

## Research Article

# Measurement-Based Vehicle Load Model for Urban Expressway Bridges

Bin Chen,<sup>1</sup> Zheng Zhong,<sup>2</sup> Xu Xie,<sup>1</sup> and Pengzhen Lu<sup>3</sup>

<sup>1</sup> College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China

<sup>2</sup> Hangzhou Municipal Facilities Supervision and Administration Center, Hangzhou 310003, China

<sup>3</sup> College of Civil Engineering and Architecture, Zhejiang University of Technology, Hangzhou 310003, China

Correspondence should be addressed to Xu Xie; [xiexu@zju.edu.cn](mailto:xiexu@zju.edu.cn)

Received 8 January 2014; Accepted 4 March 2014; Published 22 May 2014

Academic Editor: Ting-Hua Yi

Copyright © 2014 Bin Chen et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Significant changes in vehicle loads have occurred in China due to the development of the automobile industry and transportation within the past two decades, particularly the rapid increase in traffic flow and the large-scale emergence of heavy trucks. However, research into vehicle loadings on urban bridges is not well developed. In this study, based on traffic flow data collected using a weigh-in-motion system installed on an expressway in an urban logistics zone, we analyzed the traffic flow, vehicle types, and gross vehicle weight (GVW) features and developed models for the vehicle load and fatigue load. According to the axle space, axle types, and axle number, the trucks in the traffic flow were classified into 10 representative vehicle types. The probability distribution of the GVW was fitted to a three-class mixed log-normal distribution. Using the improved Gumbel method, we determined the extreme value distribution of the vehicle loadings in the purpose reference period and assessed the vehicle loadings of urban bridges. In addition, using the equivalent damage theory, six equivalent vehicle models were established according to the measurements of the axle weight and axle space, thereby obtaining a simplified model of fatigue vehicle loadings on urban expressway bridges.

## 1. Introduction

The traffic load is one of the main variables that affect bridges. The traffic load models used in the current standard applied throughout China are based on the analysis of vehicle data collected in 1997 on four national highways during five daytime periods (each of 12 hours) [1]. However, rapid economic growth, especially during the last 20 years, as well as the development of the automobile industry and transportation, means that the traffic flow has increased continuously, especially the number of heavy vehicles, thereby leading to major changes in vehicle loads [2, 3]. In addition, the traffic loads of urban bridges (bridges on urban road) and highway bridges (bridges on highway) are quite different (i.e., the proportion of heavy vehicles and vehicle types), so it is not reasonable to design urban bridges using the traffic load models of highway bridges. Compared with the massive volumes of survey data related to highway bridges, the study of urban bridges is very limited in China. Only a few cities such as Shanghai and Guangzhou have carried out

such investigations [4, 5]. However, the vehicle loads of urban bridges have not been described accurately because of the poor technology used and the selection of inappropriate road types. It is known that the safety of urban bridges is affected by the traffic loads on suburban roads, logistic zone roads, and transit roads. Therefore, it is necessary to analyze the actual traffic loads of these roads and to develop advanced models that are suitable for bridge design and evaluation.

Weigh-in-motion (WIM) systems are advanced traffic investigation devices, which were designed as new tools that allow researchers and engineers to obtain traffic flow information. They can also be used to study the vehicle loadings of modern bridges. The vehicle load data collected by WIM systems can provide a comprehensive overview of the traffic flow without considering human factors. These data are an important basis for studying road traffic conditions and for obtaining the vehicle load characteristics. Many researchers, including Nowak et al. [6, 7], O'Brien et al. [8–11], Fu and You [12, 13], Miao et al. [14–16], and

Ruan et al. [17, 18], have used WIM data to analyze the traffic flow characteristics, to develop traffic load models, to study extreme vehicle loadings and their distributions, and to simulate traffic flows. In the current bridge design standard, vehicle loads and lane loads are two different traffic load patterns, which are used for different design purposes. In the theoretical framework based on reliability, the vehicle load is used as a certain fractile (normally 0.95) of the extreme value distribution of the vehicle load during a specific reference period. Based on the parent distribution of the GVW and using one day's maximum distribution as annual data, Chinese researchers, such as Mei et al. [19], Guo et al. [20], and Lan et al. [21], obtained the extreme value distributions for a reference period using a compound renewal process, thereby obtaining the vehicle loadings. Based on the probability distribution of the measured vehicle loads as they passed and the total amount of vehicles, Gong et al. [22] determined the probability distribution function of the extreme value for periods of 1 day, 1 year, 20 years, 50 years, and 100 years. All of these previous approaches use the parent distribution of the GVW to obtain the extreme value distribution of the vehicle loads. Thus, the results were highly dependent on the fitting accuracy of the parent distribution of the GVW and their theoretical basis. However, these approaches are computationally expensive and are used rarely in practical engineering applications. In addition, the fatigue of components (especially steel) is becoming increasingly important and attracting more attention in the field of bridges with traffic growth and vehicle weight increases. With large axle weights and high passing frequencies, the bridge decks directly under the wheel pressure are at risk of failure due to fatigue [23]. At present, the design codes for bridges in the UK, USA, Japan, and European countries classify the fatigue strength according to the structural details based on the corresponding design spectrum and fatigue vehicle models. However, the codes used in China are relatively old and there are no explicit formulations for calculating the fatigue of components with specific loading patterns, loading values, and fatigue stress amplitudes, although some improvements have been made. For example, Chen et al. [5] proposed a fatigue load spectrum that considered two traffic surveys from 1994 and 1995 on the Shanghai inner ring road bridge number 3. Based on field measurements of vehicles on highway bridges covering six different provinces all over the country, Zhou et al. [24] also obtained a fatigue load spectrum and the corresponding standard vehicle model for highway bridges using the equivalent fatigue damage theory. However, these traffic surveys were measured mainly by people, rather than machines, which may have entailed unpredictable errors when calculating the axle weight, axle space, and the numbers of vehicles of various types. They were also limited to highway bridges and studies of urban bridges have been reported only rarely.

Based on a dynamic WIM system, the vehicle types and gross vehicle weights were obtained from traffic flow data collected on an urban expressway in a logistics zone, and the improved Gumbel method based on the extreme value theory was used to obtain the extreme value distribution of the vehicle loadings in a specific reference period and

the vehicle loadings. This method was based on observations of the daily extreme gross vehicle weight values, which has the advantages of simplicity, stability, and easy application in engineering. The fatigue load spectrum was also studied. Based on measurements of the axle weight and axle space, six equivalent vehicle models were established using the equivalent fatigue damage theory and a simplified fatigue vehicle load model was developed for urban expressway bridges.

## 2. Urban Expressway Traffic Condition

*2.1. Data Measurement and Process.* Several logistics markets, related to food, steel, and other commodities, are found in the northern part of Hangzhou city, Zhejiang Province, China, which is regarded as the area with the heaviest truck traffic. The road pavement structure in this area has a high damage rate because of bad traffic conditions and four serious accidents related to bridge failure occurred in recent years. To understand the traffic conditions of overloaded vehicles in this area, the department of Road Management in the city of Hangzhou placed a WIM system at the end of a bridge to develop a real vehicle model of urban bridges, as well as to facilitate bridge safety management and the development of an overloading control program, (Figure 1). This WIM system is the first example on urban roads in the province of Zhejiang and it aims to monitor the passage of vehicles 24 hours each day. A WIM system uses bending path pads to measure the weights of vehicles that pass by. The magnetic loop detectors are located on both sides of a bending path pad, which is used to separate the vehicles and to acquire information such as the lane and velocity. As a vehicle passes, the following data are acquired: vehicle arriving date and time, lane number, vehicle speed, number of axles, axle weight, axle spacing, vehicle license, license type, and a photograph of the front of the vehicle.

Using the WIM data records, we could extract different traffic flow characteristic parameters and analyze the traffic flow features. The WIM was installed and put into use in June 2012. Full traffic data were obtained for 18 months, which reflected the traffic conditions and vehicle information at the monitoring location. Vehicles weighing  $\geq 3$  tons were considered to be trucks. According to the provisions of the highway management departments of China, a GVW  $> 20$  t indicated 2-axle vehicles,  $> 30$  t indicated 3-axle vehicles, GVW  $> 40$  t indicated 4-axle vehicles, GVW  $> 50$  t indicated 5-axle vehicles, and GVW  $> 55$  t indicated 6-axle vehicles, which were considered to be overweight. The raw data collected were preprocessed before the analysis, where the preprocessing method combined the characteristics of the original data and it used methods [25, 26] that eliminated obvious errors and meaningless data.

*2.2. Traffic Condition.* We used the data from a two-week period (July 16 to 29, 2012) to analyze the GVW characteristics. The selection of such a period is sufficiently representative to show the statistical characteristics of the measured road. The total number of vehicles was 176470 and vehicles

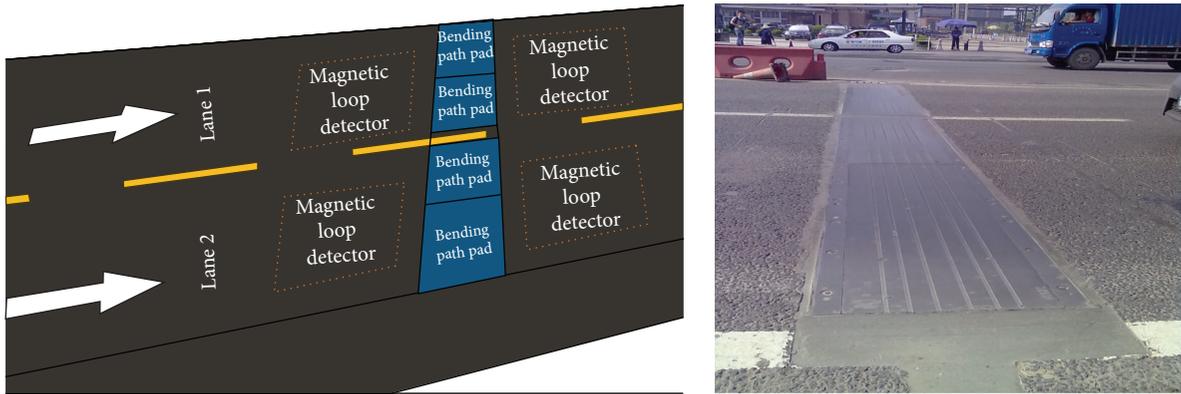


FIGURE 1: Dynamic weigh-in-motion stations on an urban expressway in Hangzhou, China.

TABLE 1: Statistical characteristics of the gross vehicle weights.

Date	Total amount	Average (t)	Standard deviation (t)	Coefficient of variation	Maximum (t)	Minimum (t)
Jul. 16	16475	3.52	5.32	1.51	93.75	1.40
Jul. 17	18882	3.68	6.25	1.70	88.15	1.40
Jul. 18	13776	3.66	6.20	1.69	94.60	1.40
Jul. 19	14227	3.72	6.77	1.827	111.20	1.40
Jul. 20	12239	3.77	6.50	1.72	115.65	1.40
Jul. 21	10985	3.93	7.20	1.83	95.35	1.40
Jul. 22	9634	3.62	6.44	1.78	94.60	1.40
Jul. 23	10540	3.32	5.43	1.63	91.85	1.40
Jul. 24	10553	3.49	6.08	1.74	104.15	1.40
Jul. 25	11793	3.34	5.62	1.68	100.90	1.40
Jul. 26	9729	3.24	5.06	1.56	79.10	1.40
Jul. 27	9847	2.99	4.11	1.37	85.20	1.30
Jul. 28	11493	2.96	4.05	1.37	77.20	1.40
Jul. 29	11326	2.86	4.00	1.40	80.70	1.40

that weighed <3 tons comprised the majority (80.48%). In total, 34447 vehicles weighed >3 tons, which accounted for 19.52% of the total number of valid vehicles. In addition, 2203 vehicles exceeded the load standard limit set by the Highway Management Department of China, which accounted for 6.4% of all the trucks. Furthermore, 684 vehicles weighed >55 tons and the heaviest gross vehicle weight was 115.65 tons. The time distribution of the 2203 vehicles (Figure 2) shows that the number of overweight vehicles at night (87%) was far higher than that during the daytime (13%), while the second half of the night (after midnight) had more overweight trucks (68%) than the first half (19%, before midnight). Thus, the overweight problem was more severe after midnight than at other times.

A statistical analysis was performed using the GVW to determine the average, standard deviation, coefficient of variation, and the maximum and minimum daily gross vehicle weights (Table 1). The daily GVWs differed little, thereby indicating that the vehicle load was stable in the short term. The vehicle load coefficient of variation was always >1.0, thereby indicating that the vehicle loads were highly discrete, with many vehicle types and various weight ranges.

**2.3. Vehicle Classification.** Many vehicle types comprise road traffic and there are some errors in the data measured using WIM systems. Thus, extracting specific vehicle information from the data is a challenging task. Based on the axle weight, axle space, and axle types of different standard vehicle types found in the China Automobile Type Handbook [27], we classified the measured vehicle types and compared them with standard vehicle types, using the most similar standard vehicle types as the representative types of the actual vehicle. Using this procedure, we determined the representative vehicle types on the measured urban expressway, the data related to the vehicle types, and the axle weights and axle spaces, as shown in Figure 3 and Tables 2 and 3, respectively. During the vehicle classification process, we excluded vehicles that weighed <3 tons and the vehicle types that accounted for <0.01% of the total trucks.

Figure 3 shows the vehicle type classifications: V21, V22, and V23 for 2-axle vehicles; V31 and V32 for 3-axle vehicles; V41 and V42 for 4-axle vehicles; V51 for 5-axle vehicles; and V61 and V62 for 6-axle vehicles. Among the representative vehicle types obtained, 2-axle heavy trucks (V22) and 2-axle large passenger cars (V23) accounted for the highest

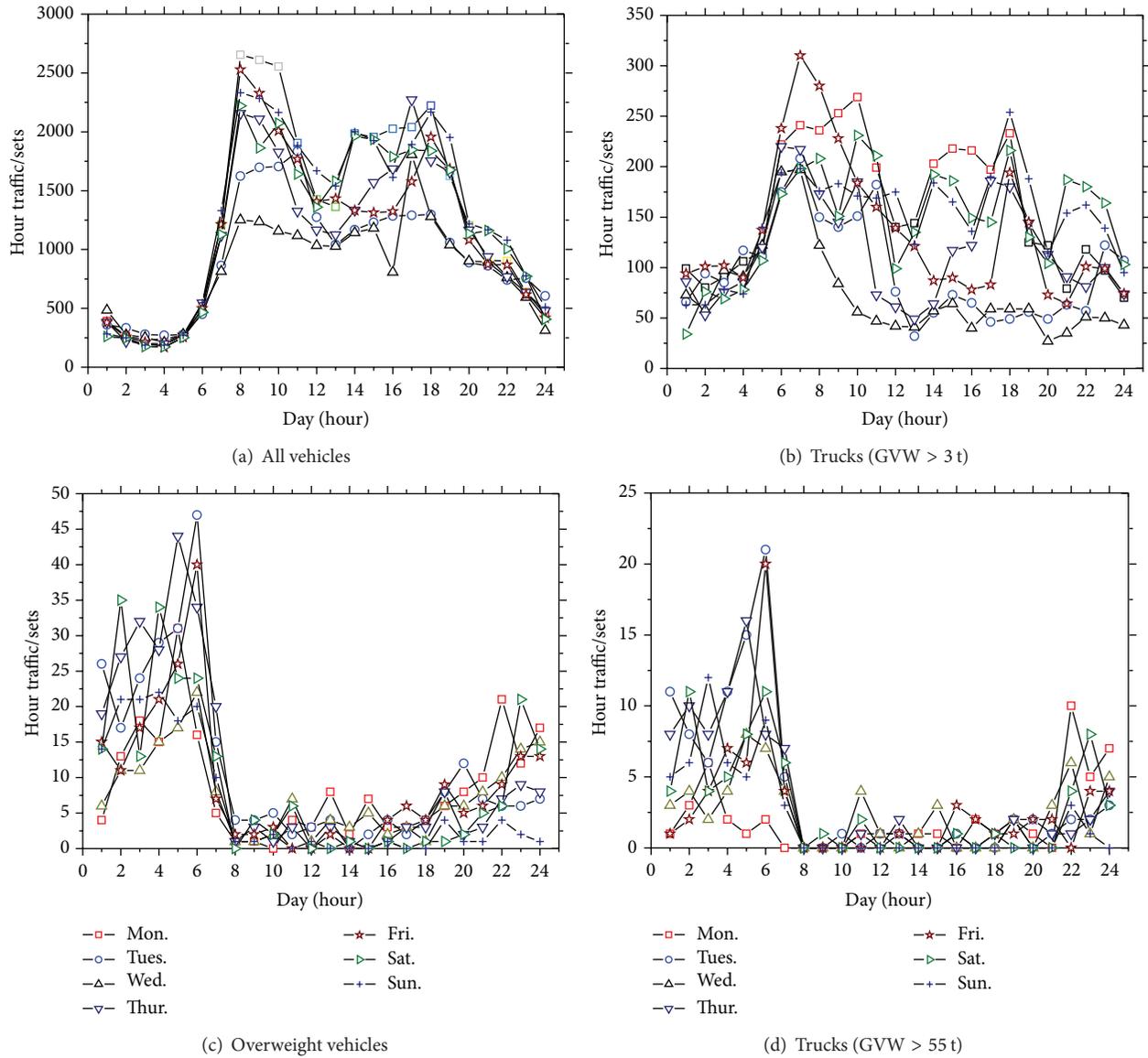


FIGURE 2: Distribution of hourly traffic during each day in one week.

TABLE 2: Vehicle classification and axle-weight statistics.

Vehicle classification		Average value and deviation of axle weight (t)					
Classification	Ratio	Axle1	Axle2	Axle3	Axle4	Axle5	Axle6
V21	8.75%	1.89 (0.54)	2.30 (1.79)				
V22	45.11%	3.40 (1.55)	7.74 (6.57)				
V23	30.30%	5.05 (1.33)	9.84 (3.30)				
V31	2.79%	4.36 (1.42)	4.48 (2.15)	10.37 (7.17)			
V32	3.09%	7.68 (3.26)	13.66 (9.08)	13.74 (9.50)			
V41	4.59%	6.85 (3.18)	7.44 (3.50)	13.97 (9.67)	15.25 (9.15)		
V42	1.82%	4.10 (0.76)	12.03 (4.30)	11.96 (4.79)	11.87 (4.65)		
V51	1.74%	5.55 (1.24)	12.53 (4.61)	11.47 (4.56)	10.75 (4.16)	11.23 (4.17)	
V61	1.03%	4.24 (0.61)	4.40 (1.35)	11.29 (4.99)	9.61 (4.95)	9.71 (4.75)	10.49 (5.19)
V62	0.78%	5.59 (0.88)	8.42 (3.80)	7.96 (3.57)	9.59 (5.59)	9.24 (5.18)	10.30 (5.54)

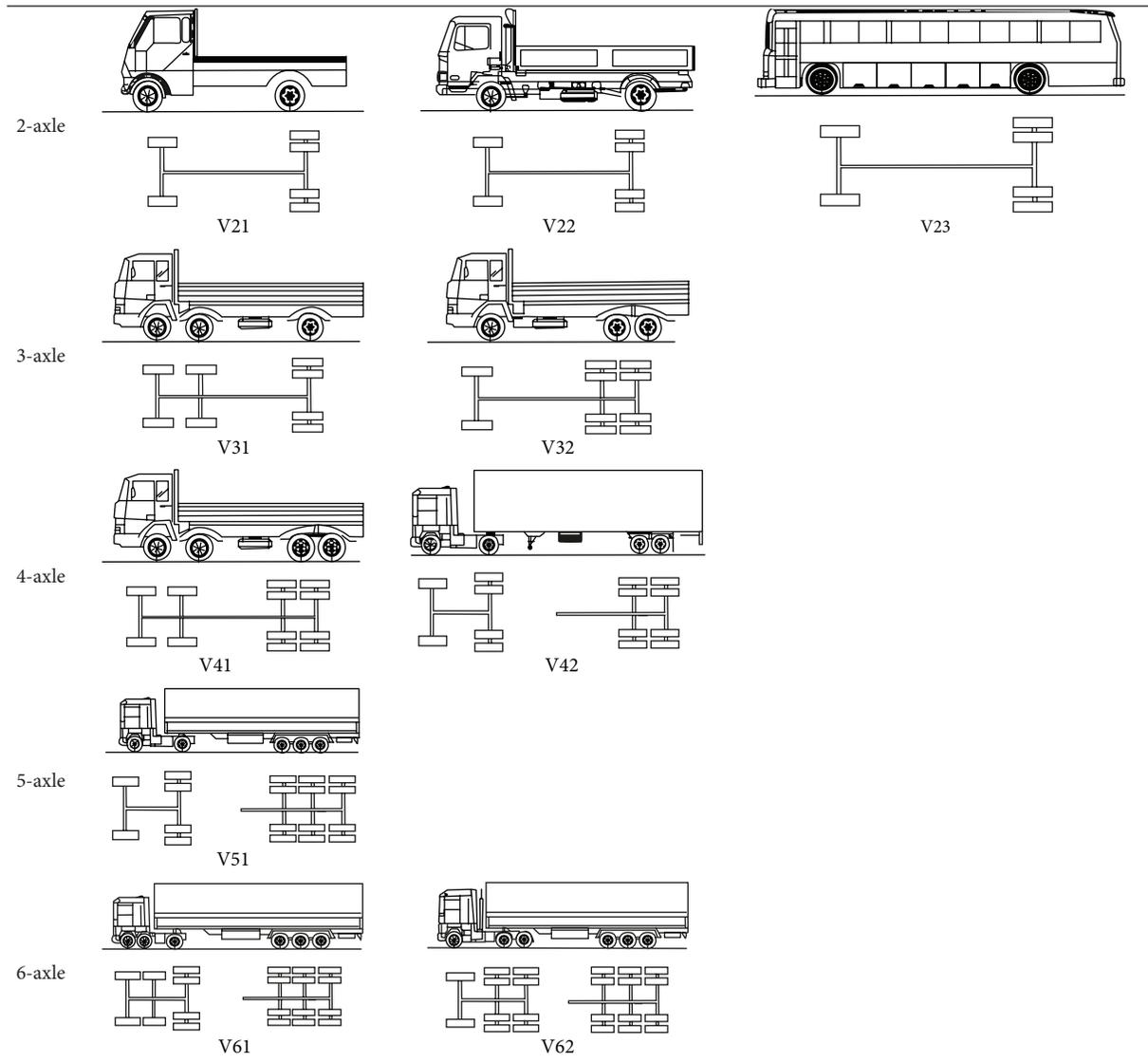


FIGURE 3: Vehicle type classifications.

TABLE 3: Vehicle classification and axle space statistics.

Vehicle classification		Average value and deviation of axle space (m)				
Classification	Ratio	Axle1	Axle2	Axle3	Axle4	Axle5
V21	8.75%	2.98 (0.35)				
V22	45.11%	4.72 (0.73)				
V23	30.30%	6.64 (0.84)				
V31	2.79%	2.10 (0.74)	5.75 (1.27)			
V32	3.09%	5.07 (1.40)	1.54 (0.58)			
V41	4.59%	2.02 (0.52)	4.76 (1.00)	1.41 (0.25)		
V42	1.82%	3.80 (0.39)	6.83 (1.01)	1.37 (0.10)		
V51	1.74%	3.73 (0.76)	6.60 (1.40)	1.43 (0.70)	1.35 (0.25)	
V61	1.03%	1.93 (0.34)	2.74 (0.52)	6.56 (1.37)	1.37 (0.21)	1.37 (0.22)
V62	0.78%	3.48 (0.55)	1.46 (0.22)	6.97 (1.72)	1.39 (0.21)	1.38 (0.21)

proportion, which characterize urban road traffic. In addition, the rear axle weights had a high standard deviation, especially for V32 and V41, thereby indicating a wide vehicle weight distribution.

### 3. Probability Model of Vehicle Loads

**3.1. Probability Distribution of GVW.** Traffic flow has various forms with strong regional characteristics. Many studies have shown that the GVW probability distribution can be represented as a multimodal distribution [19–21, 28]. This is mainly because the traffic flow comprises light, medium, and heavy vehicles, which are accompanied by different load forms, that is, empty, half full, full, and overloaded. In general, a two-class mixed normal distribution [19], inverse normal distribution [15, 29], or two-class mixed log-normal distribution [21] is used to model the GVW probability distribution.

Assuming that the GVW comprises  $n$  levels of different vehicle weight classes and that the probability density function of level  $i$  is  $f_i(x)$ , the GVW probability density function can be expressed as

$$f_X(x) = \sum_{i=1}^n p_i f_i(x), \quad (1)$$

where  $p_i$  is the proportion of the level  $i$ ,  $\sum_{i=1}^n p_i = 1$ . The probability distribution function is

$$F_X(x) = \sum_{i=1}^n p_i F_i(x). \quad (2)$$

In general, each vehicle weight class has its own probability distribution. Thus, the probability density functions  $f_i(x)$  of different vehicle weight classes are different and they depend on how the results are fitted to the data. In the present study, the distribution type of  $f_i(x)$  was the same in the equation, for example, normal or log-normal distribution, but different statistical parameters were used. The expectation maximization algorithm was used for parameter estimation, which is the one employed the most frequently and it is effective for estimating mixed distribution model parameters, which can yield satisfactory results [30].

Using normal, log-normal, and Weibull distributions, we fitted a two-lane GVW distribution and the K-S test was employed to determine the optimal cumulative distribution function. The three-class mixed lognormal distribution had the best fit (Figure 4), especially for the tail distribution, which overcame the deficiencies of using unimodal and bimodal distributions for tail fitting, and provided a good foundation for the description of vehicle loads. The parameters for the fitted distribution functions are shown in Table 4.

**3.2. Extreme Value Distribution of Vehicle Load.** In the reliability theory framework, vehicle loads used for bridge designs or assessments are based on the extreme value distributions of vehicle loads within a specific reference period. At present, the extreme value distribution is obtained mainly using

the following three methods: parent distributions, maximum distributions, and extreme value theory [31]. The extreme value theory is the main method used recently, which includes the block maxima approach and the peaks over threshold approach (POT). The former requires a large amount of data, whereas the latter requires the selection of an appropriate threshold, which determines the results.

Numerous studies have shown that the vehicle load types are highly diverse with strong regional features, so methods based on the parent distributions will include many errors. Based on the Gumbel method derived from extreme value theory, the extreme values of the measured data were used in the present study, instead of the parent distribution, to obtain the extreme value distribution of the vehicle loads. Previous research has shown that this method has good stability and it facilitates engineering applications [32]. Using this method, Fu and You [12, 33] obtained the extreme value distributions for the vehicle load effects within a reference period based on the measured data, where they used a specific fractile as the vehicle load effect value for bridge design applications.

According to the classic extreme value theory, if the parent distribution of a sample follows an exponential distribution, such as a Gaussian distribution, gamma distribution, or Weibull distribution, the asymptotic distribution of the maximum will follow an extreme value type I distribution (the Gumbel distribution). The probability function is expressed as follows:

$$F(x_e) = \exp(-\exp(-y)), \quad (3)$$

where  $y$  is a simplified variable; that is,

$$y = \alpha(x_e - \mu), \quad (4)$$

where the fitted variables,  $\mu$  and  $1/\alpha$ , are the mode and dispersion, respectively. To estimate the value, (3) and (4) are usually expressed as follows:

$$y = -\ln(-\ln(F(x_e))), \quad (5)$$

$$x_e = \mu + \frac{1}{\alpha}y. \quad (6)$$

This extreme value estimation method is based on the extreme value theory proposed by Gumbel, which is commonly known as the Gumbel method. The Gumbel method has been used widely for extreme value estimations in wind speed and flood water level applications because of the simplicity and practicality of the extreme value type I distribution.

The following equivalence probability relation can be obtained by assuming that the observed extreme values are independent:

$$F(T = t_0) = F^n(T = t_d), \quad (7)$$

where  $F(T = t_0)$  represents the extreme value distribution for one year and  $F(T = t_d)$  is the extreme value distribution in a specific reference period (the reference design period for new Chinese bridges is 100 years, i.e.,  $t_d = 100$ ). The extreme value

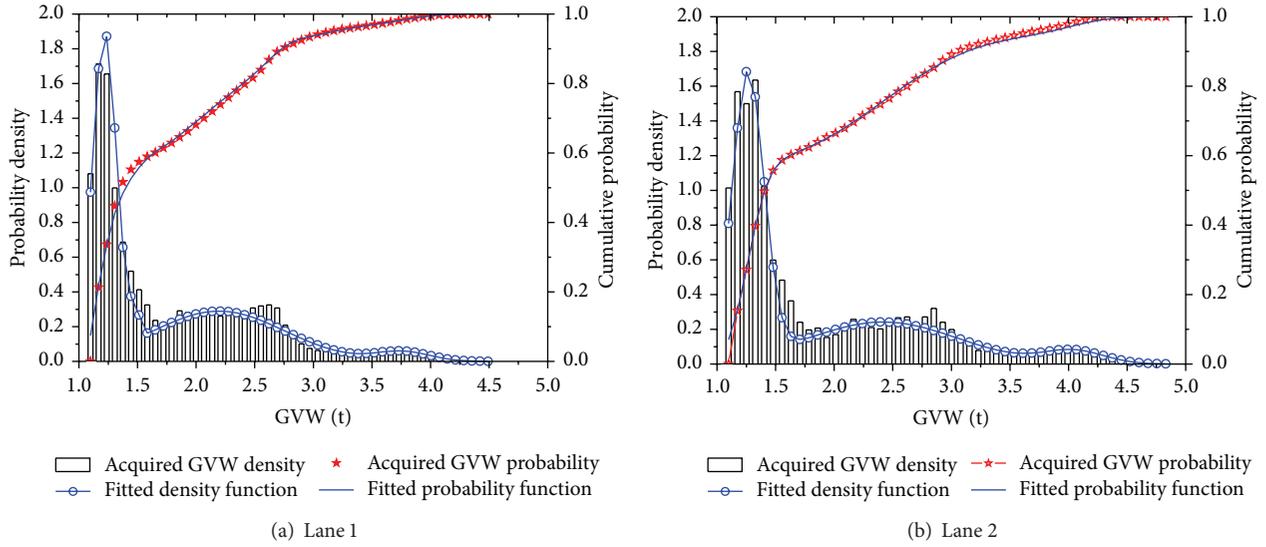


FIGURE 4: Probability density and cumulative probability of the GVW.

TABLE 4: Estimated parameters of the mixed probability distribution for the GVWs in each lane.

Lane number	First class			Second class			Third class		
	$P_1$	$\mu_1$	$\sigma_1$	$P_2$	$\mu_2$	$\sigma_2$	$P_3$	$\mu_3$	$\sigma_3$
1	0.49	1.21	0.10	0.48	2.25	0.60	0.03	4.02	0.24
2	0.56	1.27	0.14	0.39	2.42	0.65	0.05	4.05	0.26

obeys an extreme value type I distribution, so the following equation can be obtained by plugging (3) into (7):

$$\exp(-\exp(-y(T=t_d))) = [\exp(-\exp(-y(T=t_0)))]^m. \quad (8)$$

Based on (3), (4), and (8), the following expressions can be obtained:

$$\frac{1}{\alpha(T=t_d)} = \frac{1}{\alpha(T=t_0)}, \quad (9)$$

$$\mu(t=t_d) = \mu(t=t_0) + \frac{1}{\alpha(T=t_0)} \ln\left(\frac{t_d}{t_0}\right).$$

According to the method described above, the two parameters of the extreme value distribution during the specific reference period can be obtained, that is,  $\mu_d$  and  $\alpha_d$ , and the extreme value distribution function is also determined. To facilitate the application of this method, the procedure is described as follows.

- (1) The extreme values of the vehicle load are obtained for each day based on the measured data.
- (2) Arrange  $n$  observed extreme values according to the absolute value size from low to high, which are denoted as  $\{x_n\}$ , and number them according to  $i = 1, 2, \dots, m$ .
- (3) For every ranked extreme value observation, specify a nonexceedance probability  $P_i$ ,  $P_i \approx m/n + 1$ , and  $P = \{P_n\}$  is obtained.

- (4) According to (5), determine the simplified variable  $y = -\ln(-\ln P)$  and denote it as  $\{y_n\}$ .

- (5) According to (6), take the extreme value  $\{x_n\}$  as the vertical axis and simplify the variable  $\{y_n\}$  as the horizontal axis by using the least squares method to fit the data.

- (6) Based on the fitted line, the parameters  $\mu_0$  and  $\alpha_0$  can be obtained, where  $y = 0$ , the intercept is  $\mu_0$ , and the slope of the line is  $1/\alpha_0$ .

- (7) Substitute the two parameters  $\mu_0$  and  $\alpha_0$  into (9), and obtain  $\mu_d$  and  $\alpha_d$ , which are the two parameters of the extreme value distribution in the specific reference period.

- (8) Substitute the two parameters  $\mu_d$  and  $\alpha_d$  into (3) and (4) to obtain the extreme value distribution of the vehicle load in the specific reference period, which can yield the requisite extreme value for each demand guarantee rate.

According to the standards of China specifications for the design of highway bridges and culverts [1], the maximum vehicle load distribution from one day is used as the maximum vehicle load distribution for one year, assuming that observations are made only one day per year. Thus, the maximum vehicle load distribution from a design reference period of  $T$  years can be substituted by the maximum vehicle load distribution from  $T$  days. Accordingly, based on the classic extreme value theory, it can be considered that

TABLE 5: Fatigue load spectrum for urban expressway bridges.

Type of vehicle	Total axles	Vehicle parameters (axle weight, t; axle space, m)	Total weight (t)	Frequency as a percentage of traffic volume (%)
M1	2	(3.30) <sup>a</sup> [5.23] <sup>b</sup> (8.49)	11.79	16.43
M2	3	(4.79) [2.10] (5.63) [5.75] (14.57)	25.00	0.55
M3	3	(8.82) [5.07] (18.38) [1.54] (18.89)	46.09	0.60
M4	4	(7.45) [2.52] (10.35) [5.34] (17.77) [1.40] (18.22)	53.79	1.25
M5	5	(5.72) [3.73] (13.78) [6.60] (12.76) [1.43] (11.90) [1.35] (12.35)	56.50	0.34
M6	6	(5.00) [2.60] (7.77) [2.19] (11.78) [6.74] (11.89) [1.38] (11.54) [1.37] (12.57)	60.55	0.35
Amount to				19.52

<sup>a</sup>Figures in parentheses represent the equivalent axle weight.

<sup>b</sup>Figures in square brackets represent the equivalent axle space.

the extreme value distribution of the daily measured vehicle load follows an extreme value type I distribution, so the extreme value distribution of the vehicle load in a specific reference design period can be obtained.

By extracting the daily extreme measured vehicle load values for the urban expressway, parameters  $\alpha_0 = 0.0902$  and  $\mu_0 = 88.0879$  can be obtained using the procedure described above by parameter fitting estimation. Thus, the parameters  $\alpha_d = 0.0902$  and  $\mu_d = 139.1465$  can also be obtained. Using the 0.95 fractile of  $F_{X,\max}(x)$  as the design vehicle load for urban expressway bridges,  $x_{0.95} = 172.08$  tons.

#### 4. Fatigue Load Model

In the current conditions of increasing traffic loads, the effects of fatigue on bridge components have become increasingly prominent. However, fatigue load modeling research is progressing slowly in China. In our study, we obtained the vehicle type classification based on the actual traffic flow, analyzed the GVW statistical characteristics, the axle weight and axle space, and produced a probability model to describe the GVW distribution. However, it is very difficult to apply these models to engineering applications where fatigue design is required. Therefore, it was necessary to simplify the vehicle load statistical model we established. Based on published methods [5, 21], we developed a practical method for establishing the vehicle load spectrum as follows.

- (1) Vehicles with gross weights of <3 tons are ignored because these vehicles have little effect on bridge fatigue. Thus, only trucks are considered.
- (2) Based on an assumption that the vehicle axle weight and stress amplitude have a linear relationship, the axle weight of each axle for a vehicle model can be determined according to the equivalent fatigue damage theory. The equivalent gross weight of the vehicle model is the sum of the equivalent axle weights. Thus, the equivalent axle weight is calculated by

$$W_{ej} = \left[ \sum f_i \cdot W_{ij}^m \right]^{1/m}, \quad (10)$$

where  $W_{ij}$  is the axle weight of the  $j$ th axle for the  $i$ th vehicle in the same vehicle class,  $W_{ej}$  is the equivalent axle weight of the  $j$ th axle of the vehicle model,  $f_i$  is the relative frequency of the  $i$ th vehicle of the vehicle model  $f = n/N$ ,  $N$  is the total number of vehicles of the same type,  $n_i$  is the number of the  $i$ th vehicle, and  $m$  is the material constant determined by the curve, where  $m = 3$  for steel structures.

- (3) The axle spaces are calculated by

$$A_j = \sum f_i \cdot A_{ij}, \quad (11)$$

where  $A_{ij}$  is the axle weight of the  $j$ th axle of the  $i$ th vehicle in the same vehicle class and  $A_j$  is the  $j$ th axle space of the vehicle model.

Based on the axle weights and axle spaces of 10 typical vehicle types, six equivalent vehicle models can be obtained using (10) and (11), as shown in Table 5. M1 are 2-axle vehicles; M2 and M3 are 3-axle vehicles; and M4, M5, and M6 are 4-axle, 5-axle, and 6-axle vehicles, respectively. Although M2 and M3 are 3-axle vehicles, their axle spaces are quite different, which leads to different stress amplitude and cycle numbers, so M2 and M3 are classified into two models.

Table 5 shows that the number of vehicles with effects on bridge fatigue accounted for only 19.52% of the traffic volume, which is similar to the previously reported figure of 20.17% [5], although different from the level of 49.94% reported in another study [21]. This is because the former two studies were based on the vehicle fatigue load spectrum of urban bridges, whereas the latter was based on highway bridges, which received larger numbers of trucks. The equivalent axle weight was significantly greater than that reported in previous studies [5, 21], especially for M2, M3, and M4 (approximately double), which indicates that the overweight problem was severe on the expressway where the measurements were obtained. The gross weights estimated by the models were higher and they exceeded the weight limits, except for M1 and M2.

## 5. Conclusion

- (1) Based on the axle weight, axle space, and axle type, 10 representative vehicle types were classified on an urban expressway, where 2-axle heavy trucks (V22) and 2-axle motorbuses (V23) comprised the majority, which also reflected the typical characteristics of urban road traffic.
- (2) The GVWs were subjected to a statistical analysis. The GVW coefficients of variation were all  $>1.0$ , which indicated the discrete features of the truck loads. The GVW probability distribution followed a three-class mixed lognormal distribution.
- (3) Given the daily extreme values of the measured data, an improved Gumbel method was used instead of the parent distribution to determine the extreme value distribution of the vehicle loads in a specific reference period. Thus, we determined the extreme value distribution of the vehicle loads for urban expressway bridges over a 100-year design reference period and the vehicle loads (0.95 fractile) for use in new bridge design.
- (4) Based on the field measurements, six equivalent fatigue vehicle models were established for urban expressway bridges according to the equivalent damage theory, where 19.52% of the vehicles contributed to fatigue effects on the bridges. The axle weights and gross weights were relatively large in this fatigue model, and some of the gross weights were not within the weight limits.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

## Acknowledgments

This study was sponsored partially by Shanghai Planned Projects for Postdoctoral Research Funds under Grant 13R21421100. Data support from Hangzhou Municipal Facilities Supervision and Administration Center are also acknowledged.

## References

- [1] Ministry of Communications and Transportation (MOCAT), *General Code for Design of Highway Bridges and Culverts*, JTG D60-2004, Beijing, China, 2004.
- [2] T.-H. Yi, H.-N. Li, and M. Gu, "Experimental assessment of high-rate GPS receivers for deformation monitoring of bridge," *Measurement: Journal of the International Measurement Confederation*, vol. 46, no. 1, pp. 420–432, 2013.
- [3] T.-H. Yi, H.-N. Li, and M. Gu, "Wavelet based multi-step filtering method for bridge health monitoring using GPS and accelerometer," *Smart Structures and Systems*, vol. 11, no. 4, pp. 331–348, 2013.
- [4] R.-H. Wang, C. Chi, Q.-Z. Chen, and X.-X. Zhen, "Study on the model of the fatigue-loaded vehicles in Guangzhou trestle bridges," *Journal of South China University of Technology (Natural Science)*, vol. 32, no. 12, pp. 94–96, 2004.
- [5] Z. Y. Chen, W. L. Tong, and Z. Y. Sheng, "Fatigue load spectrum for urban road bridges," *China Civil Engineering Journal*, vol. 30, no. 5, pp. 20–27, 1997.
- [6] M. Kozikowski and A. S. Nowak, "Live load models based on weigh-in-motion data," in *Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management (IABMAS '10)*, pp. 2881–2888, Philadelphia, Pa, USA, July 2010.
- [7] M. Lutomirska and A. S. Nowak, "Design live load for long span bridges," in *Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management (IABMAS '10)*, pp. 3365–3372, July 2010.
- [8] E. J. O'Brien, P. Rattigan, A. González, J. Dowling, and A. Žnidarič, "Characteristic dynamic traffic load effects in bridges," *Engineering Structures*, vol. 31, no. 7, pp. 1607–1612, 2009.
- [9] B. Enright and E. J. O'Brien, "Monte Carlo simulation of extreme traffic loading on short and medium span bridges," *Structure and Infrastructure Engineering*, vol. 9, no. 12, pp. 1267–1282, 2013.
- [10] A. Getachew and E. J. O'Brien, "Simplified site-specific traffic load models for bridge assessment," *Structure and Infrastructure Engineering*, vol. 3, no. 4, pp. 303–311, 2007.
- [11] C. C. Caprani and E. J. O'Brien, "The use of predictive likelihood to estimate the distribution of extreme bridge traffic load effect," *Structural Safety*, vol. 32, no. 2, pp. 138–144, 2010.
- [12] G. Fu and J. You, "Truck loads and bridge capacity evaluation in china," *Journal of Bridge Engineering*, vol. 14, no. 5, pp. 327–335, 2009.
- [13] G. Fu and J. You, "Extrapolation for future maximum load statistics," *Journal of Bridge Engineering*, vol. 16, no. 4, pp. 527–535, 2011.
- [14] T. H. T. Chan, T. J. Miao, and D. B. Ashebo, "Statistical models from weigh-in-motion data," *Structural Engineering and Mechanics*, vol. 20, no. 1, pp. 85–110, 2005.
- [15] T. J. Miao and T. H. T. Chan, "Bridge live load models from WIM data," *Engineering Structures*, vol. 24, no. 8, pp. 1071–1084, 2002.
- [16] F. T. K. Au, M. Tong, and L. G. Tham, "Design thermal loading for steel bridges in Hong Kong," *Transactions Hong Kong Institution of Engineers*, vol. 8, no. 2, pp. 1–9, 2001.
- [17] X. Ruan, J. Y. Zhou, and X. F. Shi, "Comparative study on highway traffic flow and load properties of China and France," *Journal of Tongji University (Natural Science)*, vol. 41, no. 9, pp. 1392–1397, 2013.
- [18] X. Ruan, X. Zhou, and J. Guo, "Extreme value extrapolation for bridge vehicle load effect based on synthetic vehicle flow," *Journal of Tongji University*, vol. 40, no. 10, pp. 1458–1485, 2012.
- [19] G. Mei, Q. Qin, and D.-J. Lin, "Bimodal renewal processes models of highway vehicle loads," *Reliability Engineering and System Safety*, vol. 83, no. 3, pp. 333–339, 2004.
- [20] T. Guo, D. M. Frangopol, D. Han, and Y. Chen, "Probabilistic assessment of deteriorating prestressed concrete Box-Girder bridges under increased vehicle loads and aggressive environment," *Journal of Performance of Constructed Facilities*, vol. 25, no. 6, pp. 564–576, 2011.
- [21] C. Lan, H. Li, and J. Ou, "Traffic load modelling based on structural health monitoring data," *Structure and Infrastructure Engineering*, vol. 7, no. 5, pp. 379–386, 2011.

- [22] J. X. Gong, W. J. Li, and J. L. Zhao, "Research on probabilistic model of highway bridge vehicle loads (1)—non-controlling area," *Journal of Highway and Transportation Research and Development*, vol. 27, no. 6, pp. 40–45, 2010.
- [23] G. D. Zhou and T. H. Yi, "Thermal load in large-scale bridges: a state-of-the-art review," *International Journal of Distributed Sensor Networks*, vol. 2013, Article ID 217983, 17 pages, 2013.
- [24] Y. T. Zhou, H. Zhai, and W. G. Bao, "Research on standard fatigue vehicular load for highway bridges," *Chinese Journal of Highway*, vol. 2009, no. 12, pp. 21–25, 2009.
- [25] J. Pelphrey, C. Higgins, B. Sivakumar et al., "State-specific LRFR live load factors using weigh-in-motion data," *Journal of Bridge Engineering*, vol. 13, no. 4, pp. 339–350, 2008.
- [26] X. Y. Zhou, *Statistical analysis of traffic loads and their effects on bridges [Ph.D. thesis]*, University Paris-EST & IFSTTAR, Paris, France, 2013.
- [27] China Automobile Industry Corporation, *China Automotive Technology & Research Centre (CATRC)*, China Automobile Type Handbook, Henan Province, China, 1993.
- [28] C. C. Caprani, *Probabilistic analysis of highway bridge traffic loading [Ph.D. thesis]*, School of Architecture, Landscape, and Civil Engineering, University College Dublin, Dublin, Ireland, 2005.
- [29] C. Crespo-Minguillón and J. R. Casas, "A comprehensive traffic load model for bridge safety checking," *Structural Safety*, vol. 19, no. 4, pp. 339–359, 1997.
- [30] H. W. Xia, Y. Q. Ni, K. Y. Wong, and J. M. Ko, "Reliability-based condition assessment of in-service bridges using mixture distribution models," *Computers and Structures*, vol. 106–107, pp. 204–213, 2012.
- [31] C. C. Caprani and E. J. O'Brien, "Estimating extreme highway bridge traffic load effects," in *Proceedings of the International Conference on Structural Safety and Reliability (ICOSSAR '09)*, Osaka, Japan, 2009.
- [32] Y. Quan, M. Gu, B. Chen, and T. Yukio, "Study on the extreme value estimating method of non-Gaussian wind pressure," *Chinese Journal of Theoretical and Applied Mechanics*, vol. 42, no. 3, pp. 560–566, 2010.
- [33] G. Fu and J. You, "Extreme truck load effect prediction for bridge structural reliability," in *Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management (IABMAS '10)*, pp. 2859–2867, Philadelphia, Pa, USA, July 2010.



# Hindawi

Submit your manuscripts at  
<http://www.hindawi.com>

