Comparison between AS5100 fatigue load model and fatigue from representative traffic

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ABSTRACT: Bridges provide an irreplaceable role in road transportation, and so it is vital to properly manage them. The traffic loading caused by trucks is decisive in bridge design and assessment, because it not only controls the strength design, but critically also the fatigue life. The current Australian bridge fatigue model in AS5100.2 was mainly developed by Prof. Paul Grundy in 2004. In this model, the bridge fatigue damage caused by each heavy vehicle is quantified as a certain number of M1600 load model vehicles. Although this model fulfilled the need at the time, it may not precisely predict the fatigue damage. Thus, this research compares the fatigue damage predicted by code with the fatigue damage caused by representative traffic, using extensive simulations of real traffic scenarios. This paper contributes to the development of the next generation of the AS5100 fatigue load model based on extensive collections of new traffic data.

1. INTRODUCTION

Bridges are an important component of the road transportation system, giving vehicles the capability of traveling at different heights of the same land spaces and crossing obstacles such as rivers and cliffs. In civil engineering, bridge design mostly focuses on strength checks. However, fatigue checks deserve as much attention as strength checks as it is a frequent cause of failure. Over the service life of the bridge, the varying loads caused by traffic may result in millions of loading cycles on the bridge, which can lead to a gradual reduction in the strength of the bridge components until they fail. The simplified fatigue load models in bridge standards typically aim to produce equivalent fatigue damage from real traffic to simplify the fatigue design or assessment process for bridges. The existing Australian bridge fatigue load model is included in AS5100.2. This model equates the fatigue damage caused by Australian traffic to the fatigue damage caused by a certain number of the standard M1600 load (without the accompanying UDL). Although the model addressed a need for fatigue prescriptions, it has several limitations that could lead to discrepancies between its estimation and the true value of fatigue damage attained in practice. Hence, the main contribution of this study is to examine the ongoing applicability of the AS5100.2 fatigue model by making a comparison to the fatigue damage caused by present Australian representative traffic and the model-predicted damage. In addition, some of the findings from this study provide insights into the next Australian bridge fatigue model.

2. AS5100.2 FATIGUE LOAD MODEL

The current AS5100.2 fatigue load model was mainly developed by Prof. Paul Grundy, Monash University (Grundy and Boully, 2004). The model was calibrated using weigh-in-motion (WIM) data mainly collected from four Melbourne roads in 2002: Hume Freeway, Western Freeway, Calder Freeway and Melba Highway. The load effects caused by the measured traffic were calculated using influence lines. There were several assumptions applied in the derivation of the model, including on dynamic effects and traffic growth.

2.1. Model illustration

AS5100.2 provides two fatigue load models: 1) for local effects: 70% of the load effects of a single A160 axle; 2) for global effects: 70% of the load effects of a single M1600 moving traffic vehicle. The critical load model is selected. The calculations for the numbers of their peak-stress cycles being used in bridge fatigue capacity check are from eq. (1) and eq. (2), respectively.

The number of fatigue stress cycles, N, depends on the load. For the local effects loading it is:

$$N = \text{ADTT} \times \ (4 \times 10^4) \times r \tag{1}$$

And for global effects, it is:

$$N = \text{ADTT} \times (2 \times 10^4) \times L^{-0.5} \times r \tag{2}$$

where ADTT is the average daily truck traffic (i.e. trucks with total mass over 3.5 tonnes) per lane per day; the route factor, r is given in Table 1; the effective span L (in metres) is defined by either the actual bridge span or the length that the load effect being considered on the bridge deck. For bridges that span longer than three metres, the 70% M1600 model without UDL (eq. (2)) is applicable.

Table 1: Route factors, r, in AS5100.2 model.

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

2.2. Model tools

The S-N curve fatigue theory (Wöhler, 1860), Rainflow Algorithm (Lee and Tjhung, 2011), and Miner's Rule (Miner, 1945) were used in the derivation of the AS5100.2 model. The S-N curve theory quantifies the material fatigue process as periodic stresses' ranges and their corresponding number of cycles when fatigue failures happen. It consists of two slopes, where the slope changes on the constant amplitude fatigue limit (CAFL). For structures whose stress ranges are above the CAFL, new fatigue micro-cracks will initialize. Contrarily, any existing micro-cracks will develop. The Rainflow algorithm extracts the amplitude variations and their corresponding repeating times from a data signal. By applying Miner's rule to the Rainflow outcomes, the fatigue damage caused by complex stresses is accumulated.

2.3. Assumptions

Based on the S-N curve fatigue theory, the total fatigue damage in M1600 is given by:

$$\frac{\sum((1+\alpha_i)\,S_i)^m\, n_i}{((1+\alpha_{M1600})\,S_{M1600})^m} \tag{3}$$

in which the dynamic amplification factor under each load is assumed to be:

$$\alpha_i \equiv \alpha_{M1600} \tag{4}$$

where S_i^m is the i-th load amplitude from the rainflow algorithm, n_i is the corresponding number of cycles of the i-th load amplitude, S_{M1600}^m is the largest load amplitude of the bridge when a M1600 load passes, and the exponent m corresponds to the two slopes of the S-N curve ($m = 3$ for stress greater than the CAFL and $m = 5$ when the stress is less than the CAFL).

As determining the dynamic factors α_i for each traffic load effect was infeasible at the time, the model assumes eq. (4) so that the dynamic factors in eq. (3) for the traffic loads and the M1600 truck load cancel. Finally, the fatigue damage per truck (quantified by M1600 load) is taken to equal the total fatigue damage divided by the number of trucks passing the bridge.

2.4. Model limitations

The first limitation of AS5100.2 fatigue load model is that it may no longer match 2020's Australian traffic condition since the WIM data used to calibrate it was collected in 2002. During the intervening two-decade period, there have been substantial changes caused by economic developments and amendments in transportation policy on Australian heavy vehicle numbers and weights. Although the AS5100.2 model had integrated redundancy for future traffic growth, it remains necessary to verify the continuing applicability of the model under recent Australian traffic conditions.

Secondly, the heavy vehicles were envisaged to cross bridges on their own in a single lane; combinations of multiple random truck crossings were not considered. This is not consistent with real-world traffic, since it is commonly observed that multiple trucks cross a bridge at the same time, especially on bridges with longer spans. Therefore, the model's predicted bridge fatigue damage might be biased.

Lastly, the AS5100.2 fatigue model may not be able to precisely match the real fatigue damages for all bridge components. Referring to eq. (2), the measurements of corresponding damages for different bridge components only rely on the criteria of the span L selection. However, a single equation may be insufficient, considering the wide variety of bridge components and their traffic loading responses. The consequence of using the current fatigue model is that some bridge components' fatigue designs could be over-radical or over-conservative.

3. METHODOLOGY

This research was based on numerical simulation, where an in-house Python package, PyBTLS, was used. PyBTLS can simulate traffic data, perform load-effect calculations, and conduct some simple statistical analyses (e.g., block-maximum analysis (OBrien et al., 2015), peak-over-threshold analysis (OBrien et al., 2015), Rainflow algorithm, etc.). In this research, the Rainflow algorithm was applied to the load-effect data during the simulation. Once the simulation was completed, the outputs of the Rainflow algorithm were used to calibrate the fatigue model following eq. (3).

Consistent with AS5100.2, we adopted the same assumption for the dynamic factor α. Other general assumptions in this research included that 80% of the trucks were driven on the slow lane, cars were equally allocated on the lanes, and the traffic in different lanes is independent.

The core running processes of PyBTLS are shown in Figure 1. The approach used is similar to that in Melhem et al. (2020). Each PyBTLS configuration has been discussed in the following subsections.

3.1. *Traffic generation*

For the traffic generation in this study, the input WIM garage was collected from the West Gate Bridge (WGB) in 2016. The West-Gate Bridge consists of ten lanes in two directions (five lanes each), and the WGB garage file was summarized from the bridge's slow-lane WIM. Since the West Gate Bridge is part of the Melbourne M1 freeway, which is one of the busiest freeways in Australia, the WGB garage file is deemed representative of Australian trucks. Instead of using the congested headway model as most bridge strength research, (Bruls et al., 1996) indicated that the freeflow headway model may result in worse fatigue damage for a bridge. This indication has also been observed in this research.

Trucks with more than nine axles were neglectable because they were rare in the garage. Figure 2 illustrates the truck compositions (classified by axle number) of the WGB garage file, and Table 2 shows the maximum, mean and standard deviation values of each truck composition. The multiple peaks of a distribution of a specific truck class in Figure 2 indicate the full-load, half-load or empty status of trucks.

The hourly traffic flow profile (not volume) is based on data from a German motorway where the road traffic was characterised by high, low and flat patterns for different traffic conditions. These three traffic patterns have previously been applied in the Austroads bridge assessment project, by Melhem et al. (2020). In this work, the three traffic patterns were scaled to suit the 2020 truck traffic volumes of Hume Freeway, Western Freeway, Calder Freeway and Melba Highway. These volumes were taken from publically-available data sources (Department of Transport, Victoria, 2020), where the measured data are 5300, 1700, 1100 and 2100 trucks per day, respectively. However, due to traffic disrup-

Table 2: 2016 West Gate Bridge WIM data gross weight statistics (kN).

	2-axle	**3-axle**	**4-axle**	**5-axle**	**6-axle**	**7-axle**	**8-axle**	**9-axle**
Maximum	352.2	570.9	736.7	611.2	792.6	899.5	872.1	1384.1
Mean	72.2	141.1	173.1	227.5	282.2	384.2	382.7	436.8
Standard deviation	33.7	50.3	78.3	74.6	109.9	181.0	181.6	188.2

tions caused during the COVID-19 pandemic, scaling was based on the truck flow (Munawar et al., 2021). The 2020 statistics of the truck population for the four Melbourne roads are illustrated in Table 3.

In general, 2-, 3-, 6- and 9-axle trucks were the four most common types in 2020 Australian traffic, and the average truck weights increased with the number of axle numbers (except the uncommon 8-axle truck).

3.2. Bridge settings

The AS5100.2 fatigue load model was developed based on one influence line: that of mid-span bending moment in a simply-supported bridge. Here, we assess the limitations of this, by considering four influence lines, often related to locations of fatigue failure. The four influence lines used in this work are the mid-span bending moment for a simply supported bridge, the left-support shear force for a simply supported bridge, the mid-support bending moment for a continuous two-span bridge, and the left-support shear force for a continuous two-span bridge.

The bridge span has a profound influence on the quantifying of bridge fatigue damage, due to the number of axles, axle groups, and vehicles that can be present and influence the number and amplitude of load cycles that occur. To get a comprehensive fatigue model from the PyBTLS simulation, the bridge spans range from 3 to 100 metres for simply-supported bridges and from 15 to 100 metres for continuous two-span bridges (equal spans).

3.3. Selections of traffic duration and time step

For a representative fatigue model, the simulation period needs to be sufficiently long to ensure the typical traffic scenarios have happened on the bridge. Maljaars (2020) demonstrated that a 1-month traffic sample has led to an acceptable fatigue damage variation and a longer period resulted in a smaller variation. As explained in OBrien et al. (2021), the load calculation in PyBTLS is discrete in time. To avoid inaccuracies in this work, a 1-year (250 days, excluding weekends and vacations) traffic duration and a very small 0.01-second time step were chosen to progress the vehicles across the influence lines.

3.4. Amplification due to traffic growth

A robust fatigue model must have an allowance for the future growth of truck flow and truck weight. Without these redundancies, the coefficient in eq. (2) is 3422 (i.e. $365 \times 75 \times 0.125$) instead of 2×10^4, so the amplification in AS5100.2 is 5.85. For the code model, the predicted annual growth rates were 3.1% for the truck flow and 3.3% for the truck weight, which were observed from the Hume Freeway traffic, and were envisaged to last for 50 years only (Grundy and Boully, 2004). Thus, the average annual growth over a 75-year period is then 2.4% and this value is used for the comparison with the 2020 traffic. This comparison is exact for 75 years, but potentially inexact for shorter periods due to the complex growth trajectory assumed in the AS5100.2 model. The *i*-th year increment of fatigue damage N_i is quantified by:

$$N_i = [365 n_i \times ADTT_0] \left[iR^i - (i-1) R^{i-1} \right] \quad (5)$$

where $ADTT_0$ is the average daily truck traffic used to calibrate the model, R is the average annual growth rate (1.024 here), and n_i is the unit fatigue damage per truck.

3.5. Average vehicle speed

Interestingly, average vehicle speed is not usually considered in bridge fatigue research even though it can have a significant effect. For the same traffic flow, a higher mean vehicle speed results in a

Table 3: Truck volume by axle number for 2020 data (trucks/direction/day).

Site	2-axle	3-axle	4-axle	5-axle	6-axle	7-axle	8-axle	9-axle	Total
Hume Freeway	1751	875	240	250	1393	108	23	327	4968
Western Freeway	585	292	80	83	465	36	7	109	1658
Calder Freeway	380	190	52	54	303	23	5	71	1079
Melba Highway	721	360	98	103	574	44	9	134	2045

smaller vehicle density, so that the average number of trucks simultaneously crossing the bridge will reduce thereby altering the fatigue damage accumulation. This research set three different mean vehicle speeds (80 km/h, 100 km/h, and 110 km/h for fast-lane traffic and 60 km/h, 80 km/h, and 100 km/h for slow-lane traffic, respectively) for the simulation of Hume Freeway high-pattern traffic, to investigate the influence of the mean vehicle speed to bridge fatigue damages.

4. RESULTS

4.1. Fatigue Damage

Figure 3 presents the main outcomes of this research. It is found that the flat-pattern flow profiles have similar unit fatigue damage values to the corresponding low-pattern flows, so they are not plotted. From eq. (6) to eq. (9), the design life and growth yields a $5.85 \times 75 \times 365 = 160144$ factor. The selections of 365 days per year and 75 years are for consistent comparison to the AS5100.2 model.

The cumulative fatigue damages predicted by AS5100.2 (using both 2002 and 2020 traffic, 1500 and 5300 trucks per day, respectively) and by the models calibrated from the representative 2020 traffic for bridges with 15 and 100 m spans are plotted in Figure 4. Additionally, Figure 5 shows the plots of the same traffic patterns but with different mean vehicle speeds.

4.2. Calibrated Curves

Figure 3 also shows calibrated fatigue damage curves (as red lines) that may provide a basis for refinement of the AS5100.2 model. These are determined as multipliers of the ADTT, as follows:

- Simply supported mid-span bending moment:

$$160144 \times 0.125 \times L^{-0.7} \qquad L \geq 3 \text{ m} \tag{6}$$

- Simply supported left-support shear force:

$$160144 \times 0.088 \times L^{-0.7} \qquad L \geq 3 \text{ m} \tag{7}$$

- Continuous mid-support bending moment:

$$160144 \times 0.004 \qquad L \geq 15 \text{ m} \tag{8}$$

- Continuous left-support shear force:

$$160144 \times 0.02 \times L^{-0.4} \qquad L \geq 15 \text{ m} \tag{9}$$

5. DISCUSSION AND CONCLUSION

According to Figure 3, the unit fatigue damages are consistently overestimated by the AS5100.2 model across all scenarios, especially for the continuous two-equal-span bridges. After considering the traffic growth, the AS5100.2 model shows considerable conservatism in Figure 4, which is abnormal and requires further investigation. By using eq. (5), for 15 m and 100 m span bridges, the differences in the predicted 2020 fatigue damage between AS5100.2 (2002) and AS5100.2 (2020) is 24506 × M1600 truck and 9491 × M1600 truck, respectively. The corresponding differences between AS5100.2 (2002) and the simply supported mid-span BM model by representative traffic are 2230 × M1600 truck (15 m) and 5413 × M1600 truck (100 m), respectively. The discrepancies in fatigue damages indicate the incongruity of compound traffic growth between prediction and reality. The differences in unit fatigue damages between bridge loading areas are caused by the various stresses under the same traffic load. In addition, Figure 3 and Figure 5 demonstrate that the unit fatigue damage per truck has a higher value when the traffic flow and density are less, for bridges with spans longer than 20 m, so the total fatigue damage

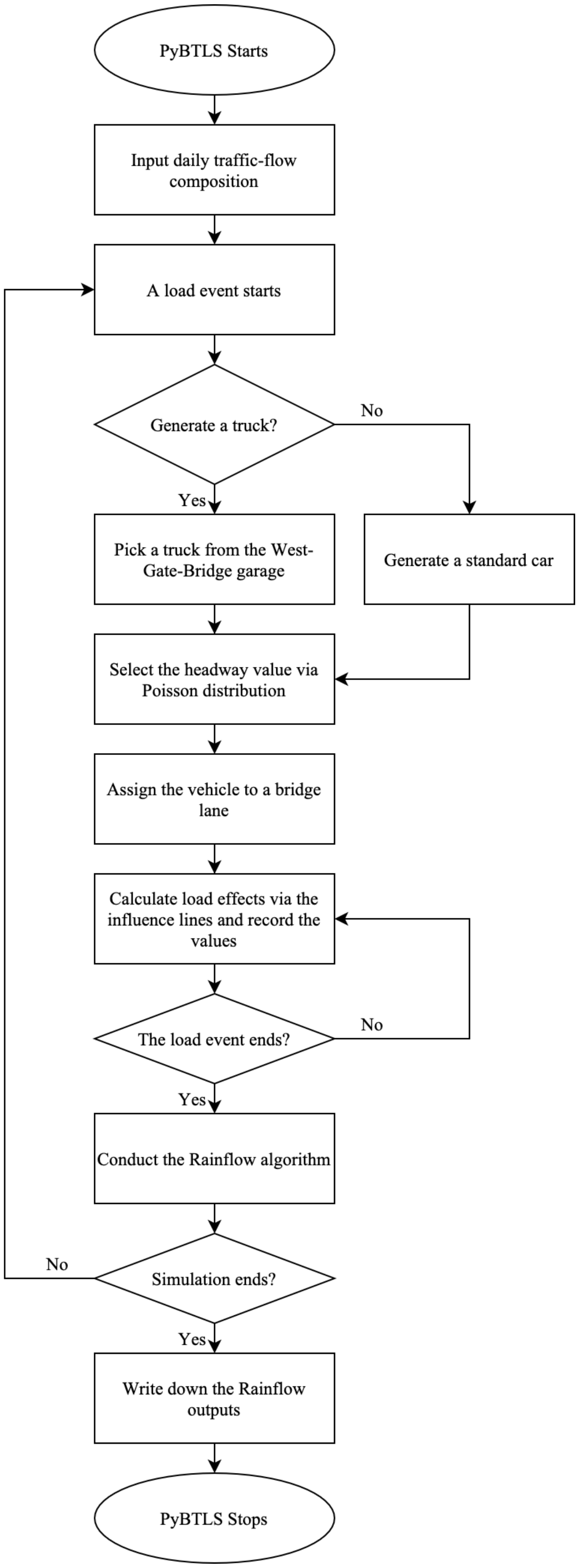

Figure 1: PyBTLS workflow in this study.

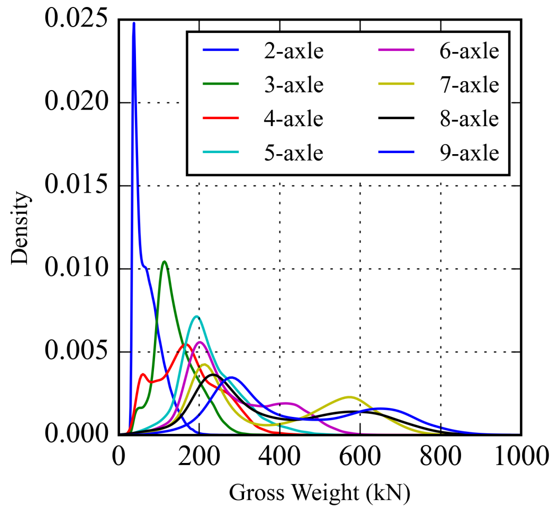

Figure 2: 2016 West Gate Bridge WIM data truck composition.

may not be linear to the traffic volume for long-span bridges.

A limitation of this research at present is the route factor calibration cannot be conducted, since the only garage file was from an urban freeway. For other route types, such as rural roads and other urban roads other than freeways, their truck features will vary significantly. Therefore, for a more comprehensive fatigue model in future research, the collection of diverse sources of WIM and traffic count data is vital.

A further limitation of the work is the precision of the ILs for practical purposes. All ILs considered here are theoretical and cover the entire bridge length, but the ILs for real bridge components have complex shapes with tributary lengths only a portion of the bridge length. Thus, using ILs modelled by bridge monitoring data or finite element analyses would be beneficial.

In summary, this preliminary research reveals some potential deficiencies of the AS5100.2 fatigue model to Australian bridge fatigue design and assessment. A revised fatigue model could be a series of formulas calibrated for specific types of bridge components, so the bridge fatigue design and assessment will be more precisely tuned to contemporary Australian traffic loading.

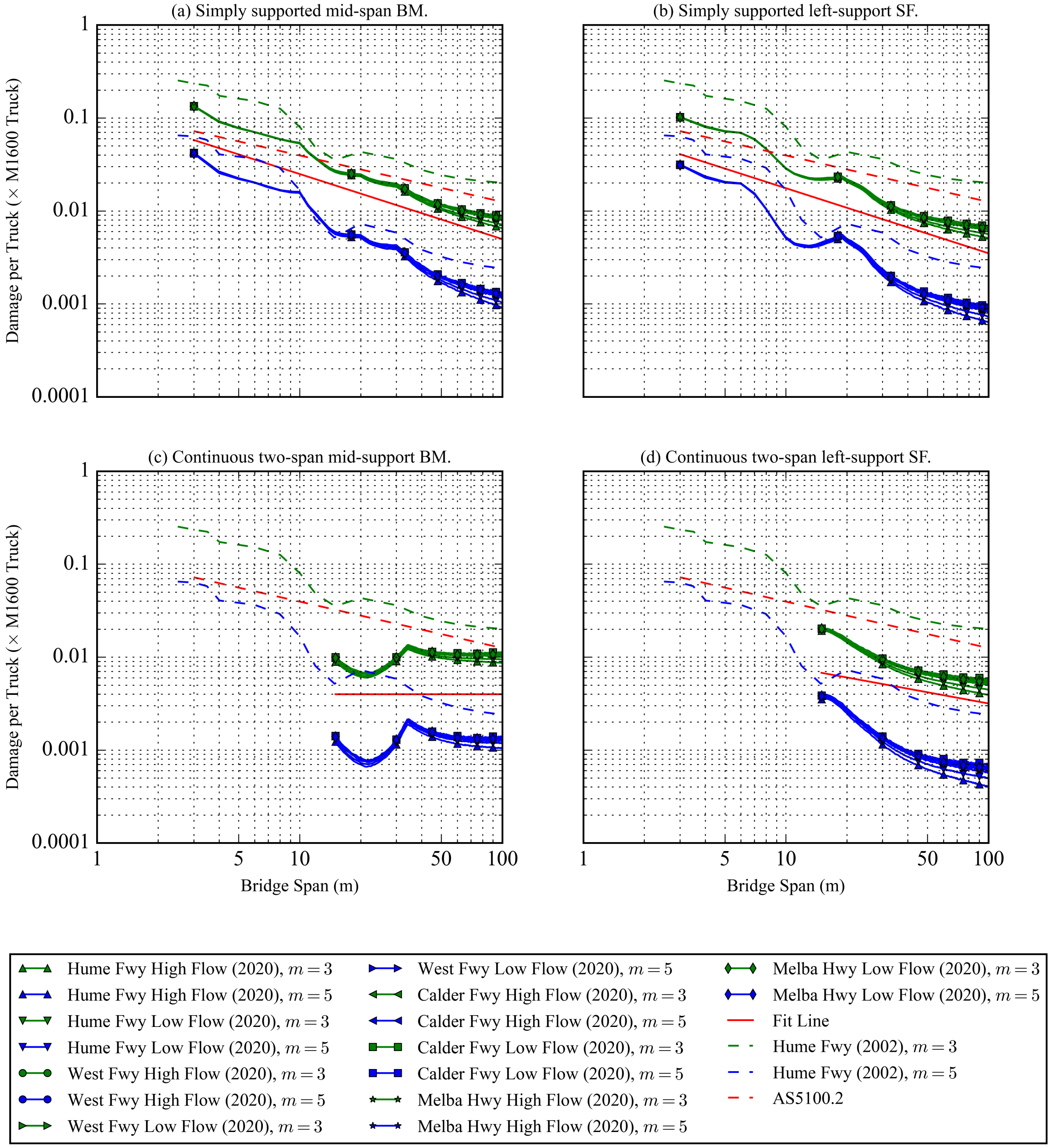

Figure 3: The unit fatigue damage calibrated to 2020 Melbourne traffic.

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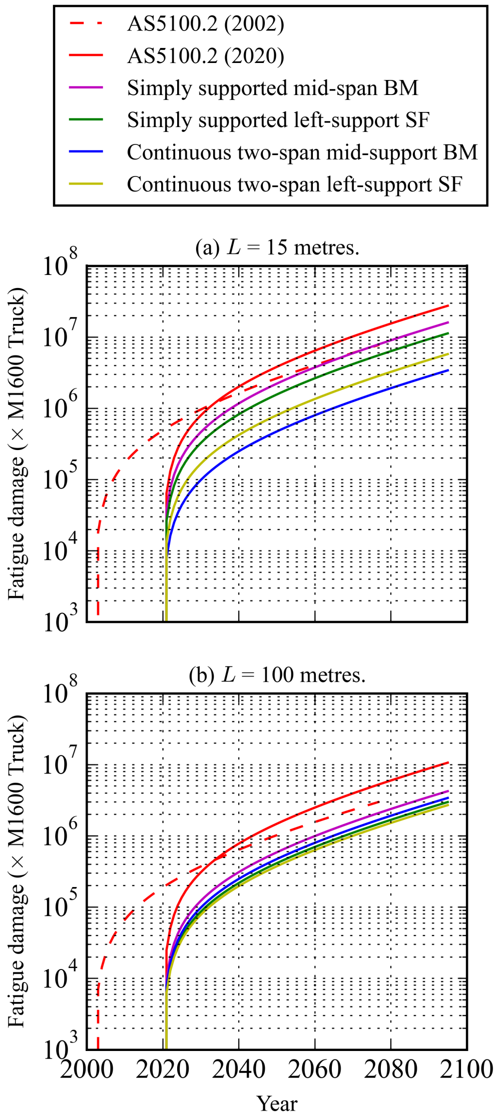

Figure 4: Predicted evolution of cumulate fatigue damage for the 2002 and 2020 traffic according to the AS5100.2 model.

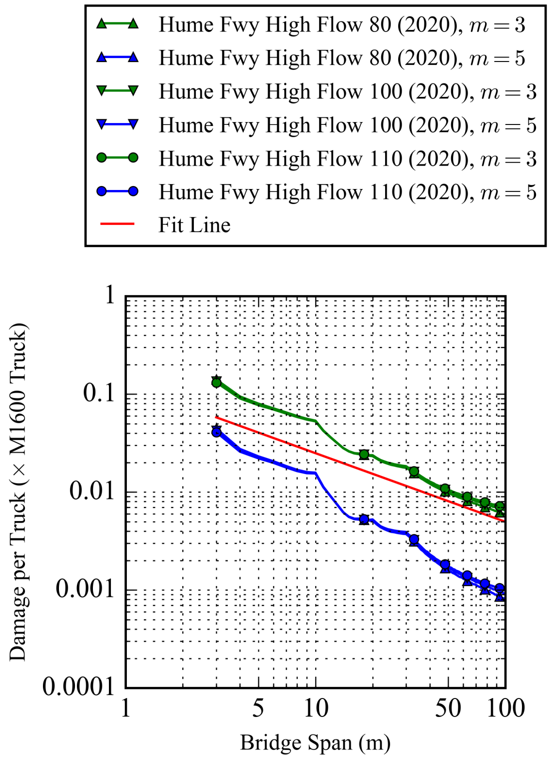

Figure 5: The unit fatigue damage by the high-pattern Hume Freeway traffic (2020) with different mean vehicle speeds.

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