Calibration of Vehicular Live Load Site Factors to Design of Urban Bridges

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Summary

This paper presents the development of an algorithm and the equations needed during the phases of simulation and statistical analysis with respect to the reliability analysis of the live loads of vehicles on bridges. It has as its main objective, the prognosis of Absolute Maximum Moments and Shears (MCMA) versus time, in terms of Average Daily Truck Traffic (TDPVP) in a single lane and moving in one direction. The group of structures studied in this article include single span bridges with spans between 10 and 60 m long. The solution of the problem is found in the relationship between the probabilities to exceed the biggest value observed in occurred events n with the expected events N in the future, considering the instant time where the first maximum value of the effects happened (i.e. return period of MCMA). The result is the evaluation on bridges of the site traffic conditions of all type of roads including those located in urban cities.

Keywords: Bridge Codes, Live Load Model, Calibration, Site Factors, Structural.

1. Introduction

The economic growth in large cities of developing countries such as Mexico has prompted an interest to build new bridges and to repair or upgrade those already built in order to accommodate the corresponding increase in the number of vehicles and the truck loads. These activities are commonly carried out with foreign codes using Models of Live Loads of Vehicular (MCVV) on bridges representative of traffic conditions different from those prevailing in roads and cities where they are used. This fact, together with the deterioration of state and federal roads and bridges as a consequence of the lack of a system of control of weight and sizes for an always increasing number of overweight and oversized trucks that circulate on roads and bridges in the region, has put into scrutiny the validity of their original designs and has motivated research activities in Mexico to determine the attained actual safety level with the different MCVV as recommend the "non-local" codes, e.g., [1]. Recently, there has been efforts to establish the traffic characteristics and loads that circulate on roads and bridges in Mexico [2]. Having accomplished the objectives of these efforts; the existing research has led to the development of a MCVV that not only represents current conditions but also those conditions that will prevail in the future consistent with the assumed useful life of the bridges. The strategy used in this investigation [3] is based on the theory of structural reliability using as random variables the real vehicular loads and resistances. The concept was that a MCVV, with adequate load and resistance factors, should guarantee a target safety level in accordance with those used in current codes. To accomplish this, the calibration of Vehicular Live Load Site Factors (FSCVV) with the most representative and existing MCVV and its load and resistance factors are recommended. The FSCVV were resolved, comparing a target reliability index β = 3.5 and the mean of the overall reliability for the group of analyzed structures. The reliability analyses are carried out after characterizing the statistical properties of the basic variable of live load, and the vehicular traffic conditions defined by the combination of TDPVP and Percentage of Heavy Trucks (PVP) in a single lane and direction. This paper devotes to the development of an algorithm and the equations needed during the simulation and statistical analysis phases involved with determining the necessary information data and the corresponding statistical parameters required by the reliability analysis. The information obtained with this algorithm was extensive compared to previous works, and it does not result proportional to the number of vehicles used during the simulation, e.g. [4]. The equations involved produced the prognostics of Absolute Maximum Moments and Shears (MCMA) versus time, in terms of Average Daily Truck Traffic (TDPVP) in a single lane and direction. The growing of MCMA versus time reflected by the results is in good agreement with the actual regulations in Mexico.

2. Simulation Phase

The simulation phase has as its purpose the gathering of the largest possible amount of data related to effects, such as Absolute Maximum Moments and Shears (MCMA), produced by the traffic of vehicles on a bridge. To accomplish this, a load system is constructed to characterize the traffic of vehicles, as required when analysing their passage over the bridges, and to calculate the MCMA.

The load system, represented by a continuous train of loads, has characteristics related to the traffic composition and a constant headway representative of the vehicular traffic scenario under simulation. Three simulation scenarios were considered: the first is associated with the free traffic of trucks one by one and the second and third scenarios of simulation represented the obstruction of the traffic by one or more light and heavy vehicles on the bridge. The differences between the second and third simulation correspond to the traffic composition needed to define different local traffic characteristics. Table 1, shows the traffic composition and vehicular headway implemented in each simulation. In the load system, the weights and distances between the axes of vehicles were previously specified for the case of light vehicles (car and buses) and directly obtained from gauging data for the case of trucks (heavy vehicles). The number of data and the gauging time involved correspond to 180,944 trucks and 114 days [5]. The load system was assembled by defining the sequence of the vehicles using random numbers as a process of experiments with multinomial distribution [6]. The process consists in *ns* successive independent experiments where the results of each experiment should be: car, bus, or truck. The probabilities of success of the results were considered constant and were associated with the desired percentage in the traffic composition. The *ns* experiments are the total number of vehicles expected in the load system, their amounts depend on the number of gauging trucks and the percentage in the traffic composition. The number of loads and length of the final assembled load system depends on the vehicular composition and the amount of gauging information. The load system (train of loads) can be longer and more complex (number of loads) as a result of bigger percentages of cars needed in the traffic composition during the simulation.

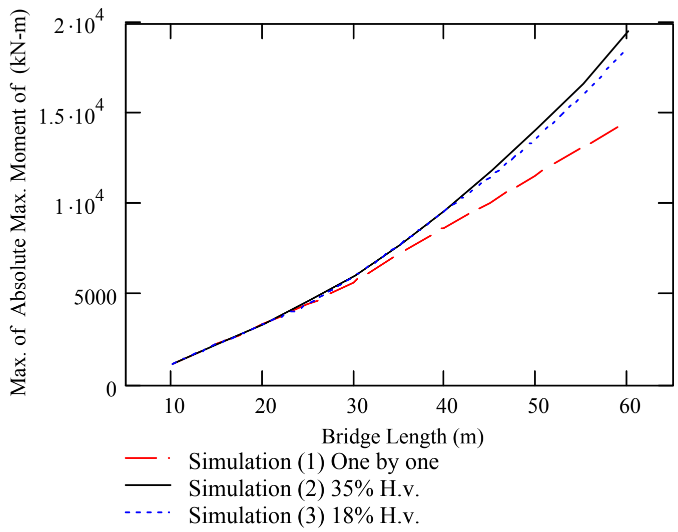

Figure 1, Max. of Abs. Max. Mom. in the simulations.

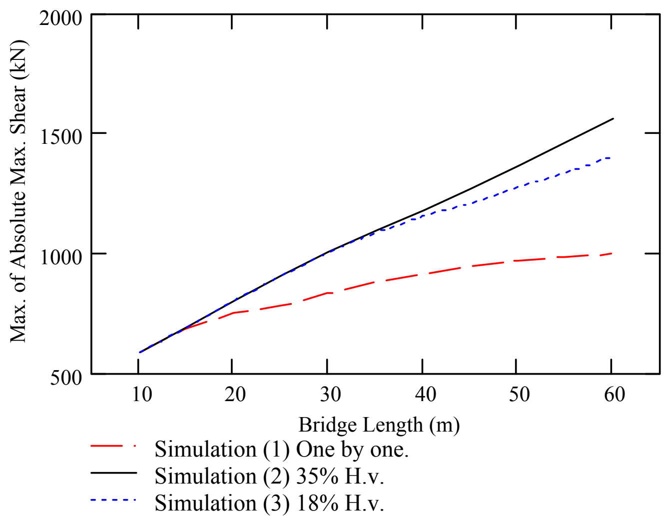

Figure 2, Max. of Abs. Max. Shear in the simulations.

The analysis of the MCMA was done using an algorithm based in the method of maximum shear and moments [7]. Figures 1 and 2; show the maxima of the MCMA resulted in the different simulations.

Simulation	**Trucks**	**Cars**	**Buses**	**Headway**
(1)	100 %	0 %	0 %	Bridge length
(2)	35 %	48 %	17 %	4 m
(3)	18 %	73 %	9 %	4 m

Table 1 : Simulation's parameters of traffic composition and vehicular headway.

3. Statistical Analysis Phase

The statistical analysis phase involves the development of a procedure to characterize the statistical properties of the basic variable of live load ($f_N(x), \mu_N, \sigma_N$). The statistical study had as its objectives: 1) the selection of a type of theoretical probability density function, 2) the determination of statistical parameters of the population, and 3) the extrapolation, required for the prediction of the statistical parameters of population of future exceedence of the maximum effect, that had at first approximation the useful life of the bridges when considering specific characteristics of traffic.

The selection of a type of theoretical probability density function, $f_X(x)$, was done with the method of adjusting samples to probabilistic functions in probability papers [8]. This method considers the measuring of the standard error between the experimental accumulative distributions of frequencies of the sample against the theoretical density function evaluated with the statistics of the experimental sample, and between the different types of distribution considered: Normal, Lognorma, Gamma, Gumbel, Frechet, and Weibull. The standard error for the case of the Weibull distribution presented the smallest value, and with this observation demonstrated that the natural phenomenon of live load can be studied with theoretical probability density and distribution function of type Weibull.

The determination of the statistical parameters of the population (ε , β , and k) was done by localizing the region with the best linearity over the experimental accumulative distribution of frequencies, using as a base theory the linear characteristic of an experimental accumulative distribution of frequencies in a probability paper with scales equal to the theoretical distribution function. Then, with the ordinate to origin and slope (a, and b) determined with a linear regression of minimum squares in the region with best linearity, the statistics parameters of the population were calculated as $\beta = b$ and, $k = \exp(-a/b)$; where β is the form factor and k is the scale factor. These expressions where proposed assuming that the minimum value (ε) is always equal to cero.

The extrapolation problem was defined with regard to the existence of n observations $(x_1, x_2, ..., x_n)$ that characterize the effects produced by a series of loads generated by the traffic of vehicles on a bridge. The purpose of the extrapolation exercise was to predict the probability of over exceeding the largest value of n previous observations in N future observations.

Then, if x_n is the largest value of n previous observations, that is, $x_n = \max(x_1, x_2, ..., x_n)$, the probability of not exceeding the largest value in n observations in N future observations [9] is defined as,

$$P(X_N \leq x_n) = \frac{n}{N+n}; \tag{1}$$

as well as, the probability of exceeding x_n in N future observations is,

$$P(X_N > x_n) = 1 - P(X_N \leq x_n) = \frac{N}{N+n}. \tag{2}$$

For design, the probability of exceeding the maximum (x_n) in each previous observations $(x_1, x_2, ..., x_n)$ in the initial sample will be,

$$P(X > x_n) = p = \frac{1}{t_r}; \tag{3}$$

where $t_r = n_o + 1$ represents the return period; that is, the instant where the first maxima of absolute maximums was presented, and represent the number of observation in the initial sample plus one. Equating the equations 2 and 3 and solving for *N*, $N = n/n_o$; that is, the division of the number of the previous observations by the number of observations where the first maximum (x_n) takes place. The determination of statistical parameters of the population in *N* future observations can be done solving equations 4, and 5.

$$\mu_N = \int_0^\infty x \cdot f_N(x)dx \, ; \tag{4}$$

$$\sigma_N^2 = E_N\left[x^2\right] - \mu_N^2 \, ; \; E_N\left[x^2\right] = \int_0^\infty x^2 \cdot f_N(x)dx \, . \tag{5}$$

Where μ_N is the mean value, σ_N is the standard deviation, and $f_N(x)$ is the probability density functions, all of them correspond to *N* future observations. The probability density function, $f_N(x)$, and the corresponding distribution function, $F_N(x)$, in *N* future observations can be determined [9] evaluating the following equations.

$$F_N(x) = \left[F_X(x)\right]^N . \tag{6}$$

$$f_N(x) = N\left[F_X(x)\right]^{N-1} f_X(x) . \tag{7}$$

After substituting the selected theoretical probability density and distribution functions (Weibull) in equations 6 and 7 and solving for *x*, the prediction of the maximum of MCMA (x_n) in *N* future observations (named in reliability theory as characteristic value) can be done with equation 8.

$$x_N = k \cdot e\left\{\frac{1}{\beta}\left(\ln - \ln\left[1-p\right]^{\frac{1}{N}}\right)\right\} . \tag{8}$$

To determine the *N* future observations and the statistical parameters of the population in *N* future observations when considering specific characteristics of traffic equation 9 is proposed:

$$n = \frac{de^2 \cdot TDPVP \cdot Fc}{ds} , \tag{9}$$

where *TDPVP* represents the Average Daily Truck Traffic in a single lane and direction; *ds* the days involved in the gauging; *de* the number of days to extrapolate ($de = 365 \cdot years + ds$); and *Fc* the correction factor, determined as the ratio of the number of data (number of maximum effects) in the sample (n_o) and the number of vehicles implemented in the simulation (ns). The proposed expression expands the information of the gauging to the base return period on the following hypotheses: 1) a constant value of *Fc* throughout the extrapolation, and 2) a proportionality of TDPVP during the consider lapse of days.

Table 2, shows how the simulation scenarios were linked with the proposed extrapolations.

Extrapolation	*Pvp*	Simulation
(1)	35 %	I
(2)	18 %	
(3)	35 %	II
(4)	18 %	

Table 2 : Sceneries of simulation considered in the extrapolations.

The *TDPVP* proposed for the extrapolation was selected taking into account the actual regulations in Mexico related to the classification of roads [10]. The extrapolation was done with *TDPVP* of 50, 250, 1000, 1587 (gauging) and 3500. The *TDPVP* combined with the proposed Percentages of Heavy Vehicles (*Pvp*) in the simulations resulted in a mean traffic per day between 118 and 18900 vehicles. That covers almost all types of roads in Mexico.

Respectively, figures 3 and 4, show the MCMA data of the samples (n_o) resulting from the simulations and the correction factor used in each extrapolation. These figures show that the values of n_o and *Fc* were different in all bridges (i.e. samples), and highlights the significant difference between resulted number of effects (n_o) in the simulations and the number of heavy vehicles of the gauging data (*na*). This put into evidence the possible error of using only the number of vehicles of the sample (*na*) to do the extrapolations; which consider the $P(X > x_n) = 1 - F_N(x) = 1/na$, and assume [4] that $t_r = na$, where $na \neq n_o + 1 = t_r$. Figure 5 shows an example of the results in extrapolations (1) and (2) of the mean value (μ_N) and the characteristic value (x_n) for the case of maximum absolute moment in a bridge 15 m long.

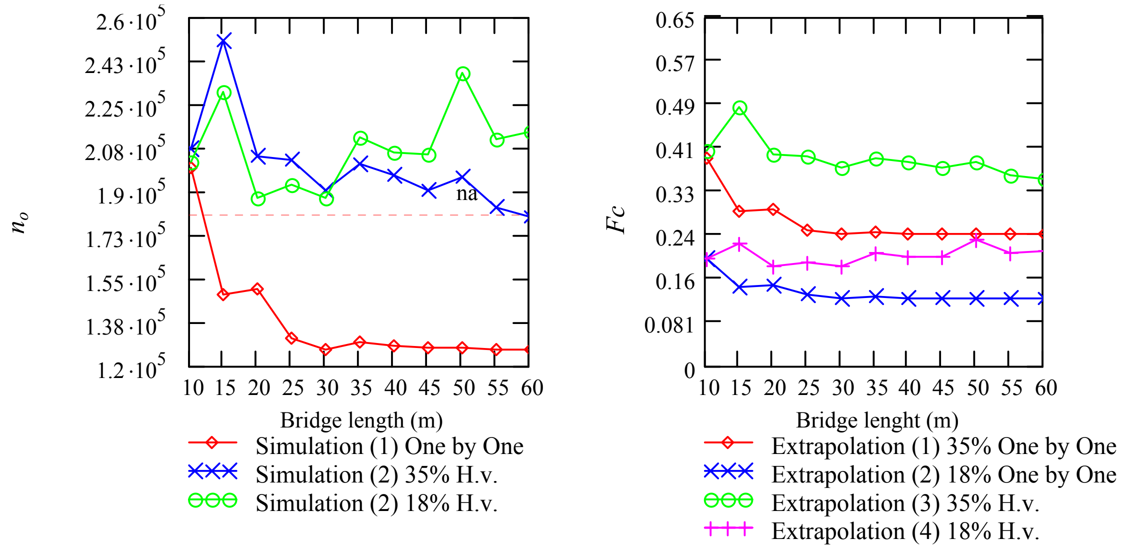

Figure 3, Variation of n_o and F_c for the case of absolute maximum moment.

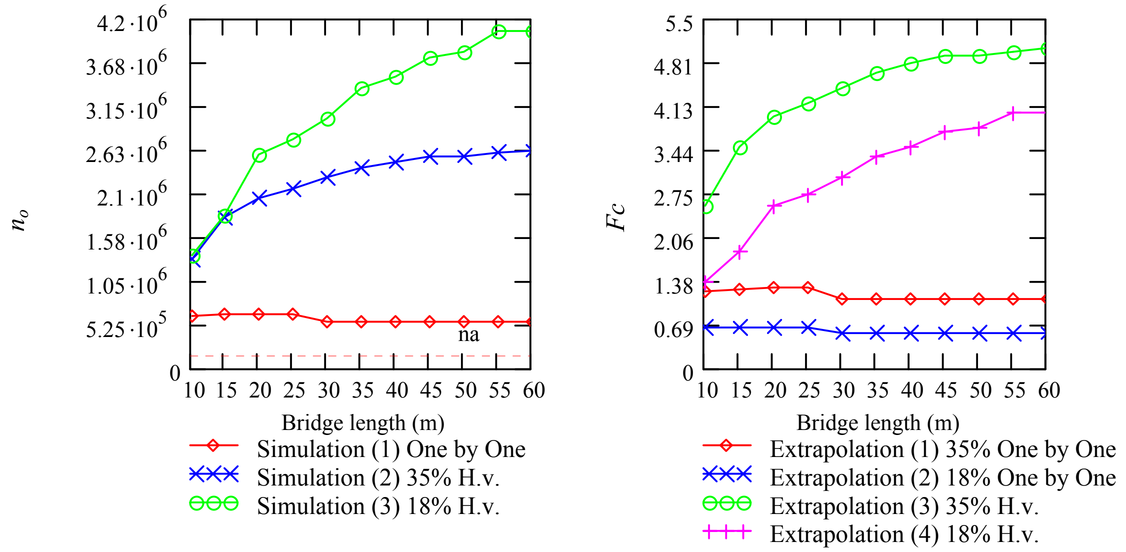

Figure 4, Variation of n_o and F_c for the case of absolute maximum shear.

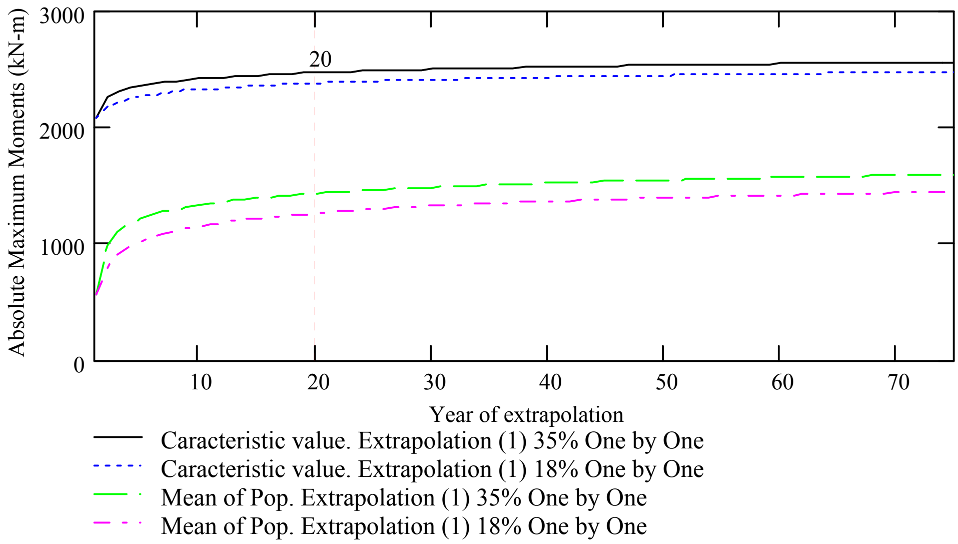

Figure 5, Time variation of the population mean and the characteristic value.

4. Discussion

The implementation of a train of loads representing the traffic of vehicles on bridges, excluding scenarios with combinations of heavy vehicles, was the first step to avoid the problem of correlating a rational time of return period with the presence of a maximum MCMA in the simulation scenario condition. The simulation of the traffic of vehicles does not include a variable length as headway, which, together with the hypothesis of the *Fc* as constant with the time as well as its dependency with the *Pvp* and bridge length, are still needed to be demonstrated. The assumption of a proportionality growth of *TDPVP* does not impact the predictions, assuming they will be to the limit in time when almost does not exist growth (e.g. 20 years). The confirmation of this assumption is still needed when considering the limit state of design of bridges like service and fatigue.

5. Conclusions

This paper presents the results of an algorithm and the equations involved in the evaluation of the live loads on bridges and the prognostics of MCMA versus time, in terms of *TDPVP* in a single lane and direction. The growth of MCMA with time shown by the results is in agreement with the actual regulations in Mexico. The procedures and equations proposes to complete the extrapolation are easy to implement in future investigations that evaluate the limit states of service and fatigue in design of bridges, where the basic variable of live load is considered. The algorithm proposed to evaluate the live loads on bridges take into account the traffic composition and implementation of the TDPVP, thereby making it possible to evaluate site traffic conditions on bridges of all types of roads including those located in urban cities.

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