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Research Article

Study on the Adaptability of Vehicle Loads in Special Lanes for Trucks on Highway Bridges

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To study the adaptation of the current automobile design load of highway bridges in China in case of separation of passenger cars and trucks, a statistical method is proposed in this paper to study the load data of special lanes for trucks. Four typical truck-based lanes were selected as the study object, from which information of continuous truck fleet was selected as the study of truck-specific lane load flow samples, and technical parameters of truck vehicles were determined. Finally, the load flow was introduced into simply supported bridges and continuous bridges of different spans, and the load effect at the control section was calculated and compared with the effect of the design load at the control section according to the current code. The results show that under the operation mode of "passenger car and truck separation," when the truck fleet passes through the simple support beam, the load effect at the control section generally does not exceed the effect of the vehicle load calculated according to the code design load. When the truck fleet passes through the continuous beam, the midspan bending moment of the continuous beam side span and the midspan bending moment of the middle span do not exceed the effect of the vehicle load calculated according to the code design load. However, the bending moment effect of the continuous beam support section exceeds the effect of the vehicle load calculated according to the design load of the code. To ensure the safety and durability of the bridge structure, the proposed lane load standard value is increased by 1.1 times and rounded up from the current Highway Bridge and Culvert Design Code.

1. Introduction

The vehicle loading, as one of the basic variable loads of the bridge, is an important indicator for the design of highway bridges. Based on actual data measured in the 1990s, China [1] established standards for vehicle loads in the design of highway bridges, taking into account actual conditions and the needs of future development. Since the Chinese vehicle load standards were developed from data actually measured in the last century, some scholars [2] point out that the adaptability of the current code design load model for highway bridges in China to the actual operating vehicle load model needs further study in the rapidly developing transportation industry. The Chinese "General Code for Design of Highway Bridges and Culverts" (JTGD60-2015) [3] also pointed out that "for the bridge and culvert with a large proportion of heavy traffic in the traffic composition, the vehicle load mode appropriate to the traffic composition of the highway should be used for calculation." Analysis of vehicle loads and load effects on highway bridges, Nowak and Szerszen [4] summarized and developed a method for calculating the maximum bending moment and shear force for different periods by investigating the measured vehicle load data and extrapolating the maximum load effect from 1 day to 75 years. Cremona [5] proposed a superiority fitting method based on Rice's formula for fitting the tail data of the vehicle load effect and then extrapolated the extreme values of the vehicle load effect for different periods. Chan et al. and Miao and Chan [6, 7] collected ten years of dynamic weighing data in Hong Kong, determined the probability distribution functions of the relevant parameters, and developed a design vehicle load model for the Hong Kong region. Fu and You [8] collected weighing data of vehicles from three Chinese provinces in China and established a load spectrum for bridge safety assessment and developed a new method for assessing the values of vehicle load effects in different periods, which was finally applied to the actual bridge reliability assessment. Caprani and Obrien [9] proposed a method to determine the extreme values of load effects by which the values of load effects for different periods were predicted to be more skewed but within a reasonable range. O'Brien and Enright [10] studied the data monitored at four weigh-in-motion in Europe and pointed out the conclusion that the existing traffic load effects exceeded the normative standard values. O'Brien and Enright [11] investigated the effects of load effects generated by random traffic on bridge damage for the dynamic weighing data collected at five European freeway sites. Zhao and Tabatabai [12] investigated two-span and three-span continuous beam bending moment and shear effects using a large amount of truck data recorded by WIM and proposed the use of a 5-axle single-unit truck model to complement the existing standard licensed vehicles in Wisconsin. McKinnon [13] analysed the impact of the increase of heavy trucks in the UK on factors and calculated and analysed the impact factors with the measured vehicle load data to obtain the predicted vehicle weight. And, the study suggested to further increase the maximum weight of trucks in the UK. Leahy et al. [14] surveyed truck data from 17 dynamic weighing stations in the U.S. and proposed a model to modify the vehicle load criteria by evaluating the U.S. Liang and Xiong [15] collected vehicle load data from a site in China and found that as the traffic volume increased, and the actual operating vehicle load effect exceeded 20% of the design load calculated according to the code. The study also illustrated that localized bridge damage could occur in the lanes where medium and large trucks are operating. Zhouhong et al. [16] found that the actual operating vehicle load of highway bridges in Jiangsu Province was 1.46 times that of the grade I vehicle load of current China's specification, based on the measured data of dynamic weighing of highway in Jiangsu Province. In addition, uncertainty and reliability theory is important for solving problems in uncertain environments to model real-world dynamical systems [17–19]. Jin and Zhu [20] provided the first-hitting time theorem for UFDE, on the basis of which Jin et al. [21] in 2020 analysed and calculated the reliability index for second-order uncertain circuits. The above-given work is an important reference for engineering reliability analysis and simulation of random traffic flow on traffic roads.

However, these studies did not consider the effect of vehicle loads on bridge structures when highway bridges are set up with lanes for trucks. As of the end of 2020, China owned 11,715,400 road-operated vehicles, of which 11,102,800 were cargo vehicles, and the proportion of cargo vehicles in the total number of operating vehicles increased in recent years [22]. As China's freight cars are moving toward larger and heavier vehicles, the impact of freight vehicles on bridge structures is drawing the attention of traffic management. Although the regulation of overloading in China has been increasing, the number of overloaded vehicles is also increasing. Overloaded vehicles often cause serious structural damage to bridges, reducing structural life and even bridge collapse [23, 24]. Another point is that when a truck drives into the highway, the truck vehicle size large easily obscures the view of small vehicles drivers, causing traffic safety hazards [25–27]. Different mobility of passenger cars and trucks, truck relatively low speed delays the passage time of the bus, reducing the efficiency of the passage of the bus and also increased the probability of traffic accidents. In order to reasonably allocate road traffic resources, improve traffic efficiency and ensure traffic safety, some scholars [28–30] proposed to adopt the operation mode of "separation of passenger cars and trucks." By separating the passenger cars and trucks on the highway bridge, the vehicle load model applicable to the passenger car lane and the truck lane is established. Since the current "General Specification for Highway Bridge and Culvert Design" (JTG D60-2015) [3] in China was formulated on the basis of the traffic operation mode of mixed passenger and freight traffic, there is no clear provision for the standard value of vehicle load for truck-only lanes yet. All the load flow data research can only originate from the existing load flow data of mixed passenger and freight traffic. How to get the load flow data of the truck-only lane by processing the existing data to meet the actual situation is the basis for the design and research of the bridge separation of passenger cars and trucks.

In order to achieve a differentiated supply service for passenger cars and trucks, transport efficiency was improved and the way for research into dedicated lanes for autonomous driving was paved; research has been carried out in Shandong province into separate highways for passenger cars and trucks as China has not yet developed vehicle load standards for lanes dedicated to trucks. And, there are few studies in the literature on the adaptability of vehicle loads on highway bridges to current codes in the case of setting up dedicated lanes for lorries. Therefore, the research done in this paper provides a reference for the development of vehicle load standard values for special lanes for trucks in China. The paper is based on the measured load flow data and statistical analysis of vehicle parameters such as vehicle type, vehicle weight, and axle weight, respectively, from which a continuous truck fleet was selected for the study of vehicle load model of trucks exclusive lane of trucks. On this basis, a random traffic flow model was developed to calculate the load effects generated by the random traffic flow through different bridges and compare them with the vehicle load effects calculated by the code design loads. Finally, the standard value of truckload standard increase coefficient was proposed to provide a reference basis for the relevant departments to develop the standard value of truckload. The rest of this paper is organized as follows: Section 2 completes the statistical analysis of each parameter of the measured vehicle loads. Section 3 establishes the stochastic traffic flow model for the truck-only lane based on the statistical results. Section 4 calculates and analyses the load effects generated by the random traffic flow through the bridge. Section 5 proposes the improvement factor of the standard value of vehicle load for the truck-only lane according to the analysis results. Section 6 concludes the paper. Section 7 content for future work and direction.

2. Statistical Analysis of Measured Vehicle Load Parameters

Firstly, statistical analysis of each parameter of the measured vehicle load was needed to establish the vehicle load model of the special lane for trucks in line with the actual operating conditions. This section is based on 11 lanes of actual measurement data collected by the highway weighing equipment of a regional highway in Hebei Province, from which four lanes of truck-based data were selected as samples, and statistical analysis of the relevant technical parameters was carried out.

2.1. Vehicle Composition. The vehicle type ratio reflects the vehicle load characteristics on each lane. The paper classified the vehicles of different lanes according to the number of vehicle axles and calculated the ratio of the number of vehicles corresponding to each axle to the total number of vehicles in that lane, as shown in Table 1.

As can be seen from Table 1, the number of two-axle vehicles in lanes 00102 and 00103 accounts for 91.4% and 77.9% of the total number of vehicles in this lane, respectively, and is typical lanes for small cars. 00105, 00107, 00108, and 00110 have six-axle vehicles accounting for more than half of the total number of vehicles in this lane and are freight lanes dominated by trucks. 00104.00106, 00109, 00111, and 00112 lanes in the two-axle vehicles and six-axle vehicles are basically equal, as a mixed lane for passengers and goods.

The data of four typical freight lanes, 00105, 00107, 00108, and 00110, were selected as samples for the analysis of truck vehicle load characteristics in this paper initially.

2.2. Gross Vehicle and Cargo Weight. The gross vehicle weight in this article includes the total mass of the vehicle and the loaded cargo. The vehicle loads of each lane were classified according to the gross vehicle and cargo weight. The number of vehicles in different vehicle weight ranges was calculated as a percentage of the total number of vehicles in that lane, as shown in Table 2.

Vehicle weight analysis shows that the number of vehicles less than 3 tons in lanes 00102 and 00103 accounts for 77.97% and 62.17% of the total number of this lane, respectively, which is a typical lane for small cars and small trucks. The number of vehicles exceeding 49 tons in lanes 00105, 00107, 00108, and 00110 accounted for 42.42%, 49.55%, 68.6%, and 47.48% of the total number of vehicles in this lane, respectively, making it a typical heavy overload lane [31]. The number of vehicles exceeding 49 tons in lanes 00104, 00106, 00109, 00111, and 00112 are all between 30% and 40% and are lightly overloaded mixed flow lanes for passenger cars and trucks. Thus, the data of four typical freight lanes, 00105, 00107, 00108, and 00110, were selected as samples for the vehicle load characteristics analysis of the paper. The number of vehicles exceeding 49 tons in lanes 00104, 00106, 00109, 00111, and 00112 are all between 30% and 40% and are lightly overloaded mixed passenger and freight lanes.

In order to visualize the distribution of vehicle weight in each lane to determine the probability distribution characteristics of vehicle weight in the sample data. The time period of 0 : 00~24 : 00 on May 15, 2011, was chosen to count the vehicle loads, and the relationship between the gross vehicle weight and the number of vehicles for all vehicle types in the four lanes was plotted, as shown in Figure 1. The frequency distribution plots of the gross vehicle weight of different vehicle types in the four lanes indicate a multi-peaked distribution of vehicle loads [32], which can be seen as a result of the vehicle loads being a combination of different types of vehicles. To further understand the overload situation of different types of vehicles in each lane, the number of different types of overloaded vehicles in the four lanes as a percentage of the total number of vehicles in that lane was counted in conjunction with our current norms [33], as shown in Table 3.

Combining Figure 1 with Table 3, it can be seen that the three peaks of vehicle load on lane 00105 occur roughly at 3.70 tons, 18.89 tons, and 50.97 tons. The first peak can show small cars, the second peak can show medium-sized cargo cars or unloaded large trucks, and the third peak can show overloaded large trucks. It far exceeds not only the specification of the six-axle vehicle load limit of 49 tons [33] but also the number of overloaded vehicles of six axles accounts for about 42.29% of the total number of vehicles in the lane, and the overloading phenomenon is serious.

Similarly, the three peaks of the vehicle load on lane 00107 appear roughly at 4.04 tons, 37.27 tons, and 53.16 tons. The first peak can indicate a small truck, the second peak can indicate a large truck without overload, and the third peak can indicate a large truck with overload. And, the number of overloaded six-axle vehicles accounts for about 44.35% of the total number of vehicles in the lane, and the overloading phenomenon is also very serious. The three peaks of vehicle load on lane 00108 appear roughly at 2.97 tons, 19.41 tons, and 52.80 tons. The first peak can indicate small cars, the second peak can indicate medium-sized cargo vehicles, and the third peak can indicate overloaded large trucks. And, the number of overloaded six-axle vehicles accounts for about 63.41% of the total number of vehicles in the lane, and the overloading phenomenon is extremely serious. The three peaks of vehicle load on lane 00110 occur roughly at 2.85 tons, 17.51 tons, and 52.10 tons. The first peak can indicate a small car, the second peak can indicate a medium-sized cargo vehicle, and the third peak can indicate an overloaded large truck. And the number of overloaded six-axle vehicles accounts for about 41.21% of the total number of vehicles in this lane, and the overloading phenomenon is serious.

2.3. Vehicle Load Probability Distribution Model and Characteristics. Vehicle composition and vehicle weight analysis results show that: 00105, 00107, 00108, and 00110 lanes are dominated by six-axle vehicles, and the number of

Table 1: Percentage of different vehicles in different lanes.

Lane number	Percentage of the number of vehicle types in the total number of vehicles in each lane (%)					
	Two axle	Three axle	Four axle	Five axle	Six axle	Seven axle
00102	91.4	2.7	1.3	0.3	3.8	0
00103	77.9	4.8	3.9	1.2	11.9	
00104	37.2	11.6	11.1	4.2	34.9	
00105	24.5	7.1	7.1	7.4	56.2	
00106	38.6	8.5	10.0	6.2	36.4	
00107	20.0	5.8	16.6	5.0	52.0	0.4
00108	13.8	5.2	5.0	6.3	68.8	
00109	35.9	7.3	10.1	6.9	39.0	
00110	27.0	7.2	9.6	5.2	50.0	
00111	39.4	7.8	7.8	4.6	39.7	
00112	26.2	5.1	8.5	16.5	39.4	

Table 2: Percentage of vehicles in different vehicle weight ranges by lane (vehicle weight in tons).

Lane number	Number of vehicles in different vehicle weight ranges as a percentage of the total number of vehicles in the respective lane (%)					
	<3	3~10	10~20	20~30	30~40	40~49
00102	77.97	4.04	10.15	3.08	1.23	0.62
00103	62.17	5.90	9.91	5.54	3.13	2.33
00104	10.85	9.25	18.15	12.99	10.50	7.47
00105	6.41	7.63	11.90	9.56	7.63	11.45
00106	10.53	11.83	16.37	12.04	10.67	6.87
00107	7.14	5.80	9.82	9.38	16.96	8.48
00108	4.07	3.49	7.85	7.27	4.65	8.14
00109	11.62	14.29	16.59	12.18	10.36	12.32
00110	8.81	7.73	13.85	12.23	9.17	9.53
00111	9.45	6.30	26.77	12.20	11.02	13.00
00112	15.86	8.28	14.48	8.28	15.17	14.48

overloaded six-axle vehicles accounts for a high proportion of the total number of vehicles in this lane, which has a greater impact on the safety of the highway bridge structure [34]. Therefore, it is necessary to study the most adverse effects of the loads generated by the truck-dominated lanes trucks passing through the bridge. Now, the number of vehicle axles is used as the basis for classification, and the probability distribution of vehicle load is fitted to the four lanes with different vehicle types.

The probabilistic characterization of statistical data usually begins with its histogram. By observing the histogram of statistical data, the characteristics of the distribution are generally understood, and then a suitable probability model is selected to fit the distribution and determine its final probability distribution. The purpose of fitting the curve is to estimate the values of the parameters that best describe the data and thus determine the expression of the function. And the process of fitting a nonlinear curve is usually described as follows:

(1) An initial function curve is first generated from the initial values

(2) Iteratively adjusting the parameter values to bring the data points closer to the curve

(3) Stop when the minimum distance reaches a stopping criterion, bringing the curve closer to the points on the data and calculating the best parameter values

The Levenberg–Marquardt (L-M) algorithm is a commonly used iterative algorithm that combines the Gauss–Newton method with the steepest descent method. The algorithm is applicable to the fitting of nonlinear curves. The numerical solution of the nonlinear minimisation is determined by a finite number of iterations when the result is achieved. And, the conformity of the curve to the corresponding probability distribution and the goodness of the fit can be determined in several following ways:

(1) The Reduced Chi-square value, which is also called Scale Error with square, is equal to the sum of squared residuals (RSS) divided by the degrees of freedom. Typically, it indicates the degree of direct difference between the observed and fitted values. A Reduced Chi-square value close to 1 indicates a good fit, which means that the difference between the observed and fitted data is consistent with the error variance.

(2) R^2 value is called the coefficient of determination. It is calculated as shown in equation (1). The closer the fit is to the data points, the closer the R^2 is to a value of 1, but a larger value of R^2 does not necessarily mean a better fit, as degrees of freedom also affect this value.

$$R^2 = 1 - \frac{\text{RSS}}{\text{TSS}}. \quad (1)$$

Here, RSS is the residual sum of squares; TSS is the total sum of squares.

(3) The adjusted R^2 value, which takes into account degrees of freedom, is a better measure of the fit.

$$R^2 = 1 - \frac{\text{RSS/dfError}}{\text{TSS/dfTotal}}. \quad (2)$$

In this paper, the Levenberg–Marquardt algorithm is used for parameter estimation. The maximum number of iterations set in this paper is 400 and the iterations are

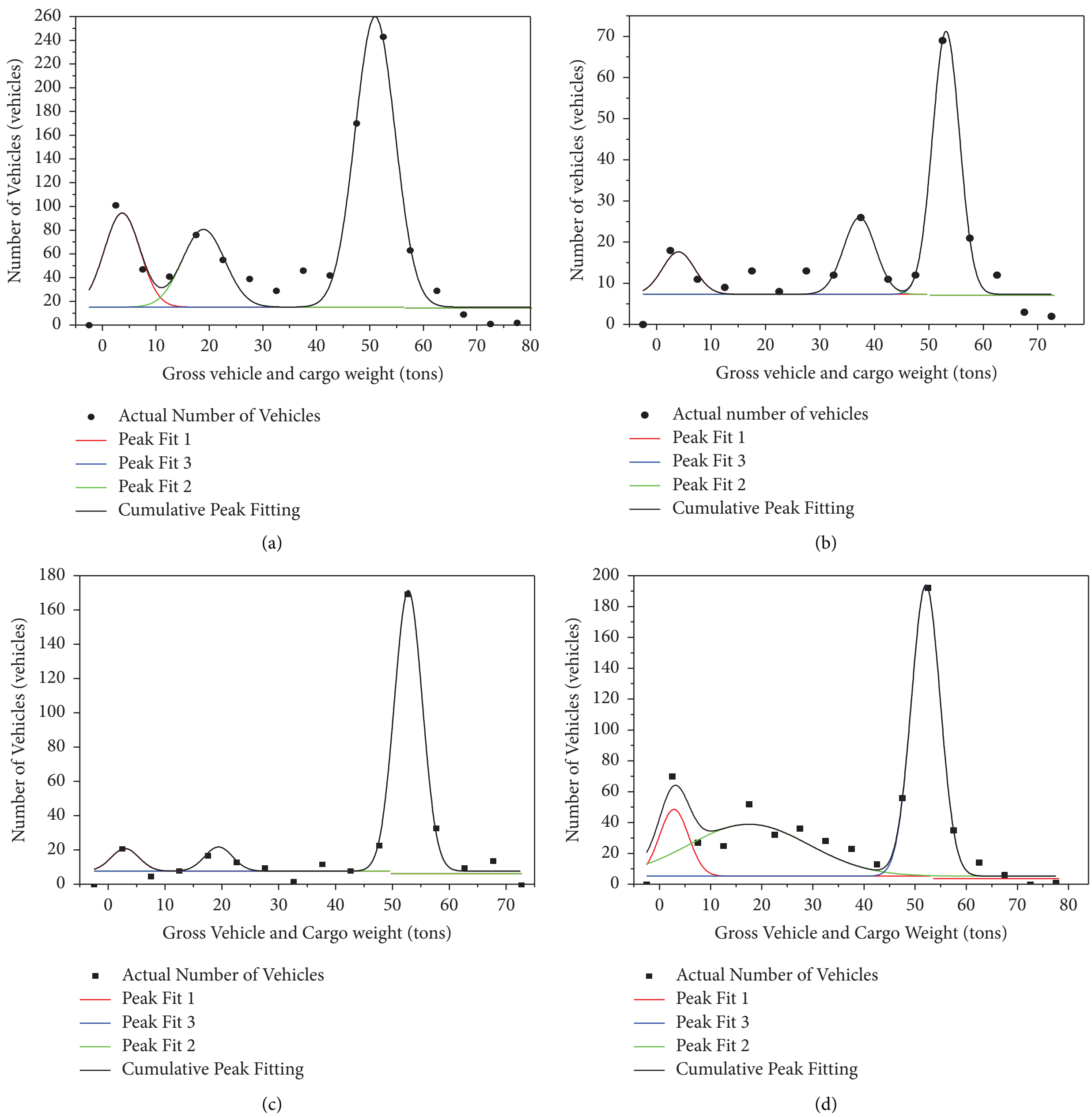


Figure 1: Histogram of the frequency distribution of vehicle loads for different lanes. (a) Lane 00105. (b) Lane 00107. (c) Lane 001008. (d) Lane 00110.

Table 3: Percentage of different vehicles in different lanes.

Lane number	Percentage of the number of vehicle type in the total number of vehicles in each lane (%)					
	Two axle	Three axle	Four axle	Five axle	Six axle	Seven axle
00102	91.4	2.7	1.3	0.3	3.8	
00103	77.9	4.8	3.9	1.2	11.9	
00104	37.2	11.6	11.1	4.2	34.9	
00105	24.5	7.1	7.1	7.4	56.2	
00106	38.6	8.5	10.0	6.2	36.4	
00107	20.0	5.8	16.6	5.0	52.0	0.4
00108	13.8	5.2	5.0	6.3	68.8	
00109	35.9	7.3	10.1	6.9	39.0	
00110	27.0	7.2	9.6	5.2	50.0	
00111	39.4	7.8	7.8	4.6	39.7	
00112	26.2	5.1	8.5	16.5	39.4	

stopped when the Reduced Chi-square value reaches 1×10^{-9}.

Taking lane 00105 as an example, the fitted curves of the gross vehicle and cargo weights of the six-axle trucks on this lane are as shown in Figure 2. The model converged after five iterations after parameter estimation and goodness-of-fit tests. At a significance level of 0.05, the six-axle truck vehicle weight consistently obeyed the single-peaked distribution based on the Gaussian model, and the fitting formula was shown in the following equation:

$$f(x) = 0.848 + \frac{423.64}{7.51 \cdot \sqrt{\pi/2}} \exp\left(-2 \cdot \frac{(x - 51.36)^2}{7.51^2}\right). \quad (3)$$

Here, $f(x)$ is the probability density function of the gross vehicle and cargo weight; x is the gross vehicle and cargo weight (tons); Mean value $\mu = 51.36$; Standard deviation $\sigma = 3.76$; Reduced Chi-sqr = 1.994; $R^2 = 0.9901$; the adjusted $R^2 = 0.98739$.

Similarly, the vehicle loads of the remaining models on lane 00105 were fitted and goodness-of-fit tests to obtain the type of vehicle weight distribution for each model. The probability distribution of the gross vehicle and cargo weight of the two-axle car obeys the Allometricl distribution, and the probability distribution of the gross vehicle and cargo weight of the three-axle car, four-axle car, and five-axle car obey the single-peaked Gauss distribution, and the fitted curve shows in Figure 3. The results of the correlation fit for each model are shown in Table 4.

2.4. Axle Weight. In order to further study the axle weight distribution ratio of different vehicle models on the four lanes, the measured axles weight data were used as the basis for statistical collation of all vehicle axles weights on the four lanes. On this basis, the proportion of axle weight allocated to each vehicle model was summarized, as shown in Table 5.

2.5. Wheelbase. The wheelbase information of the vehicles in the WIM data was statistically analysed, and the types of axle groups that appeared particularly infrequently were discarded. And, combined with China's "Limits of Dimensions, Axle Load and Masses of Motor Vehicles, and Trailers and Combination Vehicles" (GB1589-2016) [33], the wheelbase information of several models required in the study of this paper was obtained, and the final results are shown in Table 6.

2.6. Headway. Since the data of this survey came from the weight charge data of highway toll stations, its vehicle axle weight, vehicle weight, and other information are more accurate, but the headway time distance does not reflect the general running state of the vehicle [3]. Research [1, 35] has shown that the information of each vehicle parameter can be considered as mutually independent random variables in the vehicle load model. Therefore, this study was based on the original weight-based tolling system, and the headway on a highway truck running lane was investigated in the field by recording the headway of each vehicle arriving at a certain

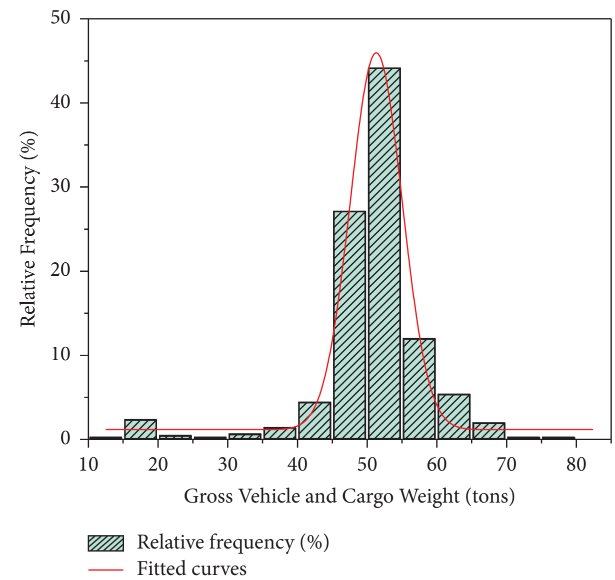


FIGURE 2: Fitted probability distribution of gross vehicle and cargo weight for six-axle vehicle.

section of the road. Owing to this paper mainly studying the automobile load effect of bridge structure under general operation conditions, the traffic jam condition was not considered for the time being. The fitted distribution of headway for each lane was shown in Figure 4.

As an example, the headway of lane 00105 was statistically analysed. The vehicle loads counted from 0 : 00 to 24 : 00 on May 15, 2011 were selected, and the relationship between the number of vehicles and the headway time distance was shown in Figure 4(a). The model converged after nine iterations after parameter estimation and goodness-of-fit tests. At a significance level of 0.05, the distribution appears to be characterized by a single peak distribution based on the Lognormal model, and the fitting formula is shown in equation (4). The results relating to the goodness of fit of each function are shown in Table 7.

$$f(x) = 8.93 \times 10^{-5} + \frac{2.22}{\sqrt{2\pi} \cdot 0.73x} \cdot \exp\left\{\frac{-[\ln(x/5.83)]^2}{2 \times 0.73^2}\right\}. \quad (4)$$

Here, $f(x)$ is the probability density function of the headway; x is the headway (s); Mean value $\mu = 5.83$; Standard deviation $\sigma = 7.60$. As can be seen in Figure 4(a), the number of vehicles increases and then decreases within 1~36 s, with the peak occurring when the headway is 3.75 s. In the headway spacing of the 1~12 s range, vehicles are more and more densely arranged; in the headway spacing of the 12~36 s range, the number of vehicles is less and it tends to flatten out, the effect of headway spacing on the most unfavorable load of small and medium span bridge structure in this range has been little effect.

3. The Truck Special Lane Vehicle Load Model

3.1. Truck Load Modelling Method. It is inappropriate to study the truckload model method on the trucks special lane

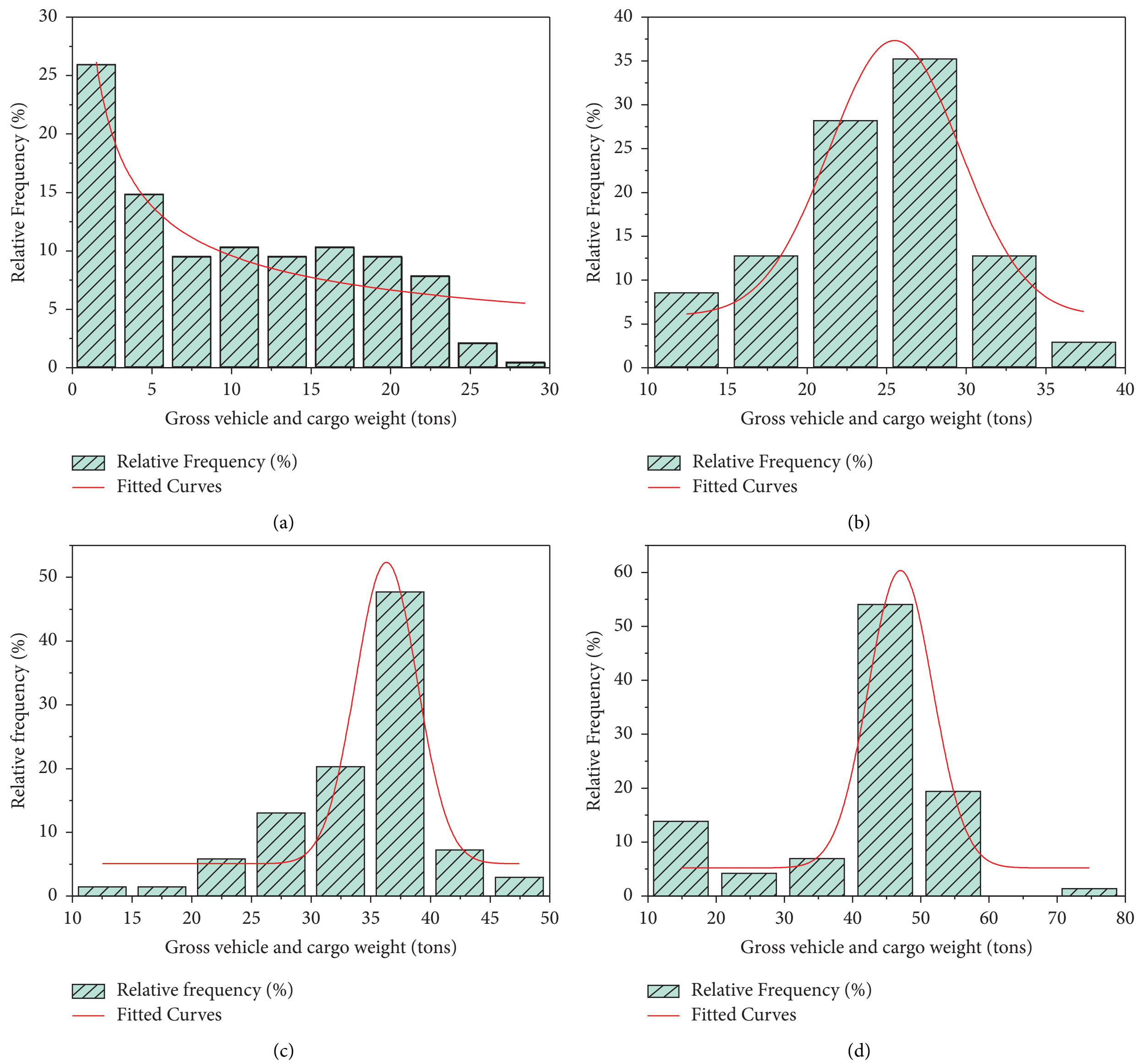


Figure 3: Histogram of the frequency distribution of vehicle loads for different lanes. (a) Two-axle vehicles. (b) Three-axle vehicles. (c) Four-axle vehicle. (d) Five-axle vehicle.

Table 4: Results related to goodness of fit.

Vehicle type	Two-axle	Tri-axle	Four-axle	Five-axle
Reduced Chi-sqr	8.04395	13.60317	23.24337	39.39197
R^2	0.85295	0.96455	0.94588	0.94488
Adjusted R^2	0.83457	0.91137	0.90529	0.88976

directly with the load flow data of mixed car and truck because the load flow data of mixed car and truck contains all the vehicle types on the bridge and cannot reflect the load flow situation of the trucks special lane. Considering that there are no actual operating highway bridges in China where passenger cars and trucks drive separately, the load flow data of lanes for special trucks cannot be directly retrieved as samples. Therefore, in order to study the effect of the load flow of the truck lane on the bridge, the four truck-based mixed passenger and cargo load flow data were used as samples. Then, the continuous truck fleet was selected from the original data to study the distribution law of its gross vehicle weight and headway time distance. Finally, the random traffic flow model is constructed and the resulting load effects are calculated. The advantage of using this method for data processing was that the data were handled, taking into account the actual traffic conditions, and data such as passenger cars were removed to make the sample data more consistent with the research needs of passenger cars and truck separation.

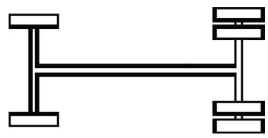
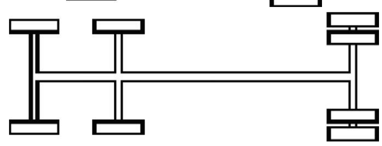
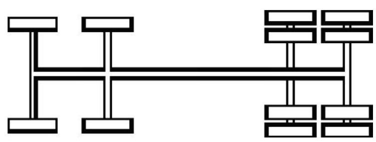
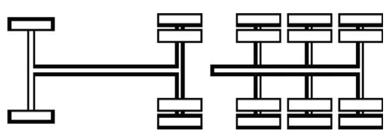
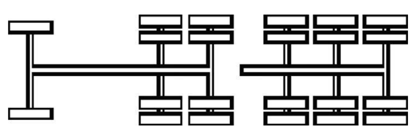
3.2. Representative Vehicles. Combined with the model composition and vehicle load statistical analysis, considering the four lanes on the number of six-axle vehicles accounted for the total number of vehicles in this lane proportion have

Table 5: The proportion of axle weight of each model.

Vehicle type	Axles 1	Axles 2	Axles 3	Axles 4	Axles 5	Axles 6
Two-axle	0.3	0.7				
Triaxle	0.15	0.2	0.65			
Four-axle	0.15	0.15	0.35	0.35		
Five-axle	0.1	0.25	0.216	0.217	0.217	
Six-axle	0.05	0.175	0.175	0.2	0.2	0.2

axles 1, axles 2, axles 3, axles 4, axles 5, and axles 6 in the order from the front to the rear of the vehicle.

Table 6: Vehicle wheelbase information statistics.

Vehicle type	Vehicle axle type	Vehicle wheelbase (mm)
Two-axle vehicle		4050/4200/4700/530
Three-axle vehicle		1950 + 5350
Four-axle vehicle		1850 + 4600 + 1350
Five-axle vehicle		3500 + 6830 + 1310 + 1310
Six-axle vehicle		300 + 1300 + 7190 + 1310 + 1310

exceeded 50%, and the proportion of overloaded six-axle vehicles in each lane is more than 40%. Therefore, the six-axle vehicle can be used as the representative model of the special lane for trucks.

3.3. Axis Weight Distribution Ratio. Since the weight distribution ratio of each axle for the same vehicle model with the same axle group type on the road is very random, it is also very complicated to build a separate axle weight distribution ratio model to apply to the study. In order to simplify the axle weight distribution ratio model, the axle weight distribution ratio of the six-axle vehicle is determined as 0.05 for the front axle, 0.35 for the twin axle, and 0.6 for the triple axles as the axle weight distribution of the six-axle vehicle based on the study in Section 2.4.

3.4. Wheelbase. Based on the above-given statistical results for the vehicle wheelbase, the vehicle model and the impact line lay down were simplified to calculate the most adverse load effect. The vehicle wheelbase of the six-axle vehicle was determined as 3300 + 1300 + 7200 + 1300 + 1300 (mm) in this study.

3.5. Probability Model of Gross Vehicle and Cargo Weight and Headway. According to the method of vehicle load model construction for truck-specific lanes, the load flow data of continuous truck fleets were selected to study the probability distribution of their gross vehicle and cargo weight and headway.

Taking lane 00105 as an example, the fitted curves for the vehicle loads of the continuous truck fleet are shown below. The model converged after eleven iterations after parameter estimation and goodness-of-fit tests. At a significance level of 0.05, the Gaussian distribution is obeyed, as shown in Figure 5(b), and as shown in the following equation:

$$f(x) = 1.22 + \frac{408.31}{6.88 \cdot \sqrt{\pi/2}} \cdot \exp\left\{-2 \cdot \frac{(x - 51.51)^2}{6.88^2}\right\}. \tag{5}$$

In equation (5), $f(x)$ is the probability density function of the gross vehicle weight; x is the gross vehicle weight (tons); Mean value $\mu = 51.51$; Standard deviation $\sigma = 3.76$. And, Reduced Chi-sqr = 2.52976; $R^2 = 0.98807$; the adjusted $R^2 = 0.98481$.

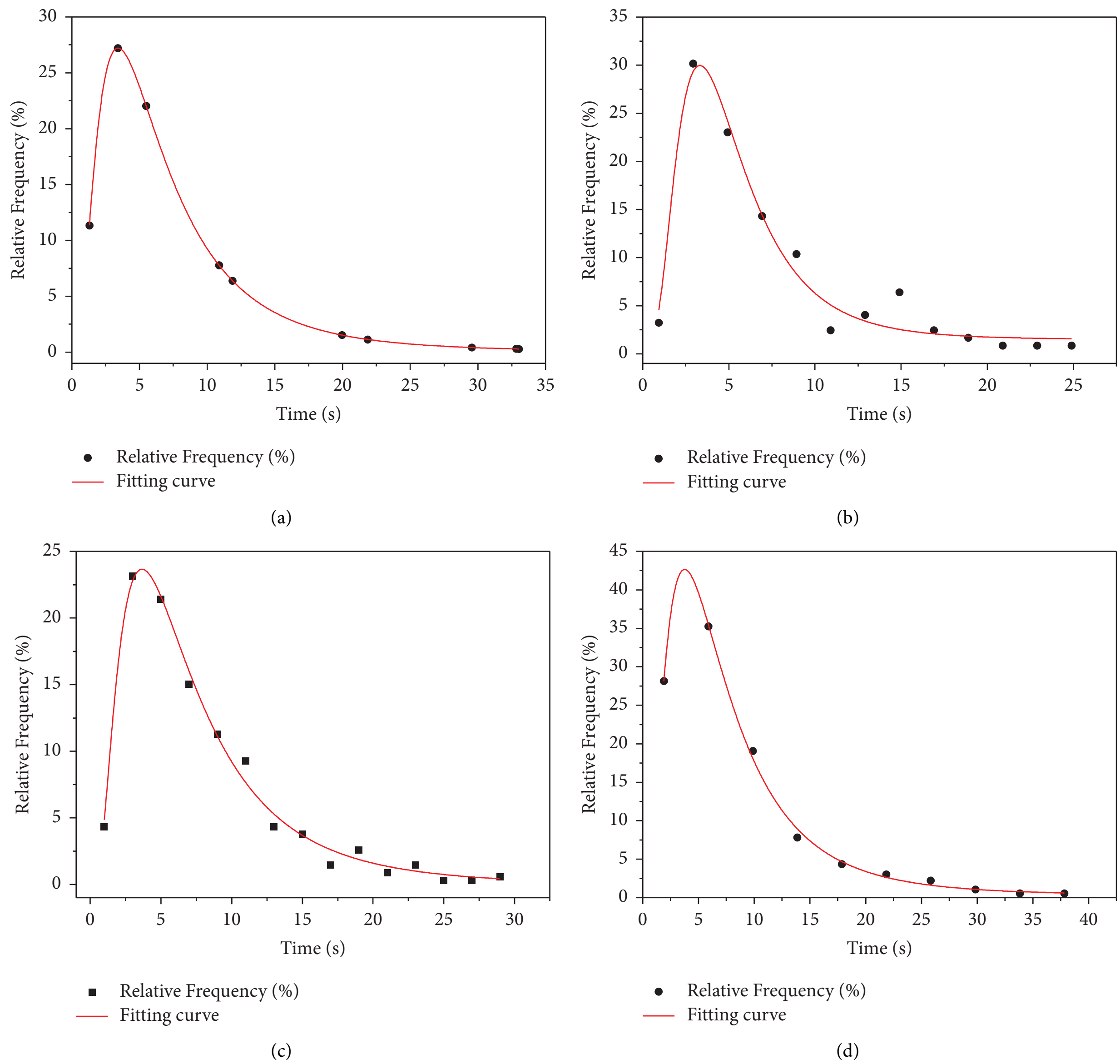


Figure 4: Distribution of headway fitting for each lane. (a) Lane 00105. (b) Lane 00107. (c) Lane 001008. (d) Lane 00110.

Table 7: Results related to goodness of fit.

Lane number	00105	00107	00108	00110
Reduced Chi-sqr	0.68504	3.58826	0.66789	1.22686
R^2	0.98971	0.9696	0.99112	0.98145
Adjusted R^2	0.9875	0.9547	0.9887	0.97798

The fitted curves for the headway of consecutive lorries on lane 00105 are shown below, giving a lognormal distribution by parameter estimation and K–S test, as shown in Figure 5(b), and as shown in the following equation:

$$f(x) = 0.14 + \frac{1.97}{\sqrt{2\pi}\cdot 0.75x}\cdot \exp\left\{\frac{-[\ln(x/5.74)]^2}{2\times 0.75^2}\right\}. \quad (6)$$

Here, $f(x)$ is the probability density function of the headway; x is the headway (s); Mean value $\mu = 5.74$; Standard deviation $\sigma = 6.52$; Reduced Chi-sqr $= 5.94151$; $R^2 = 0.99554$; the adjusted $R^2 = 0.9942$.

3.6. Monte Carlo Method to Generate Random Traffic Flow Correlation Parameters. Based on the study of the vehicle load model for the truck-only lane, the vehicle load and the headway time distance are treated as two mutually independent random variables. And, random numbers obeying their respective probability distributions are generated according to the Monte Carlo method [36–38], as shown in Figure 6. After the

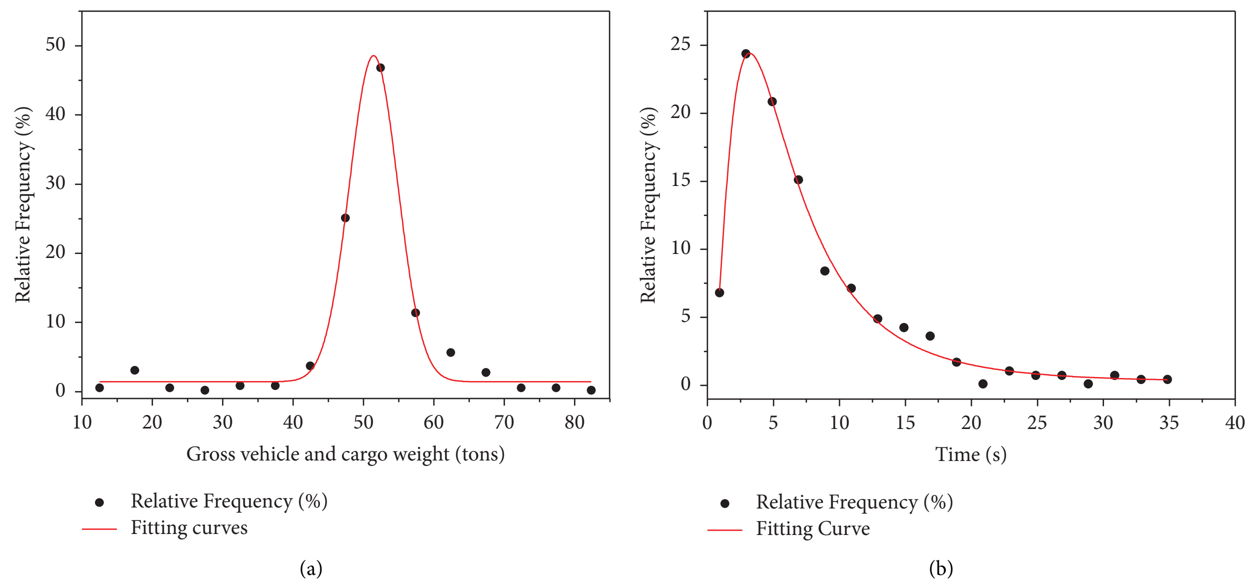


Figure 5: Fitting distribution of relevant parameters for continuous truck fleet in lane 00105. (a) Probability density distribution of vehicle loads. (b) Probability density distribution of headway.

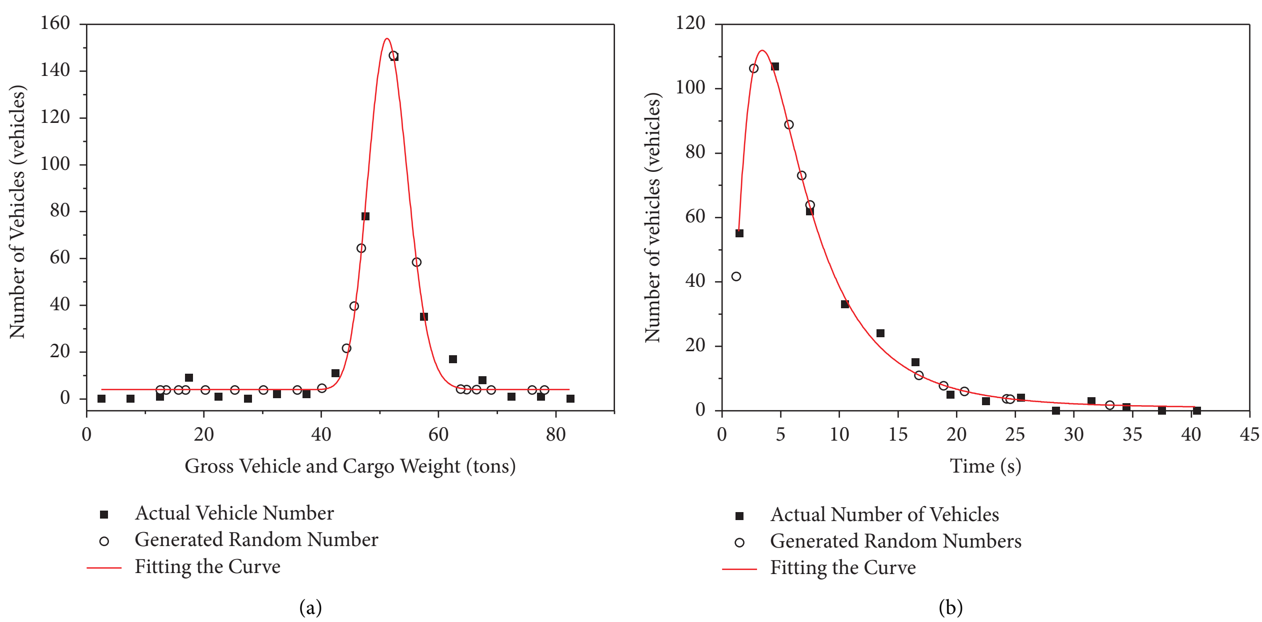


Figure 6: Monte Carlo method for generating continuous truck fleet load flow parameters. (a) Random number generated by vehicle load. (b) Random number generated by headway.

combination, they are randomly disrupted and arranged on the girders according to the given axle weight distribution ratio as well as the axle spacing to simulate the random load flow through the bridge.

4. Truck Special Lane Truck Load Effect Calculation

The random traffic flow generated by the Monte Carlo method was imported into the impact line, and the load flow was moved forward in certain steps using the moving load impact line loading method to record the impact values generated by each vertical load in each state. Then, the value of the load effect on the control section of the bridge was calculated until the loading stopped when the last vehicle of the load flow left the bridge. Finally, the maximum effect in every 30 states is screened out and the probability density analysis of the daily maximum effect was performed.

Before the development of "General Specification for Highway Bridge Culverts" (JTG D60-2015) [3] in China, the

"Reliability Study of Highway Bridges" was conducted by the "Highway Bridge Vehicle Load Research" group, and the statistical laws of vehicle load effects in China were also studied. In the statistical analysis of vehicle load effects, the researchers did not collect load information for cars within one year. Due to the limited data, the researchers assumed that "the change in vehicle operating conditions over the course of a year would not be significant." Therefore, the cut-off distribution of the one-day maximum of the load effect is considered as the cut-off distribution of the one-year maximum of the load effect, so that the relationship between the distribution of the maximum of the load effect and the distribution of the daily maximum of the load effect during the design reference period is obtained. The specific analysis methods are as follows.

Dimensionless parameter K is taken as the statistical object of vehicle load. The formula for calculating K is shown in the following equation:

$$K = \frac{S}{S_K}. \quad (7)$$

Here, S is the effect value of control section calculated according to the load flow arranged on the bridge; S_K is the most unfavorable effect value of the control section under the current highway bridge design code for highway class I load; K is the ratio of S and S_K and K_{SQ} is the 0.95 quantile value of the probability distribution function of the maximum effect ratio of S and S_K in the design base period. By replacing the probability distribution of the annual maximum effect ratio with the probability distribution of the daily maximum effect ratio, the probability distribution of the maximum effect ratio of the load effect within the design reference period is calculated as shown in equation (6). The design base period for bridges in China is 100 years.

$$\begin{aligned} F_T\left(K_{SQ}\right) &= F(K)^T \\ &= F(K)^{100}. \end{aligned} \quad (8)$$

Therefore, the calculation of the value of K_{SQ} at $F_T(K_{SQ}) = 0.95$ quantile can be translated into the value of K at the quantile where $F(K) = 0.95^{1/100}$. The value of K_{SQ} can be calculated by analyzing the distribution function of the maximum value of the daily maximum effect ratio. A similar approach was taken due to the limited data in this paper.

4.1. Simply Supported Beam. Select simply supported beams with spans of 10 m, 13 m, 16 m, 20 m, 25 m, 30 m, 35 m, 40 m, 45 m, and 50 m as samples and calculate the value of load effect generated by the control section when the load flow passes through the simply supported beam. Simply supported beams with span diameters of 10 m, 13 m, 16 m, 20 m, 25 m, 30 m, 35 m, 40 m, 45 m, and 50 m were selected as samples, and then the span moment and branch shear force of the simply supported beam were calculated when the load flowed over the simply supported beam.

Taking the lane 00105 as an example, the value of the load effect produced by the bearing section of a simply supported beam with a span diameter of 30 m under the action of random traffic is calculated. And, compared with the effect of carload action calculated according to the code design load, the probability distribution of the daily maximum effect ratio was drawn. The frequency histogram and cumulative frequency distribution of the ratio of the daily maximum effect of the shear force at the support point of the 30 m simply supported beam are shown in Figure 7.

The probability density expression is shown in the following equation:

$$f(x) = 0.724 + \frac{9.203}{0.174 \times \sqrt{\pi/2}} \times \exp\left(-2 \times \frac{(x - 0.737)^2}{0.1742^2}\right). \quad (9)$$

Here, $f(x)$ is the probability density function of the pivot shear ratio; x is the pivot shear ratio; Mean value $\mu = 0.737$; Standard deviation $\sigma = 0.0870$; $K_{SQ} = 1.028\sigma = 6.52$; Reduced Chi-sqr = 7.1066; $R^2 = 0.97885$; the adjusted $R^2 = 0.96827$.

The cumulative frequency distribution function formula is shown in the following equation:

$$y = 98.539 + \frac{2.421 - 98.569}{1 + \exp(x - 0.685/0.0408)}. \quad (10)$$

Here, y is the cumulative probability distribution function for the pivot shear ratio; x is the pivot shear ratio.

Similarly, the pivot point shear forces and midspan bending moments generated by a continuous truck convoy on four lanes passing through simply supported beams of different spans are calculated. The ratio of these to the load effect produced at the control section by the design load according to the current code is calculated. The K_{SQ} value at the 0.95 quantile of the maximum distribution function during the design base period was calculated by parameter estimation.

In order to make the statistical results more intuitive, the calculated results are plotted on the coordinate axes for statistical analysis, where the horizontal coordinate is the span diameter of the simply supported beam and the vertical coordinate is the ratio of the control section effect, as shown in Figure 8.

As shown previously in 00105 lane, continuous truck fleet through the span diameter of 10 m, 25 m, 30 m, and 35 m simple beam, the span bending moment appeared K_{SQ} greater than 1 and the pivot point shear in the simple beam span diameter of 30 m and 35 m also appeared K_{SQ} greater than 1; in 00107 lane, continuous truck fleet through the span diameter of 30 m simple beam and the span bending moment appeared K_{SQ} greater than 1; in 00108 lane, 00110 lane on the continuous truck fleet of load effects were not more than according to the current code design load at the control section of the effect.

The K_{SQ} at the same control section of the simple-supported beam of different spans of the four lanes are

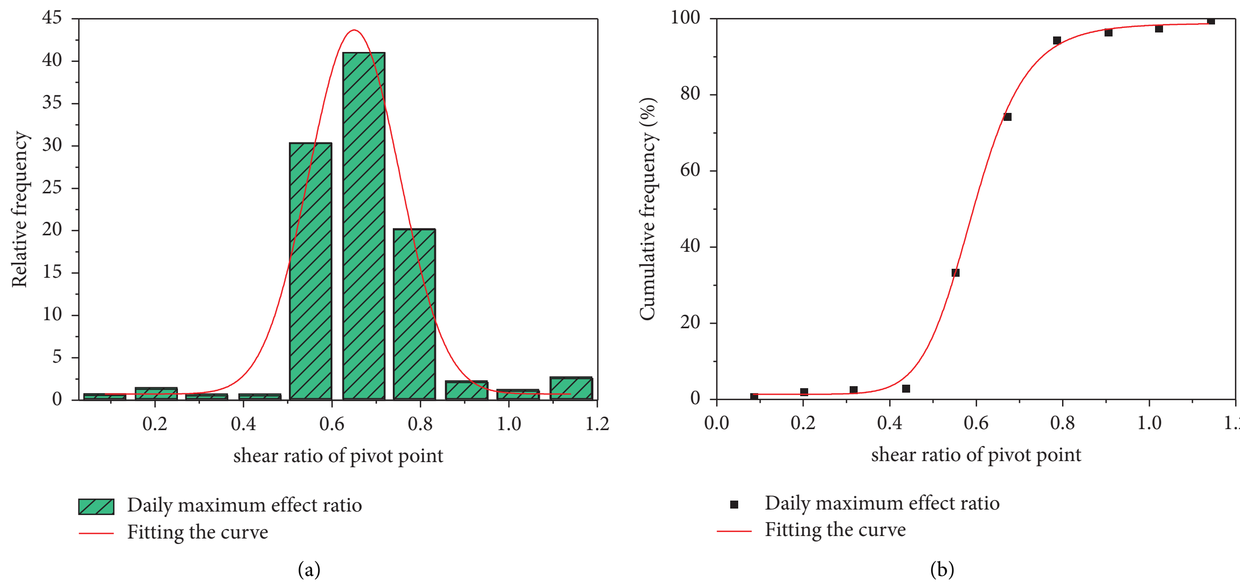


FIGURE 7: Daily maximum support shear ratio probability distribution for simply supported beams. (a) Frequency histogram. (b) Cumulative frequency distribution histogram.

summed and averaged. Finally, the average value of K_{SQ} at each control section of the four lane continuous truck convoy through the simply supported beam is obtained, as shown in Table 8.

4.2. Continuous Beams. Bridge spans of 3×20 m, 3×25 m, 3×30 m, 3×35 m, and 3×40 m were chosen as the three-span continuous girders to calculate the value of the load effect produced by the control section of the continuous girders when the load flow passed. Thus, the midspan bending moment of the side span, the midspan bending moment of the middle span, and the bearing section bending moment are calculated. Then, the ratio of the effect of the vehicle load was calculated with the current code design load. Finally, the probability distribution model of the ratio of the maximum daily effect was drawn.

For example, when the continuous truck fleet passes through the 3×25 m continuous girder bridge, the frequency histogram of the ratio of the daily maximum effect of the span moment at the midspan of the bridge is shown in Figure 9.

The probability density expression is shown in the following equation:

$$f(x) = 1.881 + \frac{3.966}{0.0675 \times \sqrt{\pi/2}} \times \exp\left(-2 \times \frac{(x - 0.693)^2}{0.174^2}\right). \quad (11)$$

Here, $f(x)$ is probability density function of the midspan moment ratio for the middle span of the continuous beam; x is the midspan moment ratio for the middle span of the continuous beam; Mean value $\mu = 0.693$; Standard deviation $\sigma = 0.0338$; $K_{SQ} = 0.803$; Reduced Chi-sqr = 4.5785; $R^2 = 0.98447$; the adjusted $R^2 = 0.97781$.

The cumulative frequency distribution function formula is shown in the following equation:

$$y = 93.129 + \frac{-0.290 - 93.129}{1 + \exp(x - 0.668/0.0235)}. \quad (12)$$

Here, y is the cumulative probability distribution function of the midspan moment ratio for the middle span of the continuous beam; x is of the midspan moment ratio for the middle span of the continuous beam.

The values of the load effects produced by the control section when continuous trucks pass through the continuous beam of different spans on the four lanes are counted. And, then their effects are calculated and compared with those produced by the design loads at the control section according to the current code. The K_{SQ} value at the 0.95 quantile of the maximum distribution function during the design base period was calculated by parameter estimation. In order to make the statistical results more intuitive, the calculated results are plotted in the coordinate axes for statistical analysis, with the horizontal coordinate being the span diameter of the continuous beam and the vertical coordinate being the control section effect ratio, as shown in Figure 10.

From Figure 10, it can be seen that the load effect generated on the bearing section of the continuous truck convoy passing through the three-span continuous beam at lane 00105 has exceeded the code effect. And, the load effect is greater than 1 at the middle of the span of the 3×30 m continuous girder side span. At lane 00107, the load effect generated by a continuous truck fleet passing through a three-span continuous beam on its support section has largely exceeded the normative effect, where $K_{SQ} = 0.9911$ at the 0.95 percentile value of the moment ratio at the support

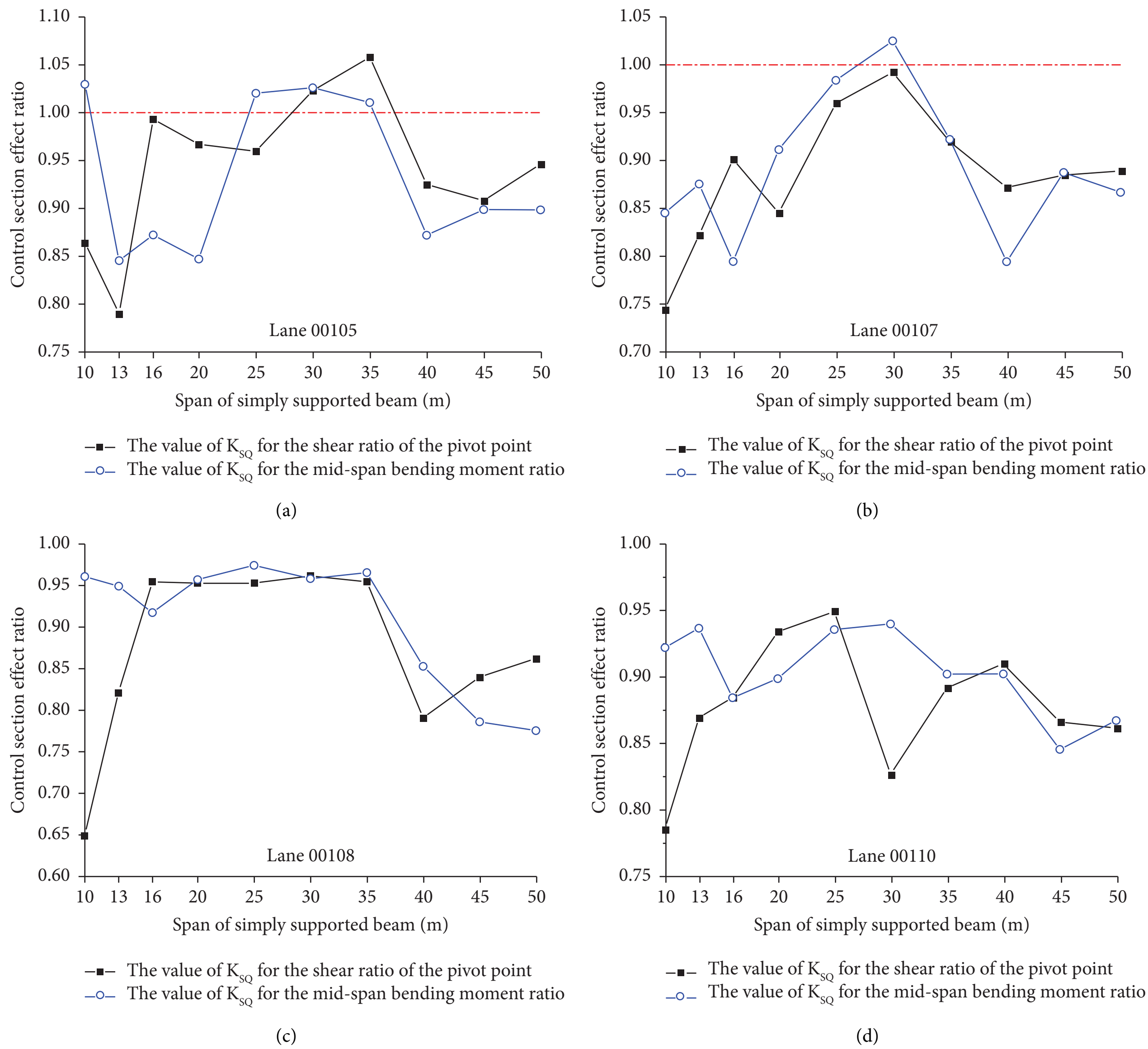


Figure 8: Ratio of maximum effect of control section for random vehicle flow across simply supported beam.

Table 8: Mean value of K_{SQ} for each control section after consolidation.

Lane number	Pivot sections	Midspan section
00105	0.9430	0.9315
00107	0.8825	0.8900
00108	0.8736	0.9094
00110	0.8774	0.9031
Average value	0.8971	0.9085

section of a continuous beam with a span of 3 × 30 m. In lanes 00108 and 00110, the load effect on the support section of the continuous truck fleet passing through the three-span continuous beam has basically exceeded the effect of the vehicle load calculated according to the code design load. The midspan span midbending moment and the side span midbending moment in general do not exceed the load effect produced by the code.

Finally, the average value of K_{SQ} at each control section can be obtained by summing the K_{SQ} of the same control section of the four lanes of different span continuous beams, as shown in Table 9.

5. Results and Discussion

Based on the analysis of the above data, it can be seen that in the case of passenger car and truck separation, when the continuous truck passes through the simply supported beam, the average K_{SQ} values of the bearing shear ratio and the span moment ratio are less than 1, which are 0.8941 and 0.9085, respectively. It shows that with the current continuous truck data as the load flow sample for truck-only lanes, the effect produced on the simply supported girders will generally not exceed the vehicle load effect specified in the code. However, the individual span of the simply

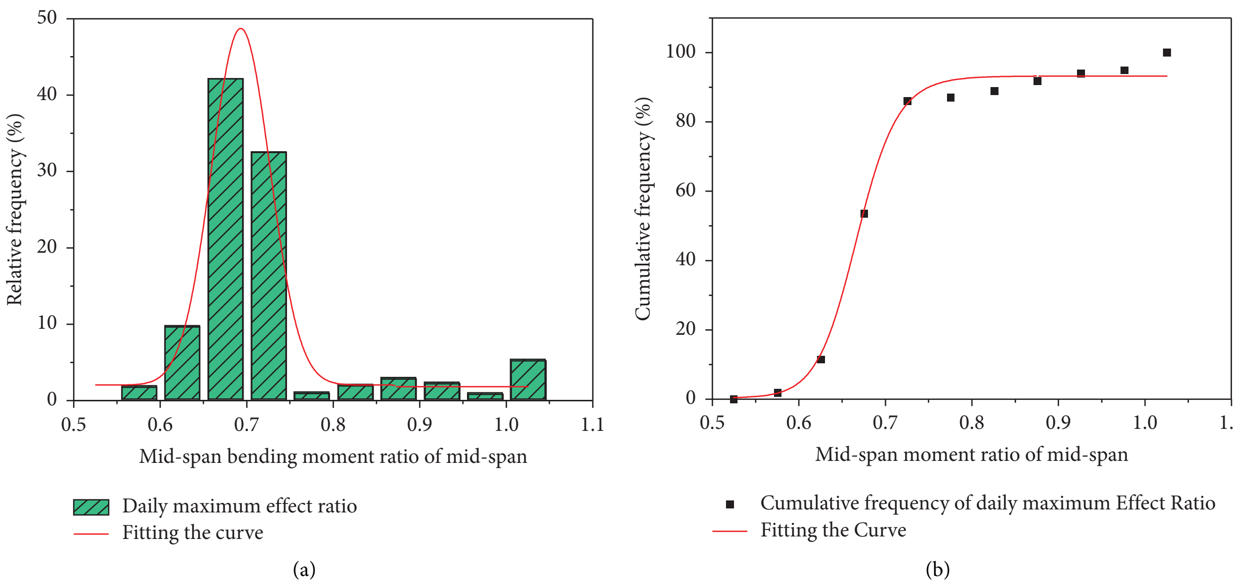


Figure 9: Probability distribution of the daily maximum moment ratio of the midspan section of the middle span of the continuous beam. (a) Frequency histogram. (b) Cumulative frequency distribution histogram.

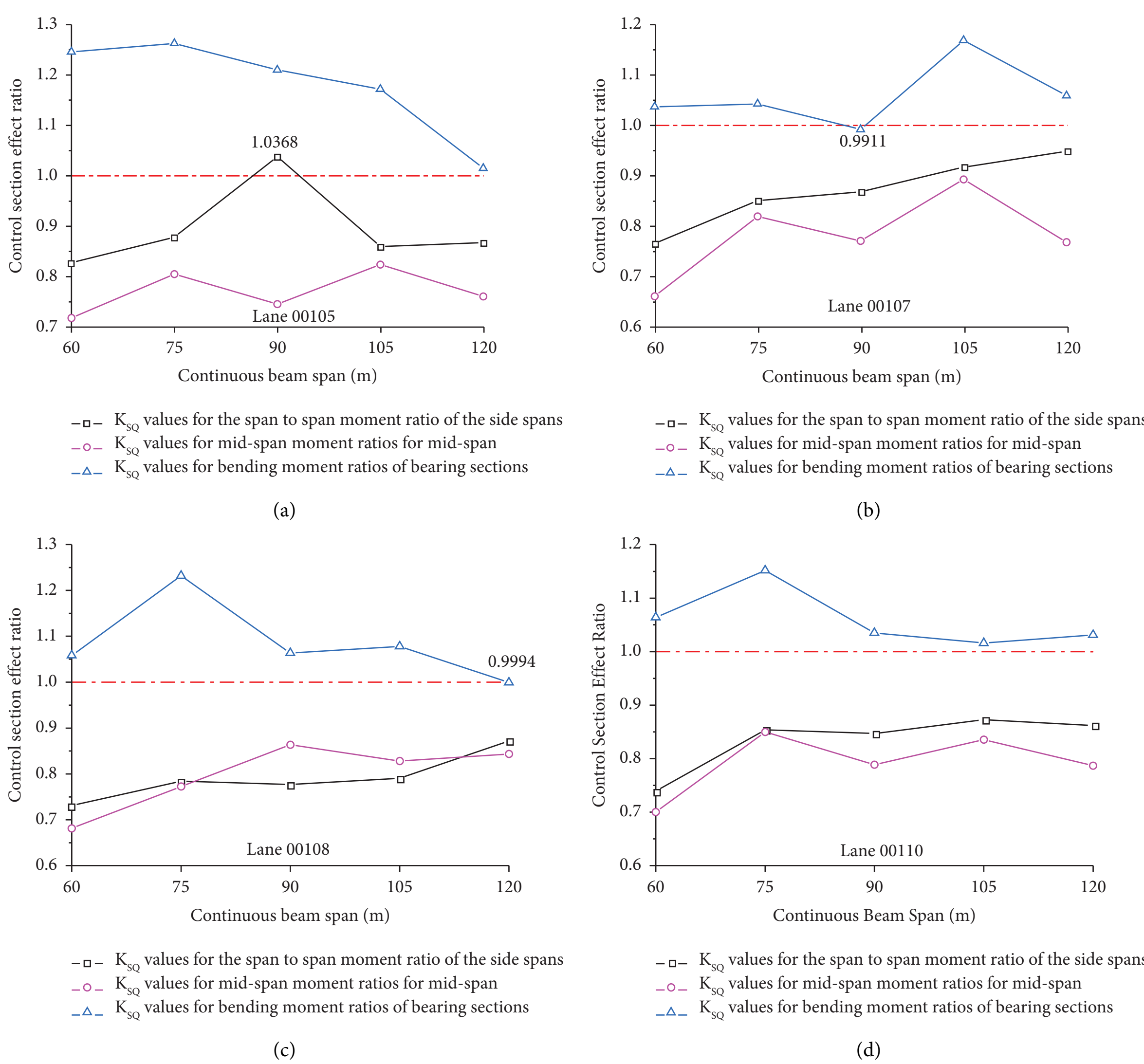


Figure 10: Ratio of maximum effect of control section for random vehicle flow through continuous beam.

Table 9: Mean value of K_{SQ} for each control section after consolidation.

Lane number	Midspan section of side span	Midspan section of middle span	Pivot section
00105	0.8927	0.7687	1.1806
00107	0.8689	0.7809	1.0592
00108	0.7909	0.7978	1.0861
00110	0.8350	0.7922	1.0595
Average value	0.8469	0.7849	1.077

Table 10: Standard values for vehicle loads in Chinese codes.

Continuous Beam (m)	$L0 \leq 5$	$5 < L0 < 50$	$L0 \geq 50$
$q_k\,(kN/m)$	10.5	10.5	10.5
p_k	180	$4\,(40 + L_0)$	360

Table 11: Suggested values for vehicle loads in the lane for trucks (road class I load).

Continuous Beam (m)	$L0 \leq 5$	$5 < L0 < 50$	$L0 \geq 50$
$q_k\,(kN/m)$	12	12	12
p_k	300	$20/9\,(130 + L_0)$	400

supported girder bridge appears in the calculation analysis to be greater than 1, which should be noted in the design.

When the continuous truck passes through the continuous beam, the average value of K_{SQ} at the 0.95 quantile of the probability distribution of the maximum ratio of the span moment of the side span and the span moment of the middle span in the design reference period is less than 1, which are 0.8469 and 0.7849, respectively. It shows that the load flow samples of the current continuous truck data as a truck-only lane will not produce the effect of the span moment of the side span and the span moment of the middle span on the continuous beam in excess of the vehicle load effect specified in the code. However, the average value of K_{SQ} at the 0.95 quantile of the probability distribution of the maximum ratio of the bearing section bending moment in the design reference period is greater than 1 for 1.0772. It shows that the load flow sample of the current continuous truck data as the lane for trucks has produced a load effect on the continuous girders that exceeds the vehicle load effect calculated by the code design load. It may eventually cause adverse effects on the safety of the bridge structure in use.

In the current Chinese design code for highway bridges (JTGD60-2015) [3] the vehicle loads are divided into lane loads and vehicle loads. The lane loads are used to calculate the design criteria for different span sizes of live loads, while the vehicle loads are used for local calculations. The lane load consists of a uniform load q_k and a concentrated load p_k. The vehicle load used for our motorways is a highway class I. The specific values are shown in Table 10.

When the bridge structure is in a small elastic deformation range, the load effect produced by the load acting on the bridge is proportional to the magnitude of the load value. The proportionality factor is independent of the load and is only related to the location of the load and the type of bridge structure. In general, bridges are assumed to be in a state of elastic deformation in the design of bridge structures.

Therefore, according to the calculation method of car-load in this paper, a bridge design load effect is calculated as shown in the following equation:

$$S = qA + Py. \tag{13}$$

Here, A indicates the area of the influence line within the range of the uniform load; y indicates the value of the vertical scale of the influence line at the concentration of the load; the uniform load q and the concentrated load P are the recommended value of the vehicle load in the code.

Typically, once the bridge type has been determined, the load effect influence line function has a unique expression and the load arrangement that produces the most adverse load effect is determined. Therefore, A and y in equation (13) are constant, while the uniform load q and the concentrated load P can also be determined according to the code. In order to achieve the purpose of this paper to correct the standard values of the current lane loads, an equal proportional correction is made to the regulated lane loads. By introducing a correction factor k for q and P, the vehicle load effect is calculated as shown in the following equation:

$$S = k(qA + Py). \tag{14}$$

The calculation of the correction coefficient can be referred to the treatment of the subject group "Research on vehicle loads on road bridges" in China. According to the results of the calculation and treatment of vehicle load effects in Section 4, the ratio of the dimensionless amount of load effects during the design basis period, K_{SQ}, is taken as the correction factor.

Therefore, based on the above studies and analyses, the lane loads in the code have been suitably amended. That is when highway bridges are designed for truck-specific lanes, appropriately increase the coefficient of the load pattern in the code to improve the design bearing capacity of the bridge, and then improve the safety of the bridge. According to the results summarized in Table 7, the mean value of K_{SQ} for the bearing section bending moment is 1.0772. The vehicle load effect on the bearing section exceeds the vehicle load effect specified in the code and can have an adverse effect on the safety of the bridge structure in use. Therefore, we recommend that the standard values of concentrated and distributed loads in the current design code for highway bridges be increased by 1.1 times and rounded, and the specific value criteria are recommended as shown in Table 11.

6. Conclusions

In this paper, based on four mixed passenger car and truck vehicle load sample data, from which a continuous truck fleet was selected, truck-specific lane vehicle load model studies and truck-specific lane vehicle load adaptability studies were conducted respectively, with the following conclusions:

(1) The data on the mixing of passenger cars and trucks on the four lanes showed that the number of six-axle vehicles accounted for the highest percentage of the total number of vehicles in each lane, and the number of six-axle heavy-duty overloaded vehicles accounted for the highest percentage of the total number of vehicles in each lane. Therefore, it is necessary to study the impact of six-axle vehicles on bridges.

(2) Using the current data as a sample, when a highway bridge is set up with special lanes for trucks, the load effect generated by the truck fleet passing through the simply supported beam will not exceed the vehicle load effect calculated according to the current code design load in general. When a truck convoy passes through a three-span continuous beam, the vehicle load effect in the midspan of the side span and the midspan of the middle span section will not exceed the vehicle load effect calculated by the code design load in general. However, the effect of the carload generated at the bearing section exceeds the effect of the carload calculated according to the design load of the specification. It could adversely affect the safety of bridge use and endanger the safety and durability of the bridge structure.

(3) According to the study and analysis of the measured data, in the case of passenger-car truck separation, highway bridges in the design of special lanes for trucks, we recommend that in China's current highway bridge design code lane load standard value based on 1.1 times higher and take the whole.

7. Future Work

The construction of separated highways for passenger cars and trucks is conducive to improving the efficiency and safety of traffic and is also the basis for future research on automated driving lanes. Current research on separated bus-truck motorways is mainly focused on the field of traffic simulation, while the analysis of vehicle loads in the case of separated bus-truck traffic is almost nonexistent. The researcher will carry out further research in the following directions in the coming time.

(1) Through the analysis of existing data to choose a more suitable method to obtain more objective, more scientific, and reasonable statistical information of continuous truck load flow

(2) Calculation of the load effects on bridges with complex systems and oversized spans

(3) Consider the case of setting up multiple lanes for trucks and calculate the transverse discount effect, longitudinal discount effect, and vehicle impact force

Data Availability

The EXCEL data used to support the findings of this study have not been made available because these data come from third parties and there are restrictions on the availability of the data.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Supplementary Materials

The data collected in the supplementary material are the headway of highway vehicles. It was collected in August 2020 at a section of a highway in Henan Province, China. (*Supplementary Materials*)

References

[1] Project Group, "Research on vehicle loading on road bridges," *Highways*, vol. 7, pp. 8–12, 1997.

[2] L. Nai-wei, L. Yang, and X. Xin-hui, "Extrapolating method of extreme load effects on long-span bridge under actual traffic loads," *Journal of Traffic and Transportation Engineering*, vol. 18, pp. 47–55, 2018.

[3] M. China, *General Specifications For Design Of Highway Bridges And Culverts*, JTG D60-2015, Bejing, China, 2015.

[4] A. S. Nowak and M. M. Szerszen, "Bridge load and resistance models," *Engineering Structures*, vol. 20, no. 11, pp. 985–990, 1998.

[5] C. Cremona, "Optimal extrapolation of traffic load effects," *Structural Safety*, vol. 23, no. 1, pp. 31–46, 2001.

[6] T. H. Chan, T. Miao, and D. B. Ashebo, "Statistical models from weigh-in-motion data," *Structural Engineering & Mechanics*, vol. 20, no. 1, pp. 85–110, 2005.

[7] T. Miao and T. H. Chan, "Bridge live load models from WIM data," *Engineering Structures*, vol. 24, no. 8, pp. 1071–1084, 2002.

[8] 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.

[9] C. C. Caprani and E. J. Obrien, "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.

[10] E. J. O'Brien and B. Enright, "Modeling same-direction two-lane traffic for bridge loading," *Structural Safety*, vol. 33, no. 4-5, pp. 296–304, 2011.

[11] E. J. O'Brien and B. Enright, "Using weigh-in-motion data to determine aggressiveness of traffic for bridge loading," *Journal of Bridge Engineering*, vol. 18, no. 3, pp. 232–239, 2013.

[12] J. Zhao and H. Tabatabai, "Evaluation of a permit vehicle model using weigh-in-motion truck records," *Journal of Bridge Engineering*, vol. 17, no. 2, pp. 389–392, 2012.

[13] A. C. McKinnon, "The economic and environmental benefits of increasing maximum truck weight: the British experience," *Transportation Research Part D: Transport and Environment*, vol. 10, no. 1, pp. 77–95, 2005.

[14] C. Leahy, E. J. O'Brien, B. Enright, and D. Hajializadeh, "A review of the HL-93 bridge traffic load model using an extensive WIM database," *Journal of Bridge Engineering*, vol. 20, 2014.

[15] Y. Liang and F. Xiong, "Measurement-based bearing capacity evaluation for small and medium span bridges," *Measurement*, vol. 149, Article ID 106938, 2020.

[16] Z. Zhou-hong, Z. Cheng, and Y. Ze-gang, "Vehicle load model for highway bridges in Jiangsu province based on WIM," *Journal of Southeast University (Natural Science Edition)*, vol. 50, pp. 143–152, 2020.

[17] T. Jin, H. Ding, B. Li, H. Xia, and C. Xue, "Valuation of interest rate ceiling and floor based on the uncertain fractional differential equation in Caputo sense," *Journal of Intelligent and Fuzzy Systems*, vol. 40, no. 3, pp. 5197–5206, 2021.

[18] T. Jin, H. Ding, H. Xia, and J. Bao, "Reliability index and Asian barrier option pricing formulas of the uncertain fractional first-hitting time model with Caputo type," *Chaos, Solitons & Fractals*, vol. 142, Article ID 110409, 2021.

[19] T. Jin, X. Yang, H. Xia, and H. Ding, "Reliability index and option pricing formulas of the first-hitting time model based on the uncertain fractional-order differential equation with Caputo type," *Fractals*, vol. 29, no. 1, Article ID 2150012, 2021.

[20] T. Jin and Y. Zhu, "First hitting time about solution for an uncertain fractional differential equation and application to an uncertain risk index model," *Chaos, Solitons & Fractals*, vol. 137, Article ID 109836, 2020.

[21] T. Jin, H. Xia, and H. Chen, "Optimal control problem of the uncertain second-order circuit based on first hitting criteria," *Mathematical Methods in the Applied Sciences*, vol. 44, no. 1, pp. 882–900, 2021.

[22] "Statistical bulletin on the development of the transport sector in 2020," *Ministry of Transport*, pp. 92–97, 2020, https://www.gov.cn/xinwen/2021-05/19/content_ 5608523.htm.

[23] C.-P. J. Chou, "Effect of overloaded heavy vehicles on pavement and bridge design," *Transportation Research Record*, vol. 1539, no. 1, pp. 58–65, 1996.

[24] W. Han, J. Wu, C. S. Cai, and S. Chen, "Characteristics and dynamic impact of overloaded extra heavy trucks on typical highway bridges," *Journal of Bridge Engineering*, vol. 20, no. 2, Article ID 05014011, 2015.

[25] R. Mussa, "Safety and operational evaluation of truck lane restriction," *Proceedings of the Journal of the Transportation Research Forum*, vol. 43, no. 2, pp. 117–127, 2004.

[26] S. Ishak, B. Wolshon, X. Sun, M. Korkut, and Y. Qi, *Evaluation of the Traffic Safety Benefits of a Lower Speed Limit and Restriction of Trucks to Use of Right Lane Only on I-10 over the Atchafalaya Basin*, Louisiana Transportation Research Center, Baton Rouge, LA, USA, 2012.

[27] S. Moridpour, E. Mazloumi, and M. Mesbah, "Impact of heavy vehicles on surrounding traffic characteristics," *Journal of Advanced Transportation*, vol. 49, no. 4, pp. 535–552, 2015.

[28] B. N. Janson and A. Rathi, *Feasibility of Exclusive Facilities for Cars and Trucks*, Oak Ridge National Lab, Oak Ridge, TN (USA), 1990.

[29] L. Xiang ping, "Study of passenger and freight separation road system," *Urban Roads Bridges & Flood Control*, vol. 6, no. 3, pp. 44–46+47, 2011.

[30] J. E. Vidunas and L. A. Hoel, "Exclusive lanes for trucks and cars on interstate highways," *Transportation Research Record*, vol. 1576, no. 1, pp. 114–122, 1997.

[31] S. Sekar, "Enforcement program on administer the vehicle with overload or over-limited in whole country," *Transportation Research*, vol. 2, pp. 12–16, 2004.

[32] G. Tong, L. Ai-jun, and Z. Da-liang, "Multiple-peaked probabilistic vehicle load model for highway bridge reliability as-sessment," *Journal of Southeast University (Natural Science Edition)*, vol. 38, pp. 763–766, 2008.

[33] P. N. Standard, "Limits of dimensions, axle load and masses for motor vehicles, trailers and combination vehicles," 2016, https://www.chinesestandard.net/PDF.aspx/GB1589-2016.

[34] X. Zhou, *Structural and Economical Impacts of Heavy Truck Loads on Bridges*, Louisiana Tech University, Ruston, LA, USA, 2007.

[35] D. Liang, D. Chun-xia, and Z. Shao-wei, "Research on load standard of highway bridges suitable for heavy load traffic," *Highways*, vol. 32, pp. 30–36, 2011.

[36] H. Niederreiter, "Quasi-Monte Carlo methods and pseudo-random numbers," *Bulletin of the American Mathematical Society*, vol. 84, no. 6, pp. 957–1041, 1978.

[37] E. J. O'Brien and C. C. Caprani, "Headway modelling for traffic load assessment of short to medium span bridges," *Structural Engineer*, vol. 83, pp. 33–36, 2005.

[38] 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.