.0076 for the Log-Normal distribution and for the Gumbel distribution 0.0073. The fit of the Cumulative Distribution Function (CDF) to the data was tested using the Kolmogorov-Smirnov (K-S) test [3] at a significance level of 10 % (e.g. $\alpha = 0.10$). Only the best-fit Log-Normal and Gumbel distributions passed this test. To simplify subsequent computations, the best-fit Gumbel distribution with β = 2 247 kg and μ = 5 583 kg was selected to describe the “weight” of the intermodal shipping containers.

Fig. 1 AHSVS-PLS (image courtesy of Neil Peacock)

The bias coefficient and variability of the overall weight is quantified assuming curb “weight” to be deterministic, at 22 900 kg [4]. It has been demonstrated by MacDonald [2], based on the flown weights of Canadian military vehicles, that this is a reasonable assumption for this vehicle type. Only the intermodal shipping container weights (i.e., the payload) therefore contribute to the overall vehicle weight variability.

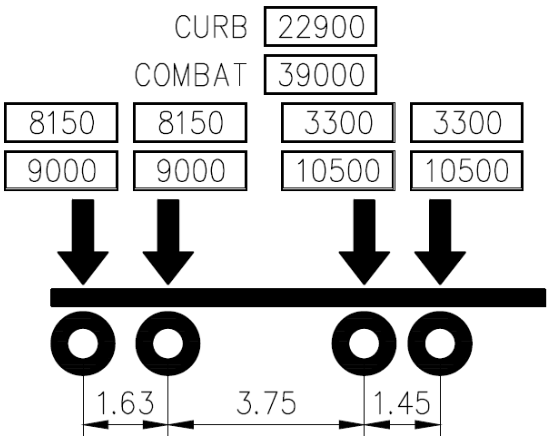

Fig. 2 AHSVS-PLS idealized axle loads [kg] and spacing [m]

With these assumptions, the best-fit Gumbel distribution for the event “weight” of the AHSVS-PLS can be derived. Tab. 1 presents the central tendency and dispersion parameters, bias coefficients (defined as the mean GVW divided by the nominal combat weight) and CoV for the event vehicle, which represents the overall population of AHSVS-PLS vehicles. It is more common to quantify bridge traffic loadings for design or evaluation at Ultimate Limit States using the maximum load that would occur over a one-year period (e.g., Kennedy et al. [5]). Therefore, Tab. 1 also presents the parameters derived for annual traffic volumes of 100, 1 000, 10 000 and 100 000 vehicles per year. As the event data are assumed to follow a Gumbel distribution, the maximum annual "weights" also follow Gumbel distributions with the dispersion parameter, β_A, given by:

$$\beta_A = \beta\,, \tag{1}$$

and the central tendency parameter, μ_A, given by:

$$\mu_A = \beta \ln(n / n_i) + \mu\,, \tag{2}$$

where:

- β and μ are the dispersion and central tendency parameters of the event distribution;
- n is the number of vehicles per year; and
- n_i is the number of vehicles for the reference population (in this case n_i = 1 for the event distribution).

Tab. 1 AHSVS-PLS "weight" quantification

AHSVS-PLS Configuration Curb / Combat [4]	Gumbel Parameters	Event	Maximum Annual		
			100	1 000	10 000
22 900 kg / 39 000 kg	μ [kg]	28 483	38 831	44 005	49 179
	β [kg]	2 247	2 247	2 247	2 247
	Bias	0.764	1.029	1.162	1.294
	CoV	0.096	0.072	0.064	0.057

2.2. LAV III-ISC (Wheeled-Fighting)

Fig. 3 shows the uparmoured LAV III-ISC, a vehicle that primarily serves as an Armoured Personnel Carrier (APC) for one infantry section, but can also be armed to provide additional firepower. This vehicle is best categorized as a military fighting vehicle and so it serves a very different function than the AHSVS-PLS. Fig. 4 shows the idealized axle loads in kg for the curb "weight" (above) and combat "weight" (below).

Nominally, the combat "weight" of a fully laden LAV III-ISC consists of a curb "weight", including uparmour, of 16 744 kg and a payload of 3 256 kg. It is assumed that the curb weight of the LAV III-ISC can be considered deterministic. Lacking field data, Tab. 2 presents the assumed parameters for the various operational payload components of the LAV III-ISC GVW. Unknown operational payloads are assumed to vary uniformly across the range of each parameter shown, which is intended to conservatively envelope, by neglecting vehicles with less than the nominal combat weight, the actual parameter range. Each component of the GVW was assumed independent.

Using the data summarized in Tab. 2, 10 000 vehicle weights were randomly generated, yielding the simulated event data shown in Tab. 3. The Log-Normal distribution best fits these simulated event data and was used to derive the CDF of the annual maximum weight using the mapping:

$$F_A(x) = [F_E(x)]^n = \left[\Phi\left(\frac{\ln(x / \breve{m}_x)}{\sigma_{\ln(x)}}\right)\right]^n, \tag{3}$$

where:

- $F_A(x)$ is the cumulative probability at weight x for the maximum observed value of n observations;
- $F_E(x)$ is the event cumulative probability at x;
- $\sigma_{\ln(x)}$ is the Log-Normal distribution dispersion parameter; and
- $\breve{m}_x$ is the Log-Normal distribution central tendency parameter.

Several different annual traffic volumes were considered, yielding the statistical parameters summarized in Tab. 3.

Fig. 3 LAV III-ISC (image courtesy of Neil Peacock)

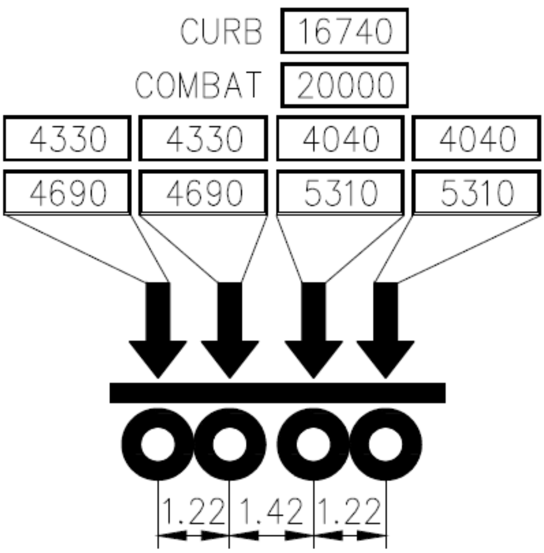

Fig. 4 Assumed LAV III-ISC idealized axle loads [kg] and spacing [m]

Tab. 2 LAV III – ISC operational loads

Component of GVW	Nominal Quantity	Mass [kg]	Assumed "Weight" Variability for Idealization	Notes
Curb Weight including Uparmour	–	16 744[6, 7]	Deterministic	
Payload A	–	340[8]	(Total Nominal)*(Uniform Distribution 1 to 1.5)	Inventoried Items
Payload B	–	1 620	(Total Nominal)*(Uniform Distribution 1 to 2)	Miscellaneous Equipment / Stowage
Crew and Personnel with Combat Gear	10[6]	1 300	(Nominal Quantity) + (Discrete Uniform Distribution 0 to10)	Mass of each soldier 136.5 kg [9]
Total (Combat Weight)		20 000[6]		

Note: Payload is normally distributed with parameters μ = 4 904 kg, σ = 643 kg

When the annual traffic volume equals 100 or more vehicles per year, the weight of the maximum annual vehicle is best described by a Gumbel distribution. One might therefore expect that the dispersion factor β would remain constant. The dispersion factors shown in Tab. 3 change slightly for each value of n however, because, the Gumbel fit to the values determined using a Log-Normal event distribution is good but not perfect.

Tab. 3 GVW of LAV III-ISC

LAV-III-ISC (Uparmoured) Nominal "Weights" Curb / Combat [6]	Log-Normal or Gumbel Parameters	Event (Log-Normal)	Maximum Annual (Gumbel)		
			100	1 000	10 000
16 744 kg / 20 000 kg	$\breve{m}_x$ or μ [kg]	21 632	23 258	23 820	24 294
	$\sigma_{\ln(x)}$ or β [kg]	0.031	257	213	187
	Bias	1.082	1.170	1.197	1.220
	CoV	0.030	0.013	0.011	0.010

2.3. Leopard 2A4M Tank (Tracked-Fighting)

Fig. 5 shows the Leopard 2A4M tank. It is also a military fighting vehicle, primarily used to provide direct weapon fire support, and so designed primarily to ensure the mobility and survivability of the primary weapon system. When compared to the LAV III-ISC, a larger proportion of its GVW is the curb weight; mostly due to requirements for the primary weapon system and armoured protection.

The curb weight of the Leopard 2A4M tank, 59 484 kg, can be assumed to be deterministic [2]. It consists of the Leopard 2A4M tank chassis, main gun and turret, Add-on-Armour (AoA), slat armour system, and full fuel load. Tab. 4 presents the assumed parameters for the various operational load components. The crew, consisting of four persons at 75 kg each, is also assumed deterministic. The nominal masses of the various operational weights are quantified from various DND sources and are sufficient to increase the nominal curb weight to the nominal combat weight. These operational weights are assumed to vary uniformly across the range of each parameter shown, which is again intended to conservatively envelope the actual parameter range. The potential for an additional operational load of up to ten infantry riding on top of the tank is also considered. Each component of the GVW was assumed independent.

Fig. 5 Leopard 2A4M tank (Image from www.casr.ca/101-army-armour-leopard-2a4m.htm)

Tab. 4 Leopard 2A4M tank operational loads

Component of GVW	Nominal Quantity	Combined Nominal Mass [kg][10]	Assumed "Weight" Variability for Idealization	Notes
Curb "Weight" (fully fueled with AoA and Slat Armour)	–	59 184	Deterministic	
Crew	4	300	Deterministic	75 kg per person
Payload A	–	1 000	(Total Nominal)*(Uniform Distribution between 1 and 1.5)	Inventoried Items
Payload B	–	730	(Total Nominal)*(Uniform Distribution between 1 and 2)	Miscellaneous Equipment / Stowage
Infantry Section Transport	0	0	(Discrete Uniform Distribution between 0 and 10)	Mass of each soldier 136.5 kg[9]
Total "Weight"		61 214		

Using the data summarized in Tab. 4, 10 000 vehicle weights were randomly generated, yielding the event statistics shown in Tab. 5. Above the 35th percentile, a Weibull distribution has an excellent fit to the simulated data, (passing the K-S test at a significance level of 10 %). The annual maximum statistical parameters for the Leopard 2A4M tank GVW are also shown in Tab. 5.

Tab. 5 GVW of Leopard 2A4M tank

Leopard 2A4M Nominal "Weights" Curb / Combat [10]	Weibull or Gumbel Parameters	Event (Weibull)	Maximum Annual (Gumbel)		
			100	1 000	10 000
59 184 kg / 61 214 kg	μ [kg]	62 710	63 523	63 743	63 900
	k or β [kg]	118	105	73	56
	Bias	1.021	1.039	1.042	1.044
	CoV	0.008	0.002	0.001	0.001

3. Relationship between Payload Weight Fraction and Vehicle Weight Variability

The assumption that curb weights are deterministic and only payload weights are stochastic causes the curb weight to influence the statistical parameters for the overall load. A particular payload may be associated with a vehicle depending upon its function. The statistical parameters for the GVW will therefore likely be related to the payload weight fraction, γ, defined as:

$$\gamma = \frac{W_P}{W_V}, \tag{4}$$

where W_P is the nominal payload and W_V is the nominal vehicle combat weight. The nominal vehicle weight can be computed from the curb weight of the vehicle, W_C, as:

$$W_V = \frac{W_C}{(1-\gamma)}. \tag{5}$$

Since the curb weight is assumed deterministic, the mean vehicle weight, $\overline{W_V}$, is given by:

$$\overline{W_V} = \delta_P W_P + W_C, \tag{6}$$

where δ_P is the bias coefficient of the payload weight. Using Eq. (4) to eliminate W_P and Eq. (5) to eliminate W_V, Eq. (6) can be written as:

$$\overline{W_V} = W_C\left(\frac{\gamma\delta_P}{1-\gamma}+1\right). \tag{7}$$

The bias coefficient of the vehicle weight, δ_V, is simply the ratio of Eq. (7) to Eq. (5):

$$\delta_V = \gamma(\delta_P - 1) + 1. \tag{8}$$

Since all variability of the vehicle weight is due to the payload, the standard deviation of the vehicle weight, σ_V, equals the standard deviation of the payload weight, σ_P. After some manipulation, the standard deviation of the vehicle weight is:

$$\sigma_V = V_P \delta_P W_C \frac{\gamma}{1-\gamma}, \tag{9}$$

where V_P is the CoV of the payload. By dividing Eq. (9) by Eq. (7) the CoV of the vehicle weight, V_V, is:

$$V_V = \frac{V_P \delta_P \gamma}{\gamma(\delta_P - 1) + 1}. \tag{10}$$

The payload bias coefficient and CoV for the various levels of maximum annual volume of vehicles as calculated from Eq. (8) and Eq. (10) respectively is summarized in Tab. 6. The payload for the two fighting vehicles (LAV III-ISC and Leopard 2A4M) is characterized by a high bias and low CoV, while the AHSVS-PLS, a military transport, is characterized by a payload with a low bias and high CoV.

Tab. 6 Payload bias coefficient and CoV for annual maximum vehicle

Annual Maximum n = # of vehicles	$n = 1$		$n = 100$		$n = 1\,000$		$n = 10\,000$	
Vehicle	δ_P	V_P	δ_P	V_P	δ_P	V_P	δ_P	V_P
AHSVS-PLS	0.43	0.42	1.07	0.17	1.39	0.13	1.71	0.10
LAV III-ISC	1.50	0.13	2.04	0.05	2.21	0.04	2.35	0.03
Leopard 2A4M tank	1.63	0.15	2.18	0.03	2.27	0.01	2.33	0.01

4. Axle Loads

To assess the reliability of short-span bridges, the statistical parameters for axle loads are required. In this section, suitable parameters are derived from the GVW parameters.

4.1. AHSVS-PLS (Wheeled-Transport) Axle Load

As shown in Fig. 6, the four axles of the AHSVS-PLS are in fact two tandem axles. Thus the axle loads can be estimated from the total load by idealizing the AHSVS-PLS as a simply supported span between the tandem axle centers. When the eccentricity of the payload resultant force extends beyond the rear tandem axle, a cantilever is assumed. Based on the nominal curb "weight" and axle loads for the AHSVS-PLS, the curb weight is represented as a point load (shown as black arrows labelled "C") located 1.52 m from the front support. The nominal maximum payloads are also represented as point loads (shown as white arrows labelled "P"), applied at 0.56 m in front of the rear support of the AHSVS-PLS. It is assumed that, if there is no eccentricity of the shipping container centers of gravity, the payload will act at this point for any given weight. Thus simple statics can estimate the loads on each axle, assuming that the tandem axle loads are shared equally.

To generate realistic axle loads, intermodal shipping containers were randomly generated by simulation given known eccentricities of the shipping container resultant force. Most of the available eccentricities are held by ETS Consulting, United Kingdom (http://ets-consulting.org/). The data made available by Brassington [11] for the current study indicated that for shipping containers less than 30 tonnes, the eccentricities are closely approximated by a Half-Normal distribution with standard deviation, σ, of 0.226 m. For shipping containers greater than 30 tonnes, a Half-Normal distribution with σ of 0.140 m is appropriate. Thus the variability of the eccentricity of the container resultant force is less for the heaviest shipping containers, perhaps because, for the heavily loaded containers it is more difficult in practice to load the container asymmetrically. It was therefore assumed that the longitudinal eccentricity of the container resultant force is normally distributed about the midpoint of the container.

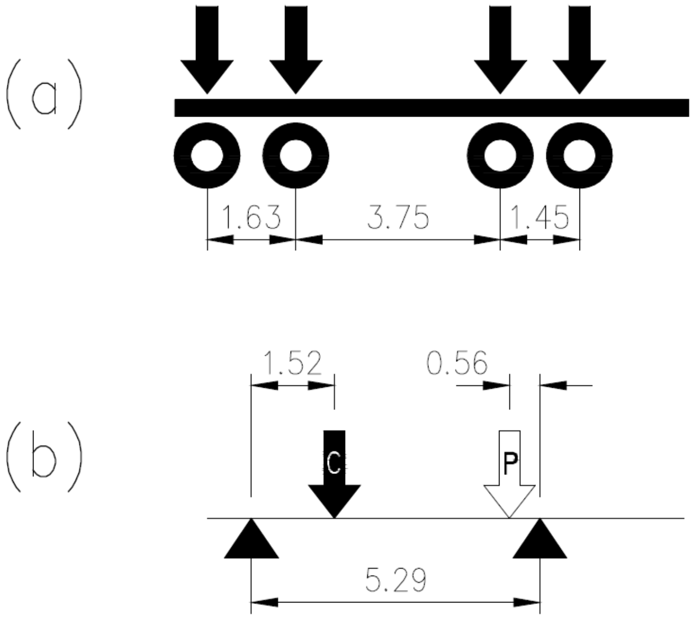

Fig. 6 Idealization of AHSVS-PLS, spacing given in metres
(a) Vehicle axle spacing; (b) Idealized representation

A total of 10 000 vehicles were generated and analysed to yield the event axle loads shown in Tab. 7. The loads on the first and second axles are primarily due to the curb weights and so the bias coefficient is close to 1.0 and the CoV is small. The loads on the third and fourth axles are primarily due to the shipping container weights and, although they average only 60 % of the nominal combat value, have a much greater CoV.

Tab. 7 AHSVS-PLS event axle load idealization

Axle	1^{st} and 2^{nd}	3^{rd} and 4^{th}
Mean [kN]	83.5	62.5
Bias coefficient	0.946	0.607
Standard Deviation [kN]	2.1	12.7
CoV	0.026	0.203

4.2. LAV III-ISC (Wheeled-Fighting) Axle Load

The bias coefficient and variability of the payload eccentricity for the LAV III-ISC is not available in the literature, so it was assumed that the payload only acts on the 3^{rd} and 4^{th} axle, with the load being shared equally. This results in changes to the payload only affecting the rear two axles.

Tab. 8 shows the statistical parameters for the LAV III-ISC event axle loads, as generated by simulation. The bias and CoV are greater for the 3rd and 4th axles because the payload is assumed to be carried only by these two axles. Had the payload been assumed to act such that some of the payload would have been shared with the front axles the bias and CoV of the rear axles would have been lower. In considering shear and moment for short spans it is conservative to assume the payload acts only on the rear axles as this produces a greater bias and CoV in axle loads (which correspond to greater bias and CoV for the live load moment and shear acting on the span). In lieu of information relating to the center of gravity for vehicle payload and expected eccentricity of payload, this is a reasonable assumption when considering axle loads acting on short spans.

Tab. 8 LAV III-ISC event axle load idealization

Axle	Nominal [kN]	Mean [kN]	Bias	Standard Deviation [kN]	CoV
1st and 2nd	46.0	42.3	0.919	N/A	0
3rd and 4th	52.1	63.8	1.226	3.2	0.049

4.3. Leopard 2A4M Tank (Tracked-Fighting)

For tracked vehicles, the vehicle load is generally assumed to be uniformly distributed over the contact area of the tracks [12]. In fact, there are peaks of pressure where roadwheels are located along the track [13]. Given this, it is necessary to check the local load applied beneath the tracked vehicle roadwheel [12]. Furthermore, the load in each roadwheel may not be equal, depending on how the vehicle is loaded. For long-span bridges the impact of these slight differences in roadwheel loads is negligible. For short-span bridges, particularly those with spans approaching the length of track, these differences may be significant. Case #1 in Fig. 7 shows the perfect case where loads are distributed equally between roadwheels, thus creating essentially a Uniformly Distributed Load (UDL) along contact surface of the tracks. In practice, some roadwheels may have heavier loads than others. If these heavier loads are near the middle of the vehicle, as represented by Case #2 in Fig. 7, a greater maximum moment than that caused by a UDL would be produced. The heavier loads might also be concentrated to one end of the vehicle as shown in Case #3 in Fig. 7, which would produce a greater maximum shear.

In Cases #2 and #3 of Fig. 7, the load distribution would be caused by differences in the largest roadwheel load and smallest roadwheel load. For Case #2 (for moment) or Case #3 (for shear), if the largest magnitude of the distributed load is 35 % larger than the least magnitude, the increase in moment or shear with respect to Case #1 is less than 5 %.

5. Generalized Approach – Probabilistic Quantification of Military Vehicle GVW

5.1. Proposed Military Vehicle Categories

As previously shown, military transport vehicles have inherently different payloads than fighting vehicles. It is therefore reasonable to treat these vehicles differently when determining the probabilistic quantification of the GVW. As such, the following four categories of vehicles are proposed: Wheeled-Transport (W-T), Wheeled-Fighting (W-F), Tracked-Transport (T-T), and Tracked-Fighting (T-F).

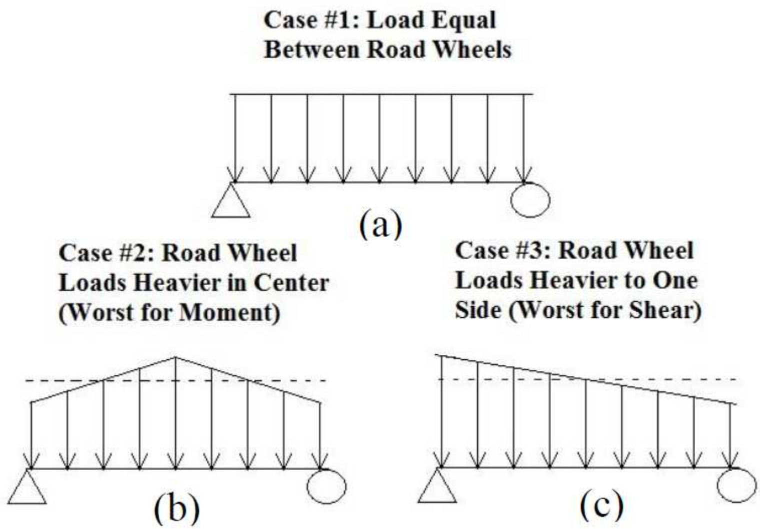

Fig. 7 Tracked vehicle load distribution cases:
(a) Idealized load; (b) Worst case for moment; (c) Worst case for shear

Tab. 9 identifies typical military vehicles based on their intended function, such as: Transport (Tpt.), Armoured Personnel Carrier (APC) or Tank. These three functions also pertain to the three vehicles investigated previously in this paper: AHSVS-PLS (Transport); LAV III-ISC (APC); and, Leopard 2A4M (Tank), respectively. The ranges of payload weight fractions, for these vehicles are 38 to 60 % for transport vehicles, 7 to 21 % for APCs, and 2 to 13 % for tanks. The payload weight fractions for transport vehicles are clearly distinct from those for the other two categories. It might therefore be appropriate to define Fighting vehicles (such as Tanks or APCs) as those with payload weight fractions less than 25 % and Transport vehicles as those with payload weight fractions greater than 35 %. Vehicles with payload weight fractions between 25 % and 35 %, such as an APC with a trailer attached, require additional investigation to be classified as Transport or Fighting.

5.2. Statistical Gross Vehicle Weight Parameters for Other Unsurveyed Vehicle Populations

Statistical GVW parameters have been derived for three specific military vehicles. These parameters may be applicable to similar military vehicles of interest. However, in lieu of better information, vehicle-specific statistical GVW parameters might be estimated using the payload weight fraction. This is beneficial because the statistical parameters for the vehicle loads on longer spans are similar to those for the vehicle weight [5]. Tab. 10 presents typical payload statistical parameters by Military Vehicle Category for transports, armoured personnel carriers and tanks. It is derived using the bias and CoV from Tab. 6, and the average payload weight fractions from Tab. 9 for military transports, APCs and tanks.

Tab. 9 Payload "weight" fraction for Canadian Armed Forces Vehicles

Vehicle Name	Type	Payload Weight Fraction
Leopard 1ARV [14]	Tank	0.02
Badger AEV (Leo C2 Variant) – Uparmoured [15]	Tank	0.03
Badger AEV (Leo C2 Variant) [15]	Tank	0.03
Leopard 2A4M – Uparmoured [10]	Tank	0.03
Leopard 2A6M [10]	Tank	0.03
Leopard 2A6M – Uparmoured [10]	Tank	0.03
Leopard C2 MBT –Uparmoured [16]	Tank	0.05
Leopard C2 MBT [16]	Tank	0.06
Leopard 2 ARV [10]	Tank	0.12
AVERAGE PAYLOAD WEIGHT FRACTION – TANK		0.04
Coyote [17]	APC	0.06
Bison (Ambulance) – Uparmoured [18]	APC	0.07
M113-A3 (TLAV) – Uparmoured [19]	APC	0.08
Bison (Ambulance) [18]	APC	0.08
Bison (EW) [20]	APC	0.14
LAV LORIT [7]	APC	0.14
LAV III-ISC – Uparmoured [7]	APC	0.16
LAV III-ISC [6]	APC	0.19
LAV III-Engr w Blade [6]	APC	0.21
AVERAGE PAYLOAD WEIGHT FRACTION – APC		0.13
Heavy Logistics Vehicle Wheeled – Uparmoured [21]	Tpt.	0.38
Heavy Logistics Vehicle Wheeled [21]	Tpt.	0.41
AHSVS-PLS [22]	Tpt.	0.41
Heavy Equipment Support Vehicle [23]	Tpt.	0.49
AHSVS-PLS with Trailer [22, 24]	Tpt.	0.53
AHSVS-24t Tractor with 72 Tonne Trailer [25]	Tpt.	0.60
AVERAGE PAYLOAD WEIGHT FRACTION – TRANSPORT		0.47

Tab. 10 Military vehicle payload bias coefficient and CoV

Annual Maximum n = # of vehicles		$n = 1$		$n = 100$		$n = 1\,000$		$n = 10\,000$	
Vehicle Description	Vehicle Category	δ_P	V_P	δ_P	V_P	δ_P	V_P	δ_P	V_P
Military Transport	W-T, T-T	0.428	0.415	1.070	0.168	1.392	0.129	1.712	0.104
Armoured Personnel Carrier (APC)	W-F, T-F	1.503	0.132	2.043	0.046	2.209	0.037	2.350	0.032
Tank	T-F	1.633	0.151	2.176	0.029	2.266	0.014	2.327	0.014

6. Discussion

The method used to estimate variability of the AHSVS-PLS combat weight provides a good starting point for investigating other traffic populations. This could indicate if further resources are necessary to weigh military transport vehicles, and so obtain more reliable data to calibrate live load factors for military transport vehicles at Ultimate Limit States.

The methods used to quantify the LAV III-ISC and Leopard 2A4M tank weight variability are based on heuristic assumptions concerning different operational loads that affect the vehicle weight. Given the high level of control, itemized breakdown, and standardization of military fighting vehicle loads, it is possible to make these conservative assumptions with greater confidence than if the payload was uncontrolled. Even though vehicle weight data from the field are required to validate these assumptions, they still yield a useful method of comparing the expected weight variability in different categories of military vehicles.

It has generally been assumed that there is higher control in military vehicle loads than civilian vehicle loads [26], thus leading to lower weight variability. Based on the observed weights of intermodal containers from Afghanistan and qualitative descriptions of loading practices provided by military personnel while conducting research for this paper, this assumption may not always be valid, specifically during conflict operations. For example, the AHSVS-PLS military transport had similar statistical parameters for load as Canadian non-permit traffic, indicating no greater load control between the military and civilian traffic. In using conservative assumptions for the LAV III-ISC and Leopard 2A4M tank loadings, it was illustrated that the weights of these vehicles are less variable because the curb weight, assumed deterministic, is a significant portion of the GVW.

7. Summary and Conclusions

Using heuristic assumptions combined with available data, the statistical parameters for the Gross Vehicle Weight (GVW) and axle loads for three military vehicles have been quantified. This is a necessary prerequisite to employ Limit State Design (LSD) methods, including the assessment of existing bridges for military vehicles, at Ultimate Limit States.

The GVWs of military fighting and transport vehicles were found to have different probabilistic parameters. Given this, four vehicle classifications are recommended for military vehicles: Wheeled-Fighting (W-F); Wheeled-Transport (W-T); Tracked-Fighting (T-F); and Tracked-Transport (T-T). This reflects the difference in the payload weight fraction for fighting (0.02 to 0.25) and transport vehicles (0.35 to 0.60), and the associated differences in the parameters quantifying the GVW.

This paper illustrates that some military vehicles have large curb weights and light payloads, and so have total weights approaching the nominal vehicle combat weight. Reducing the payload weight fraction, i.e., the ratio of the payload to the nominal vehicle combat weight, reduces the overall vehicle weight variability. The following conclusions can be made:

- The statistical parameters for the GVW of military vehicles differ depending on the general configuration and function of the specific vehicle. Specifically, military fighting vehicles have a lower CoV than military transport vehicles.

- The lower weight variability of some military vehicles is less due to effective load control but rather is an inevitable outcome of the design and intended functionality of the vehicle itself.
- The statistical parameters to quantify the GVW of military vehicles can be estimated using the payload weight fraction.

Acknowledgement

The authors would specifically like to thank the Department of National Defence, Air Movements and the National Movement and Distribution System Support Center for providing data regarding intermodal container weights flown from Afghanistan by the Canadian Armed Forces.

Also, we acknowledge the Canadian Department of National Defence and the National Sciences and Engineering Research Council (NSERC) for financial support, as well as access to technical information pertaining to this research.

Finally, the authors would like to extend a special thanks to the late Dr. Rusmir Tanovic (deceased 2015), of the Royal Military College of Canada. He has worked closely with the authors, providing relevant insight concerning the research reported in this paper to ensure it is compatible with current military bridge evaluation and complimentary to other research initiatives.

References

[1] CAN/CSA S408-2011, *Guidelines for the Development of Limit States Design Standards, CSA Special Publication.*

[2] MACDONALD, A.J. *Applying Probabilistic Methods to the NATO Military Load Classification System for Bridges*. [Master Thesis]. University of Western Ontario – Electronic Thesis and Dissertation Repository. Paper 2570. Available from: <http://ir.lib.uwo.ca/etd/2570>, 2014.

[3] BENJAMIN, J.R. and CORNELL, C.A. *Probability, Statistics, and Decision for Civil Engineers*. New York: McGraw-Hill, 1970, p. 466-475, 667 p.

[4] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Palletized Loading System Vehicle (C-20-B80-003/MA-001)*. Ottawa, ON: Department of National Defence, 2011.

[5] KENNEDY, D.L., GAGNON, D.P., and ALLEN, D.E. Canadian Highway Bridge Evaluation: Load and Resistance Factors. *Canadian Journal of Civil Engineering*, 1992, vol. 19, no. 6, p. 992-1006.

[6] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Chassis, Light Armoured Vehicle (LAV), Armoured Personnel Carrier (APC), Wheeled, 8x8, Diesel (C-30-560-000/MA-001)*. Ottawa, ON: Department of National Defence, 2011.

[7] WLAV CHASSIS MANAGEMENT TEAM LEADER, DEPARTMENT OF NATIONAL DEFENCE, OTTAWA. *L2-084 CofG Calcs Update.pptx* [Private Communication], 2014.

[8] SNC. *SNC Tech Product Brochure – 5.56 mm, 7.62 mm and 9 mm Ammunition.* [cited 2013-10-31]. Available from: <http://www.gd-otscanada.com/imports/pdf/en/fiche_techniquel.pdf>.

[9] US ARMY CENTER FOR ARMY LESSONS LEARNED. *The Modern Warrior's Combat Load, Dismounted Operations in Afghanistan April-May 2003*. [cited 2017-01-30]. Available from: <http://thedonovan.com/archives/modernwarriorload/ModernWarriorsCombatLoadReport.pdf >, 2003.

[10] LEOPARD REQUIREMENTS OFFICER, DIRECTOR LAND REQUIREMENTS 3-4-3, DEPARTMENT OF NATIONAL DEFENCE, OTTAWA. *ATTLA for Air Shipments.xls* [Private Communication 2013-11-22].

[11] BRASSINGTON, B., ETS CONSULTING, PITSTONE, BUCKINGHAM-SHIRE, UNITED KINGDOM. *RE: Seeking Reference for Data Presented in ILO Publication: "Safety in the Supply Chain in Relation to Packing of Containers" ISBN 978-92-2-124227-7* [Multiple private communications between Jan 2014 to Apr 2014].

[12] NATO Standardisation Agreement (STANAG) 2021. *Military Load Classification of Bridges, Ferries, Rafts and Vehicles*. Edition 6.

[13] WONG, J.Y. *Terramechanics and Off-road Vehicle Engineering, Terrain Behaviour, Off-road Vehicle Performance and Design* (2nd Edition). Oxford: Elsevier, 2010.

[14] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Armoured Recovery Vehicle Taurus, C-30-733-000/MA-001*. Ottawa, ON: Department of National Defence, 2006.

[15] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Armoured Engineer Vehicle Badger. C-30-734-000/MA-001*. Ottawa, ON: Department of National Defence, 2006.

[16] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Tank Leopard C2 MBT (Bilingual). C-30-731-000/MA-001*. Ottawa, ON: Department of National Defence, 2006.

[17] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Chassis, Light Armoured Vehicle (LAV), Reconnaissance (Recce), Wheeled, 8x8, Diesel (Bilingual), C-30-600-A00-/MA-001*. Ottawa, ON: Department of National Defence, 2010.

[18] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Light Armoured Vehicle (LAV), Wheeled, 8x8, Diesel, Bison Ambulance (Bilingual), C-30-656-000/MA-001*. Ottawa, ON: Department of National Defence, 2010.

[19] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Carrier, Personnel, Full Tracked, Armoured, M113A3 with AN/MWG-505, C-30-775-000/MA-001*. Ottawa, ON: Department of National Defence, 2011.

[20] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Light Armoured Vehicle (LAV), Wheeled, 8x8, Diesel (Bilingual), C-30-650-000/MA-001*. Ottawa, ON: Department of National Defence, 1997.

[21] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Data Summary, Truck, Cargo, 10 Tons, 6x6, HLVW, Model H808 with Self-Recovery Winch (Bilingual), C-30-406-000/MA-000*. Ottawa, ON: Department of National Defence, 2006.

[22] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Palletized Loading System Vehicle (C-20-B80-003/MA-001).* Ottawa, ON: Department of National Defence, 2011.

[23] MILITARY TODAY. *Western Star* [online]. Trucks. [cited 2012-11-01]. Available from: <http://www.military-today.com/trucks/western_star_m4866s.htm>

[24] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Operating, Maintenance and Illustrated Parts Instructions for Pallet Loading System Trailer, C-30-874-000/MS-000*. Ottawa, ON: Department of National Defence, 1999.

[25] CANADIAN DEPARTMENT OF NATIONAL DEFENCE. *Tractor 24 t Data Summary (C-30-B80-004/MA-001)*. Ottawa, ON: Department of National Defence, 2011.

[26] KIM, Y.J., TANOVIC, R., and WIGHT, R.G. Load Configuration and Lateral Distribution of NATO Wheeled Military Truck for Steel I-Girder Bridges. *Journal of Bridge Engineering*, 2010, Vol 15, p. 740-748.