Traffic load modelling and factors influencing the accuracy of predicted extremes

Alan O'Connor and Eugene J. O'Brien

Abstract: Design and assessment of highway bridges requires accurate prediction of the extreme load effects expected during the proposed or remaining life of the structure. Traditionally these effects are calculated using conservative codified deterministic loading models. While this conservatism is relatively insignificant in design, it may be critical in assessment. Advances in weigh-in-motion (WIM) technology, i.e., the process of weighing trucks travelling at full highway speeds, have increased the availability of accurate and unbiased site-specific traffic records. Assessments performed using WIM data are generally accepted as less conservative than those performed using generalized codified loading models. This paper briefly describes traffic simulation using WIM statistics. The implications of the accuracy of the recorded data and the duration of recording and of the sensitivity of the extreme to the method of prediction are investigated. Traffic evolution with time is also explored. The conclusions are of interest to engineers performing assessment of existing bridges.

Key words: bridge, load effects, characteristic values, simulation, traffic flow, Monte Carlo, weigh-in-motion.

Résumé : La conception et l'évaluation des ponts routiers demande de prévoir avec prévision les effets de charges extrêmes attendues durant la durée de vie proposée ou restante de la structure. Traditionnellement, ces effets sont calculés en utilisant des modèles déterministes de charge conservateurs et codifiés. Bien que ce conservatisme n'affecte que peu la conception, il peut être très important lors de l'évaluation. Les récents progrès dans la technologie du pesage routier dynamique (WIM : « weigh-in-motion »), c.-à-d. le processus de peser les camions alors qu'ils voyagent à des vitesses d'autoroutes, ont augmenté la disponibilité d'enregistrements de circulation précis, non biaisés et spécifiques à un site. Les évaluations effectuées en utilisant les données WIM sont généralement acceptées comme étant moins conservatrices que celles effectuées en utilisant des modèles codifiés de chargement d'usage généralisé. Le présent article décrit brièvement la simulation de la circulation en utilisant les statistiques WIM. Les implications de la précision des enregistrements, la durée d'enregistrement et la sensibilité des charges extrêmes par rapport à la méthode de prédiction sont étudiées. L'évolution de la circulation dans le temps est également abordée. Les conclusions intéresseront les ingénieurs qui évaluent les ponts existants.

Mots clés : pont, effets de charge, valeurs caractéristiques, simulation, débit de la circulation, Monte Carlo, pesage routier dynamique.

[Traduit par la Rédaction]

Introduction

Of the load effects to be determined in bridge assessment, the most variable are those induced by traffic loads. Traditionally, these effects have been determined in calculations employing deterministic loading models. Deterministic-loading models have in the past been derived based on practical experience or more recently in model calibration studies.

Received 2 February 2004. Revision accepted 13 September 2004. Published on the NRC Research Press Web site at http://cjce.nrc.ca on 26 March 2005.

A. O'Connor.[1] Department of Civil Engineering, Trinity College Dublin, Museum Building, Dublin 2, Ireland.
E.J. O'Brien. Department of Civil Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland.

Written discussion of this article is welcomed and will be received by the Editor until 30 June 2005.

[1]Corresponding author (e-mail: alan.oconnor@tcd.ie).

In both cases the parameters of the model, traditionally a uniformly distributed load and a concentrated load component, are selected such that they will provide in excess of the predicted maximum loading effects, which a broad range of structures may be expected to experience during their design life. In the calibration studies performed for the normal loading model for Eurocode 1 (CEN 1994), maximum lifetime effects were calculated for span ranges from 5 to 200 m for 1–4 flow lanes and for structural forms ranging from simply supported to multiple continuous spans to fixed-fixed beams (O'Connor et al. 2001). It is apparent, therefore, that the requirement to be widely applicable results in considerable conservatism in deterministic loading models. This conservatism is relatively unimportant in the design of new highway structures when considered from a cost perspective. However, in the assessment of existing structures, it can be significant, particularly if it leads to a specified requirement for unnecessary rehabilitation–replacement of a serviceable structure. In recognition of this, assessment practitioners and researchers have increasingly attempted to take account of site-specific

 doi: 10.1139/L04-092

traffic data in the determination of maximum load effects (Enevoldsen 2001; Bailey 1996; Jacob et al. 1989; Nowak 1994, 1993).

One of the most effective procedures for the collection of real time traffic records is termed weigh-in-motion (WIM). This is the process of weighing trucks while they are travelling at full highway speeds using sensors embedded in the pavements or strain gauges attached to a bridge deck (Dempsey and O'Brien 1995).

There can be little argument that maximum load effects determined from site-specific data will provide a better indication of the serviceability–safety of a structure than effects determined from generalized loading models. In reducing the conservatism in the process, however, it is important to have some understanding of how factors, such as the accuracy of the recorded data or the duration of recording, influence these predicted extremes.

This paper discusses the statistical techniques commonly used in flow simulation and investigates the factors that influence the accuracy of the extremes predicted in these simulations. The results of direct simulations performed using recorded data are compared with those calculated using the Monte Carlo method, thereby validating its appropriateness for use in such simulations.

Monte Carlo simulation is a statistical technique often employed where it is desirable to randomly generate data using known or assumed statistical distributions (Ang and Tang 1975), in this case for vehicle and axle weight, speed, spacing, etc. within assumed vehicle classes. The technique is used to exploit knowledge of the statistical characteristics of the data to virtually increase the amount of data available, e.g., from one week's continuously recorded data to 10 week's simulated data, or to generate different loading scenarios, i.e., congested flow, flow following an accident and (or) lane closure, etc. that may not have been directly recorded.

Mathematical traffic models

The mathematical traffic models employed in this paper may broadly be broken into two distinct groups: (*a*) those describing the traffic as a whole, i.e., proportion of vehicles in each lane, proportion of vehicles in each vehicle class, vehicle spacing, etc. and (*b*) those describing the vehicles within each class, i.e., gross vehicle weight, axle weight, vehicle geometry, speed, etc.

Models of these random variables are required for Monte Carlo simulation of theoretical traffic records. Many statistical models exist to describe the random variables governing traffic flow. Those employed in this paper are briefly discussed in the following sections.

Traffic characteristics

Theoretical traffic flow simulations may only be performed where knowledge of the site-specific traffic characteristics are known. In the past, parameters were estimated through subjective decisions or limited surveys of traffic flow (Nowak 1993, 1994; Agarwal and Cheung 1987). The availability of WIM data permits traffic characteristics to be directly determined from continuous traffic flow measurements.

Vehicle proportions and classification

Accurate traffic flow simulation requires determination of the constituents of the total vehicle flow in each simulated lane, which are site-specific random variables. Estimation of these proportions may be made through traffic counting exercises or from available WIM records (Agarwal and Cheung 1987; Agarwal and Wolkowicz 1976; Bakht and Jaeger 1988; Prat 1991; Bruls et al. 1996*a*, 1996*b*; Calgaro 1997; O'Connor et al. 2001).

A vehicle classification system is required for Monte Carlo generation of traffic records. Table 1 illustrates the vehicle classification system adopted for this paper that was also employed in the recalibration studies for the normal load model of Eurocode 1, Part 3, *Traffic Loads on Bridges* (O'Connor et al. 2001). This system permits determination of the vehicle class proportions in addition to the statistical moments for each class. Thereby describing the distributions of gross weight, individual and group axle weight, etc.

Inter-vehicle spacing

In many traffic studies, the distribution of inter-vehicle spacing (i.e., headway) is of interest and is modelled by a form of exponential distribution because traffic flow is idealized as a Poisson process (Harman and Davenport 1979). The Gamma distribution, which is a natural generalization of the exponential distribution, is adopted in this study to model inter-vehicle spacing.

Vehicle characteristics

In generating vehicle flow simulations, it is important to accurately describe the random variables of gross vehicle weight, axle weight, axle spacing, length, speed, etc. The availability of WIM records permits accurate modelling of the controlling distributions within each vehicle classification outlined in Table 1.

Figure 1 demonstrates the twin peaked bimodal distribution of gross vehicle weight (GVW) for class A113 defined in Table 1, i.e., 5-axle vehicles with rear tridem axle. This form of distribution is typical for gross weight (Harman and Davenport 1979; Jacob 1991; Nowak 1993; Bailey 1996; O'Connor et al. 2001). The first mode contains the partially loaded trucks, whereas the second involves the fully loaded trucks.

Traffic flow simulation

The governing variables of the statistical distributions chosen to represent the traffic and vehicle characteristics, i.e., mean values and standard deviations, etc., are calculated using the WIM data recorded on site. Upon recognition that the WIM records may not have recorded all possible traffic situations, a technique, such as Monte Carlo simulation, may then be employed to regenerate traffic records for any chosen scenario. The procedure will make use of the site-specific vehicle characteristics of vehicle and axle weights, etc., but can modify traffic flow distributions to simulate any chosen situation. For example, if mixed flow conditions are

Table 1. Vehicle classification system.

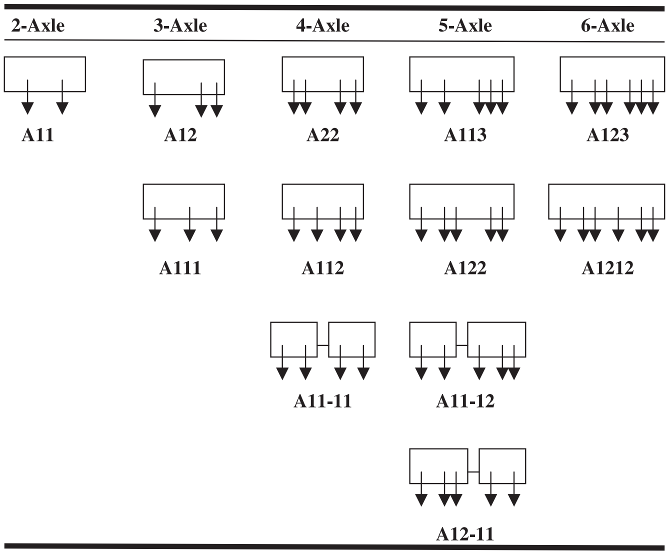
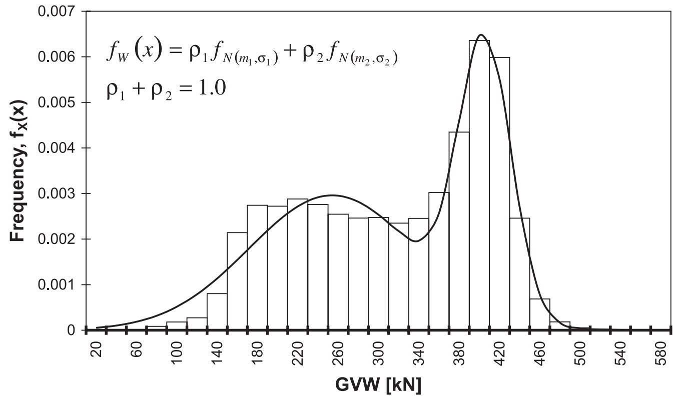


Fig. 1. Gross weight distribution class A113.



required, i.e., a combination of free flowing and congested lanes, the speed and headway distributions for congested lanes will almost be deterministic, whilst they will remain statistically variable for lanes with free flow.

The scenarios selected for Monte Carlo generation should be representative of those expected for the structure during its lifetime. In the recalibration studies performed for the normal loading model of Eurocode 1 (CEN 1994), a range of scenarios were chosen representing normal, congested, mixed flow, and accident–emergency flow situations (O'Connor et al. 2001).

For the purpose of this paper, three flow scenarios are considered. The scenarios, hereafter denoted mixed4, mixed2, and free2, represent four and two lanes of mixed flow and two lanes of free flow, respectively. Mixed flow is taken here to mean that one lane is congested with the remaining lanes being free flowing. These scenarios have been selected as they are considered representative of the majority of traffic flow conditions to which typical four and two lane bridges are subjected. Neither hazard conditions nor full congestion are considered in this paper. It is important to point out that for two lane structures, the maximum load effects will be experienced by free flowing conditions for span lengths less than approximately 30 m and by mixed flow conditions for spans in excess of this (O'Connor et al. 2001; Nowak 1993; Bailey 1996). The threshold span lengths are a function of the load effect under consideration. The explanation of this cross over in the governing scenario comes from the inclusion of a dynamic amplification factor in the results of free flowing simulations to account for the interaction between vehicles and the structures they traverse. For span lengths <30 m the governing load case in both mixed and free flow is provided by two fully loaded articulated vehicles or axle groups side by side, at, or near the critical influence ordinate independent of the flow scenario considered. Consequently, when the dynamic factor is applied to the results of the free flowing scenario, it governs the extreme. For span lengths in excess of 30 m, more than two vehicles are present on the span in the extreme, and so the mixed flow case governs. For four lane structures, the load effects provided from mixed flow are generally in excess of those induced by four free-flowing lanes. It is noted that in mixed flow cases, dynamic amplification is only applied to the free-flowing lanes.

The WIM traffic records used in both direct simulation and in Monte Carlo simulation are taken from those used in the recalibration of the normal load model of Eurocode 1 (O'Connor et al. 2001). The specific data were recorded over a 7-d period in 1997 on two carriageways of a main motorway on mainland Europe from Paris to Lille in France. During this period, continuous WIM measurements were taken on four lanes, two in each direction. A total of 86 455 trucks were recorded, where a truck is classified as a vehicle with a gross weight of >3500 kg.

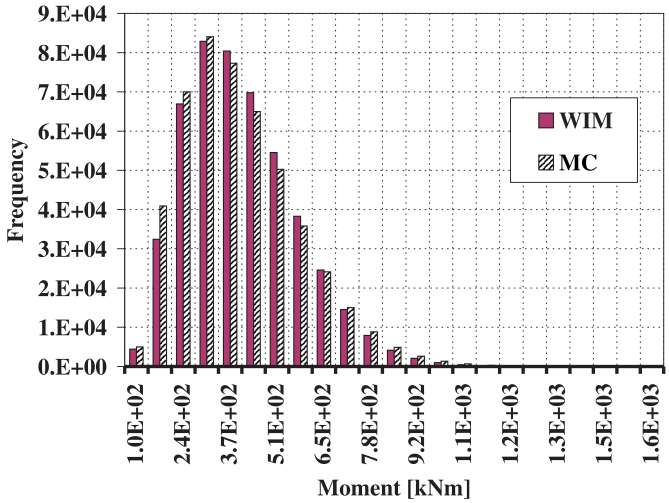
The load effects considered for comparison in this paper are the midspan moment in a simply supported beam, the continuous support moment in a two span beam,and the total load on the span, hereafter denoted I_{SS}, I_{CTM}, and I_{UNI}. These effects are chosen, as they are often found to govern in the calibration of traffic load models (Jacob et al. 1989; Bruls et al. 1996*a*, 1996*b*; O'Connor et al. 2001). For simplicity in this study, the influence surfaces were generated ignoring transverse distribution effects. In the recalibration of the normal load model of Eurocode 1, transverse effects were modelled (O'Connor et al. 2001).

Extreme load effects

The results of traffic load simulations are employed in statistical extrapolation to determine the extreme load effects that the specific structure is predicted to experience during its remaining life. Three statistical distributions are considered in the following paragraphs to determine the sensitivity of the predicted extreme load effect to the extrapolation chosen.

The first technique considered is based upon fitting an exponentially decaying function to the computed level crossing histogram of load effect. The level crossing histogram is computed by counting the number of times a specified level of load effect is exceeded in simulation and storing the results in the form of a histogram. An example of a level crossing histogram is illustrated in Fig. 2. The level crossing histogram shown demonstrates good agreement for the load effect considered between simulation using WIM data directly and the result of Monte Carlo simulation employing

Fig. 2. Level crossing histogram.



the characteristics of the recorded data. Extrapolation to determine the characteristic values is performed using Rice's formula. Rice's formula is not itself normal but has a normal tail, which governs the extrapolation (Cremona 1989, 1995). This distribution is given as

$$[1] \qquad p(x) = \frac{1}{2\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}\exp[-(x-\bar{x})^2/2\sigma_x^2]$$

$$= k\exp[-(x-m)^2/2\sigma^2]$$

The distribution is fit to the tail of the level crossing histogram at the optimal censoring level (i.e., optimal number of class intervals to be used in the fit) determined by the Kolmogorov *K*-test to a specified confidence level (Benjamin and Cornell 1970). The distribution may then be used for extrapolation of a given load effect to predict the maximum values to a specified probability of exceedance. The interested reader is referred to papers by Cremona (1989, 1995) for more information on obtaining an appropriate fit.

To compare with the extremes predicted by fitting Rice's distribution, the extreme value distributions of the Gumbel family were also employed. A Weibull (i.e., Gumbel type III) distribution results when the maximum values are sampled from a parent frequency distribution having a finite upper bound (Weibull 1951). An alternative distribution is the Gumbel I distribution. In this case, the maximum values are sampled from a parent distribution with no upper bound (Gumbel 1958).

The principle of tail equivalence (Castillo 1991; Maes 1995) is employed in determining an appropriate extreme value distribution. The extreme value and parent distributions, $G(x)$ and $F(x)$, respectively, are considered tail equivalent if

$$[2] \qquad \lim_{x\to\infty}\frac{1-G(x)}{1-F(x)} = 1$$

where the extreme value distribution $G(x)$ is modelled by either the Gumbel I or Weibull distribution, given by eqs. [3] and [4], respectively.

$$[3] \qquad G(x) = \exp\{-\exp[-(x-\lambda)/\delta]\} \quad -\infty < x < \infty, \qquad \delta > 0$$

$$[4] \qquad G(x) = \exp\{-[(\lambda - x)/\delta]^{\beta}\} \qquad -\infty < x \le \lambda$$

The threshold, λ, and scaling parameters, δ and β, of the Gumbel law, $G(x)$, are estimated by the maximum likelihood approach (Castillo and Sarabia 1992).

The suitability of either the Gumbel or Weibull distribution is assessed by plotting the extreme data on probability paper where linearity indicates the appropriateness of the mathematical model (Gumbel 1958; Ang and Tang 1975; Castillo 1991). For short span lengths, i.e., <20 m, the Weibull distribution is considered more appropriate, as it implicitly recognises a physical upper limit for the maximum load effect on short spans as a function of the maximum possible axle and group of axle load (Bailey 1996; O'Connor et al. 2001). For longer spans, i.e., in excess of 20 m span, it is found that either distribution is appropriate. However, for medium to long span bridges, i.e., in excess of 50 m, a convex trend is observed in the right hand tail of the Weibull distribution. As the tail region is of prime importance in extrapolation, the Gumbel distribution, which is unbounded in the extreme, is more appropriate.

It is also important to consider the characteristic load effect being determined. It is found that the choice of either extreme value distribution is dependent not only upon the span length, but also upon the load effect being considered (O'Connor et al. 2001).

Comparison of the method of prediction of the extremes

Figure 3 illustrates, in ascending order, the predicted extremes of simply supported moment for scenario mixed4 (i.e., 4 lanes of mixed flow) for span lengths of 5, 10, 20, 50, 100, and 200 m. It should be noted that the extremes predicted by Rice's extrapolation were determined from the simulations using real WIM data. On the other hand, those calculated using the Gumbel I and Weibull extreme value distributions were from Monte Carlo simulations. The relative errors, with respect to the Rice extrapolations, are listed in Table 2. It is apparent that differences exist in the maximum load effects predicted by the various methods. This may be explained in terms of the use of direct and artificially regenerated data and when the different extrapolation techniques are considered. It is therefore important to ensure that adequate statistical tests are performed to ensure the most appropriate technique–distribution is selected in the prediction of extremes and that care is exercised in the use of the Monte Carlo method.

Sensitivity of the predicted extreme to statistical parameters

The use of WIM data to determine maximum load effects through direct and Monte Carlo simulation has been demonstrated. Increasingly of interest are the implications of variation in the governing statistical parameters on these predicted extremes. In this section, the implications of variation in the accuracy of recorded WIM data, analysis for time and seasonal trends, and the implications of traffic growth will be addressed in an attempt to estimate their implication for the accuracy of predicted characteristic extremes.

Fig. 3. Comparison of characteristic extreme prediction methods.

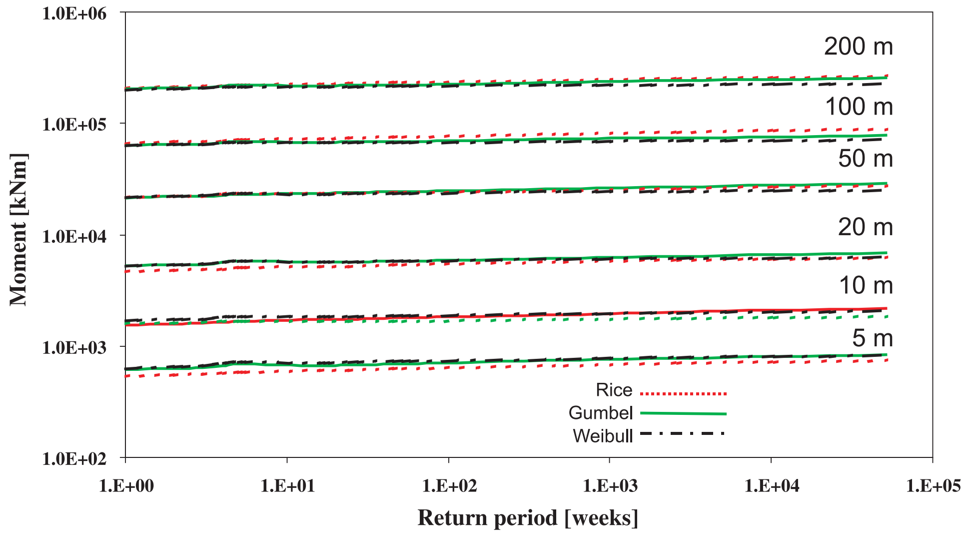


Table 2. Extrapolation results.

	% difference for a return period of		
Span (m)	1 year	20 years	100 years
5	–11.1 (–14.6)	–11.0 (–12.6)	–11.1 (–10.7)
10	10.1 (–1.1)	12.4 (1.1)	14.1 (2.9)
20	–9.1 (–5.9)	–9.1 (–3.7)	–9.1 (–1.7)
50	3.5 (6.9)	4.1 (9.1)	4.5 (10.9)
100	10.1 (13.7)	10.8 (15.9)	11.3 (17.7)
200	4.4 (10.4)	4.2 (12.2)	4.0 (13.7)

Note: Percent difference between Rice and Gumbel distributions; numbers in parentheses denote % difference between Rice and Weibull distributions.

Implications of weigh-in-motion data accuracy

Although in recent years, there have been great advances in the technology of weighing trucks, while they are travelling at full highway speeds (Moses 1979), many WIM sensors still give quite an inaccurate estimate of static weights, particularly on medium or rough pavements. This is due in considerable part to the dynamic motion of trucks and axles. In addition, factors, such as pavement inclination, sensor inaccuracy, and location of weighing station, influence the accuracy of the recorded WIM data (Dempsey and O'Brien 1995). A typical example of test results illustrated in Fig. 4 shows a substantial scatter in measured gross weights relative to the corresponding static values (Caprez et al. 2000).

In addition to sensor accuracy and site issues, the effects of calibration drift and longitudinal offset on the accuracy of recorded WIM data can be significant (Hallenbeck 1995*a*, 1995*b*, 1995*c*). It is important to determine the influence of errors in WIM data on the predicted maximum load effect values. The *European specification on weigh-in-motion of road vehicles* (COST 323 1997) is employed for the purpose of this study. In summary, the accuracy classification prescribed by the specification is based on the width of the interval within which the required percentage of the recorded sample results falls. If the required number of gross vehicle weight records are within 5% of the static values, the system is classified as Class A(5). Similarly, systems are classified as Class B(10), C(15), D(25), or E if the required number of records are within 10%, 15%, 25%, or more than 25% of the static values, respectively.

Influence of weigh-in-motion data accuracy on characteristic extremes

In accordance with the accuracy requirements of the *European specification on weigh-in-motion of road vehicles* (COST 323 1997), a varying random error was applied to a recorded WIM data file such that the resulting traffic files were classed from A(5) to E. This error was randomly imposed by the Monte Carlo simulation. In total 50 files were generated from the parent in each class from A(5) to E. Simulations were performed for the critical mixed4 scenario (i.e., 4 lanes of mixed flow) for influence surfaces I_{SS}, I_{CTM}, and I_{UNI} (i.e., midspan moment in a simply supported structure, continuous support moment in a two span structure, and total load on a span) with spans lengths varying from 5 to 200 m. In total 11 200 simulations were performed. The average error (i.e., calculated for absolute error values) and standard deviation in the predicted characteristic extreme for load effects I_{SS} are illustrated in Figs. 5 and 6, respectively. In the figures it should be noted that MC50 implies that the results were obtained from the average of 50 Monte Carlo generated traffic files, whereas MC5 represents the average from 5 Monte Carlo generated files. The implication is that having 50 files is equivalent to extending the time period for collection of data thereby increasing the quantity of available data. Similar analysis was performed for the influence surfaces denoted I_{CTM} and I_{UNI}.

For short spans, where axle rather than vehicle loads govern the characteristic load effect, the accuracy of the WIM data has a significant influence on the predicted extreme. However, it is apparent that for longer spans, where the gross weight is far more important, the influence of the inaccuracy attenuates in the mean with corresponding reduction in standard deviation. This is caused by compensation in the randomly generated axle error due to the presence of multiple vehicles longitudinally and transversely on the influence

Fig. 4. Example of accuracy (gross vehicle weights) from a strip sensor weigh-in-motion (WIM) system on a rough pavement.

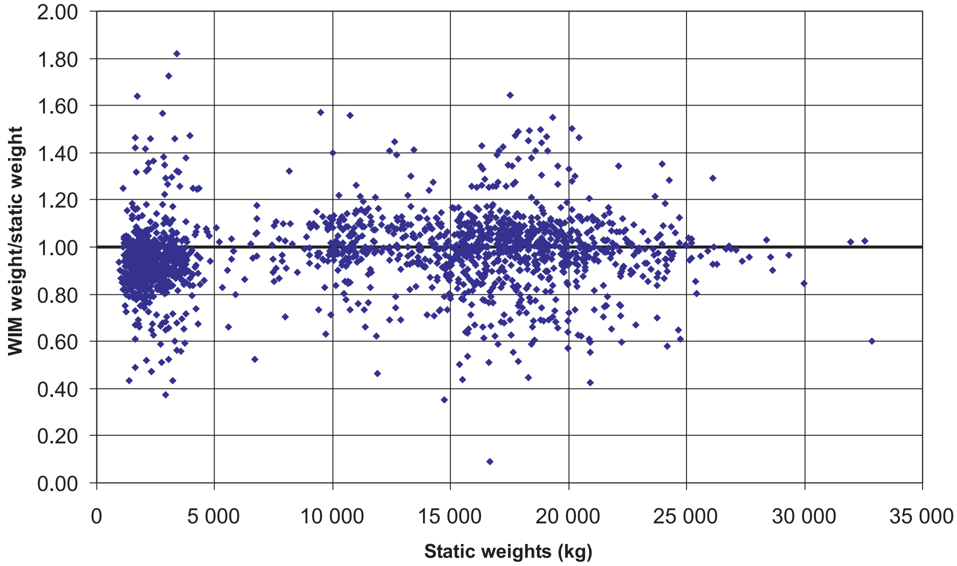


Fig. 5. Average error in characteristic extreme, I_{SS}: (*a*) MC50 and (*b*) MC5.

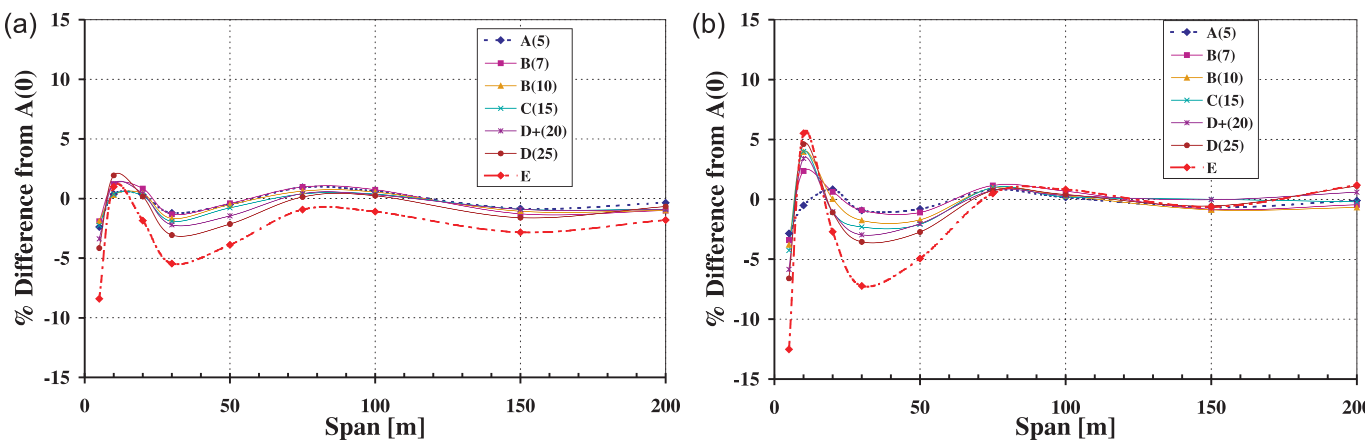
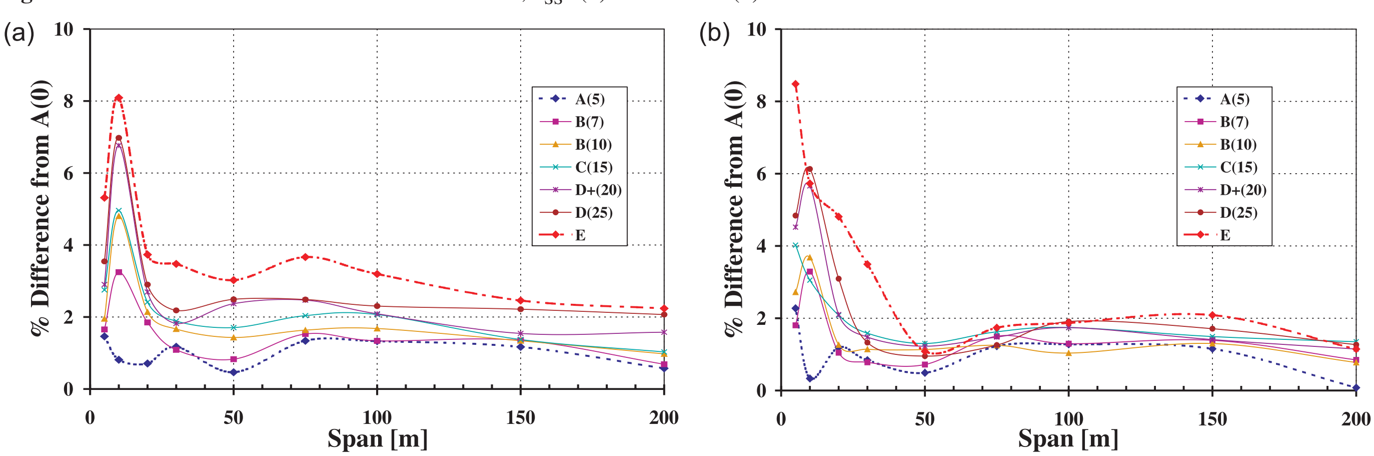


Fig. 6. Standard deviation on characteristic extreme, I_{SS}: (*a*) MC50 and (*b*) MC5.



surface. It was also found that error estimates were sensitive to the effect being determined (O'Connor et al. 2001).

A degree of sensitivity with respect to the number of data files within a given classification is also apparent. For total influence surface lengths >50 m (i.e., where mixed flow scenarios govern the extreme), the mean and standard deviation appear relatively insensitive to the number of data files. As such, a reasonable estimate of the characteristic extreme (±5%) is obtained from five files of classification D(25) for spans >50 m, provided no apparent bias with respect to the error exists in the data. However, for total spans <50 m (i.e., where free flow is important), confidence in the predicted extreme is directly related to both the data classification and the number of data files employed. As such, five files of D(25) are no longer sufficient. However, five C(15) files provided a reasonable estimate (±5%) provided no apparent bias with respect to the error exists in the data.

Thus a suitable recommendation for the required accuracy of WIM data to be used in the prediction of extremes load effects in assessment might require a minimum class C(15) system for spans <50 m, but permitting less accurate data to be used for spans >50 m, whilst requiring more data (i.e., longer duration of recording) for short spans and less data for longer spans (O'Connor et al. 2001).

Assessment of time and seasonal trends

The WIM data used in the assessment for time and seasonal trends were taken from a large-scale test of six WIM systems and four additional sensors on an urban roadway in Zurich, Switzerland (Caprez et al. 2000). Gross weights from some thousands of statically weighed vehicles were used to determine the levels of accuracy for each system with reference to the European specification on WIM (COST 323 1997). The accuracy of axle weights was not tested. The WIM sensors, which included one prototype, were tested with the assistance of a recording and processing device supplied by the organiser (Eidgenössische Technische Hochschule Zürich). Most systems encountered some problems, failures, and faults under the carefully controlled conditions of the 30-month test. However, the suppliers generally solved these after some delay.

Data from four WIM systems, A1 to A4, were analysed to examine the relationship between WIM accuracy and time or season. Two analyses were carried out. For the first, accuracy was calculated by month in chronological order. For the second analysis, three types of seasons were identified and accuracy was calculated once for each season type. A full account of the analysis is presented in Caprez et al. (2000). Overall, no time or seasonal trends could be definitively identified for any of the systems analysed.

Assessment of the influence of traffic growth

A central assumption in the extrapolation to determine extreme load effect values for design and assessment is that of stationarity of traffic (Leadbetter et al. 1983; Jacob et al. 1989; Flint and Jacob 1996). This assumption, although necessary, is questionable. Vehicle traffic is a non-stationary phenomenon with variation in both vehicle proportions and weights experienced over time as a function of economic and technological developments. As such, it is important to determine the sensitivity of predicted extreme load effects to changes in the composition of road traffic.

It was evident from studies performed in the recalibration of the normal load model of Eurocode 1 (CEN 1994) that over a period of 10 years, a significant shift in the composition of road traffic was experienced on a particularly heavily trafficked route in France. A substantial increase in the number of 5-axle vehicles (O'Connor et al. 2001) was recorded. However, the results of the simulations performed in the recalibration indicated that, although this shift has taken place in the composition of traffic, there is little apparent effect on the characteristic extremes as variation in composition has been compensated for by increased accuracy in WIM records. However, given the current accuracy of WIM systems, it is important to consider what influence future changes in traffic composition might have on extreme load effects.

For the purpose of this study, a change in the traffic composition was simulated by instituting a theoretical increase in the proportion of class A113 (i.e., 5-axle semi-trailers with a rear tridem axle) vehicles by 5%, 10%, 25%, and 50% with a corresponding reduction in the proportions of the other classes. These increases in the proportion of 5-axle vehicles lead to consequent increases in the volume of their flow by 0.75%, 1.96%, 7.3%, and 25.2%, respectively. It is noted that the total flow is unchanged, and only the distribution by vehicle type is changed.

In addition to changes in the flow characteristics, it is important to assess what influence changes in regulatory policy for vehicle weight will have on the predicted characteristic extreme. To this end, a sensitivity study has been performed where vehicle gross weights in the specified A113 class were increased by 5%, 10%, and 25%. This increase is primarily of significance in the second mode of the gross weight distribution as the first mode remains relatively unchanged.

Monte Carlo simulations were performed for the revised characteristics of vehicle weight and flow proportion. Simulations were performed for influence surfaces I_{SS}, I_{CTM}, and I_{UNI} for two and four lanes of traffic flow. As previously mentioned, simulations for two lanes of flow, free (free2), and mixed (mixed2) were performed resulting in an envelope of characteristic extremes. For four lanes, the characteristic extremes were determined for the mixed flow scenario (mixed4). Statistical extrapolations were performed for a period of 50 years with a 5% fractile.

It is found that variation from the predicted extreme is far more dependent upon increase in gross vehicle weight than upon increases in the proportion of heavy vehicles in the flow (O'Connor et al. 2001). It is apparent that a growth in the proportion of heavy vehicles in the flow has a small influence of approximately 10% (maximum) for I_{SS} for spans <50 m, and that this error attenuates with increasing span length. The standard deviation on this error for I_{SS} is also highest for shorter spans, again attenuating with increasing span length. The influence of growth for I_{CTM} is found to be negligible (approx. 5%) for short spans, approaching 0% with increasing span length. Also again, the standard deviation is found to be a function of span length.

It is found that the factor that could have major influence on predicted extremes in the future is a change in regulatory policy regarding allowable gross vehicle weight. On the other hand, increases of up to 50% in the volume of heavy vehicles in the flow affect the predicted extreme by less than 10% for short spans with this difference reducing with increasing span length. This finding is borne out by a US study, in which it was found that "… Changes in traffic volume have less effect on the β-safety level than those in enforcement type …" (Fu and Hag-Elsafi 1995).

Conclusions

The aim of this paper is to present commonly used traffic flow simulation models, and to determine their appropriateness for bridge assessment. It was also intended to determine the factors influencing the accuracy of the extreme load effects predicted by these models. Although theoretical models are unable to exactly reproduce the load effects induced by actual traffic data, they do provide reasonable estimates of the extremes, and the accuracy of these estimates is found to be dependent upon the load effect considered. The accuracy of the extremes predicted by Monte Carlo generated files is found to increase with increasing span length in inverse proportion to the variance in the extreme. A comparison between various extrapolation techniques demonstrates the importance of appropriate selection of an extreme value distribution. The influence of the accuracy of recorded WIM data is demonstrated to be a function of span as well as of load effect with accuracy more critical for shorter span lengths, whereas the effects of increasing inaccuracy were seen to attenuate with span. The time-dependent and seasonal analysis do not provide any clear proof of a seasonal trend and, in some cases, there is evidence of an absence of such a trend. In performing an analysis for the effects of future growth, it is determined that the factor that could have major influence on predicted extremes in the future is a change in regulatory policy regarding allowable gross vehicle weight. On the other hand, increases of up to 50% in the volume of heavy vehicles in the flow have a much less significant effect. Finally, the sensitivity of characteristic extremes to the duration of recording and by implication the amount of available data is seen to be a function of the effect and span under consideration.

References

Agarwal, A.C., and Cheung, M.S. 1987. Development of loading-truck model and live-load factor for the Canadian Standards Association CSA-S6 code. Canadian Journal of Civil Engineering, **14**: 58–67.

Agarwal, A.C., and Wolkowicz, M. 1976. Interim report on Ontario commercial vehicle survey, research and development branch. Ontario Ministry of Transportation and Communications, Downsview, Ont.

Ang, A.H-S., and Tang, W.H. 1975. Probability concepts in engineering planning and design. Vol. 1. Basic principles. John Wiley & Sons, New York.

Bailey, S.F. 1996. Basic principles and load models for the structural safety evaluation of existing road bridges. Ph.D. thesis no. 1467, École Polytechnique Fédérale de Lausanne, Switzerland.

Bakht, B., and Jaeger, L.G. 1988. Bridge design for multiple presence of vehicles. Engineering Research and Development Branch, Ontario Ministry of Transportation and Communications, Downsview, Ont. Research Record SRR 88-05.

Benjamin, J.R., and Cornell, C.A. 1970. Probability, statistics and decision for civil engineers. McGraw-Hill Book Co., New York.

Bruls, A., Calgaro, J.A., Mathieu, H., and Prat, M. 1996*a*. ENV1991 — Part 3: The main models of traffic loads on bridges; background studies. Proceedings of IABSE Colloquium, Delft, The Netherlands. ETH-Hönggerberg, Zurich, Switzerland. pp. 215–228.

Bruls, A., Croce, P., Sanpaolesi, L., and Sedlacek, G. 1996*b*. ENV1991 — Part 3: Traffic loads on bridges; calibration of load models for road bridges. Proceedings of IABSE Colloquium, Delft, The Netherlands. ETH-Hönggerberg, Zurich, Switzerland. pp. 439–453.

Calgaro, J.A. 1997. ENV 1991-3 Traffic loads on bridges – background studies. Laboratoire Central des Ponts et Chausées, Paris, France.

Caprez, M., Doupal, E., Jacob, B., O'Connor, A.J., and O'Brien, E.J. 2000. Test of WIM sensors and systems on an urban road. International Journal of Vehicle Design, Heavy Vehicle Systems, **7**(2/3): 169–190.

Castillo, E. 1991. Extreme value theory in engineering. Academic Press, Boston.

Castillo, E., and Sarabia, J.M. 1992. Engineering analysis of extreme value data: selection of models. Journal of Waterway, Port, Coastal, and Ocean Engineering, **1182**: 129–146.

CEN. 1994. ENV 1991-3 Eurocode 1: Basis of design and actions on structures. Part 3: traffic loads on bridges. European Prestandard ENV 1991-3, Draft N119, European Committee for Standardisation, Technical Committee 250, Brussels.

COST 323. 1997. European specification on weigh-in-motion of road vehicles. Draft 2.2, EUCO-COST/323/5/1997. Cost Transport, EC/DGVII, Brussels.

Cremona, C. 1989. Évaluation des effets extrêmes du trafic sur les haubans d'un pont. Bulletin de liaison des LPC, **164**: 64–77.

Cremona, C. 1995. Extrapolation des effets du trafic sur les haubans d'un pont. Bulletin de liaison des LPC, **199**: 71–80.

Dempsey, A.T., and O'Brien, E.J. 1995. The accuracy of bridge weigh-in-motion systems for the determination of truck weights. Proceedings of the 1st European Conference on Weigh-in-Motion of Road Vehicles, Zurich, Switzerland. ETH-Hönggerberg, Zurich, Switzerland. pp. 315–322.

Enevoldsen, I. 2001. Experience with probabilistic-based assessment of bridges. Structural Engineering International, **11**(4): 251–260.

Flint, A.R., and Jacob, B.A. 1996. Extreme traffic loads on road bridges and target values of their effects for code calibration. Proceedings of IABSE Colloquium, Delft, The Netherlands, ETH-Hönggerberg, Zurich, Switzerland. pp. 469–478.

Fu, G., and Hag-Elsafi, O. 1995. Bridge evaluation for overloads including frequency of appearance. *In* Applications of statistics and probability. *Edited by* M. Lemaire, J.-L. Favre and A. Mebarki. A.A. Balkema, Rotterdam. pp. 687–692.

Gumbel, E.J. 1958. Statistics of extremes. Columbia University Press, New York.

Hallenbeck, M. 1995*a*. Seasonal patterns of truck loads and volumes in the United States. Proceedings of the 1st European Conference on Weigh-in-Motion of Road Vehicles, Zurich, Switzerland. ETH-Hönggerberg, Zurich, Switzerland. pp. 121–129.

Hallenbeck, M. 1995*b*. Quality assurance and automated error selection for WIM and AVC equipment in the long term pavement performance (LTPP) project. Proceedings of the 1st European Conference on Weigh-in-Motion of Road Vehicles, Zurich, Switzerland. ETH-Hönggerberg, Zurich, Switzerland. pp. 279–287.

Hallenbeck, M. 1995*c*. Description of the long term pavement performance traffic database. Proceedings of the 1st European Conference on Weigh-in-Motion of Road Vehicles, Zurich, Switzerland. ETH-Hönggerberg, Zurich, Switzerland. pp. 369–377.

Harman, D.J., and Davenport, A.G. 1979. A statistical approach to traffic loading on highway bridges. Canadian Journal of Civil Engineering, **6**: 494–513.

Jacob, B.A. 1991. Methods for the prediction of extreme vehicular loads and load effects on bridges. Report of subgroup 8, Eurocode 1.3, LCPC, Paris.

Jacob, B.A., Maillard, J.B., and Gorse, J.F. 1989. Probabilistic traffic load models and extreme loads on a bridge. Proceedings of the ICOSSAR '89 5th International Conference on Structural Safety and Reliability, San Francisco, 7–11 August 1989. *Edited by* A.H-S. Ang, M. Shinozuka and G.I. Schuëller. American Society of Civil Engineers, New York. pp. 1973–1980.

Leadbetter, M.R., Lindgren, G., and Rootzén, H. 1983. Extremes and related properties of random sequences and processes. Springer-Verlag, New York.

Maes, M. 1995. Tail heaviness in structural reliability. Proceedings of the 7th ICASP Conference on Applications of Statistics and Probability, Paris, 10–13 July 1995. *Edited by* M. Lemaire, J.-L. Favre and A. Mebarki. Published for CERRA (International Association for Civil Engineering Reliability and Risk Analysis) by A.A. Balkema, Rotterdam. pp. 997–1002.

Moses, F. 1979. Weigh-in-motion system using instrumented bridges. ASCE Journal of the Transportation Division, **95**(TE3): 233–249.

Nowak, A.S. 1993. Live load model for highway bridges. Structural Safety, **13**: 53–66.

Nowak, A.S. 1994. Load model for bridge design code. Canadian Journal of Civil Engineering, **21**: 36–49.

O'Connor, A., Jacob, B., O'Brien, E., and Prat, M. 2001. Report of current studies performed on normal load model of EC1-traffic loads on bridges. Revue Française du Génie Civil (RFGC), Hermes Science Publications, **5**(4): 411–434.

Prat, M. 1991. Calibration objective effects for characteristic values. Eurocode 1, Actions on structures. Chapter 12. Traffic loads on bridges. Service d'études techniques des routes et autoroutes (SETRA), Bagneux, France.

Weibull, W. 1951. A statistical distribution of wide applicability. Journal of Applied Mechanics, **18**: 293–297.