Fatigue Design in the New Australian Bridge Design Code

P. Grundy, Em. Professor, Department of Civil Engineering, Monash University
G. Boully, Senior Bridge Engineer, VicRoads

SYNOPSIS

The introduction of SM1600 Loading in the new AS5100 Bridge Design Code provided the opportunity to bring the fatigue design rules up to date. The new loading looks ahead and accommodates the actual trends of truck traffic loading. The new standard fatigue assessment uses the concept of the equivalent number of cycles of the stress range resulting from the passage of an M1600 load, without the UDL component. A160 loading is used for very short span elements. The effective number of cycles is a function of the current number of trucks per day per lane, the route, and the span, *L*.

$$n_{M1600} = 0.70 \times (current\, no.heavy\, vehicles / lane / day) \times 2 \times 10^{4} \times L^{-0.5} \times (route\ \ factor)$$

Two "fatigue design trucks" were initially proposed which accurately developed the average fatigue damage per truck on different routes. However, they required fatigue damage calculations by the rainflow method. They were replaced by reference to the stress range of an M1600 load, which required the introduction of a factor based on span.

Advantage is taken of software which analyses Culway weigh-in-motion data for its structural effect in specific locations and for specific spans. The fatigue damage per truck varied from highest on interstate routes to lowest on urban main roads.

Current annual growth rates of the freight task – highest 6.5% on Hume Freeway – were consistent with weigh-in-motion data indicating 3.1% p.a. growth in the number of trucks, 2.1% p.a. growth in 2-axle mass and 2.5% p.a. growth in 3-axle mass for the same route. These factors compounded to give an annual growth in fatigue damage of 9-15%. These data indicate that the fatigue limit state will be highly significant for short span bridges on heavily trafficked routes in the future.

1 INTRODUCTION

This paper presents an overview of the work done in developing the fatigue provisions for the new Australian Bridge Design Code AS5100.

The principal challenges included ensuring that the fatigue design provisions:

(a) accurately represented fatigue loading for all spans and classes of route,
(b) were consistent with the vehicles and concepts underlying the new SM1600 traffic design live loading;
(c) modelled growth in heavy vehicle traffic in traffic volume, types of vehicle and vehicle and axle mass., and
(d) were consistent with fatigue design in AS4100, Steel Structures .

This paper reviews the development of the fatigue loading model. Calibration of the model against Culway weigh-in-motion data is described. Finally, projected growth in volume of traffic and magnitude of vehicle and axle mass, which is very significant, is incorporated in the fatigue loading model.

The paper is restricted to steel structures and the use of M1600 loading as the reference load. Space does not permit review of the A160 fatigue load or fatigue assessment of reinforced concrete structures.

2 BASIC FATIGUE DESIGN FOR STEEL ELEMENTS

2.1 Fatigue Strength

Bridge fatigue design follows the same rules as AS4100, with the same fatigue strengths of details as defined in that standard. A typical fatigue strength curve, one of the family, is shown in Figure 1.

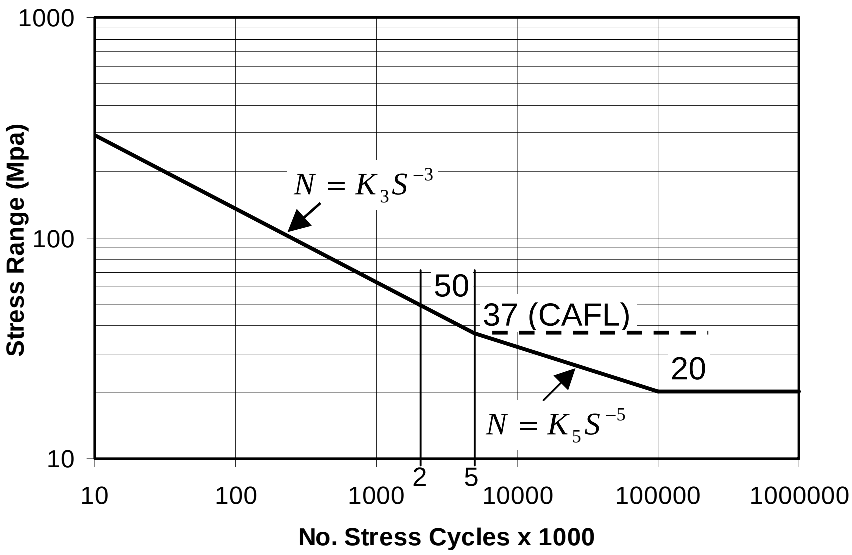

Figure 1: Design S-N Curve for Detail Category 50 under Variable Amplitude Loading (S = 50 MPa at 2 million, 37 MPa at 5 million and 20 MPa at 100 million cycles)

The two slopes of the *S-N* curve are active in bridge design because there are always many cycles below the constant amplitude fatigue limit (CAFL), but enough above this limit for all stress cycles above the cut-off at 100 million cycles to contribute to fatigue damage. For efficient design advantage must be taken of the flatter slope for stress below the CAFL.

2.2 Fatigue Loading

When a truck crosses a bridge it generates a number of cycles of stress of varying amplitude. *Fatigue damage* is defined as the fraction of the design life used. Under variable amplitude loading, using Miner's summation, damage, D, is defined by

$$D = \sum_i \frac{n_i}{N_i} \tag{1}$$

where

n_i = no. cycles applied at stress range S_i

N_i = no. cycles to design limit at stress range S_i

When D exceeds unity the fatigue limit state has been exceeded.

The fundamental concept behind the proposed fatigue loading rule for AS5100 is to represent the damage of a truck as a proportion of the damage due to *one* cycle of stress imposed by the passage of an M1600 truck without the UDL component. The amplitude of this cycle is the range from the lowest stress to the highest stress generated in that passage. The M1600 loading has been selected because this information is generated in the design process.

2.3 AS5100 Fatigue Loading Rule

The fatigue design traffic load effect is calculated as 70% of a single A160 axle or 70% of a single M1600 moving traffic load , without UDL, whichever is more severe. The load factor is 1.0 and the factor for full dynamic load allowance, $(1 + \alpha)$, is applied.

The number of cycles of the design load effect, n_{M1600}, to be applied in the fatigue design life (75 years) is:

For 70% A160 axle load x $(1 + \alpha)$:

(current no. heavy vehicles per lane per day) x 4×10^4 x (route factor). (2a)

For 70% M1600 truck load x $(1 + \alpha)$:

(current no. heavy vehicles per lane per day) x 2×10^4 x $(L^{-0.5})$ x (route factor), (2b)

where L is the span in metres.

This formulation is based squarely upon the concept of the damage per truck compared with the damage of one cycle of stress from the design truck. It includes an allowance for growth in both traffic and average axle loads, which compound annual growth in fatigue damage. It takes into account the dependency upon span of the average fatigue damage per truck compared with the reference fatigue load.

3 DEVELOPMENT OF THE FATIGUE LOAD FORMULA

3.1 Design fatigue truck versus standard M1600 truck

Roberts *et al* [1] developed a design fatigue truck which would generate the same fatigue damage on typical routes as the actual mix of heavy vehicles. This was successfully and accurately done, but it left to the designer the requirement of identifying the number and range of stress cycles with the passage of the fatigue design truck. This would require a new analysis of each structure for a design vehicle different from that used for ultimate strength and serviceability limit states, and sophisticated analysis using the rainflow or reservoir method to determine the number and amplitude of stress cycles.

Hence it was decided to use the amplitude of response to the M1600 load (without UDL) as the reference truck. This requires the development of new factors on the equivalent number of stress cycles to achieve the same fatigue damage as before. It removes the need to analyse the bridge for a fatigue truck, and the need to calculate cumulative damage.

3.2 Use of Culway weigh-in-motion data

A software package BRAWIM® developed by Grundy *et* al [2] was used to confirm the fatigue loading from the design fatigue truck and to assist in the calibration. This software analyses Culway data from a given site for a given period. In addition to providing the usual summary truck data it determines the response of a bridge with specific spans and influence functions for load effects at specific locations. The results include

- histogram of the number of peak responses versus amplitude of response,
- histogram of the fraction of time spent at each level of response
- histogram of the number of cycles versus amplitude of response (by rainflow analysis)
- equivalent number of cycles at CAFL versus response amplitude of CAFL
- histogram of the number of cars between trucks
- histogram of the number of trucks versus speed

BRAWIM® has proved very useful in the reassessment of ageing bridges. The output of response cycles by rainflow analysis has been particularly useful for calibrating the fatigue design equation.

Figure 2 is a histogram of the gross vehicle mass of trucks measured in the slow southbound lane of the Hume Freeway at Wallan, north of Melbourne, for the period January to June, 2002. The high numbers of trucks at approximately 45 and 65 tonnes correspond to fully laden semitrailers and B-doubles respectively. There are few empty trucks on this route.

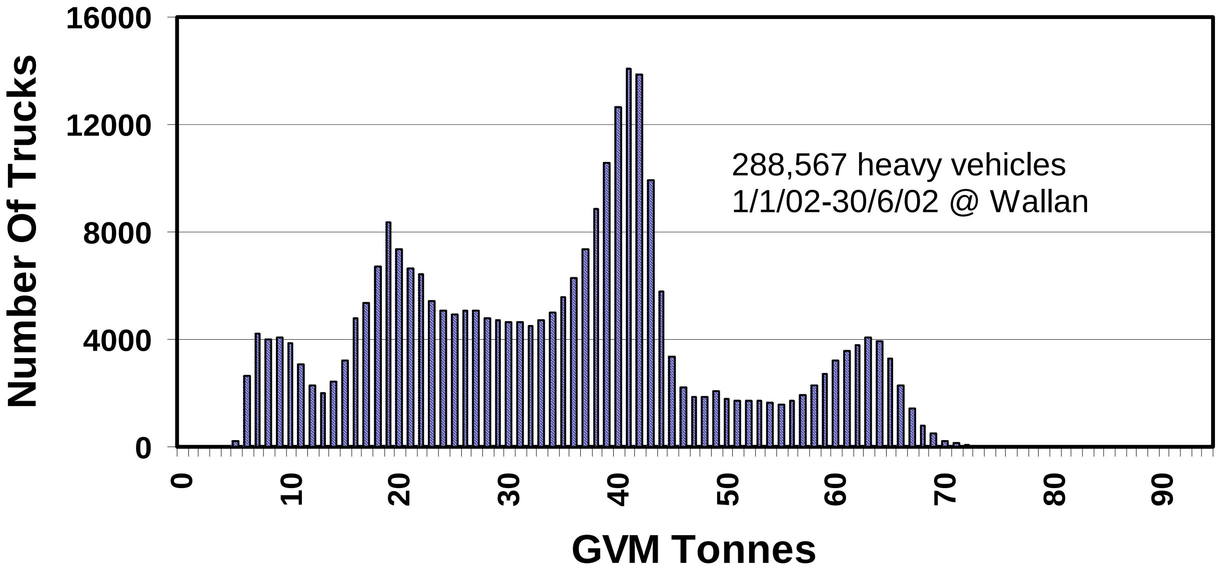

Figure 2: Histogram of Gross Vehicle Mass, Hume Freeway

Details of axle mass, sorted by axle group, are shown in Table 2. The mean axle mass is increasing 2-3 % p.a. This is significant in the estimation of fatigue life, discussed later. It is noted that at this Culway site the mean speed of trucks was 102 kph, with a standard deviation of 4.8 kph. A bridge of this span in this location would have a truck on it in the slow lane for 2.3% of the time. The volume of trucks in the fast lane was about 4% of the volume in the slow lane.

(Tonnes)	Steering	1 axle	2 axle	3 axle	4 axle
Count	288,567	37,821	306,547	272,873	69
Max per axle	13.9	15.4	13.4	14.4	12.8
Mean per axle	5.12	5.61	6.09	5.50	4.71
Std Dev'n	0.78	1.96	1.89	1.75	2.62

Table 1: Axle Mass Details, Hume Freeway at Wallan Southbound, January – June, 2002

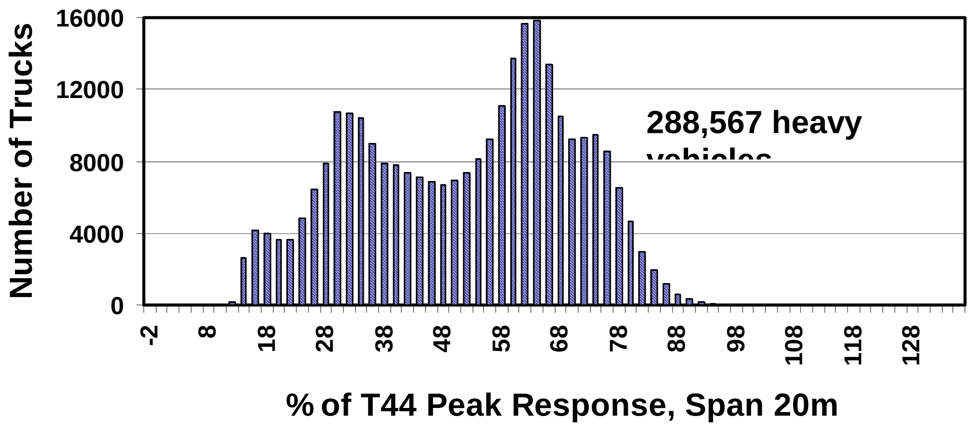

Figure 3: Peak Bending Moment Compared with T44 truck (highest 135%)

Figure 3 depicts the peak response (bending moment near mid span) of a simply supported girder bridge spanning 20 metres, compared with the response to a T44 truck. (These charts were developed prior to the introduction of M1600 loading. In this case the response to 100% T44 equals 63.5% of the M1600 load without the UDL.)

It is observed that the six highest peak responses, ranging from 135% down to 122% of the peak T44 response, included three low loaders, two mobile cranes, and a 10-axle truck with 51.2 tonnes on the rear quad axle group. Exceptional load effects come from exceptional rather than typical vehicles. However, these have negligible influence on fatigue damage, as they are so rare.

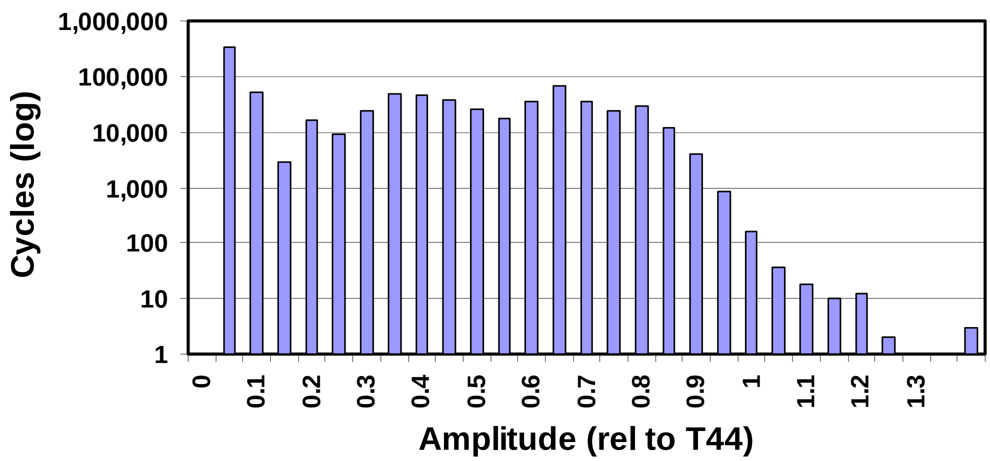

Figure 4: Count of Cycles Versus Amplitude of Response by Rainflow Method

The history of response is obtained by stepping each measured heavy vehicle across the bridge, using the influence line to calculate the response at the point of interest. A rainflow analysis is performed on the entire concatenated sequence of all trucks to produce the histogram counting the number of stress cycles. The result is shown in Figure 4.

In using this data to estimate cumulative damage using the cubic exponent $\left\{\sum n_i\, S_i^3\right\}$, one would neglect cycles with amplitude less than 0.2 x T44, being too low to cause any damage.. It is noted that cycles at amplitudes greater than 0.8 x T44 amount to only 1.2% of all effective cycles. But these cycles are important for activating the fatigue damage process by exceeding the CAFL.

3.3 Damage per Truck

To arrive at the equivalent number of cycles of S_{M1600} (stress range due to M1600 without the UDL) to produce the same fatigue damage as that from the actual truck traffic we write:

$$n_{M1600}\, S_{M1600}^3 = \sum n_i\, S_i^3 \tag{3}$$

In the example considered we find n_{T44}, corresponding to S_{T44}, is 54,604. n_{M1600}, corresponding to S_{M1600}, is 13,939. There were actually 288,567 trucks, so the *damage per truck* is 13,939 ÷ 288,567 = 0.0483 times that of an M1600 cycle of stress. The equivalent number of M1600 cycles to be applied in the design life is (damage per truck) x (No. trucks in the design life).

3.4 Effect of Span

Span has a profound influence, both on the amplitude of actual stress cycles compared with that due to M1600, and on the number of cycles. For very short span bridges each axle group is an independent load event. For short spans, around 15m, the axle groups maintain a fairly constant load effect equal to one axle group in the middle of the span. For long spans the entire truck is the load for one significant stress cycle.

BRAWIM® was used for rainflow analysis on spans ranging from 2.5 metres to 100 metres. The equivalent damage per truck was found using the exponents 3 and 5, corresponding to the two slopes of the S-N curve. The results are shown in Figure 5.

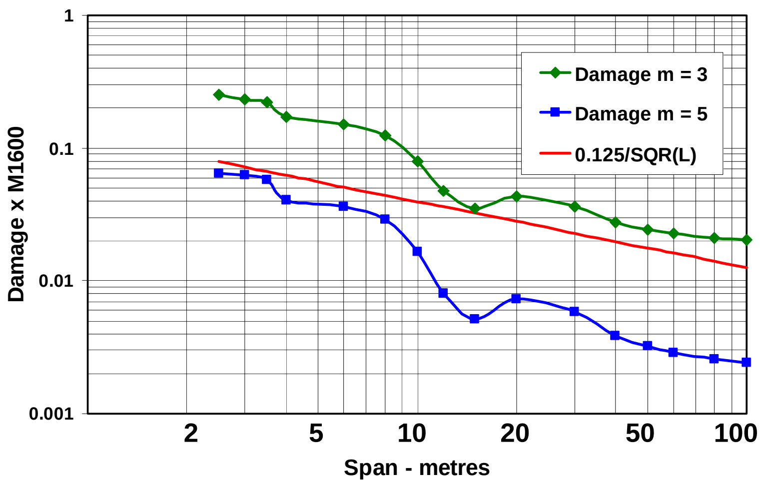

Figure 5: Fatigue Damage per Truck, Hume Freeway, 2001, Versus Span

The results indicate an order of magnitude difference between fatigue damage per truck for short spans compared with long spans. Fatigue can become the governing limit state for design of short span steel bridges on heavily trafficked routes. With dead load stresses becoming significant in longer spans, fatigue virtually disappears as a significant factor in spans exceeding 50 metres, provided proper standards of detailing are maintained and issues of differential deflection between adjacent girders are addressed.

There are two curves in Figure 5, corresponding to the two slopes of the S-N curve. If the majority of the stress cycles have an amplitude exceeding the CAFL of the S-N curve, then the upper curve applies. If the majority are below the CAFL the lower curve applies. The true average fatigue damage per truck lies somewhere between these two curves, tending to the lower curve for short spans, where there will be a huge number of significant stress cycles, and tending to the upper curve for long spans with fewer significant stress cycles.

The dip in the curves at about 15 metre span is attributed to the typical spacing between axle groups on trucks. For this span the amplitude of the stress cycle is determined by an axle group positioned at midspan (for positive bending moment). The stress does not fluctuate as it would for shorter spans when the next axle group comes on as the first axle group moves off. Beyond a span of 20 metres two axle groups on the bridge contribute significantly to the amplitude.

3.5 Standard fatigue damage per truck

A simple compromise curve expressing damage per truck lying between the bounds of m = 3 and m = 5 in Figure 5 has been chosen:

$$(\text{Damage equivalent M1600 per truck}) = 0.125\,L^{-0.5} \tag{4}$$

This curve is shown in Figure 5. One arrives at the proposed formula by estimating the equivalent number of cycles as

$$(\text{No. trucks per lane per day}) \times 365\ (\text{days}) \times 75\ (\text{years}) \times 0.125\,L^{-0.5} = 3422\,L^{-0.5} \tag{5}$$

If trucks in more than one lane affect a structural member, then trucks in all affecting lanes must be included. The proposed rule (Equation 2b) uses a constant of 2×10^4 instead of 3422. This allows for the very substantial growth in traffic volume and average axle mass anticipated for all routes over the design life of 75 years (for fatigue only).

It should be noted that for short spans less than 4 metres the alternative A160 axle load will most likely be the critical fatigue loading rather than the one with reference to M1600. A160 loading is not discussed in this paper.

3.6 Effect of Route

Hume Freeway is distinguished by being the most heavily trafficked interstate highway with the lowest proportion of empty trucks. On any other route it will be found that the fatigue damage per truck is less than that applying to Hume Freeway. An indication of how different this can be is given in Figure 6, where the histograms of peak response for bending moment of a short (8.5m) span bridge for a variety of routes. The short span highlights the sensitivity to axle mass.

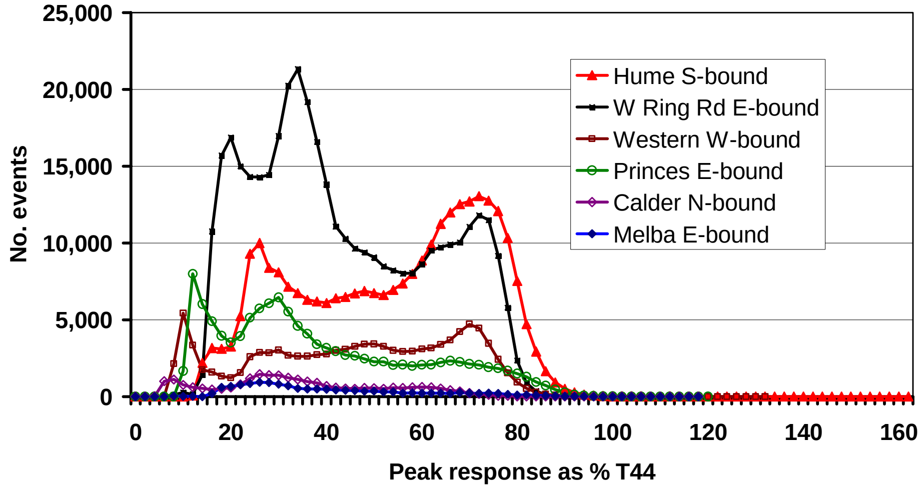

Figure 6: Comparison of Peak Response for Various Routes, Jan-Jun 2001, Span 8.5m

Although there were 395,000 trucks on the Western Ring Road (an urban freeway) compared with 282,000 on the Hume Freeway, the higher proportion of light and empty trucks meant that the total fatigue damage was about the same.

Analysing the data from these sites established different levels of damage per truck, as shown in Figure 7.

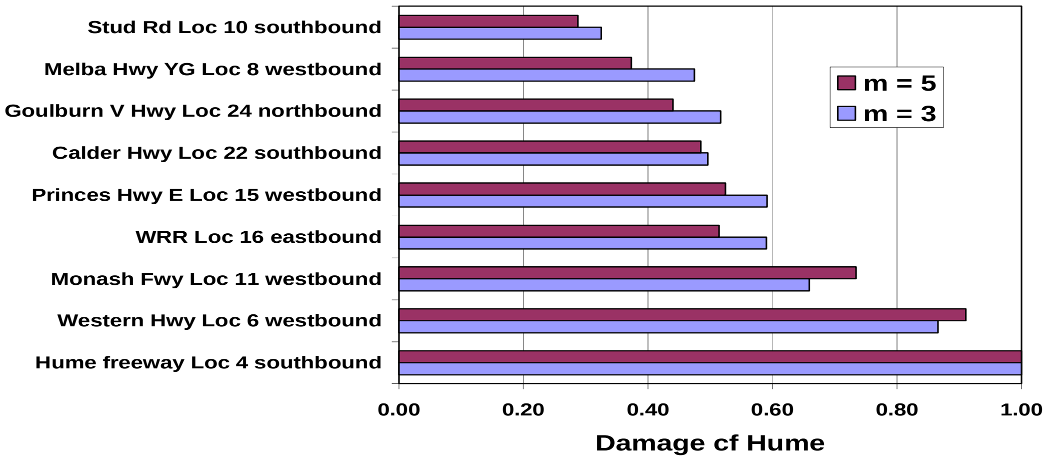

Figure 7: Relative fatigue damage/truck on different routes, compared with Hume Fwy

From these results it was possible to apply a *route factor* to the fatigue loading formula, shown in Table 2.

Principal interstate freeways and highways	1.0
Urban freeways	0.7
Other rural routes	0.5
Urban roads other than freeways	0.3

Table 2 – Route (fatigue reduction) factor

3.7 70% Reduction Factor

The fatigue loading has a reduction factor of 70% on the amplitude of the stress cycle derived from either M1600 or A160. This factor is introduced to bring the estimated stress amplitudes as close as possible to the most likely stresses in service. The two main reasons for this factor are

a) stresses are somewhat less than calculated by theoretical analysis due to the presence of load paths not considered in the analysis, and
b) trucks generally travel in the centre of marked lanes rather than extreme lateral design lane positions.

4 CURRENT AND FUTURE FREIGHT TASK

4.1 General

Culway summary data, from 1989 to 2001, was obtained for the Hume, Western, Calder and Melba Highways. This data was used to determine the number of trucks of each Austroads Category, the average mass of each truck type and the average total freight per day per lane. The majority of freight was transported on 5 and 6 axle semi-trailers in the early 1990s, trending to mainly 6 axle semi-trailers and 9 axle B-Doubles by the late 1990s.

This data was also used to determine the current freight task growth rate for each Highway and to estimate future growth rates. Reference was also made to traffic detector loop data, which classified vehicles by length. This data was used to investigate the distribution of commercial vehicles between different lanes on urban freeways.

4.2 Current Vehicle and Freight Data

The current average freight task and number of semi-trailers and B-Doubles per slow lane per day in each direction on each of the highways is shown in Table 3.

Highway	**Current freight task** Tonnes/ day/ slow lane	**No. Semitrailers**	**No. B-Doubles**
Hume Highway	27,000	950	350
Western Highway	8,000	250	130
Calder Highway	5,000	180	45
Melba Highway	1,450	50	10

Table 3: Current Freight Task and Truck Numbers

The current average mass of semitrailers and B-doubles varies according to route, as shown in Table 4. These data indicate the more efficient use of trucks for long hauls interstate.

Road type	**Semitrailers**	**B-Doubles**
Current legal limit	45.5 t	68 t
Rural freeways and highways	34 t	50 t
Urban freeways	30 t	40 t
Urban highways and roads	27 t	35 t
Other rural routes (no data)	27 t (assumed)	35 t (assumed)

Table 4 – Current average vehicle mass

4.3 Projected Future Vehicle and Freight Data

Several concurrent projections have to be made about future freight movement over the design life of new bridges. These include:

a) The increase in total freight task each year;
b) The mix of vehicle types carrying the freight;
c) The increase in tare and gross mass of each vehicle type each year;
d) The distribution of trucks in different lanes travelling in the same direction and saturation levels.

The current approximate compound growth rates in freight task for rural routes ranging from the most highly trafficked (Hume) to low (Melba) are shown in Table 5. Note that the rate of growth in freight is necessarily higher than the rate of growth in gross vehicle or axle mass.

Highway	Current Compound Rate of Growth
Hume	6.5% pa
Western	5.0% pa
Calder	5.0% pa
Melba	1.5% pa

Table 5 – Current Freight Task Growth Rates

Reference to Table 4 indicates that the average mass of current semi-trailers and B-Doubles is approximately 0.75 times the corresponding current legal mass vehicles operating on major rural highways and freeways. Lower ratios apply to urban roads and other rural roads. Assuming this ratio remains constant for future heavier vehicles, future average mass semitrailers would be about 55t and B-Doubles about 85 t based on SM1600 semitrailers of 75 t and B-Doubles of 112 t. However, if volume limits tend to restrict maximum loads more often, future average mass vehicles are more likely to be 45 t semi-trailers and 68 t B-Doubles, the same as the current maximum mass of Higher Mass Limits vehicles. This latter assumption has been used in the development of growth projections for fatigue loading.

The freight task projections are confirmed by measured growth rates in vehicle and axle masses over 2½ years on the Hume Freeway, as follows:

Gross Vehicle Mass	3.3%	
2-Axle Mass	2.1%	(Current average ~ 6.0 t/axle)
3-Axle Mass	2.5%	(Current average ~ 5.5 t/axle)
Trucks per day	3.1%	
2-Axle Groups per day	3.9%	
3-Axle Groups per day	5.4%	

These data indicate the increasing share of B-Doubles in the freight task.

It has been assumed that allowable loads on vehicles will continue to steadily increase and that the above increase in the average mass of semi-trailers and B-Doubles will occur linearly over a period of 50 years. The above data added support to the Route Factors adopted in the draft code (Table 2) supported by the evidence of Figure 7.

Drawing this information together, and applying a ceiling of 4000 trucks/day/lane we arrive at the truck traffic projections into the future for the four routes studied in detail. In the case of dual carriage ways (Hume, Western and Calder), the projections apply to the slow lane. The projections are shown in Figure 8.

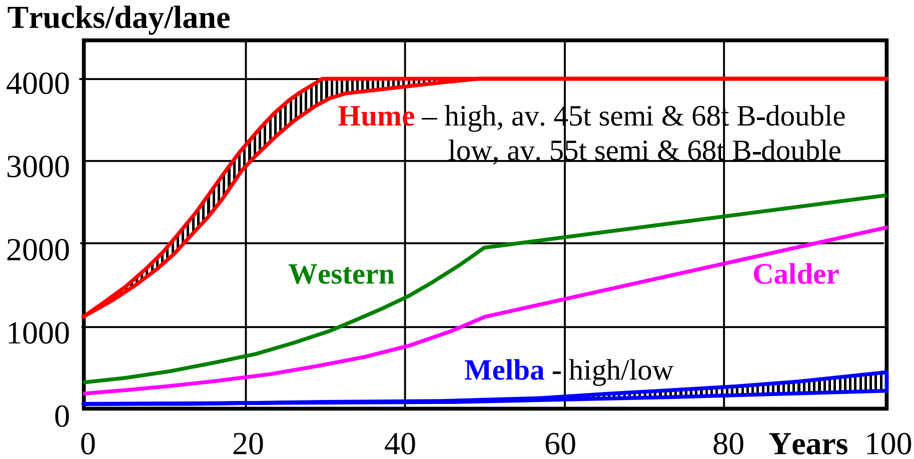

Figure 8 – Truck traffic projections from current levels on four rural routes

5 TRAFFIC IN MULTIPLE LANES

A study of Culway data reveals that more than 95% of truck traffic is in the slow lane on rural highways, whereas typically the most heavily trafficked lane on urban freeways and roads carries 55-65 % of all trucks. Where a member being assessed for fatigue supports more than one lane all the traffic in the one direction must be included in the fatigue loading. Conversely, where a member is affected by traffic in one lane only then the count of trucks is restricted to that lane.

The AASHTO LRFD Bridge Design Specifications (1998) and the Austroads Traffic Manual specify saturation levels of between 16,000 and 20,000 vehicles per day per lane. For commercial vehicle counts of between 20 and 25%, as on the Hume Freeway, a saturation level of about 4000 to 5000 trucks per lane per day is derived. Based on current freight growth rates and the assumed linear increase in allowable truck mass, it is estimated that saturation effects will start to affect flow in the slow lanes of the Hume Freeway in about 30 years, as indicated in Figure 8. If no further increase in truck mass is allowed, it is estimated that this time will be reduced to about 15 years.

Multiple presence of trucks in adjacent lanes, or in the same lane for longer spans, is so rare that it need not be considered in fatigue analysis. For example, a bridge of 15 m span on the Hume freeway in traffic at the average speed (100 kph) would have trucks present in the slow lane about 2.5% of the time, and in the fast lane about 0.12% of the time.

6 GROWTH IN FATIGUE DAMAGE

The growth analysis of Hume Freeway data referred to above was extended to determine fatigue damage per truck from Culway data. The growth depends on the span and on the exponent, m, of the S-N relationship. The results are presented in Figure 9 for bending moment at midspan. The curve for m = 5 is considered to be the better fit to growth predictions at present. To estimate the total annual growth in fatigue damage the damage per truck shown in Figure 9 must be multiplied by 1.031 to include the growth in the number of trucks. The result is a total annual growth rate in the range 9 - 15%. This is a massive rate which will slow down in the future, but not before making fatigue a very significant limit state for short span bridges on interstate highways.

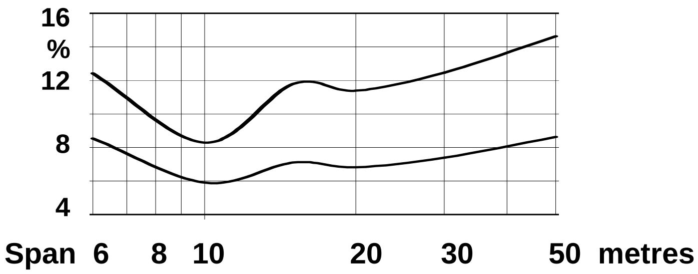

Figure 9: Growth p.a. in damage/truck

7 CONCLUSIONS

The proposed fatigue design rules of AS5100 present an accurate fatigue assessment of steel members, within the limits of uncertainty associated with fatigue, using the stress range generated by the passage of the M1600 load without the UDL.

Very large growth rates in fatigue damage are being experienced, especially on interstate highways, where fatigue will be a most significant design limit state for short span bridges.

In an environment of monitoring and maintenance, where intervention is possible to prevent actual collapse, the fatigue limit state is one where economic risk is the dominant consideration. The adoption of 75 years as the target service life implies approximately 2% probability of fatigue "failure" after 75 years.

Good fatigue design depends first of all on good detailing. Only then do the requirements of standards fine tune the design.

8 ACKNOWLEDGEMENTS

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