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# Study of a fatigue load model for highway bridges in Southeast China

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Research Paper

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## Study of a fatigue load model for highway bridges in Southeast China

Although fatigue damage has become one of the main causes of structural damage to bridges, standard vehicle models for highway bridge fatigue design have not as yet been determined in China. Relying on the WIM system, load data were collected for different types of vehicles from six provinces in Southeast China. The Miner's criterion for cumulative fatigue damage, and the equivalent stress amplitude criterion, were adopted for calculating the equivalent axle load, the equivalent wheelbase, and the fatigue damage contribution ratio. The fatigue load spectrum, including five equivalent vehicle models, was identified.

### Key words:

bridges, fatigue load model, standard fatigue vehicle, WIM system

Prethodno priopćenje

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## Istraživanje modela opterećenja za zamor mostova na autocestama u jugoistočnoj Kini

Oštećenja konstrukcija mostova uslijed zamora postala su jednim od glavnih uzroka oštećenja, ali još uvijek nisu utvrđeni standardni modeli vozila za proračun zamora mostova na autocestama u Kini. Oslanjajući se na WIM sustav, prikupljeni su podaci o opterećenju različitih vrsta vozila iz šest pokrajina u jugoistočnoj Kini. Za izračunavanje ekvivalentnog osovinskog opterećenja, ekvivalentnog međuosovinskog razmaka i omjera doprinosa zamora usvojeni su Minerov kriterij za kumulativno oštećenje zbog zamora i ekvivalentan kriterij amplitude naprezanja. Utvrđen je spekter opterećenja za zamor koristeći pet ekvivalentnih modela vozila.

### Ključne riječi:

mostovi, model opterećenja za zamor, standardno vozilo koje uzrokuje zamor, WIM sustav

Vorherige Mitteilung

**Yuzhao Liang, Feng Xiong**

## Untersuchung von Lastmodellen für die Ermüdung von Autobahnbrücken in Südostchina

Schäden an Brückenkonstruktionen aufgrund von Ermüdung sind zu einer der Hauptursachen für Schäden geworden, aber es wurden noch immer keine Standardmodelle von Fahrzeugen für die Berechnung der Ermüdung von Autobahnbrücken in China festgelegt. Sich an das WIM-System anlehnend wurden Daten über die Belastung unterschiedlicher Fahrzeugtypen aus sechs Provinzen in Südostchina zusammengetragen. Für die Berechnung der äquivalenten Achsenbelastung, des äquivalenten Radstandes und des Verhältnisses des Ermüdungsbeitrags wurden die Kriterien von Miner für die kumulative Beschädigung aufgrund von Ermüdung und das äquivalente Kriterium der Spannungsamplitude verwendet. Festgestellt wurde ein Ermüdungsbelastungsspektrum durch Verwendung von fünf äquivalenten Fahrzeugmodellen.

### Schlüsselwörter:

Brücken, Belastungsmodelle für Ermüdung, Standardfahrzeug, welches Ermüdung verursacht, WIM-System

## 1. Introduction

With the rapid development of automobile industry and transport, the number of vehicles present on highways is increasing on a daily basis. The proportion of overloaded vehicles is gradually expanding, and the fatigue life of highway bridges is sharply reducing. Highway bridges are subjected to repeated effects of vehicle loads imposed during the operation period, and the fatigue damage to structures accumulates over time, which makes the fatigue damage one of the main causes of structural damage to bridges.

The vehicle fatigue damage model plays an important role in assessing bridge fatigue. Many scholars have carried out research on this issue. Schilling [1] and Raju et al. [2] consider that the gross weight of the fatigue vehicle needs to be adjusted according to load distribution at specific locations, and that the axle load should be adjusted proportionally, so as to improve accuracy of the fatigue vehicle model. Laman and Nowak [3] selected five steel girder bridges to study the fatigue load model of steel girder bridges. The results showed that the vehicle load and stress spectrum of different components in different locations were different. They suggested a 3-axle fatigue vehicle model for representing the three to seven axles vehicle, while a 4-axle fatigue vehicle model was chosen for the places where ten or eleven axles vehicle appear. Chotickai and Bowman [4] consider that the fatigue damage level at small span bridges would be significantly exaggerated when checking fatigue according to the existing road bridge codes in the United States, and so two new fatigue vehicles were proposed. One involves the use of 3-axle fatigue vehicles on most major highways, and the other the use of 4-axle fatigue vehicles on highways where the fatigue contribution of eight-axle to eleven-axle vehicles is relatively large. Przemyslaw [5] established load spectrum and load models for the structural reliability analysis and the fatigue reliability analysis based on vehicle load observation data on thirty-two specific real bridges in sixteen states of the United States under normal service conditions.

In view of intensive construction of steel bridges in recent years [6, 7], a large number of scholars have conducted extensive and in-depth research on the fatigue load model for bridges in China. Tong and Shen [8] investigated traffic vehicles on urban roads in Shanghai. According to the principle of equivalent fatigue damage, eighteen types of daily traffic vehicles were summarized as a load spectrum consisting of six types of representative vehicles. Wang et al. [9] simplified measured vehicle load data to the fatigue vehicle load spectrum composed of a 2-axle vehicle and a 3-axle vehicle and established the fatigue vehicle load model for the Guangzhou Viaduct. Yue F. et al. [10] used the Monte Carlo method to simulate the traffic flow data collected from six toll stations on the Beijing-Fuzhou Expressway. A fatigue vehicle model suitable for bridges on the Beijing-Fuzhou Expressway was proposed, and the validity of the model was verified. Zhou et al. [11, 12] selected eight typical expressways in China to

carry out a traffic load survey, and the vehicle load spectrum of expressway bridges used for different regions was obtained based on the principle of equivalent fatigue damage. The fatigue damage level of typical span highway bridges was calculated, and the corresponding standard vehicle pattern of the vehicle fatigue load and the longitudinal correction coefficient of the corresponding span or influence line length were determined, which constructed a complete standard vehicle fatigue model for highway bridges with different bridge types. Lan et al. [13] established a fatigue load spectrum including six representative types of vehicles by using the SHM system to measure the vehicle load data for the Binzhou Yellow River Highway Bridge in Shandong Province. The logistics model was used to predict traffic volume during the service life of the bridge. Sun et al. [14] carried out simulation of the vehicle load spectrum under general and intensive traffic conditions for the National Highway 309 in China, where massive overloaded vehicle traffic is operated. The stress time history curves under general and intensive traffic conditions were obtained. The equivalent stress amplitude for fatigue reliability analysis of highway bridges was deduced based on the linear cumulative damage principle. Sun et al. [15] acquired basic traffic information for the 6<sup>th</sup> Ring Road in Beijing based on the WIM system. According to the principle of damage equivalence, the fatigue vehicle load spectrum was provided for six types of vehicles. Based on the WIM system of the Jiujiang Yangtze River Bridge, Shao et al. [16] obtained the vehicle load data and the vehicle type data via field investigations and established the fatigue vehicle load spectrum composed of seven equivalent model vehicles. Liu et al. [17, 18] proposed a standard fatigue vehicle model adequate for China's traffic load by comparing and analysing standard fatigue vehicle models in American and British codes. Xia et al. [19] collected monitoring information for the Xinyihe Bridge on the Beijing-Shanghai Expressway. Based on the Miner's linear cumulative damage ratio and the equivalent fatigue damage principle, the fatigue load spectrum of the Xinyihe Bridge, including nine representative types of vehicles, was established, and the contribution value of fatigue damage was studied. Zhai et al. [20] loaded the measured fatigue load spectrum of five different grade highways on the stress influence line of typical fatigue details of a steel box girder cable-stayed bridge, in order to calculate the fatigue damage of each detail under actual traffic flow, and determine the vehicle types that mainly caused the damage. By collecting vehicle load data from the Xiyoumen Bridge, Ma et al. [21] established the statistical distribution function of the vehicle gross weight and wheelbase of each vehicle type under different load conditions. Parameters of various fatigue load vehicles were determined using the Palmgren-Miner fatigue damage accumulation theory, and the theoretical fatigue life of U-rib butt welds was estimated. Di et al. [22] collected vehicle load data at a port highway bridge in the Zhejiang coastal area for one year. According to the number of axles and wheelbase, the vehicles were divided into seven categories. The vehicle load distribution characteristics of the port highway bridge were analysed and the equivalent

axle weight and wheelbase of each vehicle type were obtained. Finally, three key fatigue details of orthotropic steel bridge slabs of the port highway bridge were evaluated using the obtained fatigue load spectrum and the hot spot stress method.

The establishment of the fatigue load model is the basis for checking structural fatigue damage and evaluating bridge fatigue life. The European Standard (Eurocode) [23], British BS5400 code [24] and the American AASHTO code [25] have proposed their respective fatigue load models. The Chinese design code for highway steel bridges [26] has also provided the fatigue load model for steel bridges in China. It is a 4-axle vehicle model with 120 kN axle load. The wheelbase is 120 cm, 600 cm, and 120 cm, respectively. However, China has a vast territory, with huge differences in the level of economic development and the layout of industrial infrastructure. The operating rules and distribution characteristics of vehicle loads also differ. Therefore, the use of a nationwide unified fatigue vehicle load model cannot meet the requirements for refinement of this issue. But the vehicle fatigue load model based on the vehicle load data of a certain collection point is unreliable, and it can not fully reflect the actual traffic load situation in this area. In order to get an accurate fatigue load model, it is necessary to combine the vehicle load data of several typical roads in a certain area and to carry out relevant research.

As to its economy, Southeast China is one of the most active regions in the country. It is the common hinterland of the developed economic zones such as the Yangtze River Delta, the Pearl River Delta, the Southern Fujian Delta, and the Western Taiwan Straits. In recent years, the transport industry has developed rapidly and the traffic volume has increased sharply. However, there are only a few vehicle load models that can be used for simulating the actual traffic conditions in this area. Fatigue load models representing traffic conditions in Southeast China are needed to evaluate the fatigue behaviour of bridges under vehicle load. In this study, the author uses the WIM system to collect vehicle load data from six provinces in Southeast China, and conducts a systematic study on the fatigue vehicle load model affecting the safety of bridge structure. The collection, processing, and analysis of vehicle load data of representative vehicles and vehicle models in different provinces are discussed in the initial part of the paper. Subsequently, the Miner's criterion for cumulative fatigue damage and the equivalent stress amplitude criterion are used to derive formulas for calculating the equivalent axle load, equivalent wheelbase, and the fatigue damage contribution ratio. Finally, according to the formula deduced, the fatigue load spectrum and standard fatigue load model of each province and Southeast China are proposed and contrasted with research findings of other scholars.

## 2. Vehicle load data collection

An accurate establishment of the fatigue load model of highway bridges should be based on actual vehicle load data collected,

including the data related to vehicle type, vehicle gross weight, and axle load. As individual regions have specific vehicle load characteristics, it is necessary to collect vehicle load data from individual regions under study.

### 2.1. Collection point location

The WIM system was used in this study to collect vehicle load data from six provinces in Southeast China. The data were collected from September 10 to 23, 2014. The data collection includes travel time, lane number, speed, vehicle type, number of axles, axle type, axle load, and so on [27-29]. Vehicle load data were collected from nine different-class highways, namely five national expressways, two provincial expressways, and two national highways. The highway coding and collection site in each of the six provinces are listed in Table 1.

**Table 1. Measurement stations in each province**

Province	Highway coding	Collection site
Hunan	G65	Daping bridge
	National highway 107	Xinqiang bridge
Zhejiang	National highway 104	Lixiaojiang bridge
Guangdong	G55	Kengkou bridge
	G15W3	Hanjiang bridge
Fujian	S10	Gangdao bridge
	G15	Tianluo bridge
Jiangxi	G56	Xinping bridge
Guangxi	S2201	Gangjian bridge

### 2.2. Data processing

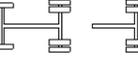
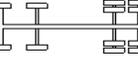
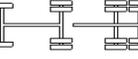
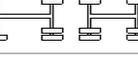
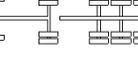
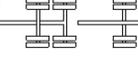
The data processing needs to be considered from two aspects: universality and particularity. In universality, data errors caused by system-related reasons should be eliminated. In particularity, some collected data have little influence on research results. If they are discarded, the calculation process can be simplified to facilitate subsequent research. These two aspects will have a great impact on the research process and its result.

The WIM system is inevitably affected by many uncertainties, such as electromagnetic interference, resulting in data distortion. In addition, system errors occur during collection of vehicle information [30]. For example, if two 3-axle vehicles, close to one another, pass through the collection site, the WIM system may identify them as one 6-axle vehicle, while one 6-axle vehicle may be mistaken for two 3-axle vehicles, or for one 2-axle vehicle and one 4-axle vehicle. In order to improve the accuracy and reliability of vehicle samples, it is necessary to eliminate potentially false vehicle data by analysing the original data. This process is mainly

carried out by comparing the vehicle data collected with the vehicle information registered by the vehicle management department through the license plate number. According to relationship between the fatigue damage level and  $m$ -th power of stress amplitude, if the weight of a light vehicle is 0.1 times that of a heavy vehicle, the fatigue damage level caused by the light vehicle is only 0.001 times that of the heavy vehicle (calculated by  $m = 3$ ). Therefore, the fatigue damage effect of a light vehicle is usually very small compared to that of a heavy vehicle. Referring to relevant research [24, 31], this paper does not consider the fatigue damage effect caused by vehicles with gross vehicle weight (GVW) of less than 30 kN. These vehicles include small

passenger car (less than 9 seats), large and medium-sized passenger car (9 seats and above), 2-axle trucks, 3-axle trucks, etc. At the same time, considering that some types of vehicles, such as seven-axle trucks, eight-axle trucks, and nine-axle trucks, account for a very small proportion of the total traffic flow, less than 0.1 % of total traffic, and that the fatigue damage to highway bridges in the actual operation process can be neglected, the proportion of vehicles of less than or equal to 0.1 % can be eliminated. After data processing, this study retained 448622 valid vehicles load data in two weeks, out of which Hunan accounts for 11.11 %, Zhejiang 5.6 %, Guangdong 19.9 %, Fujian 31.8 %, Jiangxi 22.83 %, and Guangxi 8.76 %.

**Table 2. Vehicle type classification and axle configuration**

Vehicle model	Vehicle type	Representative vehicle	Diagram	Axle configuration	Wheelbase [cm] and range of measured axle loads [kN] <sup>a</sup>
2-axle vehicle	A	small passenger car			[3.8, 14.4], 270, [4.5, 16.1]
	B	large and medium-sized passenger car			[16.4, 27.2], 520, [17.8, 34.3]
	C	goods vehicle			[5.7, 73.8], 430, [7.3, 101.7]
3-axle vehicle	D	goods vehicle			[8.9, 63.8], 430, [17.3, 111.7], 130, [15.3, 113.8]
	E	articulated vehicle			[11.4, 72.1], 230, [11.5, 131.7], 310, [12.9, 132.9]
	F	goods vehicle			[14.3, 53.8], 180, [18.5, 54.7], 560, [17.5, 121.0]
4-axle vehicle	G	goods vehicle			[18.2, 72.9], 190, [19.4, 75.6], 450, [27.5, 125.2], 130, [29.7, 129.3]
	H	articulated vehicle			[21.1, 77.4], 350, [17.3, 79.0], 730, [27.3, 155.6], 130, [21.2, 169.3]
	I	full trailer train			[17.9, 97.3], 400, [22.3, 107.4], 560, [26.2, 119.7], 340, [21.6, 121.8]
5-axle vehicle	J	goods vehicle			[18.2, 115.4], 130, [19.6, 136.9], 650, [15.4, 94.6], 130, [11.6, 91.4], 130, [14.3, 95.7]
	K	articulated vehicle			[23.9, 92.1], 350, [27.3, 107.6], 640, [15.4, 99.7], 130, [19.3, 101.5], 130, [19.8, 105.2]
	L	articulated vehicle			[22.7, 70.8], 300, [49.4, 146.3], 130, [14.6, 131.2], 720, [17.5, 131.9], 130, [12.4, 125.7]
6-axle vehicle	M	articulated vehicle			[27.9, 97.3], 130, [22.3, 107.4], 650, [26.2, 119.7], 130, [18.6, 121.1], 130, [17.4, 121.8], 130, [21.7, 122.5]

<sup>a</sup> Listed are [range of measured first axle weight (kN)], wheelbase (cm), [range of measured second axle weight (kN)].

### 2.3. Vehicle classification

More than 20 types of vehicles can be distinguished when considering a wide variety of vehicles travelling on roadways. Actual loads of each individual vehicle type are different. Therefore, it is necessary to screen and classify measured vehicle data. The fatigue damage of a highway bridge is related to stress amplitude and cycle times, which is affected by GVW and axle number respectively, and so the key basis of vehicle classification is GVW and axle number. According to the GVW and axle number, combined with the vehicle axle configuration from the Chinese Vehicle Model Manual [32], the authors of this study selected 13 representative vehicles, such as small passenger car, large and medium-sized passenger car, 2-axle goods vehicle, etc., and identified them as vehicle type A, vehicle type B, ..., vehicle type M, respectively. At the same time, 13 representative vehicles were divided according to the number of axles into five vehicle models, such as 2-axle vehicle, 3-axle vehicle, etc. Vehicle classification and axle configuration of each vehicle type are shown in Table 2.

Because of high speed of vehicles traveling on expressways, it is difficult to collect wheelbase data with WIM system or by other methods. The collected vehicle data do not contain wheelbase data. However, wheelbase is fixed at the time of leaving the vehicle factory, and its variation range is small. Wheelbase parameters of each vehicle type, presented according to Zhou et al. [12] and Shao et al. [16], are shown in Table 2. The range of measured axle loads of each vehicle type is also shown in Table 2.

### 2.4. Vehicle load analysis

Total numbers and percentages of every vehicle type were obtained for each province according to vehicle classification

given in the previous section, as shown in Table 3. In previous studies on vehicle load data, it is indicated that small passenger cars, large and medium-sized passenger cars, and 2-axle goods vehicles are the most frequent vehicle types encountered on motorways [33, 34]. In this paper, the data of vehicles weighing less than 30 kN were excluded from data processing, where the number of the small passenger car is the largest. The mentioned three types are still the largest ones in retained data. According to Table 3, the largest number of vehicles in each province belong to the vehicle type C, the largest proportion of which, 65.9 %, is found in Zhejiang. Except for Hunan, the second largest proportion was measured for vehicle type B, while the second largest proportion in Hunan is vehicle type A. In addition to 2-axle vehicles, the largest number in Hunan is type E, type G in Zhejiang, type M in Guangdong, type H in Fujian and Jiangxi, and type K in Guangxi.

The percentage of vehicle models according to axle number was obtained for various provinces, as shown in Table 4. It is not difficult to see that there are great differences in individual provinces. The largest proportion was the 2-axle vehicle, and the dominant position was very obvious in all provinces. The second largest proportion was more complex. 3-axle vehicles were dominant in Hunan and Guangdong, 4-axle vehicles in Zhejiang, Fujian, and Jiangxi, and 5-axle vehicles in Guangxi, which was closely related to the layout of the local industrial structure and the mode of economic development. It can be noted that the number of 3-axle, 5-axle, and 6-axle vehicles in Guangdong is comparable, and that the gap is not very large, unlike in other provinces. This is due to diversification of economic development in Guangdong, where each vehicle model was widely used. Mainly one or two models were dominant in other provinces.

**Table 3. Total numbers and percentages of every vehicle type for each province**

Province Vehicle code	Hunan		Zhejiang		Guangdong		Fujian		Jiangxi		Guangxi	
	[number]	[%]	[number]	[%]	[number]	[%]	[number]	[%]	[number]	[%]	[number]	[%]
A	11954	23.9	1973	7.9	7340	8.2	14271	10.0	12386	12.1	4840	12.3
B	4934	9.9	2166	8.6	20521	23.0	32693	22.9	31835	31.1	9847	25.0
C	25664	51.4	16547	65.9	38712	43.4	54642	38.3	33868	33.1	10251	26.1
D	1379	2.8	236	0.9	2258	2.5	2588	1.8	1815	1.8	1687	4.3
E	1387	2.8	262	1.0	2701	3.0	3540	2.5	3121	3.0	1296	3.3
F	225	0.5	37	0.1	1370	1.5	1181	0.8	1193	1.2	963	2.4
G	930	1.9	1790	7.1	2741	3.1	9592	6.7	3816	3.7	728	1.9
H	644	1.3	1239	4.9	1263	1.4	9965	7.0	5667	5.5	1034	2.6
I	99	0.2	191	0.8	425	0.5	2342	1.6	1924	1.9	684	1.7
J	211	0.4	91	0.4	1577	1.8	2595	1.8	1223	1.2	1673	4.3
K	413	0.8	179	0.7	1905	2.1	2361	1.7	1559	1.5	2779	7.1
L	724	1.4	314	1.3	2308	2.6	3424	2.4	1678	1.6	2560	6.5
M	1267	2.5	77	0.3	6177	6.9	3450	2.4	2333	2.3	987	2.5
Total	49831	100	25102	100	89298	100	142644	100	102418	100	39329	100

Table 4. Percentage of vehicle models in various provinces

Province	Percentage of vehicle models [%]				
	2-axle	3-axle	4-axle	5-axle	6-axle
Hunan	85.39	6.00	3.36	2.71	2.54
Zhejiang	82.40	2.13	12.83	2.33	0.31
Guangdong	74.55	7.09	4.96	6.48	6.92
Fujian	71.23	5.12	15.35	5.87	2.42
Jiangxi	76.24	5.99	11.14	4.35	2.28
Guangxi	63.41	10.03	6.22	17.83	2.51

### 3. Fatigue load model

The fatigue of highway bridges is characterized by variable amplitude, low stress, high cycle, and long life. The key to the calculation of fatigue strength (or service life) under variable amplitude repeated load is how to establish the relationship between the variable amplitude fatigue strength and the constant amplitude fatigue strength [35]. The purpose of establishing the load spectrum of vehicle models is to substitute a vehicle model for various vehicles of each type according to the principle of cumulative damage equivalence [36]. Considering the complexity of vehicles used on different highways, it was difficult to select a kind of representative vehicle as the load vehicle for fatigue assessment. Therefore, it is assumed in this study that the fatigue damage caused by  $n$  equivalent vehicle models is equal to that caused by  $n$  similar representative vehicles. The linear relationship between the axle load and the amplitude of alternating stress was assumed at the same time. The Miner's criterion for cumulative fatigue damage [37] and the equivalent stress amplitude criterion [38] were used to calculate the equivalent axle load of new vehicle models, and the sum of the equivalent axle loads was the equivalent total weight of the model vehicle.

#### 3.1. Damage level of stress cycle

The Miner's criterion holds that the damage caused by the  $n$ -th stress amplitude in the equal-amplitude stress cycle can be expressed by  $n/N$ , and the fatigue damage level under the  $n$ -th equal-amplitude stress cycle is as follows:

$$D_e = n/N \tag{1}$$

where  $N$  is the number of stress and strain cycle experienced before failure due to structural fatigue. The damage caused by stress amplitude in variable amplitude fatigue can be quantitatively expressed by  $n_i/N_i$ , and the damage can be linearly superposed. Therefore, the fatigue damage level of any constructional element under the action of the variable amplitude stress cycle can be defined as:

$$D_v = \sum \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \dots + \frac{n_n}{N_n} \tag{2}$$

where  $n_i$  is the number of times the stress amplitude acts, and  $N_i$  is the number of times of fatigue failure in the variable amplitude stress cycling test with different stress amplitudes, or the number of cycle times (fatigue life) equivalent to each stress amplitude in the constant amplitude fatigue strength curve.

According to Eq. (1), Eq. (2), and the constant amplitude fatigue curve equation [39] in the detailed exponential form:  $M(\Delta\sigma)^m = C$ , after equal-amplitude stress cycles of  $\sum_{i=1}^n n_i$  times, the fatigue damage level is:

$$D_e = \frac{\sum_{i=1}^t n_i}{C I (\Delta\sigma_e)^m} \tag{3}$$

where  $C$  is the performance parameter of structures or materials,  $\Delta\sigma_e$  is the equal-amplitude stress, and  $m$  is the material constant defined by the S-N curve. In this paper,  $m = 3$ . After variable amplitude stress cycles of  $\sum_{i=1}^t n_i$  times, the fatigue damage level is:

$$D_v = \sum_{i=1}^t \frac{n_i}{N_i} = \sum_{i=1}^t \frac{n_i}{C I (\Delta\sigma_i)^m} \tag{4}$$

where  $\Delta\sigma_i$  is the variable amplitude stress.

#### 3.2. Equivalent axle weight

The calculation of axle weight is based on the Miner's criterion for cumulative fatigue damage [35]. Each action of axles with different axle weight is equivalent to one repeated action of axle weight, and so the accumulation of fatigue damage caused by the two actions is equal.

In this paper,  $p = 1, 2, \dots, 6$  denotes the provinces (Hunan, Zhejiang, etc.),  $q = 1, 2, \dots, 5$  denotes the vehicle models (2-axle vehicle, 3-axle vehicle, ..., 6-axle vehicle, respectively), and  $l = 1, 2, \dots, 6$  denotes the number of axles;  $W_{pqjl}$  represents the  $l$ th axle weight of the  $j$ th vehicle for the  $q$ th vehicle type in the  $p$ th province.

Because the axle weight has a linear relationship with the stress amplitude caused by it, that is, the relationship between them is considered according to the elastic working state, then:

$$\Delta\sigma_{pqjl} = \beta W_{pqjl} \tag{5}$$

where  $\beta$  is the linear coefficient and  $\Delta\sigma_{pqjl}$  is the stress amplitude caused by  $W_{pqjl}$ . According to Eqs. (4) and (5), the fatigue damage level caused by the  $l$ th axle of  $r$  vehicles for the  $q$ th vehicle model in the  $p$ th province is:

$$D_{pqrl} = \frac{1}{C} \beta^m \sum_{j=1}^r n_{pqjl} W_{pqjl}^m \tag{6}$$

The fatigue damage level of the equivalent axle weight by the  $l^{\text{th}}$  axle of  $r$  times for the  $q^{\text{th}}$  vehicle type in the  $p^{\text{th}}$  province is

$$D_{\rho ql}^e = \frac{1}{C} \beta^m W_{\rho ql}^m \sum_{j=1}^r n_{\rho qj} \tag{7}$$

where  $W_{\rho ql}$  is the equivalent axle weight by the  $l^{\text{th}}$  axle of  $r$  times for the  $q^{\text{th}}$  vehicle type in the  $p^{\text{th}}$  province.

Because the damage level is equal, that is  $D_{\rho ql} = D_{\rho gl}^e$ , then:

$$W_{\rho ql} = \left( \frac{\sum_{j=1}^r n_{\rho qj} W_{\rho qlj}^m}{\sum_{j=1}^r n_{\rho qj}} \right)^{\frac{1}{m}} = \left( \sum_{j=1}^r f_{\rho qj} W_{\rho qlj}^m \right)^{\frac{1}{m}} \cdot f_{\rho q} = \frac{n_{\rho q}}{N_p} \tag{8}$$

where  $n_{\rho q}$  is the number of the  $q^{\text{th}}$  vehicle model in  $p^{\text{th}}$  province,  $N_p$  is the number of vehicles in  $p^{\text{th}}$  province.

The wheelbase of each vehicle model in each province is:

$$A_{\rho ql} = \sum_{j=1}^r f_{\rho qj} A_{\rho qlj} \tag{9}$$

where  $A_{\rho ql}$  is the equivalent wheelbase of  $l^{\text{th}}$  axle for the  $q^{\text{th}}$  vehicle model in the  $p^{\text{th}}$  province,  $A_{\rho qlj}$  is the  $l^{\text{th}}$  wheelbase of the  $j^{\text{th}}$  vehicle for the  $q^{\text{th}}$  vehicle model in the  $p^{\text{th}}$  province.

Summarizing vehicle load data for six provinces, the equivalent axle weight of each vehicle model in Southeast China is shown(10) and (11):

$$W_{ql} = \sum_{p=1}^6 f_p W_{\rho ql}, f_p = \frac{n_p}{N} \tag{10}$$

$$A_{ql} = \sum_{p=1}^6 f_p A_{\rho ql} \tag{11}$$

where  $W_{ql}$  is the equivalent axle weight by the  $l^{\text{th}}$  axle for the  $q^{\text{th}}$  vehicle model in Southeast China,  $n_p$  is the number of vehicles in  $p^{\text{th}}$  province,  $N$  is the number of all vehicles, and  $A_{ql}$  is the equivalent wheelbase by the  $l^{\text{th}}$  axle for the  $q^{\text{th}}$  vehicle model in Southeast China.

### 3.3. Fatigue damage contribution ratio

The contribution ratio of fatigue damage reflects relative damage affecting ability of each vehicle model to bridge structure. Standard fatigue vehicle will choose the most disadvantageous vehicle model for bridge structure fatigue damage.

A vehicle is composed of multiple axles, so it only generates one stress cycle when it passes through a long-span bridge, while it generates multiple stress cycles when it passes through a

small-span bridge, but it can still be equivalent to a stress cycle by using the linear damage accumulation criterion. According to Eq. (5), for a vehicle whose weight is  $W_{\rho ql}$ , regardless of span size

$$\Delta\sigma_{\rho qlj} = \beta W_{\rho qlj} \tag{12}$$

According to Eqs. (4) and (12), the bridge fatigue damage caused by the  $q^{\text{th}}$  vehicle model in the  $p^{\text{th}}$  province for a period of time is as follows:

$$D_{\rho q} = \frac{1}{C} \beta^m n_{\rho q} W_{\rho q}^m \tag{13}$$

where  $n_{\rho q}$  is the number of the  $q^{\text{th}}$  vehicle model in  $p^{\text{th}}$  province, and  $W_{\rho q}$  is the equivalent axle weight of  $q^{\text{th}}$  vehicle model in  $p^{\text{th}}$  province. Assuming that the total number of vehicles in  $p^{\text{th}}$  province is  $V_p$ , and the frequency of  $q^{\text{th}}$  vehicle model is  $f_{\rho q}$ , then according to Eqs (13),

$$D_{\rho q} = \frac{1}{C} \beta^m V_p f_{\rho q} W_{\rho q}^m \tag{14}$$

So the bridge fatigue damage caused by all types of vehicles in  $p^{\text{th}}$  province is:

$$D_p = \frac{1}{C} \beta^m V_p \sum_{q=1}^5 f_{\rho q} W_{\rho q}^m \tag{15}$$

and the fatigue damage contribution ratio of the  $q^{\text{th}}$  vehicle model in the  $p^{\text{th}}$  province is:

$$\lambda_{\rho q} = \frac{D_{\rho q}}{D_p} = \frac{f_{\rho q} W_{\rho q}^m}{\sum_{q=1}^5 f_{\rho q} W_{\rho q}^m} \tag{16}$$

In the same way, the fatigue damage contribution ratio of Southeast China is:

$$\lambda_q = \frac{D_q}{D} = \frac{f_q W_q^m}{\sum_{q=1}^5 f_q W_q^m} \tag{17}$$

where  $D$  is the bridge fatigue damage caused by all vehicles according to the data collected in Southeast China.

## 4. Fatigue load spectrum of model vehicles

In addition to axle weight and wheelbase, another important parameter of axle configuration is the wheel space. According to the Chinese Vehicle Model Manual [30] and field survey, the wheel space of all kinds of vehicles is relatively close. Most of them are concentrated in 1.8m in the range of 1.7 to 2.1 m, and the wheel space of vehicles is generally set to 1.8m in highway bridge regulations [24, 25, 40]. Therefore, in this paper, the wheel space of all kinds of vehicles is unified to 1.8 m.

**Table 5. Fatigue load spectrum for highway bridges in Hunan**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	85.4 %	34,3 (395), 57,2	91.5
3-axle	6.0 %	63,5 (318), 71,2 (246), 101,4	236.1
4-axle	3.4 %	59,6 (264), 79,0 (564), 80,2 (142), 88,1	306.8
5-axle	2.7 %	74,3 (289), 120,8 (368), 85,1 (447), 85,2 (130), 89,0	454.5
6-axle	2.5 %	73,3 (300), 90,4 (130), 104,1 (720), 83,0 (130), 86,2 (130), 90,9	527.9

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN).

**Table 6. Fatigue load spectrum for highway bridges in Zhejiang**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	82.4 %	26,2 (424), 44,6	70.8
3-axle	2.1 %	49,7 (315), 68,3 (248), 83,3	201.2
4-axle	12.8 %	30,2 (263), 55,1 (565), 44,9 (146), 46,4	176.6
5-axle	2.3 %	51,9 (289), 74,8 (367), 56,5 (449), 54,6 (130), 58,0	295.7
6-axle	0.3 %	47,1 (300), 62,1 (130), 65,5 (720), 54,8 (130), 56,4 (130), 61,7	347.7

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN)

**Table 7. Fatigue load spectrum for highway bridges in Guangdong**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	74.-6 %	40,5 (440), 78,0	118.5
3-axle	7.1 %	50,4 (291), 64,9 (300), 94,7	210.1
4-axle	5.0 %	48,3 (256), 69,4 (540), 83,2 (150), 84,4	285.3
5-axle	6.5 %	58,0 (270), 108,8 (439), 73,5 (365), 72,0 (130), 79,2	391.5
6-axle	6.9 %	55,5 (300), 81,8 (130), 89,3 (720), 78,9 (130), 75,0 (130), 87,9	468.5

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN)

**Table 8. Fatigue load spectrum for highway bridges in Fujian**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	71.2 %	29,8 (436), 53,5	83.3
3-axle	5.1 %	53,2 (293), 67,0 (287), 87,8	208.0
4-axle	15.4 %	35,5 (285), 58,2 (589), 51,4 (152), 53,4	198.5
5-axle	5.9 %	52,4 (261), 80,1 (435), 53,5 (371), 50,5 (130), 53,9	290.3
6-axle	2.4 %	52,4 (300), 65,5 (130), 68,5 (720), 62,0 (130), 67,3 (130), 87,9	378.3

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN)

**Table 9. Fatigue load spectrum for highway bridges in Jiangxi**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	76.2 %	29,8 (441), 51,5	81.3
3-axle	6.0 %	47,8 (279), 56,0 (305), 70,2	174.0
4-axle	11.1 %	35,5 (305), 56,4 (608), 50,2 (165), 48,7	193.9
5-axle	4.4 %	52,4 (271), 80,1 (451), 53,5 (352), 50,5 (130), 53,9	261.9
6-axle	2.3 %	49,7 (300), 57,6 (130), 60,6 (720), 53,2 (130), 52,4 (130), 57,4	330.9

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN)

Parameters of equivalent vehicle models for each province and Southeast China were obtained using the vehicle load statistical model and Eqs. (8) to (11), as shown in Table 5 to Table 11. The fatigue damage contribution ratio of each vehicle model in each province and Southeast China is shown in Table 12, where HN is short for Hunan, ZJ is short for Zhejiang, GD is short for Guangdong, FJ is short for Fujian, JX is short for Jiangxi, GX is short for Guangxi, and SEC is short for Southeast China.

Although Southeast China is one of the more developed regions in China, due to the influence of economic development level and industrial layout, the fatigue load spectrum and fatigue load contribution ratio of vehicle models vary greatly among individual provinces. Among them, Hunan and Guangdong have the largest equivalent vehicle weights. They are followed by Zhejiang, Fujian, and Jiangxi, while Guangxi has the smallest equivalent vehicle weight. In areas of Southeast China, the 6-axle vehicles in Hunan, Guangdong, and Jiangxi have the highest contribution ratio and would be a good choice for the standard fatigue vehicle in these provinces. The 4-axle standard fatigue vehicle was chosen in Zhejiang, and the 5-axle standard fatigue vehicle was chosen in Fujian and Guangxi. As far as the whole Southeast region is concerned, the 6-axle vehicle has also the highest contribution ratio, and so a 6-axle vehicle was chosen as the standard fatigue vehicle in the whole Southeast region, too. Figure 1 shows appropriate vehicle parameters of all standard fatigue vehicles.

It can also be seen from Table 4 and Table 12 that the contribution ratio of fatigue load is little affected by the number or frequency of vehicles, i.e. that it is significantly affected by the weight of vehicles. Although the number of 2-axle vehicles defined in Southeast China accounts for 60 % or even 80 % in some provinces, it does not have the largest contribution ratio of damage due to its smaller equivalent vehicle weight.

**Table 10. Fatigue load spectrum for highway bridges in Guangxi**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	63.4 %	42,6 (434), 68,5	111.0
3-axle	10.0 %	57,5 (303), 64,7 (294), 58,2	180.4
4-axle	6.2 %	58,7 (316), 54,5 (599), 34,3 (189), 47,6	195.1
5-axle	17.8 %	60,1 (279), 55,8 (456), 25,7 (345), 28,6 (130), 37,0	207.3
6-axle	2.5 %	61,8 (300), 44,0 (130), 43,7 (720), 25,6 (130), 31,6 (130), 42,4	249.1

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN)

**Table 11. Fatigue load spectrum for highway bridges in Southeast China**

Vehicle model	Relative frequency	Vehicle model parameters <sup>b</sup>	GVW [kN]
2-axle	74.5 %	35,8 (432), 66,7	102.5
3-axle	6.1 %	53,5 (294), 64,7 (290), 85,2	203.5
4-axle	10.0 %	40,2 (287), 59,9 (587), 56,9 (156), 59,3	216.4
5-axle	6.1 %	57,0 (271), 85,9 (439), 57,3 (366), 55,8 (130), 60,8	316.8
6-axle	3.2 %	56,5 (300), 74,2 (130), 80,9 (720), 70,4 (130), 68,6 (130), 77,8	428.5

<sup>b</sup> Parameters listed are first axle weight (kN), [wheelbase (cm)], second axle weight (kN)

**Table 12. Contribution ratio of fatigue damage**

Vehicle model	Damage ratio [%]						
	HN	ZJ	GD	FJ	JX	GX	SEC
2-axle	11.8	17.2	10.2	10.2	15.1	27. %	11.8
3-axle	8.7	8.9	4.7	9.4	9.8	14.0	7.5
4-axle	10.6	36.1	8.1	24.7	25.3	11.0	15.0
5-axle	28.0	31.2	27.6	29.2	24.3	38.8	28.8
6-axle	41.0	6.6	49.5	26.6	25.4	9.2	36.9

## 5. Comparison of existing standard fatigue vehicles

On the basis of the Miner's criterion for cumulative fatigue damage, the standard fatigue vehicle models of six provinces and Southeast China were established in this paper and compared with the research results of other scholars. In the standard fatigue vehicle model, the wheelbase and the axle load distribution are relatively fixed, which is mainly set by the automobile manufacturers according to the technical standard for vehicles. Therefore, the GVW of each vehicle model will be directly compared in this part, ignoring the effect of other factors and research methods on the model.

Lan et al. [13], Sun et al. [15], Xia et al. [19] and Liu et al. [31] obtained the local standard fatigue vehicle models by studying vehicle load data collected for Shandong, Jiangsu, Beijing, Guizhou, Zhejiang, Henan and other places in China. Among them, most scholars chose 6-axle vehicle as the standard fatigue vehicle model in the research area. Except for 318 kN in Beijing, the GVW of 6-axle standard fatigue vehicle model of other areas ranges from 531 kN to 595

kN. This is mainly due to the research data collected in the sixth ring road of Beijing, which is an urban road, and so the GVW is smaller. Among seven standard fatigue vehicle models established in this paper, the GVW of four 6-axle vehicle models varies from 330 kN to 527 kN, which is slightly smaller compared to findings made by other authors. In the areas where the standard fatigue vehicle is a non-6-axle vehicle, Liu et al. [31] chose a 3-axle vehicle as the standard fatigue vehicle model for Zhejiang and 4-axle vehicle for Guizhou. A 4-axle vehicle model with a GVW of 480 kN was selected as the fatigue load calculation model of the Chinese steel bridge code. In this paper, the author chose a 4-axle vehicle as the standard fatigue model for Zhejiang, and a 5-axle vehicle for Fujian and Guangxi. The general differences in research results can mainly be attributed to the following facts:

### a) Time of collection.

Before 2013, there was a dispute between "49 tons" and "55 tons" in the highway industry of China. "49 tons" is the technical standard for vehicles, and the national standard [41] stipulates that the maximum total design mass of 6-axle vehicles shall not exceed 49 tons. And "55 tons" is related to the limit of the maximum carrying capacity of highways, bridges, tunnels, and culverts by road designing, manufacturing and management departments. For a long time, the administrative department has not formed a unification on this issue, which has resulted in the implementation of different standards. In recent years, this problem has gradually been unified, and "49 tons" won in the end. The author's vehicle data collection occurred after 2013, while other scholars collected before 2012. With the vigorous actions to control overload vehicles, the GVW of vehicles travelling on the highway has decreased compared to previous situation. That is why the GVW of standard fatigue vehicle models obtained by the author is lower compared to findings of other scholars.

### b) Location of collection.

The location of sample data collection has a far-reaching impact on results. China has a vast territory and a widespread road network. As far as a single province is concerned, it is impossible to collect vehicle load data for each road, and so individually collected data are often partial and incomprehensive, and it is therefore difficult to truly reflect load characteristics of vehicles. In the case of Zhejiang province, the collection site of Liu et al. is G104 and G15, and the collection site of this paper is National Highway 104. The former is an expressway, and the latter is a highway, which is the main reason for the difference between standard fatigue vehicle models for the same province.

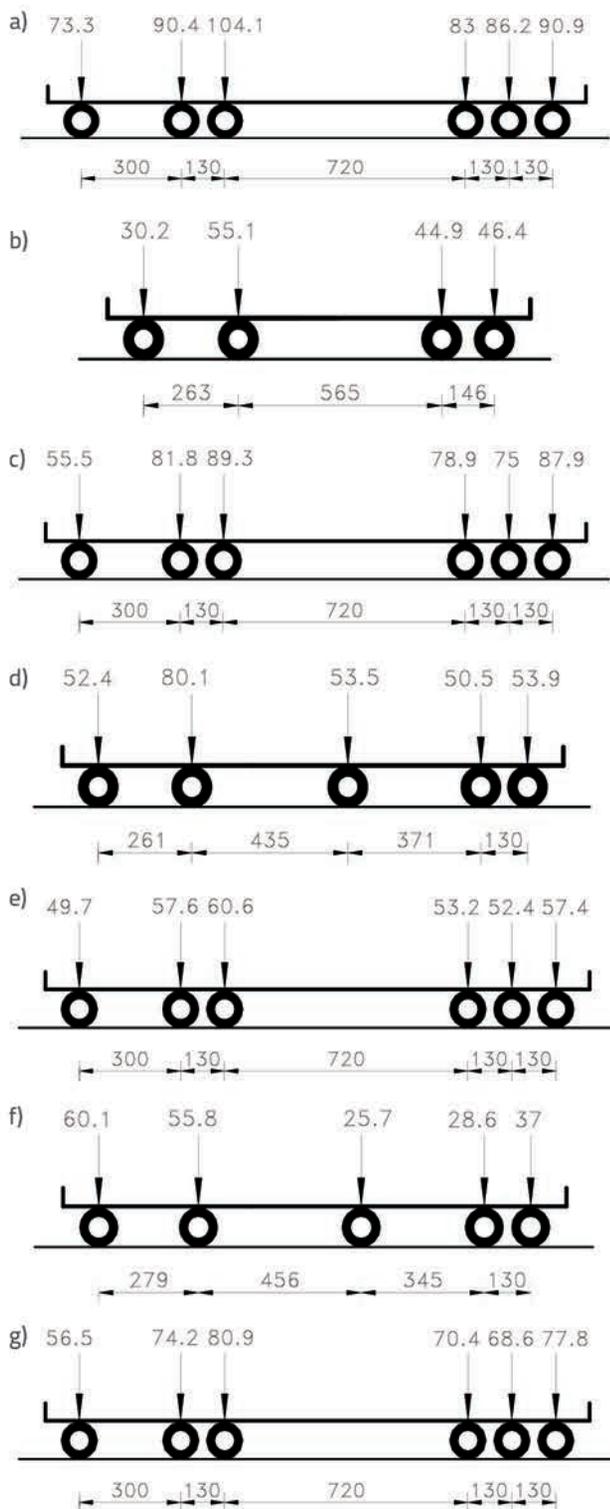


Figure 1. Standard fatigue vehicle (Note: Axle weights are in kilonewtons; wheelbases are in centimetres)

c) Differences in economic development and industrial structure. In the reform and opening up, developing the speed of traffic is an objective need for economic development. The common saying "the first road goes to the rich" has become the consensus of local governments in China. The development of economy needs the support of the transportation industry, the most prominent feature of which is the participation of large freight vehicles. Therefore, the standard fatigue vehicle model in most areas of China is a 6-axle vehicle, which is a non-special vehicle with the largest cargo capacity in China, and does not require additional administrative permission. But in less developed areas, the industrial development is relatively slow, and so the standard fatigue vehicle model is the 4-axle or 5-axle vehicle, such as in Guangxi and Guizhou provinces.

d) Influence of industry type on mode of transportation. In recent years, some provinces have been exploring more intensive and economically viable industrial models. For example, Zhejiang vigorously develops the IT economy and small commodity economy, which leads to rapid growth of the logistics industry. Unlike the 6-axle truck used in the traditional industrial model to transport coal and energy, logistics owners mainly rely on 3-axle or 4-axle vehicles to transport and transfer goods for reasons of flexibility and convenience. Therefore, the standard fatigue vehicle model obtained in Zhejiang differs from other provinces.

### 6. Conclusion

Nine data collection points were set up in six provinces of Southeast China to collect vehicle load data for various types of highways, including five national expressways, two provincial expressways, and two national highways. After data processing, a total of 13 representative vehicle types and 448622 valid vehicle data were retained. Based on the Miner's criterion for cumulative fatigue damage and the equivalent stress amplitude criterion, formulas for calculating equivalent axle load, equivalent wheelbase, and fatigue damage contribution ratio were derived in six provinces and Southeast China. Finally, seven standard fatigue vehicle models established in this paper, containing six provinces and Southeast China, were proposed and compared with the existing standard fatigue vehicle models, and the reasons for the difference in results were analysed. The following conclusions were reached:

- The largest number of vehicles in each province are type C vehicles, the largest proportion of which is found in Zhejiang. Except for Hunan, the second largest proportion of vehicles is type B, while the second largest proportion in Hunan is type A. In addition to 2-axle vehicles, the largest proportion in Hunan is type E, for Zhejiang it is type G, for Guangdong type M, for Fujian and Jiangxi type H, and for Guangxi type K.
- The percentage of vehicle models according to the number of axles was obtained for various provinces. 2-axle vehicles

- constitute the largest proportion of vehicles in all provinces. The second largest proportion of vehicles is more complex. Thus, we have 3-axle vehicles in Hunan and Guangdong, 4-axle vehicles in Zhejiang, Fujian, and Jiangxi, and 5-axle vehicles in Guangxi.
- According to the formula of equivalent axle load and equivalent wheelbase deduced in this paper, a fatigue load spectrum including five equivalent vehicle models was identified for each province and Southeast China. The ideal standard fatigue vehicle would have six axles, except for 4-axle vehicles in Zhejiang, and 5-axle vehicles in Fujian and Guangxi.
  - The contribution ratio of fatigue load is little affected by the number or frequency of vehicles, i.e. it is significantly affected by the weight of vehicles. The proportion of 2-axle vehicles accounts for 60 % or even 80 %. In some provinces, it does not have the largest contribution ratio of damage due to its smaller equivalent vehicle weight.

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