

Assessment of Bridge Response Using Weigh-in-Motion Data

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SYNOPSIS

Weigh-in-motion data gathered on highways provides statistics on gross vehicle mass (GVM), axle mass distribution, type of truck, speed, etc. It can be used to monitor freight volume and trends, and to detect illegally loaded trucks. The data is used in conjunction with vehicle mass limits to develop “design vehicles” such as SM1600 for bridge loading to be used for assessing performance against the limit states of ultimate strength, serviceability, fatigue, etc.

A system has been developed for applying the individual trucks as loads to specific bridges or to a class of bridge of given span and influence function to see how they perform under current traffic. This replaces the use of “design vehicles” with the actual historical traffic. The load effects are a function of the span and the shape of the influence line or surface. The system provides valuable insights into the performance of actual ageing bridges and it enables the direct probabilistic structural risk assessment of existing bridges.

1 INTRODUCTION

Highway transport authorities throughout the world rely on data gathered at weigh-in-motion sites for statistics on gross vehicle mass (GVM), axle mass distribution, and type of truck. The data can be used to monitor freight volume, to identify trends in traffic volume and GVM, to detect illegally loaded trucks, to monitor trends in wheel loads and frequency for pavement design and maintenance, and to identify loads being applied to bridges. For bridges, weigh-in-motion data has been used traditionally to construct probabilistic models of truck group axle masses, GVM and axle spacing. Various “design vehicles” are then developed to set performance criteria for ultimate strength, serviceability, fatigue, etc.

To review the performance of a bridge in service, the historical response to the actual truck traffic can be derived from the weigh-in-motion data on the route, or from a similar route if there is no WIM system in line with the bridge under review. To achieve this each measured truck is passed over the bridge of given span and shape of influence line to determine the response at the point of interest. Typical influence functions are shown in Figure 1.

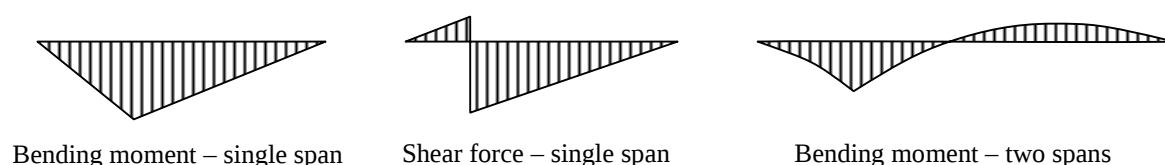


Figure 1 – Typical influence lines

It will be found that the vehicles which provide critical loading are often quite different from those used in design. Further, the assumptions regarding multiple presence of vehicles on a bridge are found to be very conservative.

2 METHODOLOGY

Spreadsheet based software BRAWIM® (Bridge Response Analysis from Weigh In Motion data) has been developed to perform a complete statistical analysis of truck data gathered at a WIM site and to determine the complete statistics of peak response, time at different levels of response, and cumulative cycles of response for fatigue damage by Rainflow analysis for a specified influence line and span [2]. A scheme is outlined in Figure 2.

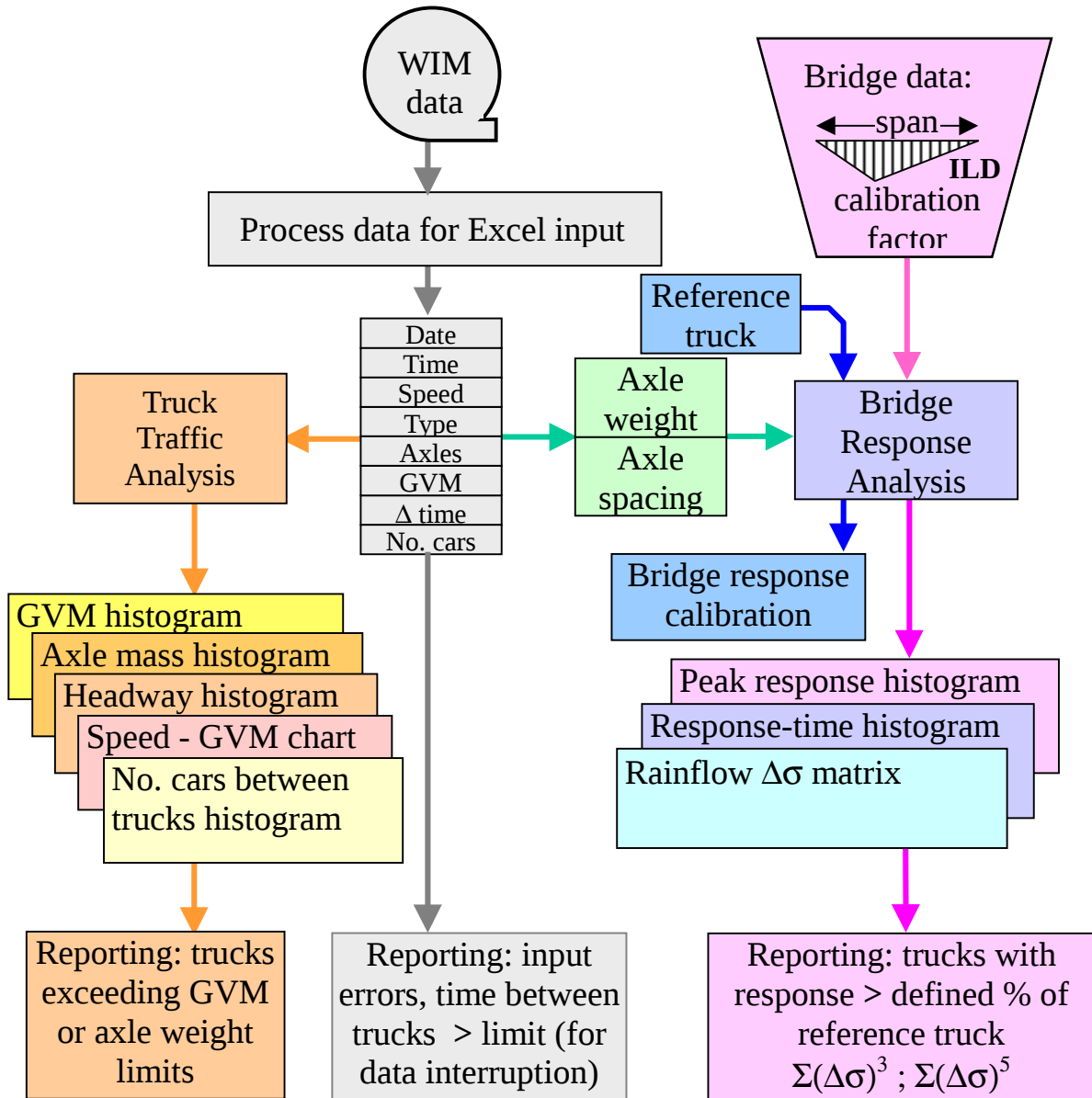


Figure 2 – BRAWIM system for extracting truck and bridge response statistics

The central (grey) part of Fig. 2 relates to weigh-in-motion data extraction. The left part identifies the truck data analysis traditionally performed. The right part encompasses the direct response analysis of specific bridges, which is the significant innovation of this software, bypassing the track data analysis. The processing is more computationally intensive, requiring a fresh analysis for each new influence line or span, but the computation time on a PC is still only a matter of minutes for each structure, and quite acceptable.

At present the system analysis the WIM data sequentially, one record (the passage of a truck) at a time. For each truck the data recorded in the CULWAY WIM system [1] include the number of axle groups, the group axle masses, the gross vehicle mass (GVM), the spacing of

axles, the time of passage to a fraction of a second, the speed of the vehicle, and the number of cars (up to 15) behind the previous truck.

Auto correction of drift of measured data using constants based on the steering axle mass of semi-trailers (A-1-2-3) is incorporated in the software [1,3].

The methodology will be demonstrated by an example. Data will be used from a CULWAY station on the heavily trafficked interstate Hume freeway, approximately 50 km north of Melbourne, covering both the slow and fast northbound lanes, for the period January to June, 2000.

3 TRUCK DATA ANALYSIS

3.1 Reporting

It is important to retain full details of trucks triggering extreme responses in the structure to authenticater extreme events. Thresholds of GVM and individual axle mass can be set, above which the full details of exceptional vehicles are retained in the spreadsheet. Typically, a threshold of 72 tonnes GVM and 12 tonnes individual axle mass will filter out more than 99% of the data, leaving a manageable file for storing results.

Culway has settable threshold axle spacings, above which vehicles are separated. A typical threshold is 9.5 metres. As a result, two trucks with headway (distance of last axle of leading truck to steering axle of following truck) less than 9.5m show up as a single truck. These are easily detected where the trucks have six or more axles, but not so easily for rigid trucks.

All data errors are reported. Some errors consist of mismatches between GVM and the sum of axle weights, and these are usually correctible. Fatal errors are extremely rare.

Reporting of gaps in data acquisition is achieved by setting a threshold in hours between successive trucks. The time of passage of the truck and the time since the previous truck are reported. A threshold of six hours on busy routes, and ten hours on lightly trafficked routes has been found appropriate. Total outage is deducted from the overall sample period in calculating traffic volumes and time dependent load effects.

3.2 Vehicle mass distribution

The GVM distribution for both lanes of the Hume freeway site, January-June 2000, is shown in Figure 3. The total truck count was 259,958 for the slow lane and 12,702 for the fast lane, averaging approximately 1,540 trucks per day in total.

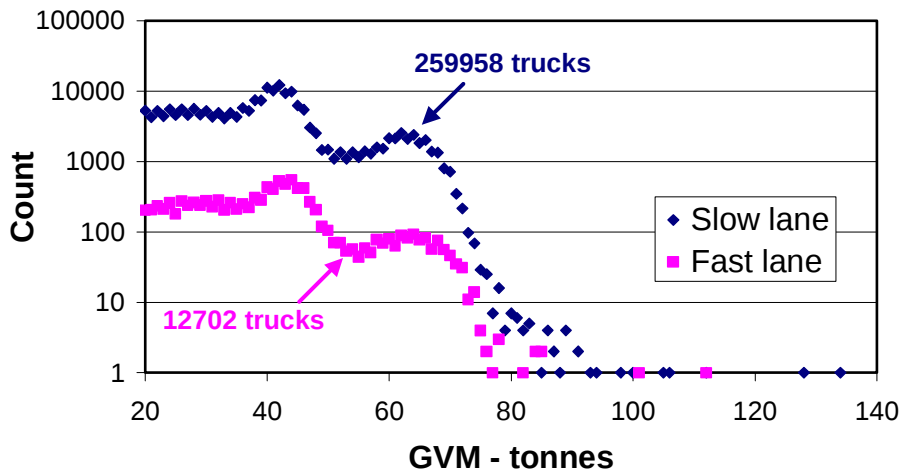


Figure 3 – Gross Vehicle Mass count in 1 tonne increments

The count is plotted logarithmically so that the very rare occurrences of high GVM can be noted. Only 45 trucks exceeded 80 tonnes. Some, including all above 100 tonnes, were two trucks together, too close to separate, with 12 or 15 axles in total. At the time of data acquisition, the legal GVM limit was 42 tonnes for a 6-7 axle semi-trailer and 68 tonnes for a B-double. There were a significant number of B-doubles in the fleet.

3.3 Axle mass distribution

Detailed counts of axle masses are obtained, according to the number of axles in the group, with steering axle mass a separate category. The results are shown in Table 1. Adding all axle groups together results in the axle mass distributions shown in Figure 4.

Quite a large number of axles exceed the various legal limits for the different axle groups. Low loaders and the rear tri-axle of B-Doubles contributed peak values. Six B-Doubles were responsible for rear tri-axle groups in the range 45-48 tonnes on the group.

	Slow Lane					Fast Lane				
Max'm	12.94	16.28	13.11	15.60	10.17	11.13	10.71	11.00	8.79	6.11
Mean	5.00	5.29	6.06	5.41	5.25	4.86	4.10	6.02	5.10	4.32
Std Dev	0.80	1.92	1.72	1.73	2.29	0.98	2.19	1.82	1.69	1.51
Tonnes	Steering	1 axle	2 axle	3 axle	4 axle	Steering	1 axle	2 axle	3 axle	4 axle
1	99	436	753	426	1	93	203	106	42	
2	3992	1637	6685	20362	2	406	348	391	1171	1
3	11021	5255	21484	24344	23	626	453	1074	1370	
4	29899	6727	26524	27172	3	1804	257	1199	1487	1
5	154684	6494	35105	29011	12	7391	242	1676	1677	
6	56907	5806	43199	45929	14	2019	228	2047	2749	1
7	2536	4836	69615	80198	5	322	192	3047	2863	
8	656	3575	58136	9089	4	35	127	2759	240	
9	135	1564	4851	243	7	3	38	357	6	
10	12	288	249	24	3		8	29		
11	10	49	35	11		1	3	2		
12	4	19	11	8						
13	1	5	1	5						
14				1						
15		2		1						
16		2		1						
Sum	259958	36696	266665	236826	74	12702	2115	12694	11605	3

Table 1 – Counts of axle mass distributions

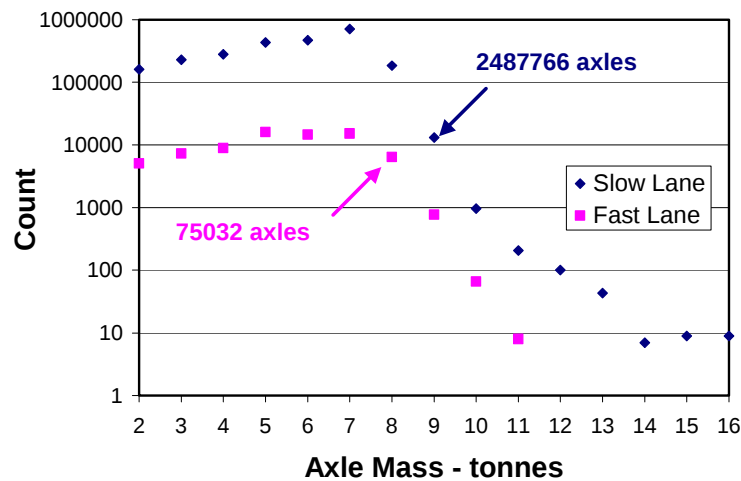


Figure 4 – Count of axles masses for all axle groups

3.4 Cars between trucks

Cars between trucks reduce bridge loads by reducing the number of multiple presences on a bridge in one lane. They also allow pavements to recover from heavy wheel loads before the next attack. The Culway system counts the number of cars between trucks, but more than 15 cars are truncated to 15. Therefore, the actual number of cars is underestimated, especially in the fast lane dominated by cars. Data on cars between trucks is shown in Figure 5

The counts for the slow and fast lanes are plotted to different scales to indicate the trends, as truck traffic in the fast lane is about 5% of the slow lane traffic. Trucks in convoy without cars are a dominant feature of the slow lane.

In addition to this information is reporting of exceptional GVM, noted above where axles of consecutive trucks were less than 9.5m apart. 23 pairs of semi-trailers or B-doubles were detected with axle headway ranging from 5.99m to 9.49m. Other cases of short headway, e.g., between rigid trucks, could not be detected by this method, but they are unlikely to be significant as they were not reported as exceptional GVM.

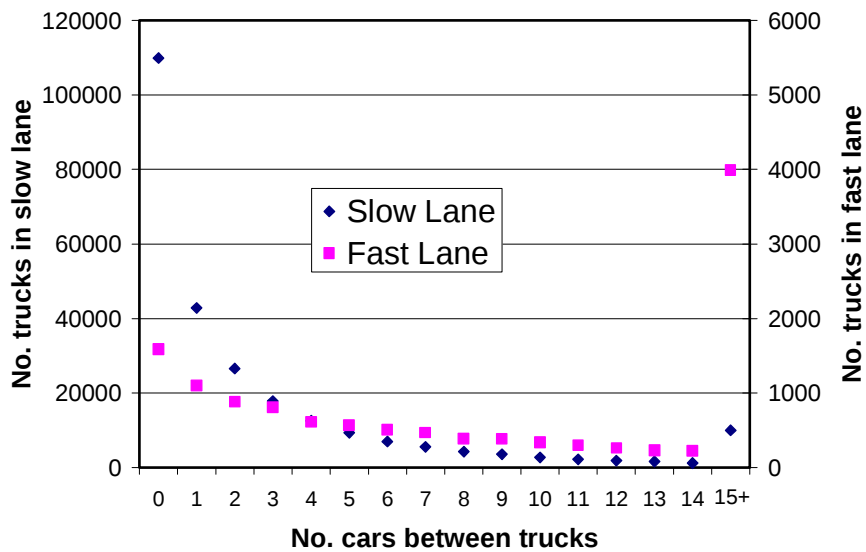


Figure 5 – Distribution of number of cars between trucks

Where traffic is regularly brought to a halt in built-up areas the interspersions of cars between trucks is an important factor in reducing peak response when the traffic is stationary.

3.5 Multiple presence in a single lane

The truck data is sufficient to draw some inferences regarding lane loading with more than one truck on a bridge [3]. The short headways reported here are only relevant to the site at which they are measured. Headway must be regarded as a random process. However, the data indicate that multiple presence is not going to influence peak response on spans less than 40m. With spans in the range 5-40m the peak response will be dominated by the loading on a tri-axle group of a semi-trailer or B-double, or the rear four axles of low loaders carrying machinery. Low loaders consistently provide critical load cases for short spans.

3.6 Multiple presence in adjacent lanes

Multiple presence in adjacent lanes will usually provide the critical load case for ultimate strength risk assessment, where loading in both lanes contribute to load effects on a structural element. The risk assessment is addressed later in this paper.

4 BRIDGE RESPONSE ANALYSIS

The right part of Figure 2 indicates the bridge response analysis. This analysis is unique to a span and influence line describing a particular bridge. It uses the output from the WIM data extraction in the form of a given configuration of axle mass and axle spacing at a given speed for each truck. It generates a quasi static bridge response.

The response can be any structural reference – moment, force, stress, deflection, etc. The response is a sequence of amplitudes corresponding to the position of the truck. Using the speed of the truck the time at each response amplitude is determined.

In the example chosen to illustrate the process the data from Hume Freeway is applied to determine the bending moment near midspan of a simply supported girder bridge spanning 15 metres. The position for measuring bending moment was $0.42 \times \text{span}$, as experience shows this to be the most likely location for maximum bending moment under a string of axle loads.

4.1 Load stepping method

The load stepping procedure is shown in Figure 6. The string of axle loads is stepped across the bridge in steps, typically 0.3m to 0.5m. The amplitude is recorded at each step. The maxima and minima are temporarily saved for extraction of the peak response and Rainflow analysis for fatigue assessment. The amplitude at each step is accumulated into a histogram of amplitude versus time spent at that amplitude.

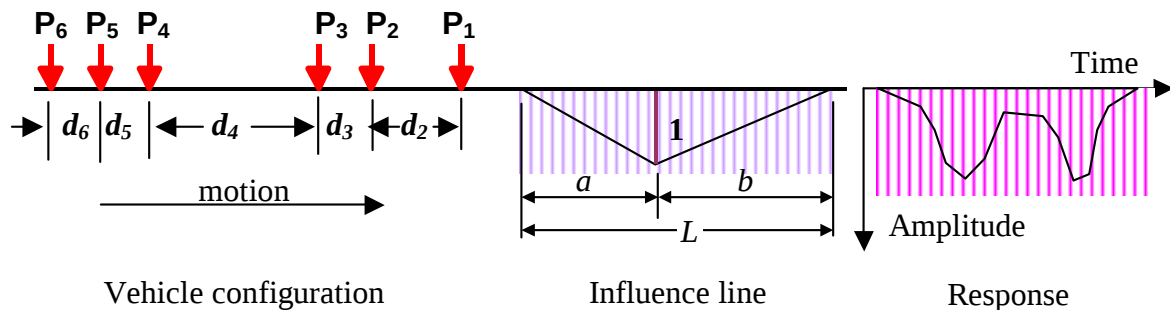


Figure 6 – Load stepping method to determine bridge response

4.2 Reference truck

Normalised spans and influence functions are used in the analysis. It is necessary to represent

the response with reference to a standard truck. Prior to the application of traffic loads, the reference truck is passed over the span to determine maxima and minima. All results are scaled as a proportion of the response to the reference truck.

The option exists to cross reference to other standard trucks. The reference truck for this case study was the Australian T44 truck, with GVM 44 tonne and 1-2-2 axle configuration, the design standard at the time. Additional standard trucks were referenced, the proposed Australian standard M1600, with nominal GVM 1600 kN and 3-3-3-3 axle configuration, and A160, a 160 kN single axle load. AASHTO and other standard trucks can be added.

4.2 Peak response

The highest maximum response for each truck is recorded in the histogram of peak response. After the completion of data processing the histogram becomes an output. The output for the case study is shown in Figure 7.

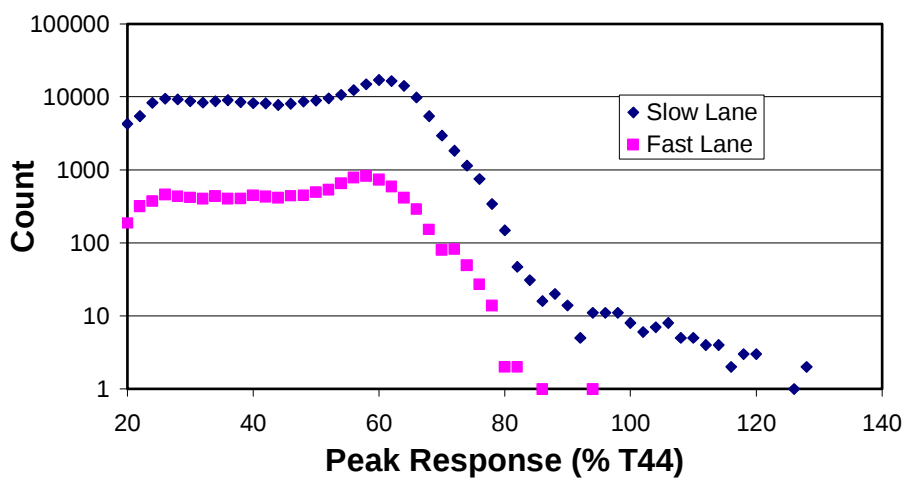


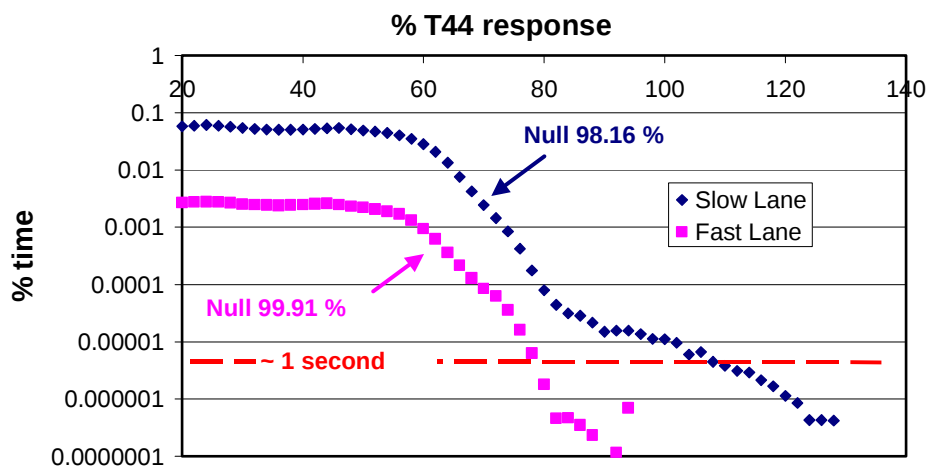
Figure 7 – Peak BM, span 15m, Hume Fwy northbound, Jan-Jun, 2000, 2% increments

In this result only 0.018% of trucks (50 no.) produced a response more than 100% of a T44 truck. Only 0.084% (224 no.) exceeded 80% of a T44 truck. The highest two responses were equal to just 80% of the response to an M1600 truck.. The highest response in the fast lane was 94% of a T44 truck.

Since many trucks have a base length longer than the span, the peak response is dominated by heavy axle groups. The majority of the high responses were due to low loaders ranging from 68 to 95 tonnes GVM, where the rear four axles on a base length of 4.9m were critical.

4.3 Time at given response amplitude

At the end of data processing the histogram of time dwelt at each level of response is



produced. The result for this case study is shown in Figure 8.

Figure 8 Time at given amplitude, span 15m, Hume Freeway northbound, Jan-Jun, 2000

It is noteworthy that the time with an amplitude greater than 100% of T44 response totalled 6.7 seconds in the six month period. The time with an amplitude greater than 80% of T44 totalled 39 seconds. These results assume that the speeds of the trucks on the bridge are the same as the speeds at the WIM site. In this case the average speed of the trucks averaged almost exactly 100 kph. (Culway sites are usually in valleys, so that trucks are up to speed.)

These results indicate just how rare the extreme responses are. To achieve a loading of 90% of the design truck in adjacent lanes, which is the prescribed load for initial design of a beam supporting both lanes, requires estimation of the joint probability of two trucks with combined effect exceeding 1.8 times the single lane load. This is discussed below.

4.4 Fatigue loading

The Rainflow analysis generates a matrix counting cycles of response in 5% increments of mean and range with reference to a T44 truck. The Rainflow count of stress ranges only, excluding mean data, is given in Table 2.

Amplitude X T44	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15	1.2	1.25	1.3
Slow Lane Count	144563	147022	63969	22826	12080	22637	21888	22497	21723	20485	22479	30014	42777	30116	8125	2378	407	65	33	28	18	17	14	6	6	1	2
Fast Lane Count	6312	6548	3649	968	588	1037	1022	1036	1054	1098	1219	1744	1835	880	250	97	15	1		1							

Table 2 – BM cycle count by Rainflow, 15m span, Hume Freeway, Jan-Jun 2000

The fatigue loading curves for the two lanes on the Hume Freeway are shown in Figure 9. These curves indicate that most of the fatigue damage is from the many cycles with an amplitude about 0.6 of that from a T44 truck. There are very few cycles with amplitude above 0.8 of that of a T44 truck. Less than one cycle in one thousand is above this level. (Cycles with amplitude less than 0.25 of that from a T44 truck are ignored.) The implications of this distribution for fatigue design will be discussed later. It is obvious that the position of the constant amplitude fatigue limit (endurance limit) of a structural detail in relation to the bulk of the fatigue loading has a critical impact on fatigue life.

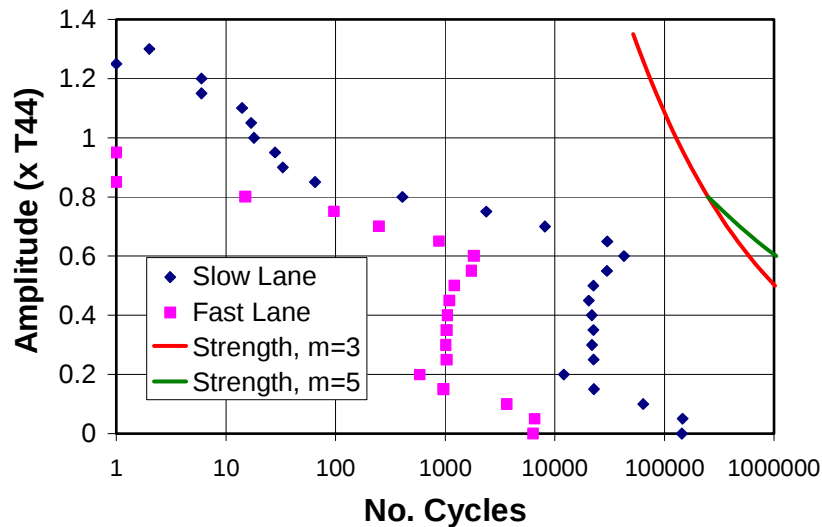


Figure 9 – Fatigue loading, BM in 15m span, Hume Freeway northbound, Jan-Jun 2000

Certainly for fatigue loading multiple presence is so rare that its contribution to fatigue damage is negligible and can be ignored.

A typical fatigue strength curve is shown in Figure 9. It can be seen that a rigorous Miner's summation of fatigue damage is easily carried out to estimate fatigue life. This facilitates a quick assessment of fatigue damage in the structure. This is the basis for verifying fatigue loading specifications in the new Austroads bridge design code, reported elsewhere in this conference [4].

4.4 Reporting extreme events

All trucks which generate a response in excess of a user set threshold, typically 1.0 x T44 response, are reported. As mentioned before, peak response is not necessarily associated with peak GVM.

5 APPLICATIONS

The software is proving to be a powerful tool for assessing existing traffic load effects and trends, and for structural risk assessment of existing bridges. Much research has been carried out on ultimate strength and time dependent effects such as corrosion and fatigue [8], but the probabilistic model of live load effect is often inadequate for a fully probabilistic assessment of the risk of failure. The following sections outline some of the applications of the software.

5.1 Traffic load models

Studies of bridge response over spans ranging from 2.5m to 100m using Culway data from intercity freeways, urban freeways and regional routes in Victoria indicate that the critical trucks for shorter spans, less than 50m, are low loaders or mobile cranes, not conventional truck-trailer configurations. One single event detected so far on several routes over several years dominates all load events. It was the rear four axles of a low loader with a total of 62 tonnes on these axles. It produced a response closely equivalent to that due to M1600 loading over spans ranging from 6m to 20m. On short spans the response was up to 60% higher than that due to T44 loading.

5.2 Traffic load trends

The analysis of bridge response over a succession of years permits a more precise prediction of trends in truck loading in terms of its effect than does an analysis of truck fleets and payload data. This study has been used to confirm projections of vehicle and axle mass growth used in defining fatigue loading in the revised Austroads bridge design code [4].

5.3 Fatigue loading and assessment

The application of the software to the development and verification of the draft fatigue loading rules of the revised Austroads bridge design code [4] is the subject of a companion paper and will not be elaborated here.

Fatigue assessment of existing bridges involves the use of WIM data to estimate the remaining life at detail at current traffic levels.

5.4 Structural risk assessment of existing bridges

Worldwide there are problems of determining the capacity of ageing bridges to carry future traffic loads. The software has been used to assess the integrity of a suite of reinforced concrete T-beam bridges, mostly built before the Second World War, but still in service in Victoria [2,6]. 154 simply supported spans ranging from 6m to 12m were checked. This study was aided by detailed assessment of strength and its sensitivity to the parameters affecting strength [7]. By assigning bias and coefficients of variation to these parameters as well as those on load effect measurement it was possible to arrive at a probabilistically based risk assessment of these bridges as a function of span and the spacing of the longitudinal beams. The results indicate high sensitivity of risk with respect to spacing of beams, and a slight improvement in reliability at 12.2m span. An unacceptable level of risk is apparent for spans of 6.1m and 8.5m, even with standard spacing of 1.8m. A suite of flat slab bridges found throughout Victoria are also under review. These continuous slab bridges have spans typically 3.6m and 4.5m.

However, this analysis assumed that the critical load case involved just one truck, taken from the prior history of trucks extracted from many WIM sites in Victoria over several years. The presence of two heavy trucks at once on these bridges, located on routes with typically less than 200 trucks per day passing, was considered of sufficient low probability to be ignored. In other words, a deterministic approach to loading was taken, leaving it to the asset manager to decide on whether to keep these old bridges, or strengthen or replace them.

5.2 Multiple presence

The deterministic load model for ultimate strength used so far in these investigations is inadequate for proper probabilistic risk assessment. An approximate method of determining peak response from multiple presence in adjacent lanes has been presented previously [5], and is currently being updated with a more rigorous method. Preliminary results indicate that the return period for concurrent loading in adjacent lanes exceeding 90% of the single T44 lane loading is of the order of thousands of years on these rural routes. It will be possible to replace this prescriptive load with a load with a 1000 year return period for being exceeded, equivalent to the wind load criterion.

The methodology is also being applied to heavily trafficked routes with dual carriageway and separate bridges for each direction of traffic. From §4.3 and Figure 8 it can be seen that even on a heavily trafficked route such as the Hume Freeway the percentage of time at high levels of response is extremely low. The method looks at the probability of the response in the slow lane being at a certain level when a given truck in the fast lane is also present. This generates a probability distribution function for combined loading, which depends as well on the load distribution factors applied to a girder for loads in an adjacent lane. For spans less than 40 metres one can ignore the possibility of two trucks present in one lane combined with a truck in the other.

For traffic halted on bridges, as happens in built-up regions, there is still room to consider the low probabilities of two extremely heavy trucks being in adjacent lanes in the right position to produce maximum load effects on the bridge.

6 CONCLUSIONS

A method of processing highway weigh-in-motion data has been developed which focuses on bridge response as much as truck statistics, taking advantage of all the truck parameters measured by the WIM system. Insights have been gained into

- characteristics of current truck traffic
- characteristics of extreme load events
- sensitivity of response to span and shape of influence function
- probabilities of extreme multiple truck presence loading on bridges
- trends in truck gross vehicle mass, axle mass and axle configurations
- fatigue loading and fatigue response spectra
- risk assessment of ageing bridges
- verification of traffic load assumptions in highway bridge design specifications

The methodology provides a powerful tool for cost effective management of ageing bridge systems and assessing the significance of future trends in truck fleets for bridge integrity.

7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of VicRoads in supplementing the resources of the Department of Civil Engineering at Monash University and co-funding this research with an Australian Research Council APAI award. The data analysis software is a product of Quadcore Pty. Ltd., Australia.

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