Highway Traffic Load Model for Bridge Design and Assessment

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1 Synopsis

Vehicular load models for use in design and assessment of long span highway traffic bridges appear in many national bridge design codes. Their origins are frequently obscure, but they are usually considered to be satisfactory if failures cannot be attributed to their use. In most developed nations, this would appear to be the case.

However, the fact of survival tells us nothing about the amount by which loading codes might be wastefully over-safe. When we come to review an older bridge against newer loading standards, it becomes particularly important that we do not employ excessively onerous load models. Loading standards for new structures are intended to provide a reasonable balance between cost and safety. However, for new bridges the extra cost of using over-safe loading standards is small compared with the cost of adding strength to existing structures. Therefore the costs to society of imposing higher modern standards onto old structures would often be better spent elsewhere. We therefore need a rational approach towards deriving assessment standards which provide the reliability that the Public requires, without excessive cost.

This paper describes the derivation of highway traffic load models for use in bridge design and assessment, based on statistical analysis of traffic data and of ‘Monte Carlo’ simulation of traffic load effects. The rationale of this procedure is discussed with reference to some published design standards, including the recently published Eurocode[1] load models. A discussion of theoretical structural reliability aspects is included, including the relationship between load and structural resistance models.

The procedure is illustrated by reference to the ‘Bridge Specific Assessment Live Loading’ model (BSALL) that is currently being applied to the West Gate Bridge in Melbourne during the current bridge refurbishment works. The paper describes the method used to establish the magnitudes of load effect which the BSALL is required to produce, and touches briefly on practical codification of the BSALL.

2 Introduction

2.1 Project Objective

West Gate Bridge over the Yarra River was originally designed in the 1960’s to carry four lanes of traffic plus a breakdown lane in each direction. The breakdown lane was only designed to be occupied locally. The current objectives include assessing the existing structure and strengthening the bridge to safely carry five lanes of modern day traffic in each direction, with no breakdown lane. The assessment and
design team requires a load model that will reflect current and reasonably predictable future traffic conditions.

The original design was based on the NAASRA Bridge Design Specification 1970 including an allowance for the NAASRA overloaded vehicle and modifications to account for long loaded lengths. Revised loading models that have appeared in Australia since then include the L44 and T44 models contained in AUSTROADS 92[2] which has been widely used in design, and the more recent SM1600 model contained in AS5100.2 -2004[3].

2.2 Background to Live Load Models

Bridge design load models can generally be classified as being either probabilistic or deterministic in origin.

Deterministic models such as those provided in AS5100 do not provide any information about probabilities that different levels of loading might be exceeded. They are normally derived from theoretical studies of effects of selected sets of legal vehicles, with allowances for overload and bridge dynamic responses. There is no mathematical procedure by which structural safety can be calculated using these models.

Probabilistic models accept that bridge loading effects are uncertain and can only realistically be described in terms of probabilities. They can be derived by statistical analysis of the effects of traffic models (obtained from vehicle measurements) on theoretical bridge models.

In theory it should be possible to develop probabilistic models for bridge loading and bridge resistance and then to mathematically calculate the probability of structural failure. Data are imprecise but, nonetheless, this task can be performed for typical bridges built to typical current design standards. That is: theoretical bridges can be designed according to codified loading and strength standards, and their failure probability can be calculated using realistic probabilistic models of loading and resistance. We define ‘structural reliability’ as being the inverse of the probability of failure. Reliability values are frequently published in the form of β values, where the reliability index, β, represents the number of standard deviations in a Normal distribution beyond which the area under the curve equals the failure probability. Lifetime values of β for typical short span bridges designed to modern standards are usually quoted as being in the order of 3.8 to 4.5 [6,9,10,15]. Thus we can determine a suitable target reliability value for our long span bridge by referring it back to the theoretical reliabilities of the large population of satisfactorily performing short span bridges. So when we come to defining our load model for our long span bridge, we can adjust the relationships between our load and resistance models until our theoretical reliability matches our original target. We can alter our models or our safety factors and thus ensure that our bridge is just as safe as other, more typical, bridges which are designed to current conventional standards.
Some published design standards define rather low loading intensities, but then apply relatively high safety factors. Some apply safety factors only to the load models, and others provide sets of partial safety factors to loads, resistances, and even to accuracy of analysis. If safety is to be maintained when changing from one design standard to another, the safety factors or the load models must be adjusted so that the final design will be remain unchanged. It is misleading to compare loading standards without including their safety factors on loads and resistances.

3 Principles of developing a BSALL

3.1 Summary of Procedure

Highway traffic load effects in the principal elements of long span bridges such as West Gate are dominated by the effects of queues of closely spaced stationary vehicles. Our BSALL development procedure is as follows:

- Take a large volume of vehicle axle weight and axle space data obtained from weigh-in-motion (WIM) sensors from traffic flowing along the road.
- Assemble these vehicle records into theoretical traffic queues in each traffic lane.
- One such queue file is created for each daily traffic record.
- Analyse the effect of this multi-lane queue sitting with its front end just placed onto a typical bridge influence line. Record the load effect of traffic on selected individual lanes and also the combined effect of traffic on selected groups of lanes.
- Move the entire queue further forwards along the bridge, and re-analyse its effects on the chosen lanes and groups of lanes.
- Continue moving and analysing load effects until the queue has entirely passed across the bridge.
- Record the maximum load effect obtained on each bridge influence line for that hourly traffic jam.
- Repeat the calculation for the next hour and continue to record hourly maximum load effects.
- Continue until all daily data are exhausted and a set of all hourly and daily load effects has been found.
- Analyse the collection of daily maxima using methods for the statistical analysis of extreme data to establish a probabilistic live load model.
- Establish the live load probability level which, if used to define the BSALL, will provide the desired target reliability.
- Repeat the process for the required range of loaded lengths and typical influence lines, and devise a codified BSALL model suitable for use in structural analysis.

These steps are now described in more detail.
3.2 Traffic Model

Traffic records were obtained from weigh-in-motion equipment placed across all eight traffic lanes of West Gate Bridge. These comprised 190 days of daily data records covering 6 months between January and July 2007. The vehicle arrival times in the flowing traffic data files were adjusted so as to form a large number of traffic jams. These traffic jams were to serve as a proxy for all the traffic jams that are predicted to take place during a very much longer period of time.

We assume in the simulation analysis that each daily traffic queue contains 24 individual convoys, each containing one hour’s traffic data. By thus re-convening the head of the all-lane traffic jam once per hour, we avoid mixing traffic from different hours of the day within any traffic jams.

Vehicles are assumed to stay in the lane in which they were recorded as travelling. Reference [5] notes that only about 5% of heavy goods vehicles typically move out of their normal travelling lane as flow becomes more congested. We recognise that these observations were made in the UK, but we believe that there is even less tendency for lane switching at West Gate, because the vehicle types are already much more randomly mixed in all lanes than they are in the UK (where heavy vehicles are not permitted to use the outermost traffic lanes) so there is little incentive for drivers of particular vehicle types to systematically change to particular lanes in the event of a queue.

We need to make assumptions on vehicle spacing in convoys. We have a variety of published proposed values for inter-axle spaces:

- The Eurocode work assumed 5 metres, based on observations in France.
- Canadian data would suggest 3.5 metres.
- US data (now very old) would suggest 4.5 metres
- UK data for goods vehicles would suggest 4.5 metres.

After some deliberation we selected a 3 metre space between axles. This is less than the European values, because Australian heavy goods vehicles are similar to those in Canada and the USA in tending to have axles placed closer to the extreme rear than they do in Europe.

In our simulation analysis, load effects are calculated every time the program’s theoretical clock steps forwards enough to move the entire convoy by a small fraction of the loaded length being considered. We consider this to be a safe-sided assumption since it only realistically applies to jams caused by accident and breakdown and not to jams caused by unstable traffic flow at times of peak flow volumes (which are much more frequent at West Gate). After interrogating the WIM data, we concluded that approximately 4% (or 1/25) of traffic crosses the bridge in heavy congestion.
3.3 Modelling of Lane Load Effects

It is common for bridge design codes to provide diminishing load intensities when the number of traffic lanes on a bridge is increased. This reflects the diminished probability of extreme loadings occurring simultaneously in every lane as the number of loaded traffic lanes increases. We obtain BSALL effects for simultaneous loading on several traffic lanes by calculating joint effects on chosen combinations of lanes. There is no convenient way to simulate and extrapolate to all possible combinations of different proportions of direct load, torsion load, concentrated loads on the centres of cross girders, etc., but the simulation procedure must provide a load model that is safe-sided in all circumstances.

Usually we begin by ordering all lanes in diminishing sequence of load intensity. However, at West Gate Bridge we found that the differences between extreme loads on each lane are not very large. After due consideration, we calculated the WIM based on reversing the order of defining the eight traffic lanes. The lanes were then re-numbered from 1 to 8 across the bridge. Then we calculated the effects of:

- Traffic in Lane 1 alone
- The sum of effects from Lane 1 plus Lane 2 on the same influence line
- The sum of Lanes 1 + 2 + 3
- The sum of 1 + 2 + 3 + 4
- and finally the sum of all lanes 1+2+3+4+5+6+7+8.

This allows us to formulate rules for traffic load on one lane, on two lanes, on three lanes, on four lanes, and finally on all traffic lanes. Note that we make the safe-sided assumption that traffic jams occur simultaneously in both trafficking directions.

3.4 Extrapolations

Since we assume that about 1/25 of all vehicles cross the bridge in close spaced convoy conditions it follows that, if we place one week’s traffic in a queue, this can be assumed to represent roughly 25 weeks of bridge time exposed to traffic jams (or half a year). Therefore, when we assemble the 27 weekly maximum values of load effects which we obtain from our traffic load effect simulation program, we effectively have a set of 27 half-yearly maximum traffic jam load effect values. We can now fit an Extremal Type 1 (Gumbel) distribution using a least squares fit to the data points on a ‘Gumbel plot'[8].

The horizontal (X) axis represents a probability scale ‘–loge(-loge(CDF))’, where ‘CDF’ = cumulative frequency distribution function for the data points. If there are ‘n’ data items, the CDF value for each item ‘m’ in an ascending list for m = 1 to n is given by m/(n + 1). The vertical (Y) axis represents the magnitude of load effect (labelled ‘moment’ in this example).

Figure 1 provides an illustration of a typical such plot from our simulation results for West Gate Bridge traffic. We found that the data points tended to lie on a good straight line fit.
The intersection of the lines on the Y axis represents the mode (usually denoted ‘U’) of the half-yearly maximum values. The slope (usually denoted ‘α’) is a measure of the dispersion (i.e. the effect of increasing the exposure time on increasing the probability of exceedence of load). The lines on this example plot begin with single lane loading (the bottom pair of lines), followed by joint loading on two lanes, three lanes, four lanes and finally on all eight lanes (the uppermost pair of lines). The ‘U’ and ‘α’ parameters define the probabilistic live load model.

The probability $P_e$ that any given value $x$ on the X-axis scale will be exceeded in any 6 month period is given by:

$$P_e = (1-\exp(-\exp(-x))).$$

So where $x = 3.3$, the probability that the associated moment will be exceeded will be 1/28 in 6 months: or approximately 1/14 per year.

We consider that the shape of this plot (and others very like it) confirms that our sample size is large enough to provide a realistic and stable model, because there is very little ambiguity about the slope of the best fitting straight lines. Once we have the extremal distribution model parameters, we can extrapolate to any probability level. The codified BSALL should ideally be selected in order to provide the most uniform possible level of structural reliability for all influence line lengths and numbers of loaded lanes when it is applied in conjunction with the partial format of the selected design code.
4 Calibration Target for Load Model

4.1 Ultimate Strength Relationships between Load and Resistance

Structural reliability theory [16] indicates that the most uniform level of reliability across many different designs will be obtained if the fully factored values of the load and resistance parameters coincide at the so-called ‘design point’ values where failure is most likely to occur.

Studies (e.g. [10]) indicate that, for highway loading, this value is equivalent to a load effect with approximately a 1/22000 probability of being exceeded in a given year. On our Gumbel plot, this would represent approximately $x = 10$. Therefore, ideally the product of the BSALL and its ULS partial factor should provide a load effect equivalent to $x = 10$ on Figure 1. We should select the load effect equivalent to $x=10$, and then divide this effect by our ULS partial load factor to obtain the BSALL in our design code. The load model is meaningless without its load factor. If we choose $x$ correctly and base our BSALL model on this value of $x$, we will obtain similar reliability even if the dispersion (i.e. the slope of the line on the chart) of every load effect varies with loaded length, numbers of loaded lanes, etc.

In the real world, this method of selecting the BSALL load level has not always been followed. Thus: when the UK load model was derived by Flint & Neill Partnership and others in the early 1980’s[6],[9], a decision was taken to standardise the highway traffic load model as being a fixed fraction of the load effect that has a 5% probability of being exceeded in a notional 120 year design life. This is approximately equal to the effect which has a 1/2400 probability of being exceeded in any one year. This ‘characteristic’ value has an $x$ value of about 7.8 and it provided reasonably uniform reliability when using the theoretical models at that time. This approach is still used in the UK: largely because there has been little if any detailed re-assessment of its merits.

The Eurocode approach is effectively very similar to that used in the UK, since it is calibrated at a probably level of 1/1000 probability of exceedence in any year (i.e. approximately 5% smaller than the 1/2400 value).

Our work at West Gate and elsewhere has shown that the dispersion of probabilistic load models is smaller at longer lengths and for multiple lane loads. Because we use too small a value of $x$ to define the point relative to which the BSALL is fixed, the long span load models become theoretically perhaps some 15% more safe-sided than the shorter span models. However, we have two main reasons for being reluctant to unilaterally re-calibrate the basis of long span bridge loading models. The first is that we would be concerned that such a model would not have the benefit either of ratification by long term usage or by wide ranging peer review (as have the Eurocode and UK models). The second reason is that this would remove the protection provided within the model for uncertainty in the modelling process itself which (as we shall discuss below) we believe becomes especially important at long loaded lengths.
5 Results: ULS Load Effect Simulation

5.1 BSALL Target Values and Codification

Figure 2 illustrates the results of the BSALL calculations based on simulation and extrapolation of load effects derived from WIM measurements. We describe these results as our ‘Target’ values. These are the model load effects defined in terms of the equivalent uniformly distributed load (EUDL) on the selected influence lines. Our experience is that the magnitude of required BSALL model is not very sensitive to the shape of the influence lines used to derive it. Thus a BSALL derived from studying the influence line for end shear in a simply supported beam produced a slightly lower model load requirement for single lane load effects, but beyond that the differences are insignificant.

![Figure 2: BSALL Simulation Target EUDL as a function of loaded length and number of lanes](image)

The final step was to formulate a set of codified rules which the bridge analysts could use in their local and global analyses. The codified model had to be optimised so that:
• It would provide a good match to the target load effects if applied to the influence lines from which it was derived
• It would merge closely with the existing short span load model used in recent Australian bridge designs so that it would ensure similar reliability for short loaded length elements as that inherent in existing modern shorter bridges
• It would be reasonably easy to automate in modern bridge analysis computer programs
• It would be as unambiguous as possible in its rules for application on a variety of influence line shapes and lengths

The load model is thus a compromise between precision of fit to the target values, and convenience for computation. At West Gate, we decided to use a load model with the same format as the AUSTROADS 92 models, but with different numerical values. A discussion of the match between the model and the target is beyond the scope of this paper, but some numbers and comparisons may be of interest.

Figure 3 compares the BSALL models for Lane 1 and for all 8 lanes together with the ‘targets’ obtained by simulation and extrapolation, with some possible alternative load model effects. All are normalised so that wherever they coincide they require approximately the same structural quantities. The total design demand of the BSALL can be seen to be very much smaller than the design demand from the M1600 (short length) and S1600 (long length) models defined in AS5100.2 -2004. The 8-lane total BSALL is much less severe at shorter loaded lengths than the older T44/L44 models, but the worst single lane BSALL is similar.

5.2 Future Traffic Growth

The BSALL procedure cannot predict future loadings and, although certain allowances for traffic growth have been made, their basis is beyond the scope of this paper. Figure 4 illustrates an obvious difficulty. Each point represents the total weight of traffic that passed on 330 successive days on a busy European bridge beginning at the end of November 2007. The low total traffic weights on Christmas day, New Year’s Day and Easter Sunday are clearly visible, as are Saturday and Sunday traffic weights. More importantly, the plot appears to show a distinct drop in
economic activity in the latter half of 2008 – an effect which was not predicted at the start of that year.

![Graph showing daily total traffic weight](image)

**Figure 4:** European record of daily total traffic weight: starting on 1 Nov 2007 (*not West Gate Bridge*)

### 6 Conclusions and Observations

This paper has described the BSALL derivation for West Gate Bridge. Many individual steps in the procedure can be modified and have been developed over many years. We find in general that the BSALL values we obtain are usually insensitive to detailed changes in methodology. Thus: alterations in traffic jam frequency models move the target values along the slopes in Figure 1 by one or two units on the X-axis, but the resulting change in BSALL (the vertical axis) is quite small.

Larger changes occur as a result of changing the make up of the traffic, and the modelling of the spaces between vehicles. We consider that this justifies retaining some of the conservatism in calibrating the BSALL and its safety margins at longer loaded lengths where such effects are most important.

Where we have many months of data (as at West Gate) it is convenient to extrapolate to our target values by looking at the statistics of extreme weekly events. If traffic in any one week is reasonably similar to traffic in any other week, this should provide us with a single population of events – which is a requirement when applying the theories of using statistics of extreme values. The real world is not as convenient as this, and (especially when observation periods are shorter) we have used other means of extrapolation (e.g. based on the entire set of hourly maximum load effects). BSALL results are then similar but will not be identical. Some 10% uncertainty is a reasonable estimate of the variations in BSALL values. This, once again, tends to justify using a long span model based on a somewhat safe-sided calibration point.
The method does not work well for long span but lightly trafficked bridges. On these, random theories about traffic jam frequencies do not provide enough realistic traffic jams to allow for extrapolating to extreme events. This is not a serious problem for designers (who will usually be satisfied to use a national standard that will provide a safe design), but is a bigger problem when assessing existing bridges.

The method can be used directly to provide live load effects in critical structural elements by simulating traffic loading on element-specific influence surfaces (i.e. using different influence lines for each lane) and completely avoiding the compromises inherent in using a codified load model. It is also possible to take flowing traffic records and undertake ‘rainflow’ fatigue load effect cycle counting. This requires the WIM vehicle arrival times to be recorded to the nearest 1/100 second.

Statistical extrapolation is not truly realistic when it takes us far outside our observed experiences. $X$ values (Figure 1) of 10 or more are far outside anything we are likely to observe. For this reason (and others) reliability calculations provide us with ‘notional’ failure probabilities. They provide a means of ensuring reasonably uniform reliability over many designs, and also provide rational means of devising safety factors which ensure that the Owner’s interests in safety are preserved when loadings and structural forms change.

7 References


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