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Multi-parameter Dynamic Traffic Flow Simulation and Vehicle Load Effect Analysis based on Probability and Random Theory

Yuzhao Liang* and Feng Xiong**

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Abstract

In order to evaluate the vehicle load adaptability of existing highway bridge at the operational stage, and provide a reference for the strategy of reinforcement and maintenance, a new model of multi-parameter traffic load flow simulation and vehicle load effect (VLE) analysis is proposed. In this paper, static traffic flow data was collected by weight in motion (WIM) system, and the characteristics of static traffic flow, such as gross vehicle weight (GVW), vehicle gap distance (VGD), wheelbase and the proportion of axle weight distribution (PAWD), was analyzed in different lanes. The program run by MATLAB was used to conduct the Monte-Carlo method on all kinds of traffic data collected and to generate the multi-parameter dynamic random traffic flow (DRTF) data. By loading DRTF data onto the influence line of the sample bridges (simply supported integral bridges of 20 m to 40 m), the maximum VLE under DRTF could be calculated and compared with the static VLE of Chinese current design code. The results showed that the fitting of GVW distribution should be used a skewed distribution or a kurtosis distribution. And under current daily traffic volume (DTV), the service condition of highway bridges can meet the requirement of traffic load. However, in the driveway of some heavy trucks, the VLE is greater than the value suggested in the current design code, which may cause partial damage to the bridge.

Keywords: *bridge engineering, simulation, dynamic traffic load flow, probability and random theory, vehicle load effect, weigh in motion*

1. Introduction

The highway bridge's safety, economy, and durability are closely related to the operational vehicle loads which must be adapted to the characteristics of traffic flow, traffic volume, the condition of transportation and future development trends. However, with the rapid development of national economy and the needs of heavy load transportation, heavy vehicles and overload vehicles frequently appear on the highway, which may cause damage to highway bridges. Therefore, the government tries to limit the heavy vehicle in a certain area of China. However, this may lead to an increase in both costs in transportation and overload control. Hence, to solve the restrictions on the development of highway transportation capacity, studying the vehicle load adaptability problem of the existing highway bridge is urgently needed.

Establishing accurate, economical, and practical analytical models on vehicle load effect (VLE) is a primary task and of great interesting to study the vehicle load adaptability of existing highway bridges. The Nowak team (1991, 1998, 2004, 2013) had carried out more in-depth research on the vehicle load during the past decades. Early studies focused on the single-lane or two-lane bridges. By using the statistical data from vehicle surveys and the bending moment with shear forces as a starting point, researchers utilized the extrapolation method to determine the maximum VLE in different periods as an important indicator for assessment of the service life of the bridge. After that, the data collected by the weight in motion (WIM) system, and the probability density distribution (PDD) of the gross vehicle weight (GVW) was given. Recently the team took the vehicle data as samples and combined the GVW and the finite element model of the bridge structure to obtain the bending moment. The main purpose was to get the statistical parameters of GVW and vehicle load bending moment. Based on the traffic statistics of New York State, Fu and Osman (2000) proposed a method to obtain vehicle load models including overload conditions, and provided the formula to calculate the resistance for bridge overload checking, which was used to evaluate the reliability of highway bridges. Gindy (2004) analyzed data from a bridge in New Jersey, USA, and obtained the maximum VLE in the design reference period of 75 years. However, the study on the randomness of the relevant parameters of the actual vehicle load was deficient. Croce and Salvatore (2001) developed a method to calculate the maximum load distribution based on the equilibrium renewal process theory in the reference period. The researchers pointed out that when the bridge influence line is greater than 20 m, the maximum VLE of the bridge mainly depends on the GVW on the influence line and the impact of the

*Ph.D. Candidate, College of Architecture and Environment, Sichuan University, Chengdu 610065, China (E-mail: yzh.liang@foxmail.com)
**Professor, College of Architecture and Environment, Sichuan University, Chengdu 610065, China (Corresponding Author, E-mail: fxiong@scu.edu.cn)

layout of each axle can be ignored. Kozikowski (2009) collected vehicle data and applied the extrapolation method to develop a specific program to calculate the maximum value of the VLE. The analysis of multiple vehicles impact on the bridge was carried out and the existing design specification was evaluated. Through the combination of WIM data and measured VLE, Davis (2007) plotted the VLE (bending moment and shear force) envelope of different span bridges. OBrien *et al.* (2009, 2013) used the data collected by WIM as samples to simulate traffic flow by Monte-Carlo method, and developed traffic load models with various probabilistic methods. Chan *et al.* (2005) and Sun *et al.* (2012) obtained measured data from WIM and established the appropriate standard vehicle load model and lane load model. Kim *et al.* (2017) analyzed the ultimate load effect of prestressed concrete and steel box girder bridges using the actual probabilistic traffic model. The results showed that the traffic volume and the proportion of heavy vehicles affected the extreme load effect significantly.

These studies were mainly based on the collected vehicle load data to analyze and study the typical parameters affecting the vehicle load model, such as GVW and vehicle gap distance (VGD), and established the model of vehicle load using mathematical statistics theory. But shortcomings remain: 1) The studies on the randomness of the relevant parameters of the actual vehicle load was deficient, 2) In previous studies, equal-weighted sum of the normal distribution function was often used to fit the vehicle load distribution, but the distribution was more complex, so the single form couldn't reflect the diversity of vehicle load data accurately, 3) Previous studies used Poisson or Weibull process to represent the vehicle loading process under different operating conditions and predict the maximum long-term load effect or evaluate the reliability of the bridge structure without considering real traffic load flow, therefore, lacking accuracy and applicability, 4) Previous studies mainly analyzed the VLE of a single lane or two lanes bridges, while the actual highway is multi-lane. Due to the different utilization rate of lanes, the VLE of each lane is different, so it is necessary to analyze the VLE of multi-lane bridges, 5) With the progress of the automobile industry, the number of vehicles driving on the road is bound to increase. In order to take timely reinforcement measures and ensure the operational safety of the highway bridge, road traffic management needs to know the changes of VLE as daily traffic volume (DTV) increases, which is relatively lacking at present.

This article adopts static vehicle load data observed from the WIM system on an expressway and conducts a systematical study on the features of vehicle load by different lanes. Firstly, the vehicle type and traffic flow variation on different lanes are discussed. Secondly, probability models reflecting vehicle static load parameters on different lanes, such as GVW, VGD, are established by means of nonlinear least squares estimation and hypothesis testing. Thirdly, the method for simulating the multi-parameter traffic flow are discussed based on the Monte-Carlo method. Finally, the vehicle static load model for different lanes and the sample bridges are proposed. The technical roadmap is shown below.

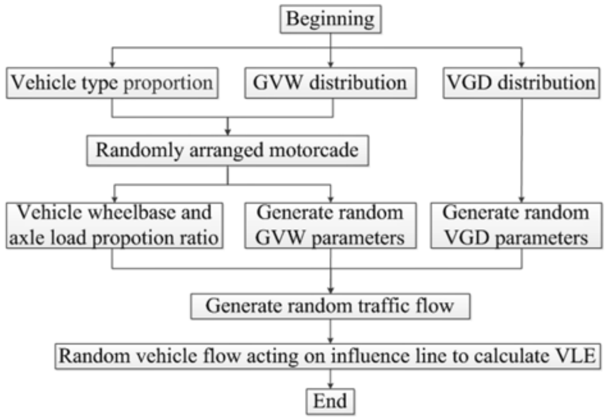


Fig. 1. The Technology Roadmap of This Study

2. Acquisition of Vehicle Load Data

Vehicle load data are crucial to bridge structural assessment. Their weight and configuration (number of axles, wheelbase and axle load) have an important impact on the highway bridge. Accurate acquisition of these actual vehicle load data, when normal traffic operation is not affect, is essential for the exact assessment of highway bridge (Chen *et al.*, 2014). The WIM system provides the neccessary assistance to obtain the real traffic data. Every measurement includes the following information, plate number, passing time, GVW, axle weight, the number of axles, the set of axles, VGD, wheelbase, vehicle type, lane position, and vehicle speed, etc. (Giorgio *et al.*, 2017; Tabatabai *et al.*, 2017; Chen *et al.*, 2018). The system consists of three basic components, including analog front-end, strain sensor, and detector coil. As a signal regulator and amplifier, the analog front-end has multiple input channels for adjusting and amplifying the signals from strain sensors. After data acquisition, the strain signal is reset to zero by the analog front-end. When the first axle of the vehicle passes through the detector coil, the strain sensor is activated. And when the last axle of the vehicle leaves

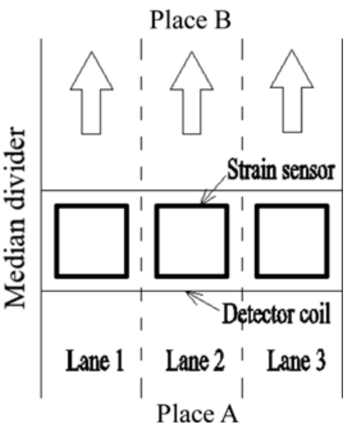


Fig. 2. Schematic of the WIM System

the detector coil, the strain sensor is closed. The data received from the strain sensor is digitized and sent to the computer, while the axle load is calculated by the influence line algorithm. Fig. 2 shows the arrangement of the WIM system in a three-lane expressway from place A to place B in China. It should be noted that WIM measurements also include dynamic strain components, but only static loads are reported and compared in this study.

The WIM system is inevitably affected by many uncertainties, such as electromagnetic interference, resulting in data distortion. In addition, systematic errors may also occur in vehicle information collection (Lydon *et al.*, 2016). For example, if two 3-axle trucks slowly and closely pass a test point, the WIM system would recognize as one 6-axle truck. And a 6-axle truck can be recognized as two 3-axle trucks, or a 2-axle truck and a 4-axle truck. In order to improve the accuracy and reliability of vehicle data, it is necessary to eliminate the potential false data by analyzing the original data. This process is mainly carried out by comparing the vehicle data collected with the vehicle information registered by the department of vehicles through the license plate number. After data correction, this study selected 168156 valid vehicle load data in a two weeks data collection (January 13, 2016 to January 26, 2016).

3 Statistical Analysis of Vehicle Load Data

It is very important to understand the statistical characteristics of vehicle load data, which is helpful to establish a more accurate vehicle load model. In order to grasp vehicle load characteristics, this paper classifies the types of vehicles and introduces the lane selection theory.

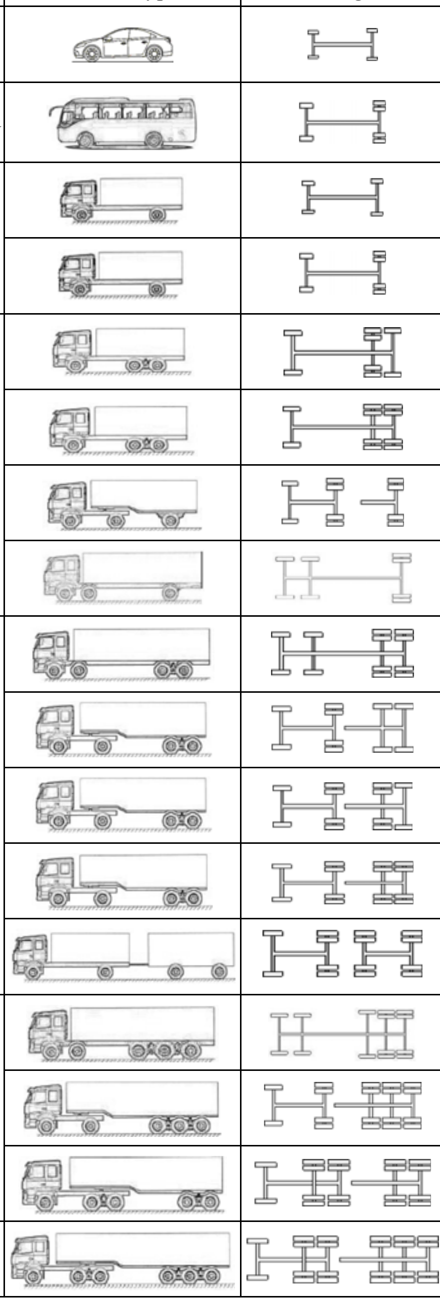
3.1 Vehicle Classification and Traffic Volume Statistics

Vehicles traveling on the highway may have a variety of sizes and speeds, such as, fast-driving small passenger car with smaller GVW and slow-driving heavy trucks with bigger GVW. In order to accurately establish the VLE model of highway bridges, it is necessary to classify the types of vehicles. From the axle configuration in chinese vehicle model manual (China Auto Industry Association, 2012), 7 types of vehicles are categorized based on the number of vehicle axles in this paper. They are small passenger car (less than 9 seats), large and medium-sized passenger car (9 seats and above), 2-axle truck, 3-axle truck, 4-axle truck, 5-axle truck, and 6-axle truck, as shown in Table 1. Table 1 also gives the recommended type of each vehicle model, which is the largest number of vehicles in this category, as the vehicle sample of later research.

3.2 Lane Selection Theory

Different drivers have a certain bias to choose a certain lane (Lu and Li, 2017; Yu *et al.*, 2018). It depends on the maneuverability of the vehicle and the personality of the driver (conservative or radical), which directly leads to the differences of vehicle load on the lane distribution, and affects the force acting on the bridge

Table 1. Vehicle Type Classification and Axle Configuration



Vehicle model	Vehicle type	Axle configuration	Note
Small passenger car			Sample
Large and medium-sized passenger car			Sample
2-axle truck			
			Sample
3-axle truck			
			Sample
4-axle truck			
			Sample
5-axle truck			
			Sample
6-axle truck			Sample

Table 2. The Volume and Proportion of Vehicles per Lane

Vehicle model	Lane 1		Lane 2		Lane 3	
	Volume	%	Volume	%	Volume	%
Small passenger car	42,091	57.79	45,481	67.64	7,679	27.35
Large and medium-sized passenger car	14,654	20.12	5,577	8.30	978	3.48
2-axle truck	12,418	17.05	10,998	16.36	8,331	29.66
3-axle truck	2,318	3.18	2,237	3.33	6,382	22.73
4-axle truck	231	0.32	729	1.09	814	2.90
5-axle truck	829	1.14	1828	2.72	3,080	10.97
6-axle truck	294	0.40	388	0.58	818	2.91

structure. Therefore, it is necessary to carry out statistics on vehicle load parameters of different lanes. Table 2 shows the volume of vehicles and the proportion of each vehicle model on each lane. Small passenger car accounts for more than half of all vehicles collected, of which 65.21% are more than 90 km/h and drives more frequently on lane 1 and lane 2 (Close to the median divider). Large and medium-sized passenger car accounts for 12.61% and drives more frequently on lane 1. 2-axle truck accounts for 18.88%, whose volume is the largest in the category of trucks. Due to their small weight, they travel faster than other trucks and more frequently on lane 1. The number of 3-axle, 4-axle, 5-axle, and 6-axle trucks account for 6.5%, 1.06%, 3.41%, 0.89% respectively, of which 97.24% are less than 90 km/h and usually drive on lane 3 (far away from the median divider). These are in line with the provisions of Chinese road traffic safety law which suggests when it exceeds three lanes in the same direction, the minimum speed of the leftmost lane is 110 km/h, the middle lane is 90 km/h, and vehicles with the speed of less than 90 km/h are on the right-most lane. So all of these data above are consistent with the real road traffic condition in China, and to a certain extent, reflects the authenticity and accuracy of data collected.

4. Vehicle Load Probability Distribution Type and Parameters

Among many parameters affecting the VLE of highway bridges, the volume of vehicles, type of vehicles, wheelbase, the proportion of axle weight distribution (PAWD) and the proportion of lane driving can be obtained by statistical methods. But there is great randomness in the data of GVW and VGD, which must be modeled through the random process. Therefore, it is necessary to first understand the PDD of GVW and VGD, and obtain the fitting function of PDD.

4.1 Probability Distribution of GVW

In this section, 21 groups of GVW data are obtained according to the classification of vehicle models and driving habits of choosing lanes. The statistics of PDD and curve fitting are carried out for these 21 groups of GVW data, as shown in Fig. 3. In this part, MATLAB (The MathWorks, Inc., 2012) is utilized to fit the PDD and draw fitting curves.

A previous study (Lin *et al.*, 2016) indicated that the vehicle loads may follow the unimodal distribution, bimodal distribution or multimodal distribution. The details are listed in the following:

$$f(x)=\sum_{i=1}^{n} w_i f_i(x) \tag{1}$$

where, $f(x)$ is the probability density function of random variable x, w_i is i-th weight of $f_i(x)$ (all the weight are 0 to 1, and the sum is 1), n is the number of components. $f_i(x)$ is a same pattern or different patterns of statistical distribution.

This paper adopts Eq. (1) to describe the vehicle loads parameters. Kim *et al.* (2017) proposed that the PDD of the GVW shows twin-peak form. The first peak represents the empty or lightly-loaded condition, and the second peak represents the heavily-loaded condition. But in China, the situation appears to be more complex. Unlike the statistics of a whole bridge, the distribution on every single lane follows diversified distributions for all types of vehicles. In this paper, Gamma distribution, multi-Gaussian distribution and t location-scale distribution are used to fit the PDD of vehicle load data, and their function are shown in Eqs. (2), (3) and (4). Gamma distribution and Gaussian distribution are commonly used. If x has t location-scale distribution with location parameter μ, scale parameter σ and shape parameter υ, then $(x-\mu)/\sigma$ has a student's t distribution with υ degrees of freedom (Etemad and Amirmazlaghani, 2018).

Gamma distribution:

$$f(x)=\frac{1}{b^a\Gamma(a)}x^{a-1}\exp\left(\frac{x}{b}\right) \tag{2}$$

Gaussian distribution:

$$f(x)=y_0+\sum_i\frac{A_i}{\sqrt{2\pi\sigma}}\exp\left(-\frac{(x-\mu_i)^2}{2\sigma_i^2}\right) \tag{3}$$

t location-scale distribution:

$$f(x)=\frac{\Gamma\left(\frac{\upsilon+1}{2}\right)}{\sigma\sqrt{\upsilon\pi}\,\Gamma\left(\frac{\upsilon}{2}\right)}\left[\frac{\upsilon+\left(\frac{x-\mu}{\sigma}\right)^2}{\upsilon}\right]^{-\left(\frac{\upsilon+1}{2}\right)} \tag{4}$$

Figures 3(a), 3(b), and 3(c) shows the PDD of small passenger car's GVW on different lanes. Since there is a slight difference in GVW between fully loaded small passenger car and empty small passenger car, the corresponding PDD shows a skewness unimodal characteristic in each lane. The skewness coefficients of GVW data for the 3 lanes are 3.6172, 6.2071 and 3.1324, respectively. So it is necessary to use a skewed distribution to fit them. The gamma distribution is a typical skewed distribution and is appropriate to describe statistical features. The parameters of fitting curves estimated by an Expectation-Maximization algorithm and a Kolmogorov-Smirnov test with a significance level of 0.05 are shown in Table 3, where Gam is short for gamma distribution, Gaus is short for Gaussian distribution and tls is short for t location-scale distribution. Figs. 3(d), 3(e) and 3(f) show the PDD of the large and medium-sized passenger car's GVW for each lane. In addition to the weight from the passengers (maximum of 60 in China), the large and medium-sized passenger car also carries luggage. Their full load and empty load are significantly different, which showing a twin-peak distribution. And a finite mixture distribution consisting of two Gaussian distributions is adopted to describe them. The parameters of fitting curves estimated are given in Table 3.

The PDD of trucks are more complex. Figs. 3(g) to 3(u) show the PDD of truck's GVW for every single lane. In general, the truck has larger weight, limited mobility, and slower speed than the small passenger car. In addition, the Chinese road traffic

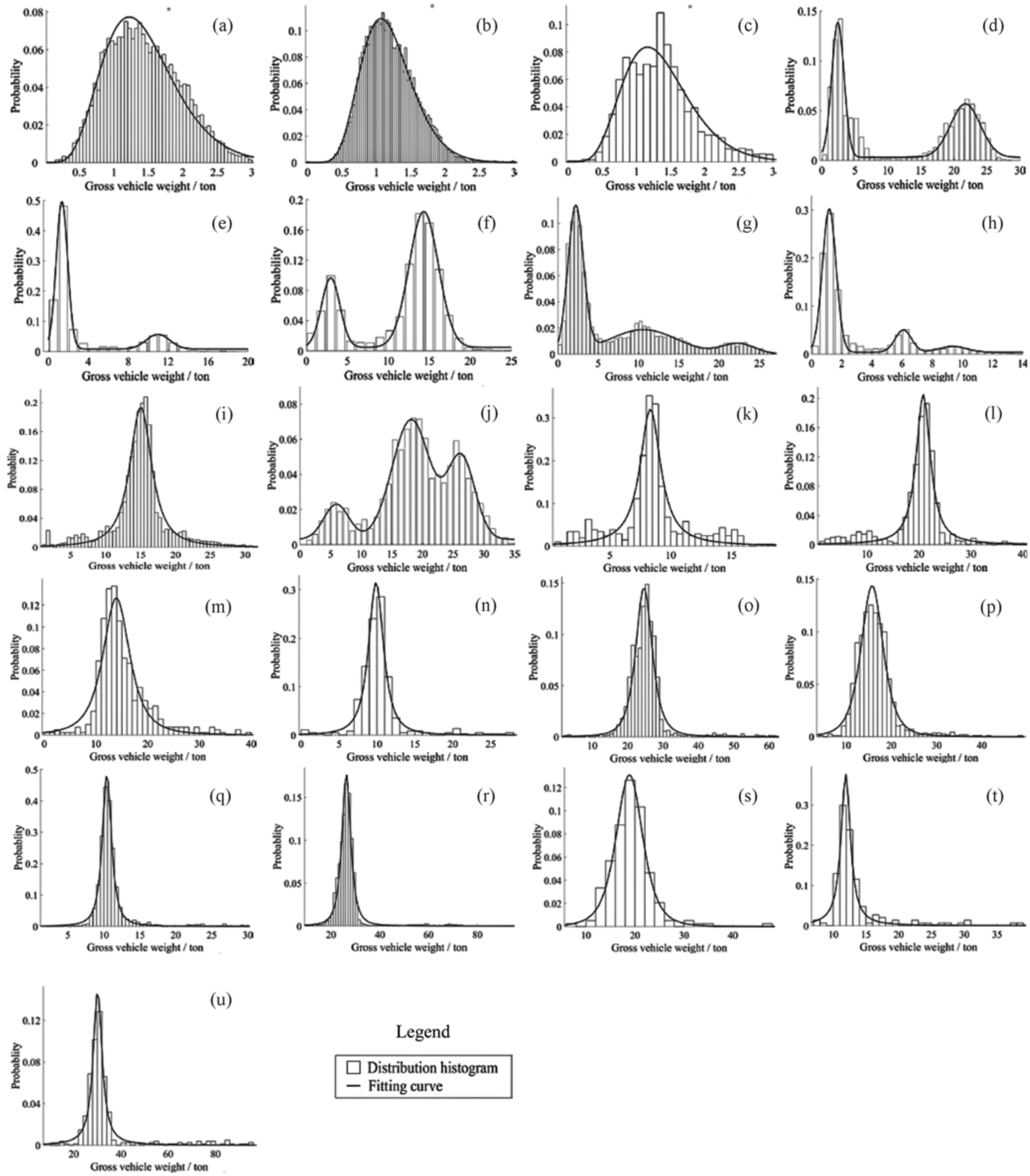


Fig. 3. PDD Histogram and Fitting Curve of GVW Data of Each Vehicle and Each Lane: (a) – (c) Small Passenger Car for Lane 1 to Lane 3, (d) – (f) Large and Medium-sized Passenger Car for Lane 1 to Lane 3, (g) – (i) 2-axle Truck for Lane 1 to Lane 3, (j) – (l) 3-axle Truck for Lane 1 to Lane 3, (m) – (o) 4-axle Truck for Lane 1 to Lane 3, (p) – (r) 5-axle Truck for Lane 1 to Lane 3, (s) – (u) 6-axle Truck for Lane 1 to Lane 3

safety law stipulates the driving lanes of vehicles with different speeds. In the other words, the fully loaded or heavily loaded truck, due to their slow speed, usually travel on the lane far away from the median divider, while the empty or lightly loaded truck drives fast, and often drives on the lane close to the median divider. The PDD histogram of each truck's GVW for each

Table 3. Fitting Curve Parameters of GVW Data

Vehicle model	Lane	Peak	Coef of skew / kurtosis	Dist. Type	Coefficient			
					a / μ_i	b/σ_i	A_i	y_0 / υ
Small passenger car	1	1	3.6172	Gam	7.0938	1.9059	-	-
	2	1	6.2071	Gam	9.6444	1.2320	-	-
	3	1	3.1324	Gam	6.7741	2.1147	-	-
Large and medium-sized passenger car	1	1	-	Gaus	2.9752	2.2544	0.2598	0.0045
		2	-	Gaus	14.3280	3.5707	0.8044	
	2	1	-	Gaus	1.3498	1.1455	0.7017	0.0082
		2	-	Gaus	10.9779	2.3477	0.1436	
	3	1	-	Gaus	2.4087	1.8705	0.3177	0.0038
		2	-	Gaus	21.7415	4.5464	0.3062	
2-axle truck	1	1	-	Gaus	2.2000	1.9219	0.2681	0
		2	-	Gaus	10.5900	8.4231	0.1976	
		3	-	Gaus	22.4000	4.1196	0.0412	
	2	1	-	Gaus	1.1701	0.8999	0.3375	0.0039
		2	-	Gaus	6.0816	1.0764	0.0626	
		3	-	Gaus	9.3654	1.8189	0.0273	
	3	1	3.0243	tls	15.0314	1.7644	-	1.5299
3-axle truck	1	1	-	Gaus	5.9372	4.0851	0.1021	0.0029
		2	-	Gaus	18.1403	6.1870	0.5285	
		3	-	Gaus	26.3092	4.4741	0.2617	
	2	1	3.8761	tls	8.3307	1.0058	-	1.0740
	3	1	3.5144	tls	15.0314	1.7644	-	1.5299
4-axle truck	1	1	4.1466	tls	13.9292	2.8149	-	2.1553
	2	1	10.1793	tls	9.8795	1.0968	-	1.6611
	3	1	15.5039	tls	24.6300	2.4881	-	2.5573
5-axle truck	1	1	9.3143	tls	15.7691	2.5782	-	3.3208
	2	1	20.1164	tls	10.4249	0.7039	-	1.5754
	3	1	23.8939	tls	26.2667	1.9712	-	1.8334
6-axle truck	1	1	9.9318	tls	18.8647	2.8467	-	3.6618
	2	1	10.3435	tls	11.9162	0.8478	-	1.0327
	3	1	9.0157	tls	30.1473	2.1825	-	1.1311

driving lane primarily presents a single peak distribution with large kurtosis and long tail characteristics. The kurtosis coefficients are all greater than 3, and t location-scale distribution with parameters of location, scale and shape is adopted for the estimation of PDD for trucks' GVW.

However, there are a few exceptions. The PDD histogram of 2-axle truck's GVW for lane 1 and lane 2, and 3-axle truck's GVW for lane 1 shows multi-peak distribution. Because there are large number of 2-axle trucks and 3-axle trucks which account for 82.56% of the total number of trucks. The vehicle weight varies from 0.7 to 31.5 tons, and it has a very wide range of GVW. These trucks have more configurations and different loading capacities, and are described by the finite mixture distribution with multiple components. On the other hand, 2-axle truck for lane 3, 3-axle truck for lane 2 and lane 3 are mainly heavy trucks with slow driving speed. Thus their PDD of GVW shows a unimodal distribution.

4.2 Probability Distribution of VGD

The highway bridges are mainly small and medium span bridges in China. Therefore, this study would focus on small and medium span bridges. The larger VGD would have a weak effect on the bridge, so the VGD data greater than 100 m were removed, and 48,410 effective data were obtained. Among them, three groups with 21,721 data, 28,032 data, and 9517 data were collected for lane 1, lane 2, and lane 3, respectively. Their PDD and fitting curves are given in Fig. 4. It can be observed that the PDD of the VGD data on every single lane follows the unimodal distribution which is described by Gaussian distribution in this study. The parameters of the fitting curves are given in Table 4, where Gaus is short for Gaussian distribution.

4.3 Wheelbase and PAWD

The wheelbase and PAWD are the key parameters for the calculation of VLE, which determine the loading location of the influence line and axle load value. Based on the survey and analysis of the measured data, and the vehicle parameters in Chinese vehicle model manual, the wheelbase and PAWD of each sample vehicle model are presented in Table 5.

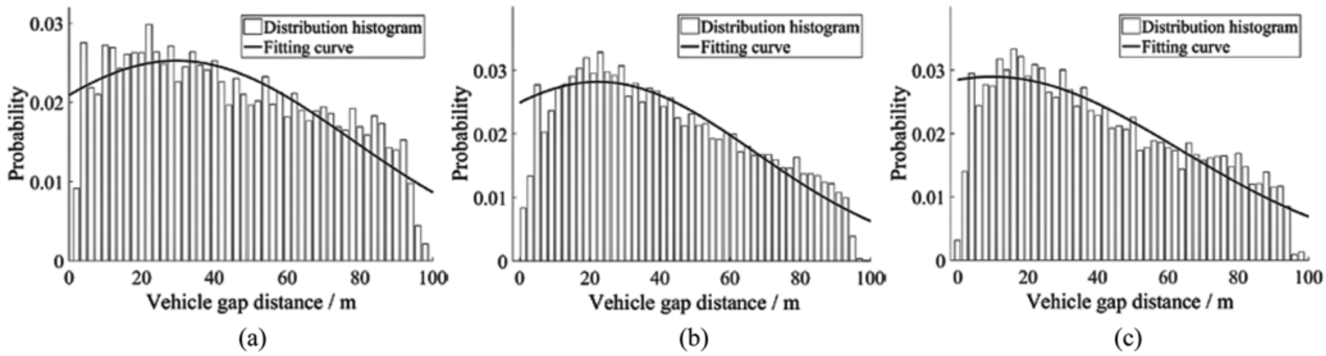


Fig. 4. PDD and Fitting Curves of VGD per Lane: (a) Lane 1, (b) Lane 2, (c) Lane 3

Table 4. Fitting Curve Parameters of VGD Data per Lane

Lane	Peak	Dist. type	Coefficient			
			μ_i	σ_i	A_i	y_0
1	1	Gaus	29.5602	48.1256	3.0452	0
2	1	Gaus	22.2822	44.9154	3.1730	0
3	1	Gaus	9.89817	53.1885	3.8600	0

Table 5. Wheelbase and PAWD of Sample Vehicle Model

Vehicle model	Wheelbase(m) / PAWD				
	L1	L2	L3	L4	L5
Small passenger car	2.6	-	-	-	-
	0.44:0.56				
Large and medium-sized passenger car	4.5	-	-	-	-
	0.46:0.54				
Axle truck	4.0	-	-	-	-
	0.35:0.65				
Axle truck	3.5	1.3	-	-	-
	0.2:0.4:0.4				
Axle truck	2.0	5.5	1.3	-	-
	0.15:0.31:0.27:0.27				
Axle truck	3.0	6.0	1.3	1.3	-
	0.1:0.3:0.2:0.2:0.2				
Axle truck	3.0	1.3	6.5	1.3	1.3
	0.06:0.2:0.2:0.18:0.18:0.18				

5. Evaluation of VLE

The vehicle driving on the highway is a typical random process. If the mathematical statistics theory is adopted to establish a static vehicle load model to calculate the VLE of highway bridges, then the calculated VLE is not universal, which cannot reflect the random characteristic of traffic flow. Therefore, on the basis of considering various traffic parameters of the random characteristics, dynamic simulation of the random traffic flow is established to model the actual traffic conditions.

According to statistical analysis results of PDD, the Monte-Carlo method was used to generate GVW and VGD data randomly in line with the distribution fitting functions. By combining the data of wheelbase and PAWD listed in Table 5 with the data of GVW and VGD generated, dynamic random traffic flow (DRTF) data can be obtained.

5.1 Establishment of Radom Traffic Flow Simulation Program

The components of highway traffic flow include GVW, VGD, wheelbase, PAWD, the proportion of vehicle type and the volume of vehicles. In this study, the DRTF is implemented in a Matlab program, and the algorithm flow chart is shown in Fig. 5. The subroutine VM(N) generates N random vehicle data which are proportional to the various models. The subroutine GVW(N) generates N random GVW data which meet the GVW distribution. The subroutine VGD(N-1) generates N-1 random VGD data which meet the VGD distribution. And subroutine DRTF(N) integrates all parameters of traffic into dynamic random traffic flow data.

5.2 Influence Line Loading Theory

In order to obtain the internal force of bridge structure under

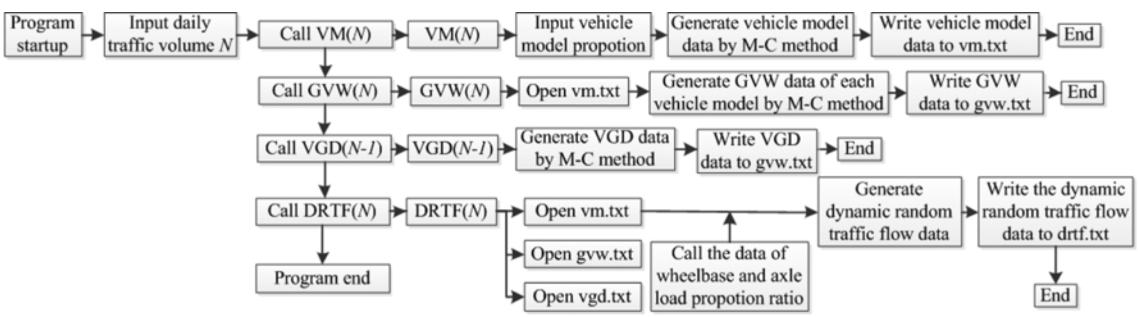


Fig. 5. Algorithm Flow Chart of Dynamic Random Traffic Flow

vehicle load, researchers need the assistance of analysis tools or effective analysis methods. At the current stage, the most popular method is influence line loading (Chaudhari and Kulkarni, 2015), which makes an internal force of space problem into a plane problem. The influence line data of bridge control section can be obtained by the finite element analysis software. In this study, CSI bridge software (Computers and Structures, Inc., 2013) is used to calculate the influence line data of the bridge specific section.

If it is assumed that the parameters of vehicles traveling on the road are unchanged in a certain period, and the effect of structural nonlinearity on load effect can be ignored for a small and medium span highway bridge. The VLE of the specific section can be calculated by loading the DRTF on the influence line of this section. Take a 3-axle truck as an example. As shown in Fig. 6(a), it is the influence line for bending moment at the mid-span section of a simply supported bridge. When a 3-axle truck passes the bridge, the bending moment of load 1, load 2, and load 3 generated by each concentrated force in the span are calculated individually. The total bending moment produced by three concentrated forces is the moment load effect (MLE) at this moment. Fig. 6(b) shows the shear influence line of the left fulcrum of a simply supported bridge. Similarly, the shear load effect (SLE) of the left fulcrum can be determined when the 3-axle truck passes the bridge.

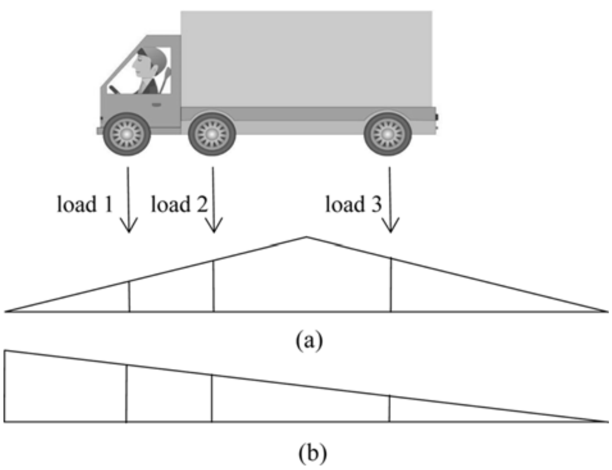


Fig. 6. Chart of Influence Line Loading: (a) The Influence Line of Bending Moment on the Middle Span of Simply Supported Beam and Vehicle Loading, (b) The Shear Force at the left Supporting Point of the Simply Supported Beam Influences the Line and Vehicle Loading

5.3 Calculation Method of Vehicle Load Effect

The vehicle load effect (VLE) under the action of DRTF can be generated by the following steps,

1. Generate DRTF of N vehicles randomly (N is the volume of vehicles manually entered).
2. Calculate the influence line data of the specific section.
3. The DRTF moves a certain length L along the bridge (Fig. 7) and the VLE of the bridge at this time is calculated and recorded.
4. When the entire DRTF has passed through the bridge, the maximum value of VLE is obtained.

According to the above steps, Matlab is used to calculate the maximum VLE. The algorithm flow chart is shown in Fig. 8. The subroutine JUDGMENT corrects the VGD according to the input bridge span S. When VGD is larger than the bridge span, the VGD is automatically set to the bridge span S. In this way, the production of an invalid loop during computation can be prevented, and to save computing cost. Subroutine illoading is used to carry out the influence line loading. Through the CSI bridge software, the influence line data of the control section is obtained. The DRTF moves 0.1 m each time on the influence line in this paper, the corresponding VLE is calculated each time, and the maximum VLE is finally screened out and recorded. If the accuracy of the calculation is improved, the distance L of each movement of the DRTF can be smaller, but the calculation time will increase.

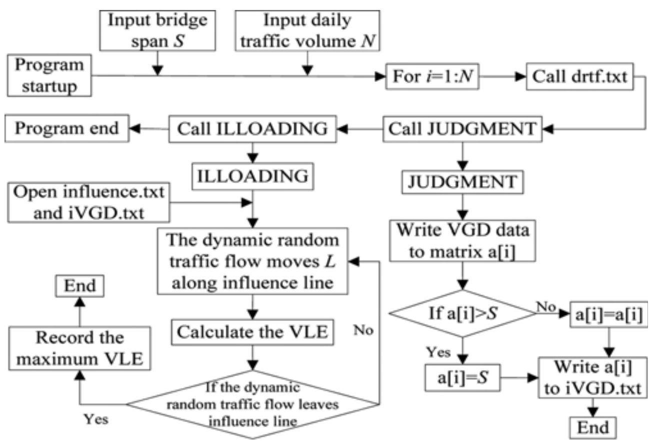


Fig. 8. Algorithm Flow Chart of Calculating VLE

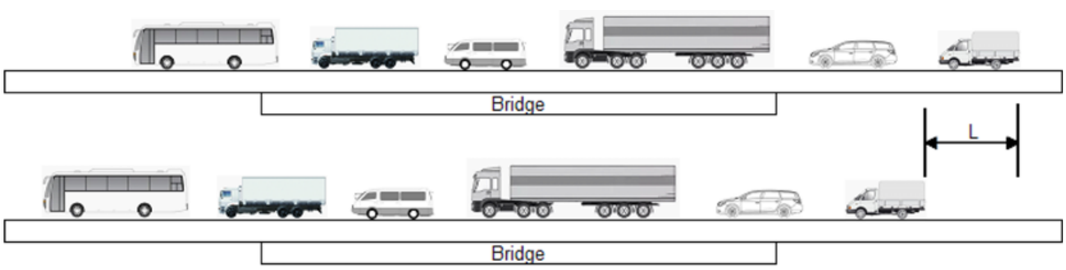


Fig. 7. Diagrammatic Sketch of DRTF Moving

5.4 Calculation of VLE of Single Lane

In this study, the most commonly used 20 m, 25 m, 30 m, 35 m, and 40 m simply supported bridges in China are selected as samples, all of which are integral box girder structures. Assuming that the proportion of lanes and vehicle models are consistent with Table 2, and the sample bridge is 3 lanes as shown in Fig. 2. The DTV is set to 12,000 which is the daily average traffic volume of two weeks' field survey. Increasing DTV will inevitably result in the reduction of VGD. Therefore, when the DTV is 24,000, the VGD is considered to be half of the DTV of 12,000. In this way, the VLE per lane can be calculated when the DTV is 24,000. And the VLE per lane of sample bridges can also be calculated using the same method when the DTV is 6,000 and 48,000. The VLE of highway bridges includes the MLE and the SLE. The VLE of the sample bridges calculated using the influence line loading principle of section 5.2 is shown in Table 6. Table 6 shows the ratio of the maximum VLE per lane calculated to the static lane load effect of the first class in Chinese highway bridge code (ministry of transport of the people's republic of China, 2015) which is the design standard for expressway bridge in China.

Table 6. Maximum VLE per Lane of Different DTV

	Span	Lane	DTV			
			6,000	12,000	24,000	48,000
Maximum MLE per lane	20 m	1	0.3721	0.4406	0.6091	0.6944
		2	0.5936	0.6915	0.9426	1.0825
		3	0.7610	0.8768	1.1655	1.3201
	25 m	1	0.3632	0.4537	0.5901	0.6816
		2	0.5903	0.7336	0.9448	1.0858
		3	0.7647	0.9310	1.1721	1.3339
	30 m	1	0.3615	0.4812	0.6074	0.7146
		2	0.5869	0.7899	1.0009	1.1337
		3	0.7692	0.9935	1.2269	1.3742
	35 m	1	0.3709	0.5223	0.6385	0.7138
		2	0.6032	0.8320	1.0141	1.1304
		3	0.6807	0.9869	1.3145	1.6109
	40 m	1	0.3739	0.5165	0.6344	0.7150
		2	0.6184	0.8484	1.0504	1.1625
		3	0.7838	1.0629	1.2879	1.4074
Maximum SLE per lane	20 m	1	0.2424	0.4087	0.4885	0.5992
		2	0.4823	0.6832	0.8236	1.1925
		3	0.7504	0.8001	1.0006	1.3565
	25 m	1	0.2643	0.4166	0.5152	0.6765
		2	0.5267	0.7058	0.8258	1.1206
		3	0.7607	0.8048	1.0302	1.3451
	30 m	1	0.3382	0.4707	0.5784	0.7514
		2	0.5823	0.7578	0.8674	1.1447
		3	0.7663	0.9161	1.0051	1.4295
	35 m	1	0.3379	0.4768	0.5952	0.7194
		2	0.5108	0.7366	0.8552	1.2538
		3	0.7869	0.8557	1.1349	1.5406
	40 m	1	0.3494	0.5562	0.6194	0.6164
		2	0.5334	0.9021	0.9328	1.3649
		3	0.8202	1.0380	1.1969	1.4983

As can be seen from Table 6, although the number of vehicles on lane 1 is the largest, both MLE and SLE are the smallest. Becasue lane 1 is mainly traveled by small passenger car and less heavy trucks. When DTV is small, each vehicle has a larger VGD, resulting in smaller VLE on each lane. With the increasing of DTV, the VLE increases accordingly. Every time the DTV increases by 100%, the VLE of each lane increases 10% – 30% at the same time. Under the current DTV of 12,000, both MLE and SLE per lane are small and does not exceed the value specified in the current code, except lane 1 of 40 m span. If the DTV grows, the VLE of both lane 2 and lane 3 approach to or surpass the value in the current code, among which the maximal surpass 60% and would definitely increase the risk of the damage to the structure.

5.5 Calculation of VLE for Sample Bridges

In this section, five kinds of simply supported bridge with three lanes integral box girder are chosen as samples whose spans ranges from 20 m to 40 m. The VLE of the bridge can be calculated as Eq. (5).

$$M_d = q_n \sum_{i=1}^{n} M_i \tag{5}$$

where M_d is the VLE of the highway bridge, M_i is the maximum VLE of lane i, q_n is the multiple lane reduction factor (MLRF), and n is the number of lanes. The MLRF can be viewed as the probability when each lane is at the most unfavorable condition at the same time (ministry of transport of the people's republic of China, 2015). Since each lane is calculated at the maximum VLE, the VLE calculation for the sample bridges is represented by the summation of VLE for individual lane multiplied by the probability mentioned above. The MLRF is set to 1.2, 1.0, and 0.78 for single lane, two lanes, and three lanes, respectively. Table 7 shows the ratio of the maximum VLE for sample bridges calculated in this paper to the static lane load effect of the first class in Chinese highway bridge code.

In Table 6, the VLE of partial lanes are more than 60% of the specified value in the current code. But the VLE for sample bridges are not very large. The maximum value is 80% of the

Table 7. VLE for Sample Bridges of Different DTV

	Span	DTV			
		6,000	12,000	24,000	48,000
Maximum MLE	20 m	0.5756	0.6696	0.9057	1.0323
	25 m	0.5727	0.7061	0.9023	1.0338
	30 m	0.5726	0.7549	0.9450	1.0742
	35 m	0.5516	0.7804	0.9890	1.1517
	40 m	0.5920	0.8093	0.9909	1.0950
Maximum SLE	20 m	0.4917	0.6307	0.7709	1.0494
	25 m	0.5172	0.6424	0.7904	1.0474
	30 m	0.5623	0.7482	0.8170	1.1085
	35 m	0.5452	0.6895	0.8618	1.1713
	40 m	0.5677	0.7654	0.9164	1.1599

specified value in the code under the current traffic volume. In another word, under the current DTV, the operational condition of the bridge can satisfy the requirement for road traffic load. Even if the DTV would be doubled in the future, the VLE calculated by the existing statistical parameters is still less than the value specified in the current design code.

6. Conclusions

This study performed an evaluation of static vehicle loads that are recorded using the WIM system located on a highway in China. About 168 thousand vehicle records were collected for a period of two weeks. Except for the small passenger car and large and medium-sized passenger car, the truck is divided into 5 groups according to the number of axles. Using the collected data, best-fit unimodal and multimodal distributions are determined for GVW and VGD in each class-axle group. Multivariate Monte-Carlo simulations on collected data in each class-axle group are conducted using MATLAB to generate DRTF data. Integrating DRTF data into the influence line of the sample bridge's key section, the maximum VLE under the DRTF can be obtained and compared with the value specified in the current Chinese design code. The following observations are made:

1. The skewness coefficient or kurtosis coefficient of GVW parameters of some vehicle model and some certain lane are all greater than 3, which indicate non-normal features, and the skewed distribution or kurtosis distribution should be used for fitting. The single lane GVW distribution of other vehicle models are adopted to fit by multi-gaussian distribution.
2. Based on the probability and random theory, a new model of multi-parameter traffic load flow and load effect is proposed to evaluate the VLE of highway operation phase. Through the calculation of VLE under different DTV, road traffic management could evaluate the rationality of designing parameters in the planning stage and obtain a reference for the operation strategy of the highway bridge.
3. The majority of sample bridge has a good load carrying capacity in the present traffic situation, and their VLE per lane is less than the value required in the current design code. When the DTV is doubled, the VLE increases 10% – 30% corresponding. If DTV continues to grow, the VLE of lane 2 and lane 3 which trucks usually travel approach to or surpass the value required in current design code, among which the maximal surpass 60% of the value required in the current design code.
4. When calculating the maximum VLE of the whole bridge, the MLRF is used, which essentially is the probability of each lane being at the most unfavorable condition at the same time. Compared with the value in the current design code, the calculated VLE are smaller. Even though the DTV will be doubled, the VLE calculated in this paper still less than the value in the current design code.
5. In general, the operational condition of the bridge can satisfy the requirement for road traffic load. However, in some lanes where heavy vehicles traveled, the calculated value of VLE will exceed the value specified in the current design code. Special attention shall be paid to daily maintenance. And necessary reinforcement measures should be taken in a timely manner.

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Not Applicable.

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