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EVALUATION OF A CURRENT VEHICLE LOAD MODEL USING WEIGH-IN-MOTION RECORDS: A CASE IN CHINA

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Abstract. In order to assess the vehicle load carrying capacity of existing bridges on the national highway G103 in Beijing, the vehicle load model for the practical traffic flow conditions needs to be determined. Based on the traffic axle load data measured by the weigh-in-motion system and the methods proposed by *General Code for Design of Highway Bridges and Culverts* (*JTG D60-2004*) and *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts* (*JTG D62-2004*), the vehicle load parameters under practical traffic flow conditions are investigated. A typical 6-axle vehicle model with a 2-1-3 axial pattern is proposed by using the statistical analysis of total weight, axial weight, etc. The live load effects of Daliushu No. 2 Bridge, one highway bridge on the national highway G103, are analyzed using the proposed model and compared to the vehicle load model given in the Chinese code. The results show that there are great differences in the vehicle load parameters and the live load effects from the proposed vehicle load model increased by 20–50% compared with the model given by the code. The overweight vehicles are potential threats to the safety of existing bridges.

Keywords: highway bridges, load capacity, statistical analysis, vehicle load model, weigh-in-motion (WIM).

1. Introduction

As the hub of highway engineering, bridge engineering is an important part of the disaster prevention and mitigation in the transport infrastructures. Vehicle load is the main live load on the bridge which is also one of the main variables to affect the safety and effectiveness of highway bridges. The vehicle load models proposed by the current Chinese codes (*General Code for Design of Highway Bridges and Culverts, JTG D60-2004. Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges, JTG D62-2004*) are established based on the analyses of vehicle data collected in 1997 on four national highways during five 12-hour daytime periods. However, the rapid economic growth and the development of automobile industry and transportation systems have led major changes to the vehicle load model in China (Yi *et al.* 2013). In addition, the unbalanced economic development in China resulted in significant differences of vehicle load from one region to another. It is known that the safety of highway bridges is affected by the traffic loads, but the limited vehicle load model study cannot propose a suitable model for the national highway G103 which is an important connection between Beijing and Tianjin. Therefore, it is an urgent necessity to analyze the actual traffic loads and develop an advanced vehicle load model for assessing security performance and load posting of highway bridges.

Weigh-in-motion (WIM) systems are advanced traffic investigation devices that are designed to obtain traffic flow information, which are widely used to study the vehicle loads of highway bridges. WIM systems installed in pavements, which function similarly to static weigh stations, can capture and record the axle weights, axle spacings, and gross vehicle weights of tracks (McCall, Vodrazka Jr 1997). For many years, researchers have done a lot of work to study the vehicle load model based on WIM data. Moses (1979) and Nyman, Moses (1985) used bridge girders (with strain gages installed) to record vehicle load effects, and the obtained responses were used to calibrate fatigue vehicle models. Several different traffic flow characteristics were analyzed and traffic load models were developed by OBrien *et al.* (2009), Caprani, OBrien (2010), Kozikowski, Nowak (2010), Lutomirska, Nowak (2010)

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and Enright, OBrien (2013) using WIM data. Chotickai, Bowman (2006), Van de Lindt *et al.* (2005) and Guzda *et al.* (2007) developed another fatigue vehicle model for bridge design on the basis of WIM records.

In the current Chinese bridge design code, vehicle load model and lane load model are two different traffic load patterns, which are used for different design purposes. The vehicle load model is decided as a certain fractile of the extreme value distribution of the vehicle load during a specific reference period in the theoretical framework of reliability (Chen *et al.* 2014). Based on the parent distribution of the gross vehicle weight and using one day's maximum distribution as annual data, Chinese researchers, such as Mei *et al.* (2004), Guo *et al.* (2011), and Lan *et al.* (2011), obtained the extreme value distributions by using a compound renewal process, thereby obtaining the vehicle load models. Miao and Chan (2002) and Chan *et al.* (2005) presented the development of a methodology for deriving statistical highway bridge load models for short span bridges in Hong Kong using WIM data. The method was subsequently applied to establish a live load model for the bridge design in Hong Kong.

Fig. 1. Daliushu No. 2 bridge

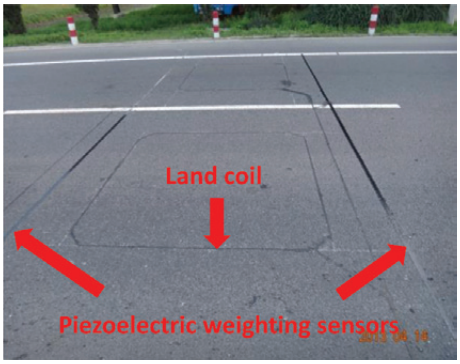


Fig. 2. Installation of WIM system

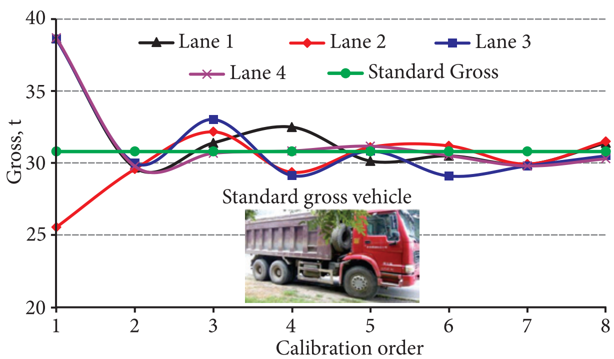


Fig. 3. Calibration curves of each lane

Because of the great differences between the standard vehicle load models in Chinese code and actual traffic flow characteristics in Beijing, as well as lack of a well-recognized method to analyze WIM data for assessing vehicle load models, a large number of WIM data including gross vehicle weights, axle loads and axle spacing were collected on national highway G103 in Beijing during this research. Statistical analyses were performed on these collected data, and a representative vehicle load model is proposed in this study for bridge design in Beijing and its surrounding districts.

2. Installation of WIM system

A 100% sample of traffic data for statistical purposes can be obtained by using a WIM system. The WIM system collects strains in the lower flanges of simply supported bridge girders and decomposes the strain time histories using influence lines to determine vehicle axle weights. The system consists of three basic components, including the analog front end (AFE), the auto-balancing of the strain transducers, and the axle detectors. The AFE acts as a signal conditioner and amplifier with several input channels to condition and amplify signals from strain transducers. When data are collected, the AFE resets the strain signals back to zero. The auto-balancing of the strain transducers is activated when the first axle of the vehicle crosses the first axle detector. As the truck crosses the axle detectors, the speed and axle spacing are determined. When the vehicle reaches the instrumented bridge span, the strain sampling is activated. As the last axle of the vehicle exits the instrumented bridge span, the strain sampling is turned off. Data received from strain transducers are digitized and sent to the computer where axle weights are determined by an influence line algorithm (McCall, Vodrazka 1997).

After a preliminary study of several bridges on different highways, considering traffic flow characteristics and site construction condition, Daliushu No. 2 Bridge with four lanes on national highway G103 was selected as the target site for installing the WIM system. As the connection between Beijing and Tianjin, G103 play an important role in material support and energy supply in Beijing. That is to say, there were too many large trucks with too many supplies passed Daliushu No. 2 Bridge to meet the demand of capital every day. The bridge was constructed in 2000, with a total span of 61.62 m, as shown in Fig. 1. In April 2013, a WIM system was installed on the bridge, as shown in Fig. 2. Land coil and piezoelectric weighting sensors were used to collected WIM data when trucks entering and exiting the instrumented bridge span.

The measurement accuracy is a very important factor during the whole recording process. Before the WIM system started to work, a vehicle with three axles and a total weight of 30.8 tons was used in the field tests to calibrate the WIM system. The vehicle passed through the four lanes with different speeds. The calibration curves are shown in Fig. 3. The maximum error of the last calibration was 2.27%, which met the requirements of precision.

3. Analysis of traffic condition

The traffic flow of Daliushu No. 2 Bridge was monitored 24 hours a day for three months and 887 122 groups of data were obtained from the WIM system. Fig. 4 showed the proportions of different vehicles with different axles. It was found that more than half of the recorded vehicles were 2-axle vehicles, including private cars, increasingly growing in number. Moreover, the proportion of 6-axle vehicles (19.45%) was much larger than that of 5-axle vehicles (3.37%), as shown in Fig. 4, including that the vehicle load model with 5 axles proposed by current Chinese code was not suitable for the traffic flow. The analysis results of gross vehicle weights and axle weights are presented in the following sections.

3.1. Statistical analysis of gross vehicle weight

The statistical analysis on the gross vehicle weight of all samples was conducted separately. The probability density function (PDF) and the cumulative density function (CDF) were obtained based on the recorded data and the results were compared with current Chinese codes (*JTG D60-2004* and *JTG D62-2004*), as shown in Figs 5 and 6. Both the PDF and the CDF curves presented significant differences compared to those proposed by current Chinese codes.

Based on the comparison of PDF and CDF of gross vehicle weight as shown in Figs 5 and 6, for vehicles with gross weight less than 20 kN, the PDF based on recorded data reached its first peak earlier than that proposed by the Chinese code. It indicates that the gross weight of the vehicle with the maximum appearance probability on this bridge was less than that proposed by the codes. On the other hand, for vehicles with gross weight less than 20 kN, the CDF based on recorded data surges rapidly up to 0.506, which exceeds the value proposed by the codes. The cumulative frequency of vehicles with gross weight between 20 kN and 200 kN reaches 0.321 for the recorded data, which is much smaller than that proposed by the codes (0.824). However, the cumulative frequency of vehicles with gross over 200 kN is 0.173 for the CDF of the recorded data, which is larger than that proposed by the codes (0.049). And the slope of the CDF of the recorded data is also larger than that proposed by the codes in this range. Namely, there are more heavy vehicles on this road.

From this investigation, it can be seen that the maximum vehicle load reaches 1245 kN, which is much larger than that proposed by codes (550 kN). As mentioned earlier, the vehicle load on the bridge presents an increasing trend. Based on the design principles of standard vehicle load, Table 1 shows the comparison of gross vehicle weight at the same probability in the recorded curve and Chinese code. For the cumulative frequency of 95%, the vehicle gross weight obtained from the recorded data and the codes are 421 kN and 200 kN, respectively. And for the cumulative frequency of 99.7%, the vehicle gross weight obtained from the recorded data and the codes are 757 kN and 550 kN, respectively.

For many previous researches, either lognormal distribution or inverse lognormal distribution was used to fit the PDF of measured data. However, those proposed probability distribution models with single peak failed to match the distribution characteristics of the recoded data with multiple peaks. The analysis results show that the CDF of corresponding lognormal distribution or inverse

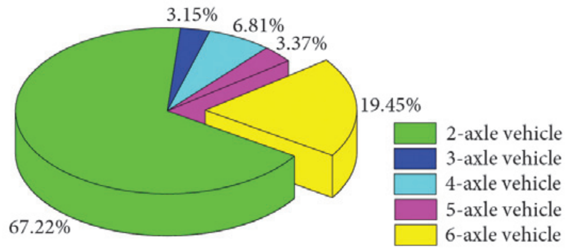


Fig. 4. Proportions of vehicles with different axles

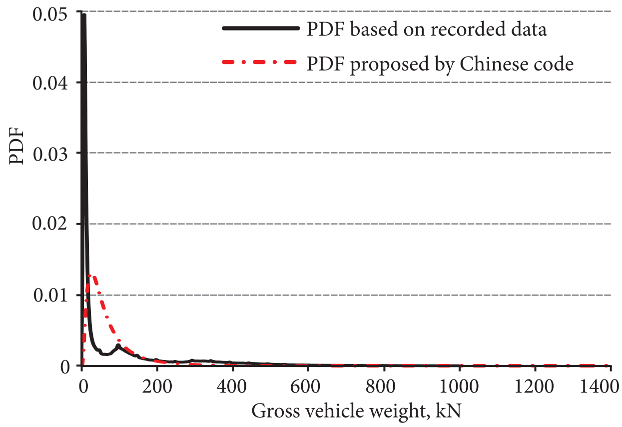


Fig. 5. PDF comparison of gross vehicle weight

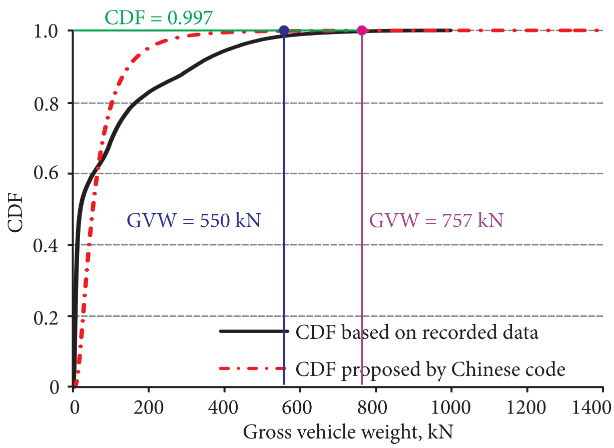


Fig. 6. CDF comparison of gross vehicle weight

Table 1. Comparison of gross vehicle weight at different cumulative frequency

Standard gross, kN	Cumulative frequency in code	Corresponding gross vehicle weight at the recorded curve, kN
100	0.7781	149
150	0.8925	313
200	0.9500	421
300	0.9855	571
550	0.9970	757

lognormal distribution is significant different from measured CDF and cannot pass the Kolmogorov-Smirnov hypothesis tests (K-S test). It is a weighted sum of two logarithmic normal distributions that matches the curve very well.

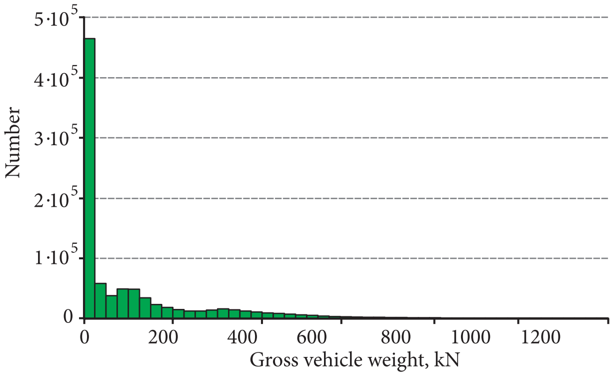


Fig. 7. Statistical histogram of gross vehicle weight

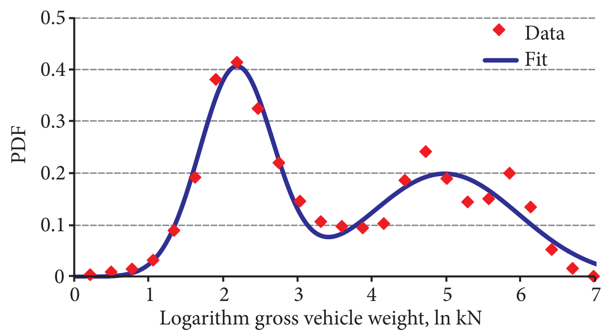


Fig. 8. PDF of the logarithm of gross vehicle weight

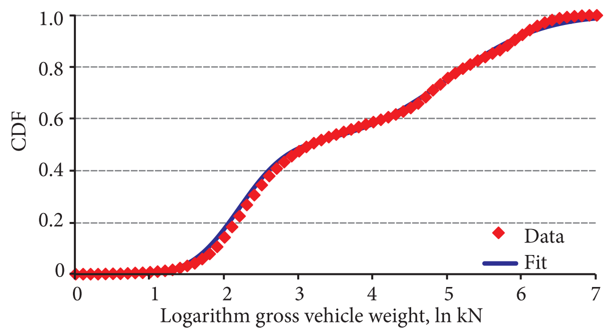


Fig. 9. CDF of the logarithm of gross vehicle weight

Figure 7 shows the statistical histogram of gross vehicle weight from August to October in 2013. The average of all the samples is 99.639 kN, the standard deviation is 144.615 kN and coefficient of variance (COV) is 1.4514, which indicated that the gross samples had a wide distribution range and a great amount of variability.

It can be assumed that the CFD of the logarithm of gross vehicle weight can be expressed as following:

$$\hat{F}(y) = p_1\Phi\left(\frac{y-\mu_{Y1}}{\sigma_{Y1}}\right) + p_2\Phi\left(\frac{y-\mu_{Y2}}{\sigma_{Y2}}\right), \quad (1)$$

where Y – the logarithm of gross vehicle weight X (Y=ln(X)); p_1 and p_2 – the weighted coefficient and $p_1 + p_2 = 1$; Φ – the CDF of standard normal distribution. Then,

$$F_X(x) = P(X \le x) = P(Y \le \ln x) = F_Y(\ln x) = \\ = p_1\Phi\left(\frac{\ln x-\mu_{Y1}}{\sigma_{Y1}}\right) + p_2\Phi\left(\frac{\ln x-\mu_{Y2}}{\sigma_{Y2}}\right). \quad (2)$$

Based on Maximum Likelihood Estimation (MLE) the parameters in Eq (2) can be obtained as following: p_1 = 0.5015, p_2 = 0.4985, μ_{Y1} = 2.184, μ_{Y2} = 4.981, σ_{Y1} = 0.4967, σ_{Y2} = 0.9986. As Y = ln(X), the gross of light vehicle follows the lognormal distribution (μ_{X1} = 10.048 kN, σ_{X1} = 5.315 kN) with a probability of p_1 = 0.5015; the gross of heavy vehicle follows the lognormal distribution (μ_{X2} = 239.751 kN, σ_{X2} = 313.578 kN) with a probability of p_2 = 0.4985 as shown in Figs 8 and 9, which can pass K-S test with a confidence level of 95%.

3.2. Statistical analysis of axle weight

Grounded on the similar methodology of the previous part, the statistical analysis on axle weight is conducted in this section.

As shown in Figs 10 and 11, the CDF based on recorded data that are lighter than 10kN increased straightly to 0.341, which exceeds the value proposed by code (0.257). The cumulative frequency of axles with loading between 10 and 50 kN reaches 0.420 as shown in the CDF curve, which is smaller than that proposed by codes (0.603). That

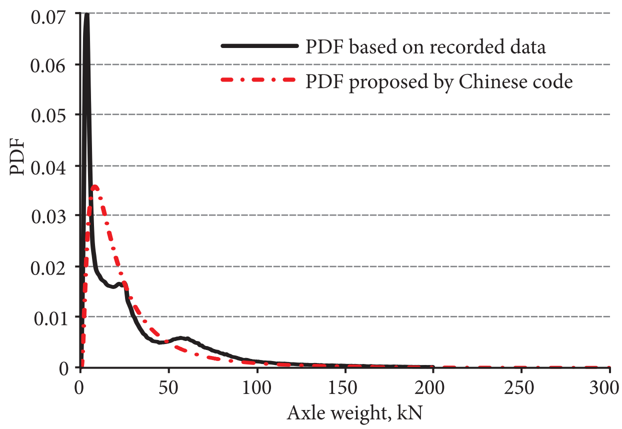


Fig. 10. PDF comparison of axle weight

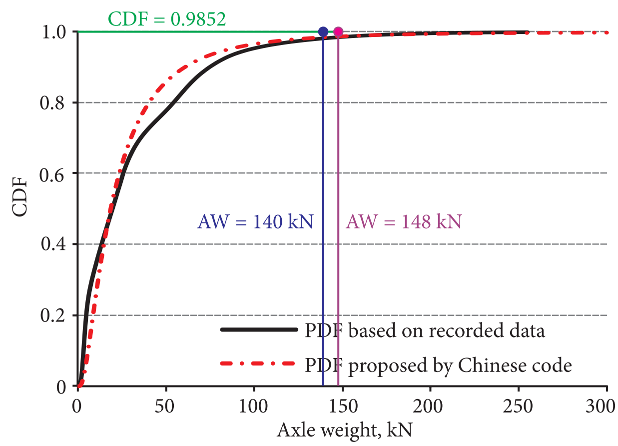


Fig. 11. CDF comparison of axle weight

is to say, vehicles with gross in the range has a smaller probability, which agrees well with the statistical analysis of gross vehicle weight. But the cumulative frequency of axles with loading over 50 kN is 0.239, which is larger than that proposed by codes (0.140).

From this investigation, it can be seen that the maximum axle load reaches 255 kN, which is much larger than that proposed by codes (140 kN). Table 2 shows the comparison of axle weight at the same probability in the recorded curve and Chinese code.

The weighted sum of two logarithmic normal distributions can also be used to fit the PDF of axle weight based the similar methodology with the previous part. All the parameters can be obtained assuming that the gross of light axle follows the lognormal distribution (μ_{X1a} = 4.8146 kN, σ_{X1a} = 2.5851 kN) with a probability of p_{1a} = 0.2956; the gross of heavy axle follows the lognormal distribution (μ_{X2a} = 51.0585kN, σ_{X2a} = 53.4487kN) with a probability of p_{2a} = 0.7044, which can also pass K-S test with assurance of 95%.

4. Vehicle model for evaluation of bridge capacity

As shown in Fig. 12, a standard vehicle load model with a gross weight of 550 kN is proposed by *General Code for Design of Highway Bridges and Culverts (JTG D60-2004)* and *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62-2004)* as the design vehicle load in the road and bridge engineering.

However, according to the statistical analysis of gross vehicle weight and axle weight in this study, the actual vehicle loads follow a multiple-peaked distribution rather than the traditional single-peaked probability distributions. It is inappropriate to apply the 5-axle standard vehicle model for the road and bridge design. Moreover, as shown in Fig. 4, the proportion of the 6-axle vehicles is 19.45% which is much higher than that of 5-axle (3.37%). On the premise of the same cumulative frequency, a new typical 6-axle vehicle with a gross of 770 kN was proposed in this study instead of 550 kN in the codes, and statistical analysis of all vehicles with 6 axles are applied to determinate a proper 6-axle vehicle load model for the road and bridge design on national highway G103.

It was found from the traffic investigation that there are mainly two axle types of 6-axle vehicles. Based on the axle weight, axle space and axle types of different standard vehicle types listed in China Automobile Type Handbook, the measured 6-axle vehicles were classified into two types as shown in Fig. 13. The former accounted for 21.16% of the total investigated 6-axle vehicles and the latter accounted for 78.84%.

Considering the difference in axle weight and axle space of these two types of 6-axle vehicles which are the primary heavy live load applied to the bridges, both the 1-2-3 axle type and 2-1-3 type axle could have a significant impact on the safety of bridges. Therefore, the parameters of these two types were analyzed to determinate their vehicle load model.

In order to obtain all axles spacing of the 2-1-3 type 6-axle vehicle, all vehicles of this type are selected for statistical analysis. Fig. 14 showed the different axle spacing. In addition to space 3 had a large variability because of the length of trailer, other axle spacing is concentrated at the average of corresponding spacing. It should be noted that

Table 2. Comparison of axle weight at different cumulative frequency

Standard axle weight, kN	Cumulative frequency in code	Corresponding gross at the recorded curve, kN
30	0.6928	41
70	0.9226	100
120	0.9776	136
130	0.9819	142
140	0.9852	148

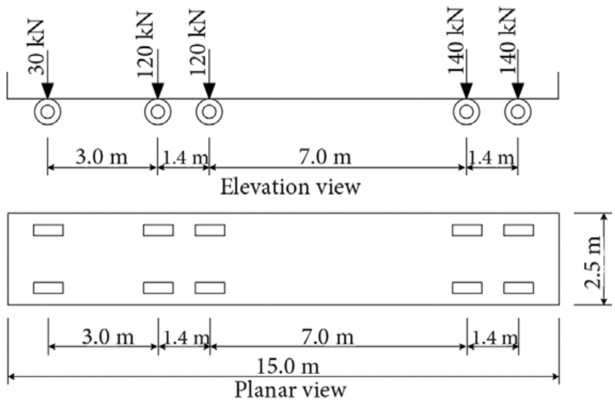


Fig. 12. Vehicle model proposed by Chinese code

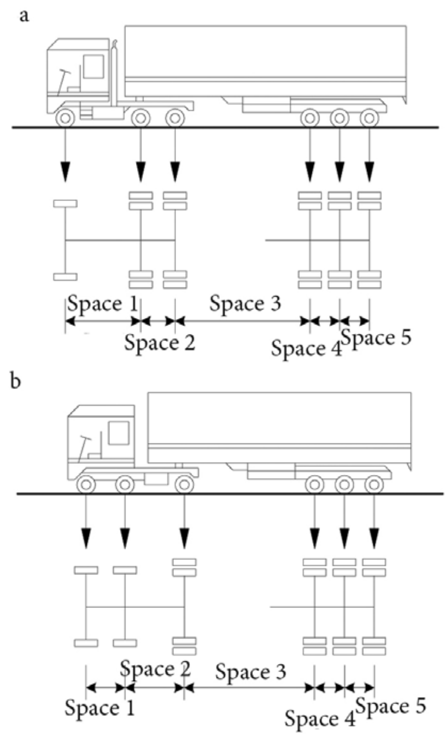


Fig. 13. Typical axle-type for 6-axle vehicle: a – 1-2-3 axle type; b – 2-1-3 axle type

space 4 was close to space 5 so that the data of space 5 were covered by the data of space 4 in Fig. 14. It is reasonable to apply the average value for every axle space. Based on the same method of statistical analysis of axle space, the axle space and axle weight of 1-2-3 type 6-axle vehicle can also be proposed as shown in Table 3.

5. Live load effect of standard and proposed vehicle model

Daliushu No. 2 Bridge is a 4-span girder bridge with single span of 11.39 m. A bridge model was established and analyzed using Midas Civil Program based on grillage analytical method. As shown in Fig. 15, the maximum deformation of this bridge under the load model described in current codes, as shown in Fig. 12, is 2.785 mm. While under the action of the proposed load model (2-1-3 axle type model), the maximum deformation is 4.187 mm, which is 1.5 times of the former result.

The response of the bridge under the live load calculated by standard and proposed vehicle model is compared in Fig. 16. S1 and M1 represent the support and middle

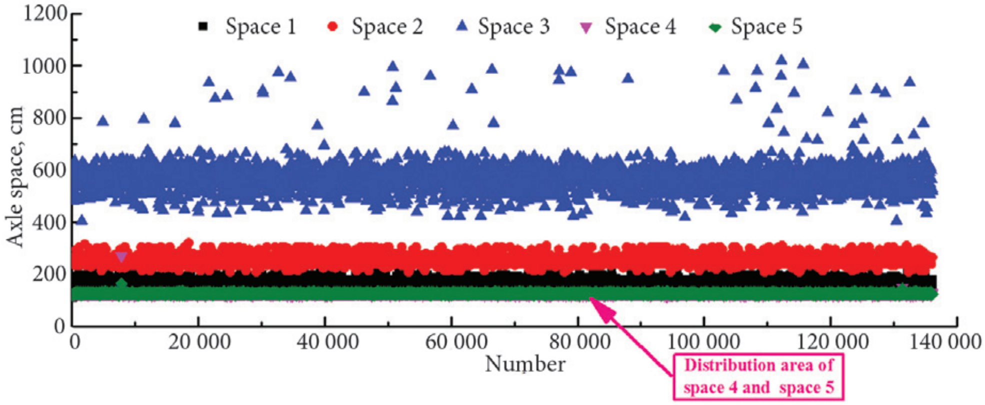
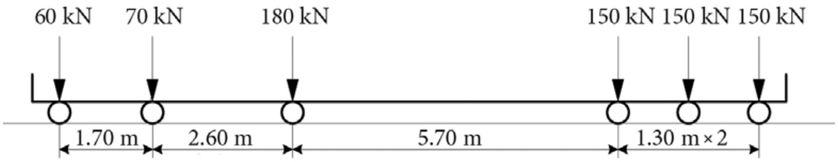
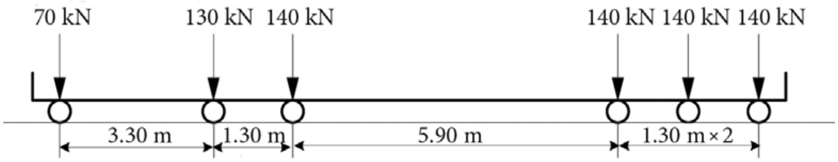


Fig. 14. All axles spacing of 2-1-3 type 6-axle vehicle

Table 3. Vehicle load model of proposed 6-axle vehicle

	Axle Type	Space 1	Space 2	Space 3	Space 4	Space 5	
Axle space, cm	2-1-3	170	260	570	130	130	
	1-2-3	330	130	590	130	130	
	Axle Type	Axle-1	Axle-2	Axle-3	Axle-4	Axle-5	Axle-6
Axle weight, kN	2-1-3	60	70	180	150	150	150
	1-2-3	70	130	140	140	140	140
Vehicle Load Model	2-1-3						
	1-2-3						

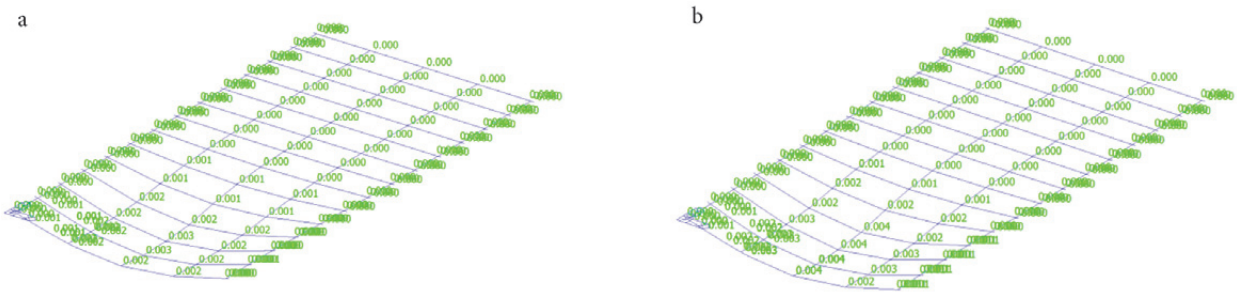


Fig. 15. Comparison of deflection between code model and measured model: a – standard load model; b – measured load model

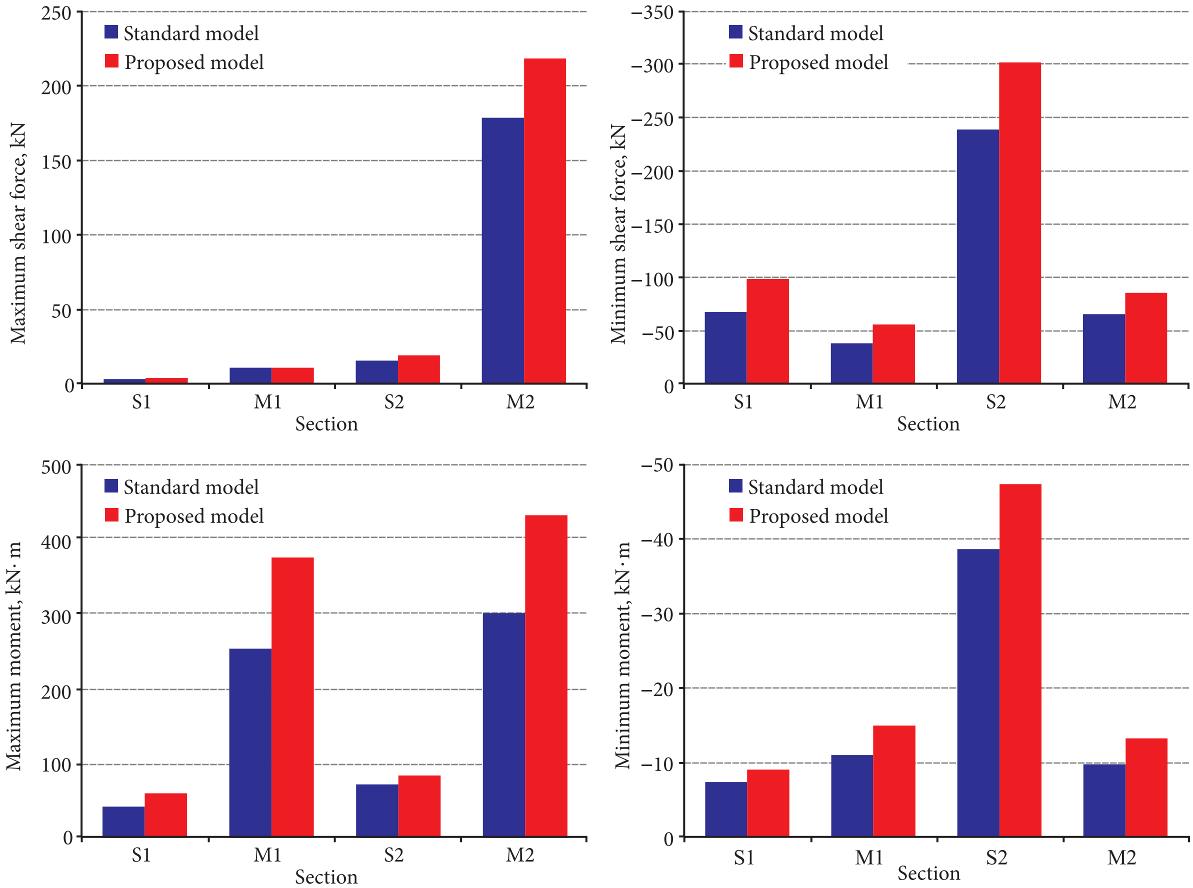


Fig. 16. Comparison of live load effect between code model and measured model

cross section of boundary beam. S2 and M2 represent the support and middle cross section of secondary-boundary beam. The results show that the maximum shear force and maximum bending moment of the bridge under the live load obtained from the proposed vehicle load model is about 1.2~1.5 times of the values calculated by the code.

6. Conclusion

With the development of automobile industry and transportation in Beijing, the standard vehicle load model in Chinese code is no longer appropriate for road and bridge design in rapidly developing cities in China. Based on the nonstop investigation of traffic using Weigh-in-Motion records for three months, the statistical analysis of gross vehicle weight and axle weight for national highway G103 was presented in this paper. The response of the target bridge subjected to standard and proposed vehicle load model were obtained from numerical simulation and compared in this study.

Several conclusions can be drawn from this research:

1. As shown in comparison of the probability density function and cumulative density function between recorded data and Chinese code, there are more light vehicles and heavy vehicles action on the bridge than the proportion proposed by Chinese code, which will significantly affect safety on the G103 highway.

2. Both gross vehicle weight and axle weight follow the weighted sum of two logarithmic normal distributions instead of only one logarithmic normal distribution proposed by Chinese code. The new distributions show good agreement with the existing traffic flow.

3. Considering the same probability of gross vehicle weight and axle weight in Chinese code, a new representative 6-axle vehicle is proposed for load capacity evaluation of road and bridge engineering on G103 highway especially for these ones designed by the earlier Chinese standard.

4. The live load effect of the girder bridge is comparatively analyzed using the acquired model and the vehicle load model in the code. The results show that the live load effect of the bridge under the action of the acquired vehicle load model is about 1.2~1.5 times the calculated values in the code.

Although the case study on G103 cannot reflect the traffic flow characteristics among all the roads and bridges in China, the new proposed vehicle load model represents the typical vehicles across G103 and reflects the changes among recent years. It can also be a reasonable reference for modifying standards in the future.

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