Study on Standard Fatigue Vehicle Load Model

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Abstract. Based on the measured data of truck from three artery expressways in Guangdong Province, the statistical analysis of truck weight was conducted according to axle number. The standard fatigue vehicle model applied to industrial areas in the middle and late was obtained, which adopted equivalence damage principle, Miner linear accumulation law, water discharge method and damage ratio theory. Compared with the fatigue vehicle model Specified by the current bridge design code, the proposed model has better applicability. It is of certain reference value for the fatigue design of bridge in China.

1. Introduction

The industrialization level of our country is in the middle and late stage of industrialization, with rapid development of economic construction, the vigorous development of the automotive industry and the social factors of the growing transport demand, the current operation of vehicle load has produced serious variation, more and more weight and overweight vehicles have appeared, which brings serious fatigue problems and hidden danger to the structure of the bridges and pavements [1-2]. Because of the wide range of highway fatigue load problems and influence factors, researchers at home and abroad had adopted the methods of investigation and statistical analysis to abstract and establish different type of standard fatigue vehicles [3-10].

However, there are still some limitations in the current researches, which lead to the fact that the established fatigue vehicle can not reflect the development and variation of current vehicle load [4-13]. The limitations included: (1) The sample size of vehicle was not enough to reflect the operating vehicles; (2) The survey time was not long enough to cover the seasonal characteristics of the operating vehicles; (3) The survey method was limited and hard to reflect the real situation of the operation load scientifically; (4) The survey area is not wide enough to reflecting regional differences of operating vehicles.

Aiming at above problems, the paper based on about 3 million weight in motion (WIM) data of truck collected from three major expressways in Guangdong Province, and the statistics characteristics of vehicle load, a standard fatigue vehicle model suitable for the middle and late period of industrialization had been worked out by applying equivalent damage principle, water discharge method and damage ratio theory.

2. Statistics of vehicle load characteristics
The three major expressways in Guangdong are connected with the provinces of Hunan, Jiangxi, Guangxi and Fujian as a whole in the middle and late stage of industrialization, which basically reflects the load situation in most parts of our country \cite{14}. By statistics of weight distribution of the whole traffic flow, the following were found in the effective samples: the maximum gross weight was 117.4 tons belonged to 6-axle vehicle; the minimum gross weight was 0.4 tons belonged to 2-axle vehicle; the average weight was 42 tons.

The weight distribution of different number of axle vehicles had been analyzed by statistics the actual measurement data. The digital characteristic of gross vehicle weight distribution is shown as table 1. The probability density distribution of truck gross weigh was showed as figure 1. The overall vehicle weight distribution was close to three-peak distribution, with the peak value of 15 tons, 35 tons and 55 tons. The distribution was similar to the thin tailed distribution after the weight exceeded 55 tons.

| Type  | Number | Proportion (%) | Maximum Value(kN) | Minimum Value(kN) | Mean Value (kN) | Limit Value (kN) |
|-------|--------|----------------|-------------------|-------------------|-----------------|-----------------|
| 2-axle| 231896 | 7.3            | 469               | 4                 | 104             | 170             |
| 3-axle| 144078 | 4.5            | 774               | 4                 | 192             | 250             |
| 4-axle| 479112 | 15.0           | 945               | 4                 | 258             | 350             |
| 5-axle| 175766 | 5.5            | 1025              | 15                | 348             | 430             |
| 6-axle| 215559 | 67.6           | 1174              | 11                | 483             | 490             |
| total | 3186412| 100.0          | 1174              | 4                 | 401             | 490             |

From the chart above: in the survey data of truck load samples, the largest proportion is the six-axle vehicle, accounting for 67.6% of all the survey data, followed by four-axle vehicle accounting for 15% of all the survey data. Then 4-axis and 6-axle vehicle are the dominant vehicle in this survey statistics. Secondly, The phenomenon of truck overrun operation on expressway was serious, the maximum weight of three to six axle vehicle are more than the current highway corresponding gross vehicle weight limits.

According to the British BS5400 code \cite{10}, the vehicle less than 30kN is neglected in the calculation of fatigue. So, after preliminary screening, the vehicle data ratio for the extraction of standard fatigue vehicles is shown in table 2.

| Type  | 2-axle | 3-axle | 4-axle | 5-axle | 6-axle | total    |
|-------|--------|--------|--------|--------|--------|----------|
| Number| 251618 | 50861  | 291498 | 29529  | 65383  | 1277342  |
| Proportion| 19.70% | 3.98%  | 22.82% | 2.31%  | 51.19% | 100%     |

3. Abstraction of standard fatigue vehicle

3.1. Equivalence of typical fatigue vehicle

According to the survey load data, the axle type and wheelbase of vehicles with different number axle are calculated respectively. In accordance with the equivalent fatigue damage principle, the equivalent axle load($w^e_i$) of each measured axle weight was obtained, $w^e_i = \sqrt{\sum f_j w^w_j}$, where $f_j$ is the proportion of axle load corresponding to the same axle vehicle. Based on the relative frequency of the same kind of vehicle appears as the weight, calculate the equivalent wheelbase value ($A^e_j$) by weighted-average method, $A^e_j = \sum (f_j A_j)$, where $A_j$ is the j wheelbase of the i axle vehicle. Then, the 5 kinds of typical vehicle loads with different axle numbers were calculated, and the results are shown in table 3 and table 4.
Table 3. Equivalent axle load of each typical vehicle

| typical vehicle | Equivalent axle load of each axle (kN) | gross weight (kN) |
|-----------------|----------------------------------------|------------------|
|                 | 1st  | 2nd  | 3rd  | 4th  | 5th  | 6th  |      |
| 2-axle          | 33.6 | 75.9 | 0    | 0    | 0    | 0    | 109.5|
| 3-axle          | 47.1 | 56.9 | 119.5| 0    | 0    | 0    | 223.5|
| 4-axle          | 54.8 | 59.0 | 112.9| 112.9| 0    | 0    | 339.6|
| 5-axle          | 55.2 | 100.8| 70.2 | 71.4 | 71.4 | 0    | 369.0|
| 6-axle          | 51.5 | 79.1 | 93.2 | 87.2 | 87.2 | 87.2 | 485.4|

Table 4. Equivalent wheelbase of typical vehicle

| typical vehicle | Equivalent wheelbase (mm) |
|-----------------|----------------------------|
|                 | 1st  | 2nd  | 3rd  | 4th  | 5th |
| 2-axle          | 4560 | 0    | 0    | 0    | 0   |
| 3-axle          | 2160 | 4610 | 0    | 0    | 0   |
| 4-axle          | 1860 | 4180 | 1360 | 0    | 0   |
| 5-axle          | 3460 | 6020 | 1800 | 1360 | 0   |
| 6-axle          | 2700 | 1680 | 7020 | 1360 | 1360|

By the equivalent wheelbase and the equivalent axle load of typical fatigue vehicle, the graph of each typical vehicle can be formed.

By loading each typical vehicle on the virtual simply supported beam with different span of 3m, 5m, 8m, 10m, 15m, 20m, 25m, 30m and 40m, different internal force and time-travel curves were obtained. Subsequently, the peak values ($\Delta M_k$) and its number ($n_k$) of the internal force can be calculated by water discharge method.

3.2. Parameters of fatigue vehicle model

According to Miner linear accumulation law, several variable amplitude fatigue internal forces can be transformed into a constant amplitude fatigue internal force ($\Delta M_i$) by formula (1).

$$\Delta M_i = \left[ \frac{\sum n_i (\Delta M_i)^3}{\sum n_i} \right]^{\frac{1}{3}}$$

Then, considering the actual number of each axle typical vehicle in the statistical data (see table 2), calculated the damage ratios by formula (2), and selected the typical vehicle with relatively larger damage ratios as the fatigue vehicle load. The damage ratios of each axle typical vehicle on virtual simply supported beam were showed as table 5.

$$\frac{D_i}{D_a} = \frac{n_i (\Delta M_i)^3}{\sum_{i=2}^{6} n_i (\Delta M_i)^3}$$

Table 5. Damage ratios of each axle typical vehicle on virtual simply supported beam

| Span (m) | 2-axle | 3-axle | 4-axle | 5-axle | 6-axle |
|---------|--------|--------|--------|--------|--------|
| 5       | 1.4    | 2.6    | 24.9   | 2.6    | 68.5   |
| 8       | 3.6    | 2.7    | 34.5   | 2.8    | 56.4   |
| 10      | 3.5    | 2.8    | 35.4   | 2.8    | 55.4   |
In table 5, it can be seen that the damage ratio of the typical vehicle composed of 4-axle and 6-axle vehicle to the virtual simple beam is more than 90% of the overall damage ratio, and it was the most suitable form for the standard fatigue vehicle, which close to the real fatigue load. Therefore, the combination of 4-axle and six-axle was chosen as the standard fatigue vehicle, and the specific parameters are shown in figure 1 and figure 2.

![Figure 1](image1.png) Four axle fatigue vehicle

![Figure 2](image2.png) Six axle fatigue vehicle

4. Comparison with the fatigue vehicle model Specified by the design code

Two kinds of fatigue vehicle model are recommended in current bridge design code\cite{15}: the fatigue vehicle model II with the weight of 445kN, the fatigue vehicle model III with the weight of 480kN, are respectively as shown in figure 3 and figure 4. When loaded the two fatigue vehicle load models and the combined fatigue vehicle load respectively on the virtual simply supported beam, and the equivalent internal force damage ratio of the three fatigue models under the same span were obtained. The results are shown in table 6.

![Figure 3](image3.png) Fatigue vehicle model II

![Figure 4](image4.png) Fatigue vehicle model III

| Span | Fatigue vehicle model II | Fatigue vehicle model III | combination fatigue vehicle model |
|------|-------------------------|--------------------------|----------------------------------|
| 2.5m | 71.1%                   | 72.0%                    | 89.2%                            |
| 5m   | 85.9%                   | 86.4%                    | 93.4%                            |
| 10m  | 88.3%                   | 89.1%                    | 90.8%                            |
| 15m  | 89.7%                   | 90.2%                    | 92.1%                            |
| 20m  | 90.1%                   | 90.3%                    | 91.9%                            |
| 25m  | 90.6%                   | 88.7%                    | 93.9%                            |
| 30m  | 91.1%                   | 88.2%                    | 94.2%                            |
| 40m  | 91.4%                   | 86.6%                    | 95.0%                            |
According to table 6, the damage ratio of the fatigue vehicle model III is closer to the real damage value when the span of the beam is 10~20m, while the fatigue model II is in good agreement with the real damage value when the span of the beam is longer than 20m. While the 4-axis and 6-axis combination fatigue vehicle model can better reflect the real fatigue damage with the span changing of the beam.

5. Conclusion
(1) Based on the weight in motion data of three artery expressways in Guangdong Province, The standard fatigue vehicle load model can be obtained by using equivalence damage principle, Miner linear accumulation law, water discharge method and damage ratio theory, which can effectively reflect the traffic characteristics of middle and late stage of industrialization area.

(2) Comparison with the fatigue vehicle model in current bridge design code, the 4-axis and 6-axis combination fatigue vehicle model can better reflect the real fatigue damage with the span changing of the simply supported beam, which is of certain reference value for the fatigue design of bridge.

Acknowledgments
These research reported was financially supported by the project of the Science and technology planning of Guangdong Provincial Department of Transportation in 2014(NO.201402022) and the project of National Science Foundation of China(NO.51278134).

References
[1] Wang T, Han W S and Huang P M 2010 Research status and prospect on traffic loading for highway bridge Journal of Architecture and Civil Engineering 4 p 31–37
[2] He D R 2015 Study on asphalt pavement performance prediction research based on the combination forecast model Highway Engineering 40(6) p 264–270
[3] Zhang J, Hu M M and Wang Y T 2016 The life estimation of anchoring structure of shanghai certain cable-stayed bridge based on WIM data Highway Engineering 41(3) p 208–211
[4] Zhou Y T, Bao W G and Qu H 2010 Study of standard fatigue design load for steel highway bridges. China Civil Engineering Journal 43(11) p 79–85
[5] Tong L W, Shen Z Y and Chen Z Y Fatigue 1997 Load spectrum of urban roads and bridges China Civil Engineering Journal 30(5) p 20–27
[6] Wang R H, Chi C and Chen Q Z 2004 Research on fatigue loading vehicle model of viaduct in Guangzhou Journal of South China University of Technology 32(12) p 9496
[7] Liu G J, Wei Z L and Yang Y Q 2014 Research on vehicular loads and fatigue load model of road bridge 2014 Journal of Highway and Transportation Research and Development 6 p 86–93
[8] Yang D X 2015 Study on Standard Fatigue Vehicle Model(Guangzhou University)
[9] Sun X Y, Ren W X and Li X X 2014 Random axle frequency value spectrum deduction of steel deck bases on WIM. Highway Engineering 39(6) p 297–301
[10] BS5400 1980 Steel, Concrete and Composite Bridge–Part 10: Code of Practice for Fatigue
[11] Nowak A S 1993 Live Load Models for Highway Bridges Structural Safety 30 p 53–66
[12] Miao T J 2002 Bridge live load models from WIM data Engineering Structures 24 1071–1084
[13] Chotickai, P and Bowman M 2006 Truck models for improved fatigue life predictions of steel bridges Bridge Engineering 11(1) p 71–80
[14] Ma J Sun S Z and Yang Q 2014 Review on China’s bridge engineering research China Journal of Highway and Transport 5(27) p 91–96
[15] General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015) 2015