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Research Article

Study on Vehicle Load Model of Baijianhe Bridge

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In order to calculate the vehicle load model of Baijianhe Bridge, based on the vehicle load data of the health monitoring system, the vehicle type, vehicle weight, wheelbase, and other information were counted and the data were processed and diagraphed to obtain the probability density distribution. At the same time, the automobile load model parameters relative to the national current code and finite element method are calculated. The results show that 2-axle and 6-axle vehicles are the main vehicle types, accounting for about 48%. The number of upstream and downstream vehicles is the same, but the number of vehicles in the lane is much higher than in the overtaking lane. The carriageway is dominated by 6-axle vehicles, while the overtaking lane is dominated by 2-axle vehicles. The probability density distribution of vehicle weight in overtaking lane obeys mixed Gaussian distribution and that in the carriageway obeys Weibull distribution. According to the measured vehicle load data, the vehicle load suitable for Baijianhe Bridge is 1.1 times the highway-I vehicle load of the current Chinese standard "General Code for Design of Highway Bridges and Culvers" (JTG D60-2015).

1. Introduction

Vehicle load is one of the important factors for the bearing capacity, reliability, and service life of a bridge. The economic development of different regions is different, and the vehicle flow is also different. Therefore, the vehicle load specified in the code [1] cannot reflect the load condition of the actual bridge during operation. In addition, the calculation of the vehicle load model in the same area can also provide a basis for the calculation of the construction of new Bridges, which is conducive to obtaining a higher precision of bridge bearing capacity and fatigue damage assessment. Reduce the influence of vehicle overload and other factors on Bridges, and improve the safety and durability of Bridges [2–5]. As for the calculation of the vehicle load model, Zong et al. [6–10] proposed to use of WIM system data for statistical analysis of vehicle load characteristics, and the use Monte-Carlo method to simulate the monitoring of section load characteristics, so as to calculate the vehicle load on the influence line. The dynamic influence line theory combined with the probability density convolution method is used to calculate the vehicle load effect. In addition, the EM method was used to fit the edge distribution of vehicle weight and vehicle weight aggregation degree. Copula theory was used to select the model. The random number generation method was used to obtain the random vehicle flow under the congested operation state. Yan et al. [11] obtained the statistical characteristics of heavy-duty highway vehicle load in Fujian Province by monitoring traffic flow data of the WIM system and compared them with the requirements of specifications. Shu and Li [12] analyzed the traffic volume of Liancheng Bridge based on UAV and manual field measured traffic volume, and obtained six kinds of vehicle load frequency spectrum, which were converted into three kinds of fatigue load vehicle model frequency spectrum based on equivalent damage principle. Lin et al. [13] established mathematical models of relevant parameters in vehicle load models, such as vehicle mass, wheelbase, vehicle type, and axle load, by using parameter estimation and nonparameter estimation methods. Then, based on the Poisson process theory, Markov process theory, and vehicle following model, the time-varying parameters of the vehicle load model such as vehicle speed and vehicle arrival time are simulated randomly. Xin et al. [14] studied vehicle lane selection and spatial distribution characteristics of the load, analyzed multi-lane load response in long loading range, proposed a new idea to consider the multilane load model, and checked the coefficient value of the conceptual model. In this paper, the vehicle load model of Baijianhe Bridge is calculated by comparing several vehicle load model calculation methods based on a statistical analysis of vehicle information and project situation.

2. Project Introduction

2.1. Project Summary. Baijianhe Bridge is located in the Ji-Jin section of the Taiyuan—Macao expressway, a key national highway, and is a landmark bridge of the Ji-Jin Expressway. The plane of the bridge is located on the circular curve $R = 1225$ m, and the ultrahigh transverse slope is 2%. The superstructure of the main bridge is $75\,\text{m} + 2 \times 135\,\text{m} + 75\,\text{m}$ four-span prestressed concrete continuous rigid frame girder bridge, which was completed in 2007. The whole bridge is divided into two parts, six lanes in total. The length of the whole bridge is 753 m, the length of the main bridge is 420 m, and the approach Bridges at both ends are 5×35 m and 4×35 m, respectively. The superstructure of the main bridge is a single box single chamber variable section box girder. The height of the middle and end beam is 3 m, the thickness of the bottom plate is 0.3 m, the height of the root beam is 7.5 m, the thickness of the bottom plate is 1 m, and the height of the box girder and the thickness of the bottom plate change according to the quadratic parabola. The substructure is a double thin-wall hollow pier, the maximum pier height is 104 m (no. 7 pier), the transverse bridge of the pier is 6.5 m; The lateral distance along the bridge is 9 m, and the foundation of cast-in-place piles with a diameter of 1.8 m is adopted. Opened to traffic in 2007, the design load standard is car—super 20, trailer-120. The overall layout is shown in Figure 1

The vehicle load model studied in this paper is based on the data from the WIM system. The WIM system arranges sections with four lanes in two directions. The upstream direction is lane 1 and lane 2, and the downstream direction is lane 3 and lane 4. The time span of data collection is one year, and the effective days are 365 days. The total number of cars collected is 2,055,802, with an average of 5,632 cars per day. The data collected includes information such as model, vehicle weight, axle weight, and speed.

2.2. Introduction to Monitoring System. The vehicle load data comes from the health monitoring and early warning system based on Baijianhe Bridge established by Shandong High-Speed Infrastructure Intelligent Monitoring and Operation and Maintenance Big Data Platform. The weighing analysis module can obtain information on passing vehicle models, vehicle weight, axle weight, speed, etc. The weighing analysis interface is shown in Figure 2.

3. Vehicle Load Parameter Analysis

3.1. Analysis of the Number of Running Vehicles. According to the number of axles of the vehicle, it can be divided into a 2-axle vehicle, 3-axle vehicle, 4-axle vehicle, 5-axle vehicle, and 6-axle vehicle, without distinguishing passenger and truck, and 2-axle and 6-axle vehicle are mainly used. The number of upstream and downstream vehicles is similar, and the number of vehicles in the lane (2 and 4 lanes) is much higher than that in the overtaking lane (1 and 3 lanes), which is almost ten times the number of vehicles. The carriageway is dominated by 6-axle vehicles, while the overtaking lane is dominated by 2-axle vehicles. The proportion of vehicle types divided by axle number is shown in Table 1. The number of vehicles passing Baijianhe Bridge in the past year is shown in Figure 3. In terms of the number of vehicles in the whole year, the number of vehicles in the two months of the May Day holiday and National Day holiday increases as a whole. In July and August 2021, the number of vehicles increases sharply due to the demand for transportation materials in Zhengzhou due to the rainstorm.

3.2. Vehicle Weight. The vehicles are subdivided into small cars, medium cars, large cars, and car trains. The proportion distribution of vehicle types is shown in Table 2. It can be seen from the table that the overtaking lane is mainly for small cars and medium-sized cars, while large cars and car trains are concentrated in the lane. As shown in Figure 4, the number of vehicles in the upbound lane is higher than that in the downbound lane, and the proportion of large cars and automobile trains is higher than that of small and medium-sized cars on the whole. The probability distribution function of total vehicle weight and vehicle weight in each lane is shown in Figures 5–9. According to the figure, the probability density distribution of vehicle weight in the overtaking lane obeys the mixed Gaussian distribution, and the probability distribution of vehicle weight in the carriageway obeys the Weibull distribution.

3.3. Wheelbase. According to the regression analysis of vehicle load data, wheelbase rules of different models are obtained, as shown in Table 3.

4. Study on Vehicle Load Model of Baijianhe Bridge

4.1. Research Method of Vehicle Load Model

4.1.1. Probabilistic Density Function Simulation Fleet Method

(1) Probability density function of total vehicle weight and total vehicle distance. According to the convolution of the vehicle weight probability density function, the total weight of the vehicle fleet can be calculated [15]. The total weight probability density function $f_n'(w_n)$ for a fleet of n cars can be obtained by n−1 convolution of $f'(w)$. The probability

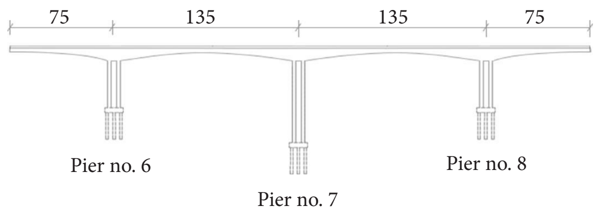

FIGURE 1: Overall layout of the bridge.

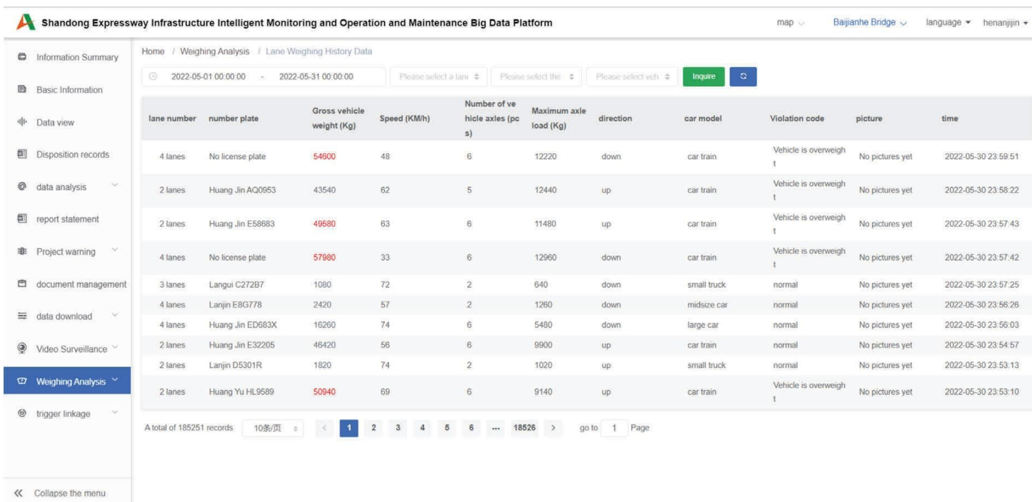

FIGURE 2: Vehicle weighing analysis interface of the monitoring system.

TABLE 1: Automobile axle number model ratio table.

Number of axles	2-Axle vehicle (%)	3-Axle vehicle (%)	4-Axle vehicle (%)	5-Axle vehicle (%)	6-Axle vehicle (%)
Proportion	48.48	0.74	2.43	0.70	47.65

FIGURE 3: Number of vehicles in recent year.

density function $f_{d_n}(d_n)$ of the total distance d_n of A fleet consisting of n cars can be obtained by the 5 convolutions of $f_{d_2}(d_2)$.

(2) Fleet influence line. When the load effect influence line length is greater than or equal to 20 m, the vehicle load effect mainly depends on the load effect on the bridge online total weight of the vehicle. Therefore, the vehicle load effect E generated by the fleet with length l_c and total weight w can be approximately obtained by multiplying the uniform load of length l_c by its corresponding maximum influence line area $A(L, l_c)$.

(3) Maximum distribution of vehicle load effect. When a team composed of n cars drives across the bridge, it can be divided into the following two situations: all of the team is on the bridge and part of the team is on the bridge. According to the equilibrium renewal theory, the probability distribution of each running state can be calculated.

Based on the distribution theorem of the random change function and the probability density function of the total weight of the fleet, the density function of the maximum load effect under the i-th running state can be deduced, and then the maximum distribution function of the load effect under the mixed running state can be calculated according to the probability distribution of the running state.

4.1.2. Monte-Carlo Method. Based on the Monte-Carlo method, the monitoring section sequence and body mass sequence were randomly recombined to simulate a random fleet. The random fleet was loaded onto the influence line, and the vehicle load effect was calculated for every 0.1 m

Table 2: Vehicle weight and vehicle type ratio table.

Lane number	Small-sized vehicle	Middle-sized vehicle	Large-size vehicle	Combination vehicle
1	78.2	16.9	3.0	1.9
2	13.6	5	10.5	70.9
3	90.0	7.5	2.2	0.3
4	28.4	10.2	38	23.4

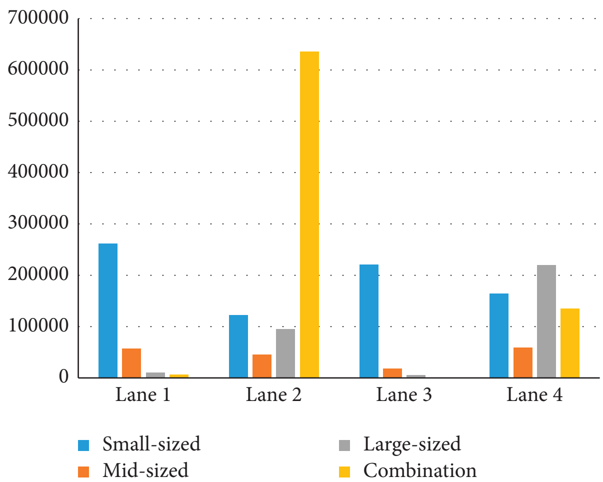

Figure 4: Statistical chart of vehicle quantity in each lane.

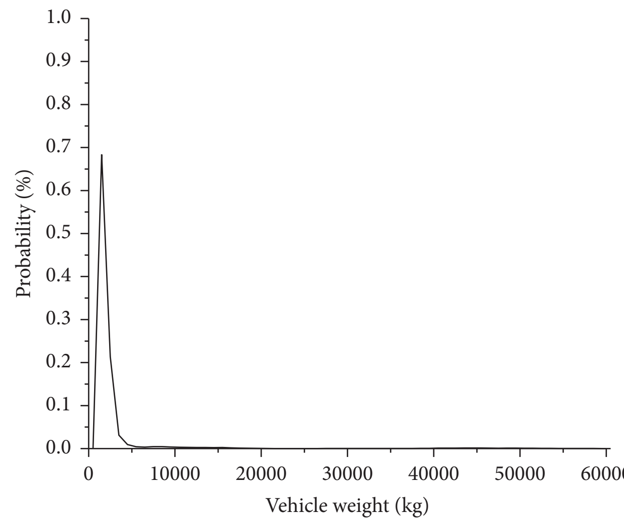

Figure 6: Probability density distribution of one vehicle weight in lane 1.

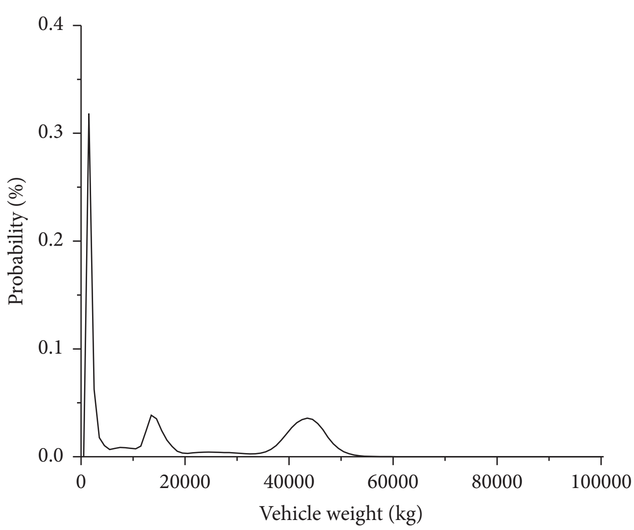

Figure 5: Probability density distribution of total vehicle weight.

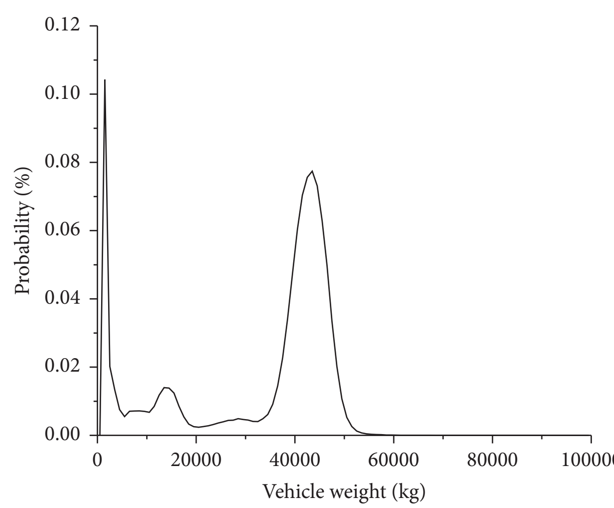

Figure 7: Probability density distribution of one vehicle weight in lane 2.

advance of the fleet. The information on the fleet and the influence line was compiled into two single-column matrices, and the row spacing was set as 0.1 m. Then the row-by-row matrix was multiplied, and the ratio of the random fleet to the standard vehicle load effect was taken as the statistical object.

4.1.3. Copulas Connect Method. Based on the expectation-maximization algorithm (EM method, a class of optimization algorithms for maximum likelihood estimation by iteration, is usually used to estimate parameters of probability models with hidden variables or missing data instead of the Newton iterative method), the edge distribution of vehicle weight and vehicle weight aggregation degree was fitted. Copula theory was used to select the model, and the random number method was used to generate random vehicle flow. Based on the equilibrium renewal process theory and bridge influence line, the maximum distribution function of the vehicle load effect in different evaluation reference periods was derived and compared with the standard vehicle load effect.

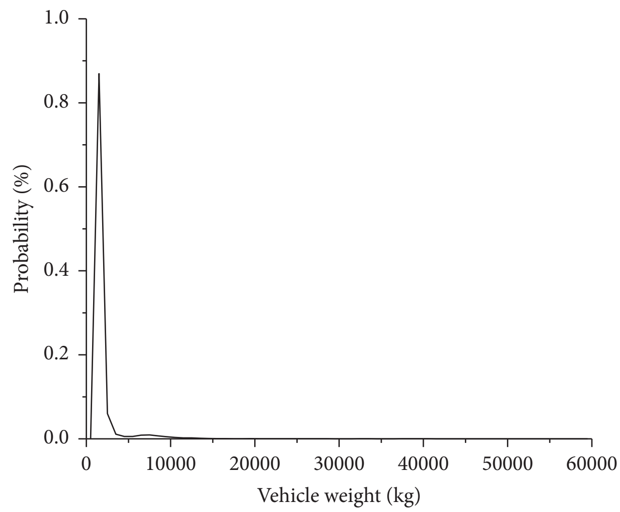

Figure 8: Probability density distribution of one vehicle weight in lane 3.

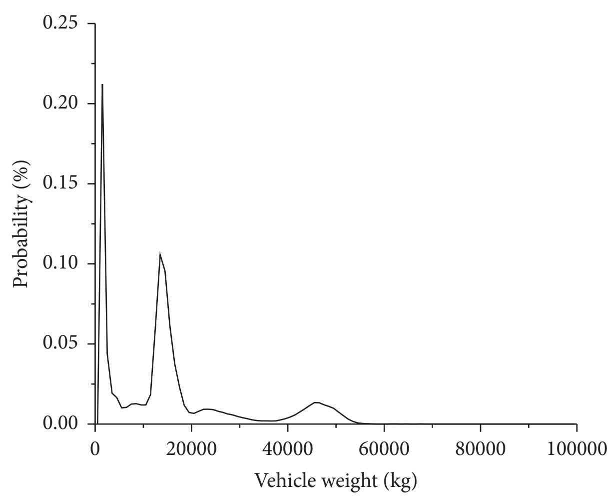

Figure 9: Probability density distribution of one vehicle weight in lane 4.

Table 3: Automobile wheelbase table.

	1~2 wheelbase (m)	2~3 wheelbase (m)	3~4 wheelbase (m)	4~5 wheelbase (m)	5~6 wheelbase (m)
2-Axle vehicle	3.2				
3-Axle vehicle	2.2	4.5			
4-Axle vehicle	2.2	5.2	1.3		
5-Axle vehicle	3.4	6.8	1.6	1.3	
6-Axle vehicle	3.6	1.4	4.8	1.3	1.3

4.2. Actual Load Effect of Baijianhe Bridge. According to the strain data probability density distribution of the measured points obtained from the bridge monitoring system, as shown in Figures 10–13, 0.95 subpoint of the strain maximum distribution function is taken as the measured load effect value.

4.3. Baijianhe Bridge Standard Comparison of Vehicle Load Model. Selecting Baijianhe Bridge as the research object, the finite element model is established, and the highway—*i* class automobile load is applied to the influence line of bending moment of the same number in the middle span of the bridge. The finite element model is shown in Figure 14.

The ratio of the actual automobile load effect measured by WIM to the standard automobile load effect calculated by the finite element method was taken as the analysis object, and the dimensionless parameter $K = S/S_k$ was taken as the model parameter, where S was the actual automobile load effect and S_k was the standard automobile load effect. The results are as follows:

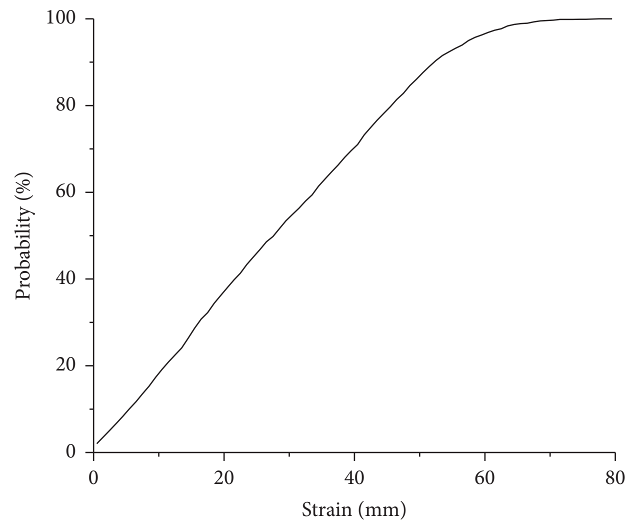

Figure 10: Strain probability distribution of measurement point.

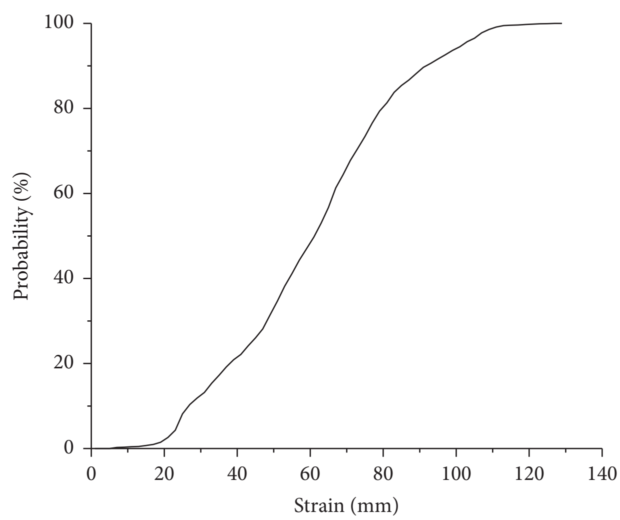

Figure 11: Strain probability distribution of measurement point 5.

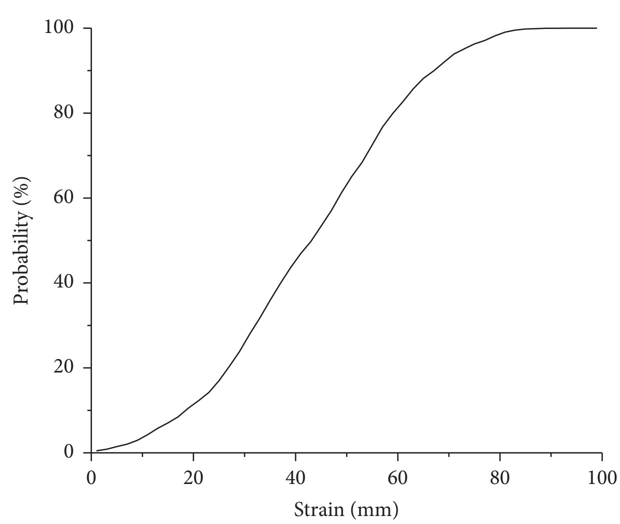

Figure 12: Strain probability distribution of measurement point.

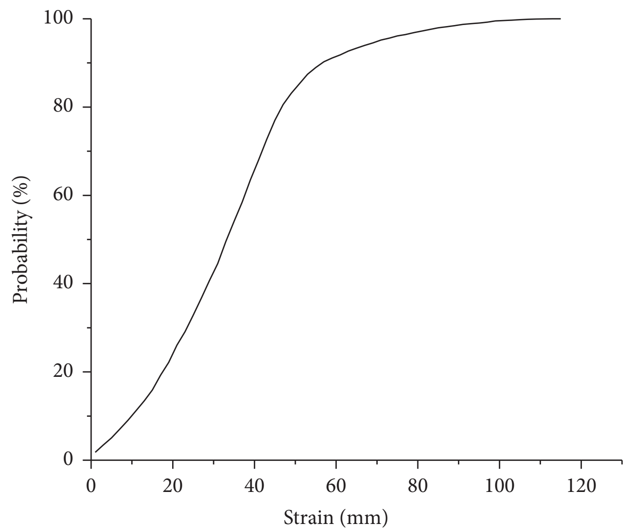

FIGURE 13: Strain probability distribution of measurement point 15.

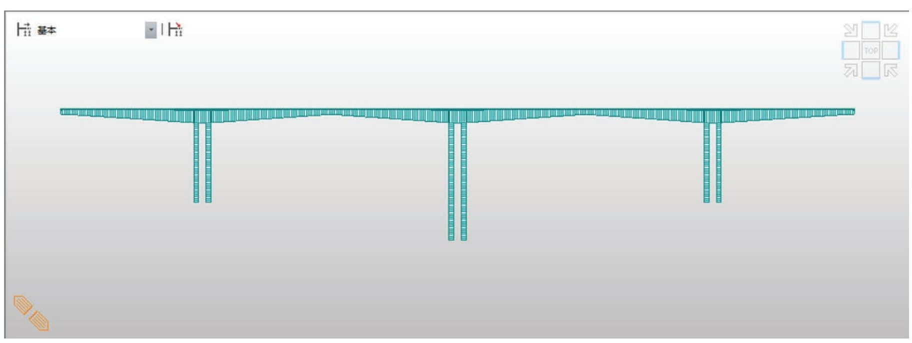

FIGURE 14: Finite element model of the main bridge of Baijianhe Bridge.

$$K = \frac{S}{S_k} = \frac{102.76}{81.137} = 1.27. \quad (1)$$

The calculated effect ratio of standard automobile load is 1.27. Considering the reduction of WIM system error by 15%, the reduced load effect ratio can be obtained as $K = 1.1$.

5. Conclusion

(1) According to the vehicle load data, 2-axle and 6-axle vehicles are the main vehicle types, accounting for about 48%. The number of upstream and downstream vehicles is similar, and the number of vehicles in the lane (2 and 4 lanes) is much higher than that in the overtaking lane (1 and 3 lanes), which is almost ten times the number of vehicles. As traffic laws and regulations stipulate overtaking on the left, large vehicles mostly drive on the right to avoid occupying the overtaking lane. Therefore, 6-axle vehicles dominate the carriageway and 2-axle vehicles dominate the overtaking lane.

(2) Probability density distribution of vehicle weight in overtaking lane obeys mixed Gaussian distribution, and the probability distribution of vehicle weight in the carriageway obeys Weibull distribution.

(3) According to the measured vehicle load data, the vehicle load suitable for Baijianhe Bridge is 1.1 times the highway—i class vehicle load of the current Chinese standard “General Code for Design of Highway Bridges and Culvers” (JTG D60-2015).

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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