Study on Vehicular Fatigue Load Spectrum for Highway Bridge Based on Measured Data

Bin Liu[1]**, Tian Wang**[1] **and Yong Liu**[1,2,a,*]

[1]*Hunan Provincial Communications Planning, Survey & Design Institute, Changsha, China*
[2]*School of Civil Engineering, Central South University, Changsha, China*
a. liushahust@163.com
**corresponding author : Yong Liu*

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Abstract: In order to study vehicular fatigue load spectrum for highway bridges， based on the vehicle data collected from the weight-in-motion (WIM) system on a certain bridge in Foshan city, Guangdong, the characteristic parameters, such as vehicle weight, wheelbases of vehicles and total weight and so on, are statistical analyzed. The vehicle is first simplified to ten types by the axis number and axis group type. Then, the axis weight, the wheelbases and weight of vehicles and lane parameters are analyzed in detail. Finally, vehicular fatigue load spectrum and Lane transverse distribution coefficient is decided based on the equivalent fatigue damage theory. The results indicated that the scheme proposed to determine vehicular fatigue load spectrum on highway bridges based on data acquisition of WIM system is accurate and effective, and can be directly used for the evaluation of the remaining fatigue life of the bridge in Foshan city, Guangdong. This proposed scheme could be further used to provide efficient reference for fatigue design and evaluation of the fatigue life of highway bridges under such a similar vehicle load, and to provide scientific guideline for the standard establish on vehicular fatigue load spectrum for highway bridges.

1. Introduction

Establishing an accurate vehicle fatigue load spectrum is an important basis and premise for fatigue damage analysis of bridge structures.

Till now, several countries like the United States, the United Kingdom, Japan and Germany have developed the fatigue vehicle load spectrum of bridge design based on a large number of actual measurements of their traffic data. Among them, The United Kingdom was one of the earliest countries that has formulated the fatigue load spectrum detailly in the tenth article of BS5400 [1], and the method of formulating fatigue load model in it was often taken as a reference for the formulation of fatigue standards of other countries. For example, the European Eurocode standard [2] has refered to the British BS5400 standard and formulates five different fatigue load models. In these 5 different fatigue load models, model 5 is a fatigue load spectrum based on measurements of on-site traffic data, which is mainly used for accurate fatigue calculation based on accumulative

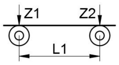
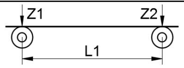
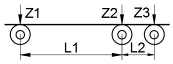
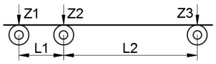
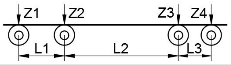
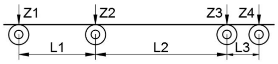
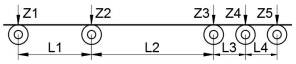
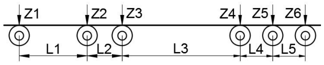
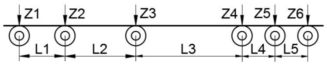
Miner fatigue damage. At present, there is no fatigue load spectrum for fatigue design and damage assessment of highway bridges in current standards in China. Compared with other countries, China's traffic vehicle load has obvious characteristics such as large traffic volume, high proportion of heavy vehicles and large overload rate. Foreign fatigue standards are not applicable to fatigue design and damage assessment of highway bridges in China. Therefore, it is of great significance to formulate fatigue load spectrum which is suitable for China's national conditions.

Based on the data collected by the vehicle weight-in-motion (WIM) system installed on one of the bridge in Foshan recording some characteristic parameters such as the axis weight, wheelbase of vehicles, gross weight, speed and overloading or not. Firstly, the vehicles are classified and grouped as V1 toV10 types according to the number of axis and the type of axis group. Secondly, a statistical analysis is established based on different types of axis weight, wheelbase, gross weight of vehicles and the traffic volume of different lanes. Finally, the fatigue load spectrum is deduced according to the principle of damage equivalence.

2. Classification of Representative Vehicle

There are many kinds of vehicles passing through every bridge in the design reference period. The parameters of axis type and wheelbase also are various. It is impossible to list each type of vehicle in the fatigue load spectrum study. Therefore, it is necessary to choose the representative types of vehicle for fatigue load spectrum through certain statistical analysis. According to the characteristics of axis group type, wheelbase and other parameters, and referring to the information of vehicle type parameters in China Automobile Model Manual [8], the vehicle is simplified into 10 categories, as shown in Table 1.

Table 1: Classification of representative vehicle.

Vehicle Type	Axles Type	Diagram
V1	/	/
V2	2 axles type a	
V3	2 axles type b	
V4	3 axles type a	
V5	3 axles type b	
V6	4 axles type a	
V7	4 axles type b	
V8	5 axles	
V9	6 axles type a	
V10	6 axles type b	

As the gross weight of V1 is less than 30 kN, which is mainly cars, small trucks and motorcycles, they have little influence on bridge fatigue damage and can be neglected, only 9 types of vehicles (V2-V10) are considered in the vehicle load model and fatigue load spectrum analysis.

3. Analysis of Characteristic Parameters of Vehicle Load Model

Establishing an accurate vehicle load model is an important basis for fatigue design and fatigue life assessment of highway bridges. Therefore, the study of vehicle load model should not only focus on traffic load data, but also need to consider the relationship between structural response (such as fatigue detail stress amplitude) and vehicle load characteristics. The fatigue stress amplitude of structural details has a certain range of influence surface. According to the size of influence surface, the fatigue problem can be roughly divided into the overall fatigue of components and the part fatigue of structural details.

Therefore, the characteristic parameter analysis of vehicle load model should include axis weight, wheelbase, wheelbase, vehicle gross weight and lane.

3.1.Analysis of Wheelbase Parameters

Wheelbase is taken as an important basis for classifying vehicle types, is an important characteristic parameter of vehicle load model. If weighted average the wheelbase of vehicle which is classified under the same representative type, we will obtain the wheelbase of each representative vehicle type. The calculation formula is as follows:

$$A_j = \sum A_{ij} / n \qquad (1)$$

In the formula, A_j is the j^{th} wheelbase of the representative vehicle type; A_{ij} is the j^{th} wheelbase of the number i vehicle under the same vehicle type; and n is the total number of vehicles under the same vehicle type.

The wheelbase parameters of each representative vehicle are calculated using the above formula are shown in Table 2.

Table 2: Representative vehicle wheelbase.

Vehicle Type	Axle type	Wheelbase/m				
		L_1	L_2	L_3	L_4	L_5
V2	2 axles type a	3.2				
V3	2 axles type b	5.3				
V4	3 axles type a	4.1	1.3			
V5	3 axles type b	1.8	5.4			
V6	4 axles type a	1.8	4.5	1.3		
V7	4 axles type b	3.6	7.3	1.3		
V8	5 axles	3.5	7.1	1.3	1.3	
V9	6 axles type a	3.3	1.3	7.2	1.3	1.3
V10	6 axles type b	1.8	2.6	8.0	1.3	1.3

3.2.Analysis of Axis Load Parameters

The weight of vehicle axis can directly reflect the strength of load and traffic flow, which has an important impact on the fatigue life evaluation of bridge deck and other components directly bearing wheel load.

According to the fatigue damage equivalence principle, the equivalent axis weight of the axis in each vehicle model are obtained. The sum of the equivalent axis weight loads is the equivalent axis weight of the model vehicle. The equivalent axis weight formula is as follows

$$W_{ej}=\left[\sum f_i(W_{ij})^m\right]^{1/m} \tag{2}$$

In the formula, the Wij is the j^{th} axis weight of the number i vehicle; the f_{i} is the relative frequency of the number i vehicle which belongs to the same vehicle type, that is, the frequency of the number i vehicle in all statistical vehicles; and the W_{ej} is the equivalent axis weight of the j^{th} axis of this vehicle.

Parameter m is the corresponding slope for the S-N fatigue strength curve of steel structure details. Referring to the American AASHTO standard, steel structure design standard, the British BS5400 standard and the European Eurocode, m=3 is selected.

The method calculating the axis weight parameters of different fatigue vehicle model from V2 toV10 is shown as in Table 3.

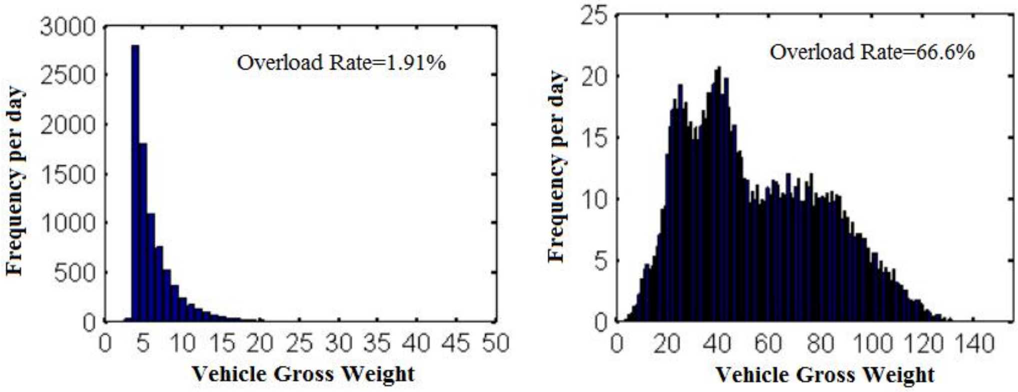
Table 3: Axle load of vehicle.

Vehicle Type	Axle type	Axle Load/m					
		Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
V2	2 axles type a	29	53				
V3	2 axles type b	62	124				
V4	3 axles type a	78	105	102			
V5	3 axles type b	72	79	146			
V6	4 axles type a	77	85	134	136		
V7	4 axles type b	65	128	118	118		
V8	5 axles	79	130	109	107	110	
V9	6 axles type a	78	121	117	123	121	123
V10	6 axles type b	63	63	145	126	122	125

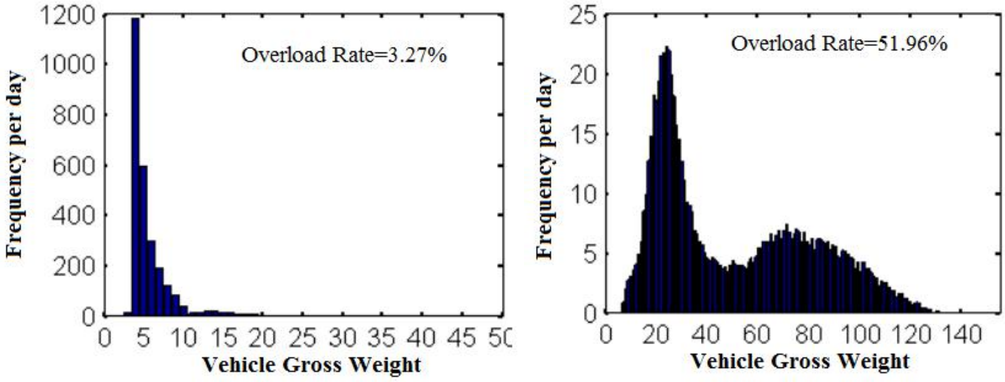
As shown in Table 3, except for the V2 type of vehicle which is listed in the right, the maximum equivalent axis weight of all the other vehicle types are over 100 kN. The maximum equivalent axis weight is type V5 which is 146 KN. Compared with the highway fatigue load spectrum in the Britain BS5400, the axis weight of representative vehicles is generally higher.

3.3.Analysis of Vehicle Gross Weight Parameters

Vehicle gross weight is the most important parameter in traffic load investigation. Based on the information of vehicle gross weight parameters collected by weight-in-motion system, the distribution of vehicle gross weight of different vehicle type is statistically analyzed. By using the numerical analysis software of Matlab, the vehicle gross weight parameters of nine vehicle models from V2 to V10 are calculated respectively. Finally, the statistical distribution of vehicle gross weight of nine vehicle models from V2 toV10 moving within the highway section under monitoring is obtained as shown in Figure 1. Vehicle overload rate, maximum vehicle gross weight and daily average traffic volume are shown in Table 5. Due to the limit length of this article, Figure 1 only lists the statistical analysis results of V2 and V9 these four different vehicle types.



a)V2 Gross Weight distribution on the right side b)V9 Gross Weight distribution on the right side



c)V2 Gross Weight distribution on the left side d)V9 Gross Weight distribution on the left side

Figure 1: The Statistical Analysis Chart of Vehicle Gross Weight (unit:t).

As can be seen from Figure.1

1) For V2 vehicle type, the change trend of the vehicle gross weight distribution on the left and right bridge in the section which has been monitored is the same, both of them are single peak skewness distribution, what's more, the vehicle gross weight is not heavy in general.

2) Except for the V2 vehicle type, the vehicle gross weight of other vehicle types (V3 to V10) is multi-peak distribution, and the vehicle gross weight is heavy in general. This is because there are various types of vehicles from V3 to V10, and the overload rate is in average big, basically in average is more than 30%, the maximum is up to 69%.

3.4.Analysis of Lane Parameters

When the transverse position of the moving vehicles on the bridge is different, the stress of the bridge structure varies greatly. In engineering practice, traffic load flow is also not uniformly distributed in each lane.

Based on the numerical analysis software of Matlab, this section has analyzed the distribution pattern of vehicle types in each lane, and has obtained the lane distribution table of each vehicle type in the highway section which has been monitored as shown in Table 4.

Table 4: Lane distribution of vehicle.

Vehicle Type	lane1		lane2		lane3		lane4		lane5	
	Vehicle	Ratio/ %	Vehicle	Ratio/ %	Vehicle	Ratio/ %	Vehicle	Ratio/ %	Vehicle	Ratio/ %
V1	7400.2	71.6	1691.8	49.4	2075.2	20.5	1947.6	29.4	10630.9	99.2
V2	2625.6	25.4	764.6	22.3	3159.6	31.2	1737.7	26.3	72.5	0.7
V3	141.1	1.4	321.6	9.4	2533.6	25.0	1457.5	22.0	5.8	0.1
V4	37.9	0.4	288.7	8.4	313.8	3.1	219.8	3.3	2.2	0.0
V5	26.6	0.3	43.4	1.3	424.9	4.2	237.3	3.6	1.1	0.0
V6	20.3	0.2	81.3	2.4	295.6	2.9	201.1	3.0	0.9	0.0
V7	7.0	0.1	20.9	0.6	278.4	2.7	172.2	2.6	0.3	0.0
V8	11.3	0.1	41.9	1.2	324.9	3.2	212.1	3.2	0.5	0.0
V9	51.1	0.5	145.5	4.2	577.5	5.7	349.1	5.3	2.0	0.0
V10	17.2	0.2	25.5	0.7	157.4	1.6	83.8	1.3	0.5	0.0
V2~V10	2938	28.4	1733	50.6	8066	79.5	4671	70.6	86	0.8
Total	10338		3425		10141		6618		10717	

As can be seen from Table 4:

The percentage of V2 toV10 vehicle types in heavy lanes (3# and 4# lane) has been significantly higher than that in other lanes, and the bridge test results also showed that fatigue diseases at the diaphragm arc opening were also mainly concentrated in heavy lanes (3# and 4# lane). The number of heavy vehicles (V2 toV10 type) in the 3 # heavy lane is significantly higher than that in the 4 # heavy lane, which is also consistent with the distribution of disease in the real situation of a bridge.

4. Analysis of Fatigue Load Spectrum

Based on the statistical analysis of the main characteristic parameters (axis weight , wheelbase, vehicle gross weight and lane) of the vehicle load model, the fatigue load spectrum is established, as shown in Table 5.

Table 5: Vehicular fatigue load spectrum.

	Axle type	Wheelbase/m					Axle load/kN						Percent
		L_1	L_2	L_3	L_4	L_5	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	
V2	2 axles type a	3.2					29	53					20.3
V3	2 axles type b	5.3					62	124					10.8
V4	3 axles type a	4.1	1.3				78	105	102				2.09
V5	3 axles type b	1.8	5.4				72	79	146				1.78
V6	4 axles type a	1.8	4.5	1.3			77	85	134	136			1.45
V7	4 axles type b	3.6	7.3	1.3			65	128	118	118			1.16
V8	5 axles	3.5	7.1	1.3	1.3		79	130	109	107	110		1.43
V9	6 axles type a	3.3	1.3	7.2	1.3	1.3	78	121	117	123	121	123	2.73
V10	6 axles type b	1.8	2.6	8.0	1.3	1.3	63	63	145	126	122	125	0.69

As can be seen from Table 5, the axis weight of each fatigue vehicle type (V2 to V10) on the right bridge is generally heavier than that on the left bridge. The percentage of fatigue vehicle type on the right bridge is also in average higher than that on the left bridge. Therefore, the fatigue load spectrum on the right bridge is adopted in the fatigue damage analysis and fatigue life assessment of the bridge.

The distribution of vehicle types across bridges and lanes is also not balanced. The traffic volume of fatigue vehicles (V2 to V10) on heavy lanes (3# and 4# lane) was analyzed statistically. The percentage of fatigue vehicles in the total traffic volume of one-way traffic for the same vehicle model was shown in Table 6.

Table 6: Ratio of heavy-traffic-lane's fatigue vehicle in the one-way traffic.

Vehicle Type	Axle type	Ratio(%)	
		Lane 3	Lane 4
V2	2 axles type a	45.3	12.5
V3	2 axles type b	60.5	18.9
V4	3 axles type a	38.6	8.4
V5	3 axles type b	68.1	20.9
V6	4 axles type a	67.7	20.1
V7	4 axles type b	29.7	9.1
V8	5 axles	45.4	14.2
V9	6 axles type a	68.0	22.2
V10	6 axles type b	69.3	21.9
V2~V10		53.5	15.8
≥4 Axles total		59.0	18.6

The data in Table 6 show that in the American standard AASHTO, the distribution coefficient P of truck lanes is relatively conservative. Referring to the American AASHTO standard, based on the results of the study on the lane distribution coefficient of fatigue vehicles in Table 7, it is suggested that the lane distribution coefficient of fatigue vehicles (heavy lane or slow lane) can be calculated by referring to Table 7.

Table 7: Ratio of heavy-vehicle traffic in a single lane (recommendation).

Heavy traffic lanes	1	2	≥3
Ratio P	1.00	0.75	0.65

5. Conclusions

Based on the vehicle data such as axis weight, wheelbase and gross weigh collected from the weight-in-motion (WIM) system and so on, are statistical analyzed. The vehicle is first simplified to ten types by the axis number and axis group type. Then, the axis weight, the wheelbases and weight of vehicles and lane parameters are analyzed in detail. Finally, vehicular fatigue load spectrum and Lane transverse distribution coefficient is decided based on the equivalent fatigue damage theory. The main conclusion is as below:

(1) Except for V2 models, the maximum equivalent axis weight of the other vehicle models is above 100kN. Compared with the highway fatigue load spectrum of British BS5400 standard, the axis weight of representative vehicle is generally higher.

(2) The change trend of the vehicle gross weight distribution on the left and right bridge of the V2 vehicle type is the same, both of them are single peak skewness distribution, and the overload rate is small (less than 4%). The other vehicle types (V3 toV10) have multi-peak distribution for the gross weight analysis, and the overload rate is big, up to 69%.

(3) The distribution of vehicle load on different lanes is seriously unbalanced. In the American AASHTO standard, the distribution coefficient P of truck lanes are relatively conservative. Based on China's actual situation and actual traffic operation, this paper proposes the recommended numbers of the distribution coefficient of fatigue vehicle lanes.

Based on the background of a bridge in Foshan City, Guangdong province, this paper presents a method of establishing the fatigue load spectrum of highway bridges using the real traffic load data recorded by the WIM system, which provides an important basis for the fatigue design and fatigue life evaluation of highway bridges, and also provides a reference for the formulation of the fatigue load spectrum standard of highway bridges in China.

Acknowledgments

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