Development of heavy truck models and their effects on girder bridges

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ABSTRACT

The traffic on highway bridges has been increasing in both volume and magnitude, which even has become one of the main reasons leading to damages and collapse of bridges. Most of the existing regulations for overloading checking are carried out based on various limits of gross vehicle weights and axle loads. However, the results of relevant researches show that weight is only a potential factor but not the dominating factor in threatening the safety of bridges. In this study, the concept of load-effect-based heavy truck is proposed for overloading checking, and then three years of WIM data were collected and used to develop heavy truck models for each truck type, based on the understanding of the characteristics and configurations of heavy trucks as well as the distribution of their main parameters. Furthermore, the typical heavy truck models selected and their possible combinations are applied to a simply supported pre-stressed concrete T-beam bridge model with three loading levels, considering one-lane, two-lane and three-lane loaded respectively, then the induced load effect, deflection and stress are discussed for 20 loading cases. The results show the bending moment caused by heavy trucks moving on multiple lanes

is 1.6 times the value of the standard truck model in Chinese specification, and the eccentric loading due to a very heavy vehicle moving on single lane usually lead to more severe effect.

Keywords: Heavy traffic; overloaded; truck configuration; load effect

INTRODUCTION

Heavy trucks represent a major load to highway infrastructure systems. Therefore, highway bridges are designed and evaluated against these loads. It is observed that, in China and other countries, both the amount and loading level of trucks have been shown a growth trend in recent years (Li 2009; Leahy et al. 2016), becoming one of the main reasons leading to damages or/and collapse of bridges. According to Fu et al. (2012), 10.83% of collapse of 157 bridges was caused by overloaded trucks during 2000 to 2012 in China. As a matter of fact, the growth of truck loads may accelerate wearing or affect durability of the highway infrastructure (Cohen et al., 2003; Wardhana and Hadipriono 2003; Biezma and Schanack 2007; Wang et al. 2016), and it is very difficult and costing to upgrade the loading capability of a bridge since it is built. Moreover, it is designed by adopting standard truck load models given in the existing bridge design specifications, which cannot cover the growth of truck loads in the future. Although these standard truck load models have been modifying and updating to take the real traffic situation into account, the faster increases of truck weight still impose higher load-carrying requirements for bridges in operating (Han et al. 2017). Note that "truck weight" here collectively refers to gross vehicle weight (GVW), axle weights, and axle configuration.

To ensure the safety of bridges, in the Federal Aid Highway Amendments Act of

1974, the federal Bridge Formula was enacted to regulate truck weight. Since then, trucks operating with a weight above the legal limit are referred to as overloads or overweight loads and currently accommodated by the permit systems available in all states of the U.S. Later, many studies have been conducted to calibrate this specified federal Bridge Formula (James et al. 1985, 1986; TRB 1990), the series of studies focused on various issue regarding truck weight regulations, estimating the impacts regarding to bridge cost, for changes in truck weight regulations and so on. Actually, truck weights (and sizes) have been regulated in China, namely, they are not allowed to exceed the counterpart limits regulated by the Department of Transportation and this kind of regulation is different from the federal Bridge Formula’s focus on bridge safety. However, due to the requirement of industrialization and economy development, many kinds of huge (on width, height, trailer length, and number of trailers) and heavy (on GVW, axle weight, wheel weight) trucks appear on highway bridges to carry some high-density commodities with divisible loads, besides, shippers will load their trucks as much as possible to reduce their cost. Needless to say, some of them are overloaded and definitely will affect the safety of the highway infrastructure. In other words, the appearance of heavy trucks is unavoidable due to some objective reasons, so that their operating management through a reasonable truck weight regulation becomes more important for protecting bridges from damage and collapse.

In the past years, the characteristics of heavy traffic and their impacts on highway bridges have been studied by Han (2015, 2018), Zhao (2017) and Yu (2019), while the effects of adjustment of truck weight regulation on the highway infrastructure also have been analyzed by Ghosn and Moses (2000), Cohen et al. (2003), Asantey and Bartlett (2005), Fu et al. (2008) and Li and Jiang (2016). However, most of the previous studies did not consider the distribution of truck load on spans during the modeling of heavy traffic, or even directly used the gross weight limit to define heavy trucks. To the best knowledge of the writers, one truck's GVW may not be the determinant but only relevant factor in producing severe load effects on bridges and its loading configuration is more important. In other words, the travelling of a truck with larger GVW but rational load distribution is much safer than a lighter one with unfavorable load configuration; therefore, the definition of heavy trucks only by setting GVW or axle weights limit is somehow arbitrary.

In this study, a load-effect-based concept is introduced to recognize heavy trucks and then their characteristics including truck types, GVWs, axle loads, axle spacings, travelling speeds etc. are analyzed to propose typical heavy truck models, moreover, the impacts of these truck models on small- to medium-span bridges are also investigated. First, the load effects induced by each truck are calculated by the influence line method, taking advantage of weigh-in-motion (WIM) data having dynamic information needed, and then their load effects are arranged in descending order, only these above the load effect induced by the standard truck model in the specification are recognized as heavy trucks, considering the importance of unfavorable load effects in truck modeling for bridge assessment. Second, the load configuration of the extracted heavy trucks are analyzed to understand their unique characteristics that are not covered by general vehicle models or design vehicles specified in the codes (Zhou 2007; Fu and You 2009; OBrienand Enright. 2013), as a consequence, typical heavy truck models are proposed for each truck type through the probability distributions of axle loads, spacings and speeds. Finally, the proposed heavy truck models are applied to the finite element model of a T-girder bridge, reflecting the current Chinese bridge construction situation, and the quantized impacts caused by their travelling are analyzed for three loading levels, representing single-lane loaded, two-lane loaded and three-lane loaded respectively. A comparison of the results of this study and code values is presented. Some recommendations are also provided for bridge operation and management.

THE OVERVIEW OF WEIGH-IN-MOTION DATA USED

Probabilistically speaking, the Average Daily Truck Traffic (ADTT) is relevant to larger GVW and axle load, since bridges with very heavy traffic volume are most likely to subject to heavy trucks. 6 WIM sites closely located in Hubei Province in China are selected because they have large traffic volume, and most important, their WIM system are found to have truck weight data with a time stamp to 0.01s, the highest time-stamp resolution available now. This high time-stamp resolution allows identification of two trucks' headway distance as short as about 0.305m at a speed of 113km/h; this resolution therefore permits an accurate and reliable estimation. For comparison, when the time stamp resolution is 1s, as used in many other provinces, the headway distance resolution will be at about 30.5m (Fu et al. 2013), which is particularly unacceptable for the computation of maximum load effects on small- to medium-span bridges.3 years of WIM data between 2011 and 2013 were collected, and all the 6 bridges have 3 lanes in one direction and 6 lanes dually. In total, data of 41,095,437 trucks were recorded in one direction, including the time stamp, the lane occupied, GVW, axle weight, axle spacing, and vehicle speed etc. Data scrubbing is firstly done to eliminate some bad data, which may satisfy any one of the criteria as follows:

1. Inconsistency time stamp;
2. Number of axles recorded less than 2 or greater than 14;
3. Individual axle weight greater than 23t (50kips) or less than 0.9t (2kips);
4. Individual axle spacing less than 0.9m (3ft);
5. Speed less than 16km/h (10mph) or greater than 160km/h (100mph).

These filtering criteria were proposed by writers (Liu 2014), after analyzing huge amount of WIM data and some apparent inconsistency were found then. Finally, 40,513,489 valid truck data were obtained.

LOAD-EFFECT-BASED HEAVY TRUCKS

Heavy trucks are hereafter referred as those produce severe load effects larger than the value in Chinese design code (JTG-60 2015), which presented a truck load model as in Fig.1.

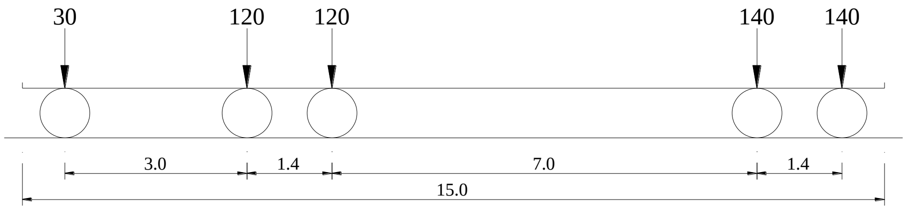


Figure 1 The standard truck load model in Chinese specification (units: m and kN)

This reference truck model has 5 axles and a total length of 15m, and detailed individual axle weight and spacing have been demonstrated in Fig.1. The load effects induced by the model is firstly calculated by the influence line method, where 3 span lengths of 16m, 20m and 25m are selected respectively, considering the construction situation of simply supported girder bridges in China, then, each truck data recorded is loaded on the counterpart span length to compare, the ones exceed the design specification are defined as heavy trucks. As a result, 62,042 trucks are identified as heavy trucks by bending moments and 141 by bearing shears.

CHARACTERISTICS OF HEAVY TRUCKS

Truck Type

The extracted heavy trucks are classified by the number of axles, such as 2-axle, 3-axle…up to 9-axle available in the collected WIM data. Then the proportion of each truck type is calculated and listed in Table 1. Absolutely, the 5-axle trucks are the dominant group representing typical industrial semi-trailer or trailer, and 6- and 4-axle heavy trucks are the 2nd and 3rd groups appearing on bridges concerned.

Table 1 The proportion of each truck type

Truck Type	**2-axle**	**3-axle**	**4-alxe**	**5-axle**	**6-axle**	**7-axle**	**8-axle**	**9-axle**
Percentage (%)	0.1	1.2	3.2	84.9	6.3	1.1	0.63	2.47

Travelling Habit

The number of heavy trucks passing through within one hour reflects their travelling habit, and too intensive apparent may impose additional load effects to bridges due to the multiple presences of heavy trucks on the same and different lanes. Fig. 2 displays the number of heavy trucks passing within each hour of a day, and the distribution presents a peak of 6,000 between 10:00AM and 11:00AM, implying 41% of these trucks prefer to travel at this time interval.

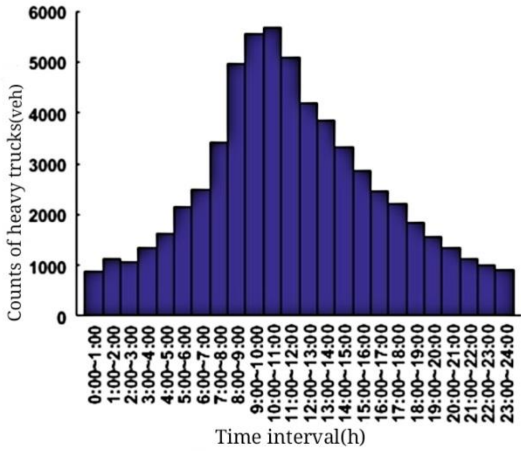


Figure 2 Truck count at 24 intervals in one day

Gross Vehicle Weight

The gross vehicle weight distribution of heavy trucks is depicted in Fig.3. The majority falls into the range of 300 to 400kN and a small part between 400 and 500kN. The peak frequency of locates around 15,000 corresponding to a GVW of 350kN and the maximum GVW is about 580kN.It is reasonable to speculate most of the 5-axle heavy trucks have a GVW of 300~400kN, since this truck type has absolutely high proportion as above. Compared with the truck weight limit issued by Ministry of transport of China and regulated only by total weight, the upper limitation is 43t for 5-axle freight (2019), and which is obviously larger than the values obtained here. However, their influences on bridge structures will be compared in the next section.

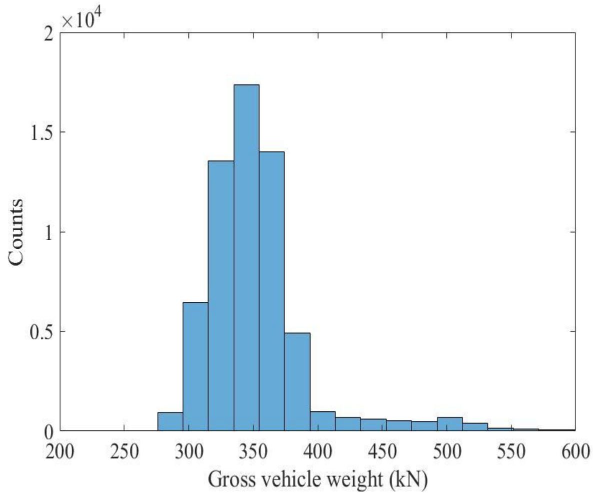


Figure 3 The frequency of gross vehicle weight of heavy trucks

Axle Load and Axle Spacing

Besides gross vehicle weight, axle load and axle spacing are other main parameters presenting the whole truck configuration and especially how the truck weight distributes along the truck length as well as the span length. From this perspective, these two parameters are directly related to the impact imposed to bridges by the passing truck. The frequency distributions of axle loads and axle spacings are displayed in Fig.4 and Fig.5 respectively.

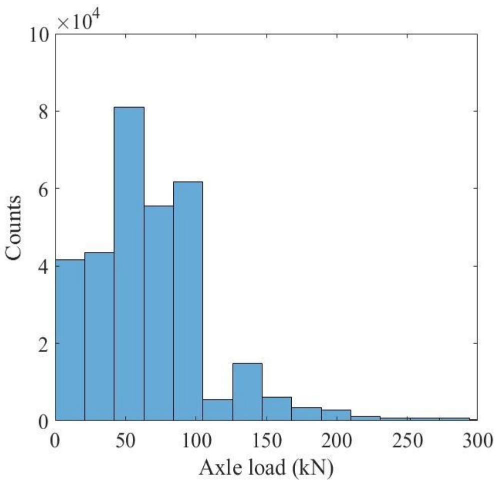


Figure 4 Frequency of axle load

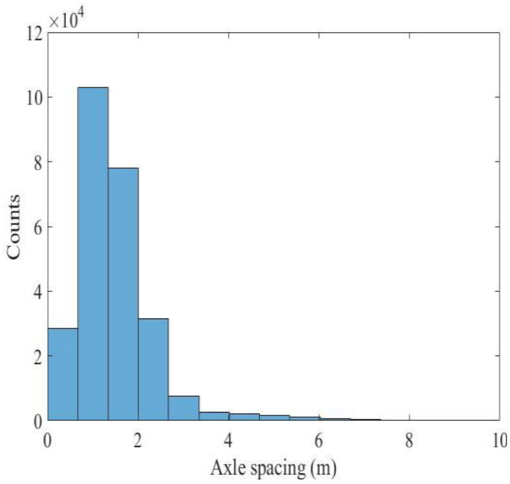


Figure 5 Frequency of axle spacing

The frequency peak of axle load and axle spacing locates around 50kN and 1.5m respectively, and the number of axle loads falling into 60kN~80kN and those of axle spacing at 1.2m and 3m are also remarkable. Needless to say, the most unfavorable load configuration is that very heavy loads intensively distribute along a short distance, causing stress concentration and local damage on superstructure elements.

Running Speed

According with the result exhibited in Fig.6, most of heavy trucks pass through highway bridges at a relatively low speed of 60km/h due to their greater weight, and the speed distribution approximately can be described by the normal distribution.

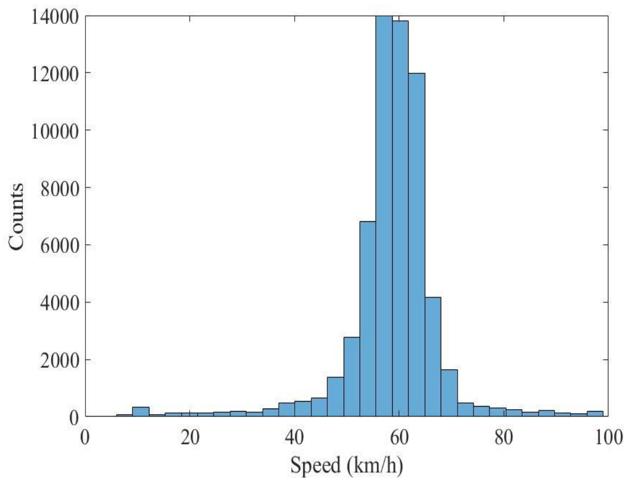
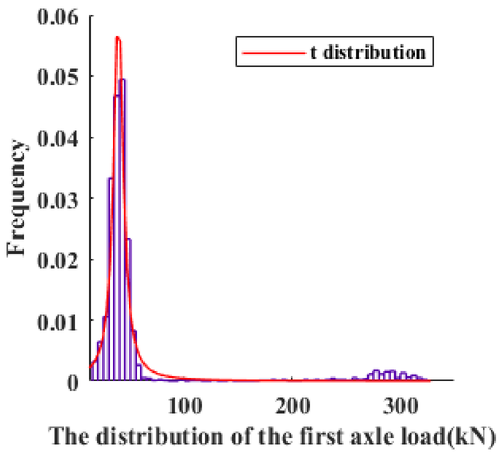


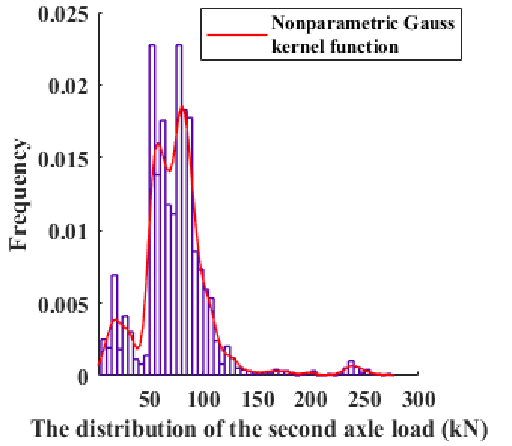
Figure 6 Frequency of speed

5 Heavy truck models

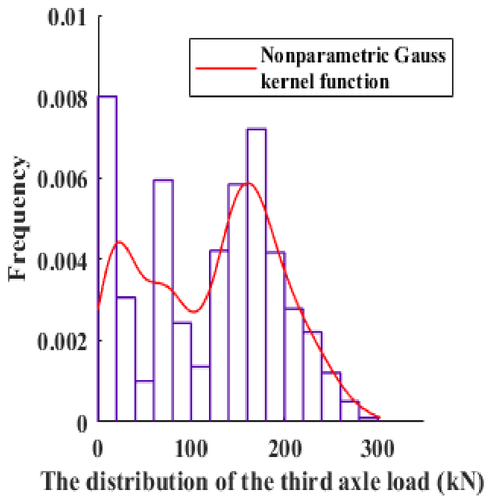
To develop load-effect based heavy truck models, the representative values of the main parameters of heavy truck are analyzed for each truck type, namely, the mean values and the standard deviations of each axle load and axle spacing are derived from the fitting analysis as well as K-S test. The fitting results and the optimal distributions for 4-axle heavy trucks are shown in Fig.7. Consequently, the proposed heavy truck models for each truck type are listed in Table 2 with schematic of axle load (kN) and axle spacing (m).



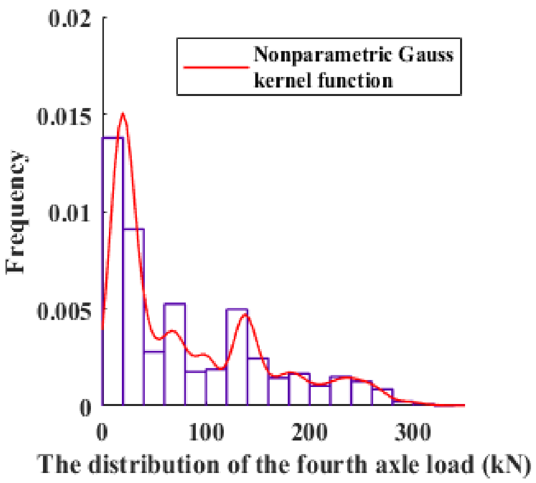
(a) Distribution of the first axle load



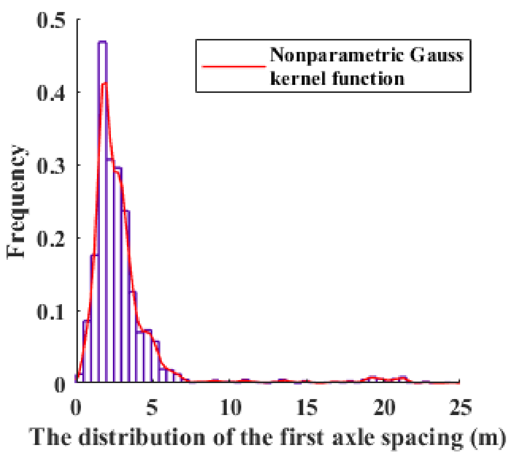
(b) Distribution of the second axle load

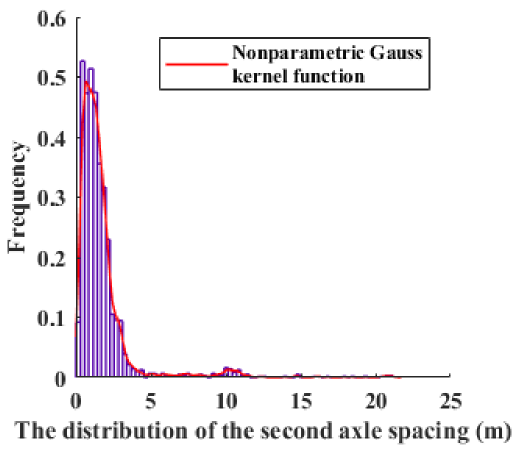


(c) Distribution of the third axle load



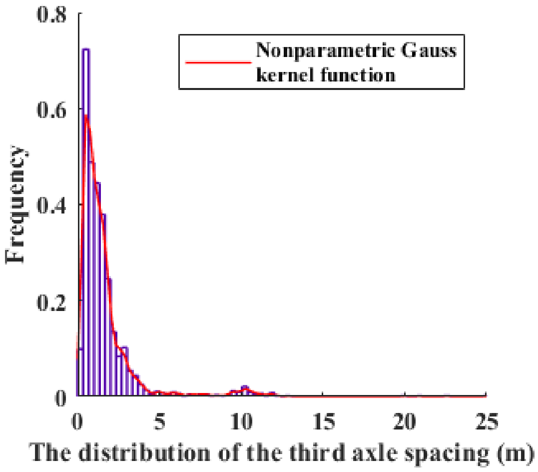
(d) Distribution of the fourth axle load



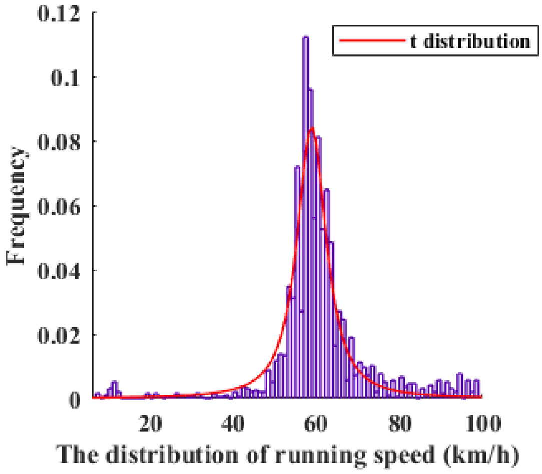


(e) Distribution of the first axle spacing

(f) Distribution of the second axle spacing



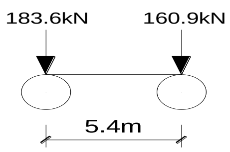
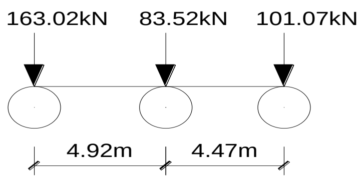
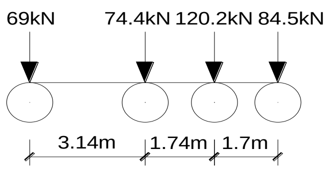
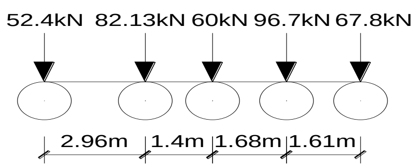
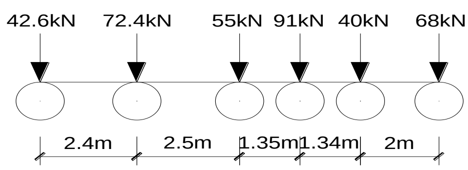
(g) Distribution of the third axle spacing

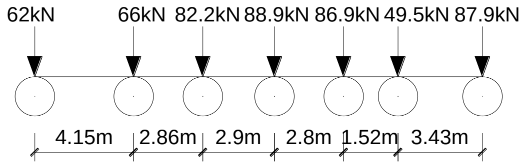
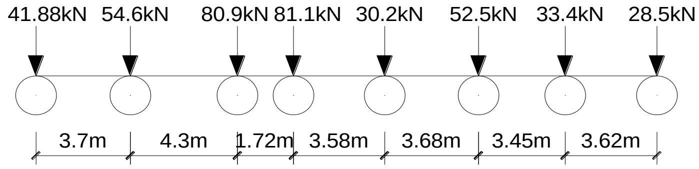
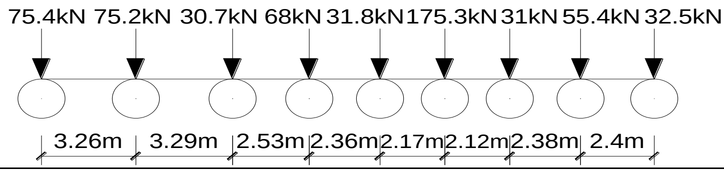


(h) Distribution of running speed

Figure 7 Fitting analysis for 4-axle heavy truck

Table 2 Heavy truck models

No.	**Number of axles**	**Schematic of axle load (kN) and axle spacing (m)**
1	2	
2	3	
3	4	
4	5	
5	6	

6	7	
7	8	
8	9	

It can be seen, the developed truck models are quite different from the one specified in Chinese design code (JTG-60 2015) above. In detail, the first axle loads of these models are larger than that of the standard one, and their axle weight varies significantly along the truck length and the relative position of axle loads is short, whereas, the axle weight of the latter presents rather uniform along the whole larger length. As a result, the distribution of the gross vehicle weight of heavy truck model is relatively intensive embodying by several concentrated loads acting on a small bridge span. To be more comparable, the proposed 5-axle heavy truck model is compared with its counterpart as the standard one since they have the same number of axle. As far as the GVW as concerned, that of standard one is equal to 550kN, and that of the proposed one is 359kN, but the former is distributed along a span length of 15m and the latter is along 7.65m, the first axle distances of the two are very close as well as the second and the fourth ones, but the third axle distances are remarkably different from each other. The shorter spacing of 1.68m for the proposed model rather that of 7.0m for the standard model may be the main factor causing larger load effect, which verifies the fact that the total weight may not be the dominant but only relevant factor in producing severe load effects on bridges and the loading configuration is more important.

THEN RESPONSE OF BRIDGE UNDER HEAVY TRAFFIC

To understand how the heavy traffic would affect bridge structure when moving on it, 20 loading cases are studied in this section to simulate real traffic scenarios including single lane loaded, two adjacent lanes and all three lanes loaded by heavy trucks running simultaneously, hereafter, they are referred as level-I, level-II and level-III respectively.

Bridge Model

Considering the fact that heavy traffic load would significantly influence the behaviors of small- to medium-span bridges (Yuan et al. 2017), moreover, the simply supported bridge type of pre-stressed concrete T-beam (PTC) are mostly adopted in the construction of small- to medium-span bridges, an actual PTC bridge with a span length of 20m is selected to develop finite element model. The cross section is shown in Fig.8. It consists of 7 girders with a height of 1.5m and the width is 15.5m with 3 traffic lanes, according with the recorded WIM data having three lanes available. Its finite element model is shown in Fig.9.

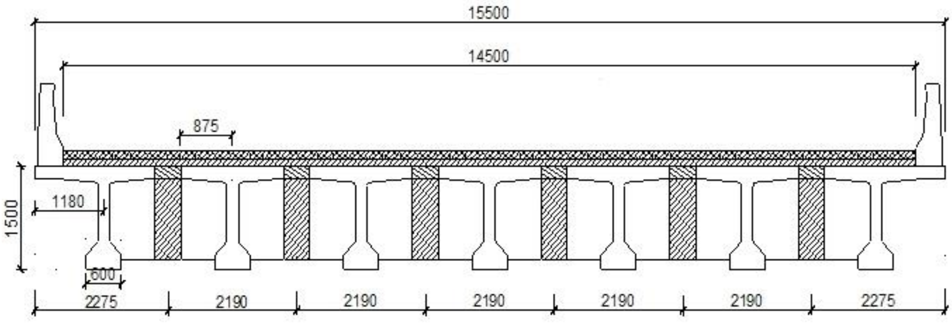


Figure 8 Cross section of the PTC bridge

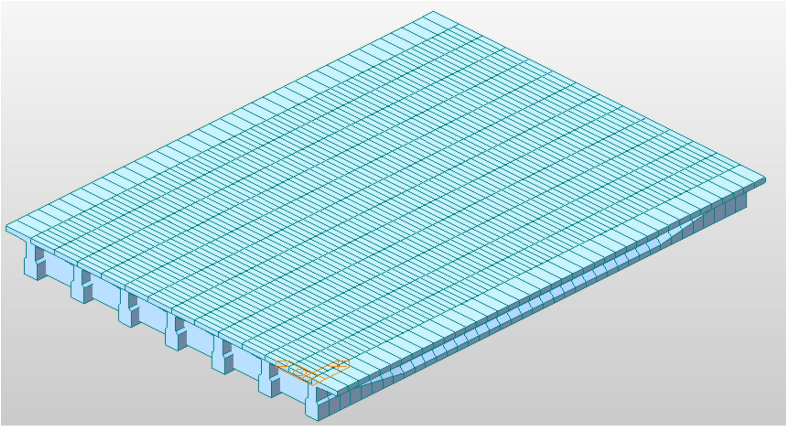


Figure 9 The finite element model of the PTC bridge

Loading method

To make the traffic simulation closer to the real scenarios, the aforementioned three loading levels are carried out, meanwhile, to obtain the severest load effects under the strength limit state, the proposed heavy truck model applied for loading are firstly selected based on the fact that axle weight limitation is also regulated by the department of transportation in many countries, specifically, a weight limitation of 140kN is set for any single axle load in China. Combining with the axle loads of the proposed heavy truck models, these models with axle weight above 100kN are selected, where 2- , 3- , 4- and 9-axle truck models are satisfied and their possible combinations are 3-axle+2-axle or 2-axle+2-axle or 4-axle+2-axle, travelling back-to-back on the same lane due to the span limit. Then, the bending moment and shear induced by the selected models as well as their combinations are calculated, the severest 5 conditions of 4-axle, 9-axle, 3-axle+2-axle, 2-axle+2-axle and 4-axle+2-axle are applied to bridges for multiple loading levels. All details of 20 loading cases are listed in table 3.

Table 3 Details of loading cases

Loading case	Loading Level	Combinations of trucks (-axle) Lane 1	Lane 2	Lane 3	Loading case	Loading Level	Combinations of trucks (-axle) Lane 1	Lane 2	Lane 3
①	I	—	4	—	⑪	I	—	2+2	—
	II	4	4	—		II	3+2	2+2	—
	III	4	4	4		III	3+2	2+2	3+2
②	I	—	9	—	⑫	I	—	2+2	—
	II	9	9	—		II	2+2	2+2	—
	III	9	9	9		III	2+2	2+2	3+2
③	I	—	3+2	—	⑬	I	—	2+2	—
	II	9	3+2	—		II	2+2	2+2	—
	III	9	3+2	9		III	2+2	2+2	2+2
④	I	—	2+2	—	⑭	I	—	2+2	—
	II	9	2+2	—		II	2+2	2+2	—
	III	9	2+2	9		III	2+2	2+2	4+2
⑤	I	—	4+2	—	⑮	I	—	4+2	—
	II	9	4+2	—		II	3+2	4+2	—
	III	9	4+2	9		III	3+2	4+2	3+2
⑥	I	—	2+2	—	⑯	I	—	4+2	—
	II	9	2+2	—		II	3+2	4+2	—
	III	9	2+2	2+2		III	3+2	4+2	2+2
⑦	I	—	4+2	—	⑰	I	—	4+2	—
	II	9	4+2	—		II	2+2	4+2	—
	III	9	4+2	4+2		III	2+2	4+2	2+2
⑧	I	—	3+2	—	⑱	I	—	4+2	—
	II	3+2	3+2	—		II	4+2	4+2	—
	III	3+2	3+2	3+2		III	4+2	4+2	3+2
⑨	I	—	3+2	—	⑲	I	—	4+2	—
	II	3+2	3+2	—		II	4+2	4+2	—
	III	3+2	3+2	2+2		III	4+2	4+2	2+2
⑩	I	—	3+2	—	⑳	I	—	4+2	—
	II	3+2	3+2	—		II	4+2	4+2	—
	III	3+2	3+2	4+2		III	4+2	4+2	4+2

Response of bridge

The bending moment, deflection and stress of the bridge structure subjected to each of these 20 loading cases with 3 levels are calculated respectively, the results and their comparison with the design specification are plotted in Fig.10 to Fig.12. From which, it can be seen the maximum bending moment produced by the loading level III is 1.6 times the value of the standard truck model in Chinese specification. Note that the bending moment of level II is smaller than that of level I, and in most conditions, the former produces larger load effects due to more trucks loading on multiple lanes. In the present case, it appears to be caused by eccentric loading of a very heavy vehicle moving on a single lane. As far as the deflection and stress are concerned, the values are within the permission specified in the design code, since the stiffness of this bridge is rather large.

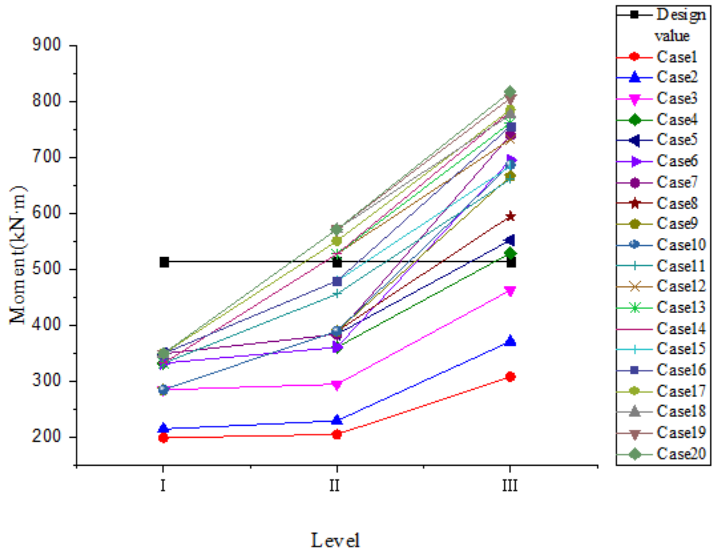


Figure 10 The maximum bending moments of 7 girders in 20 loading cases

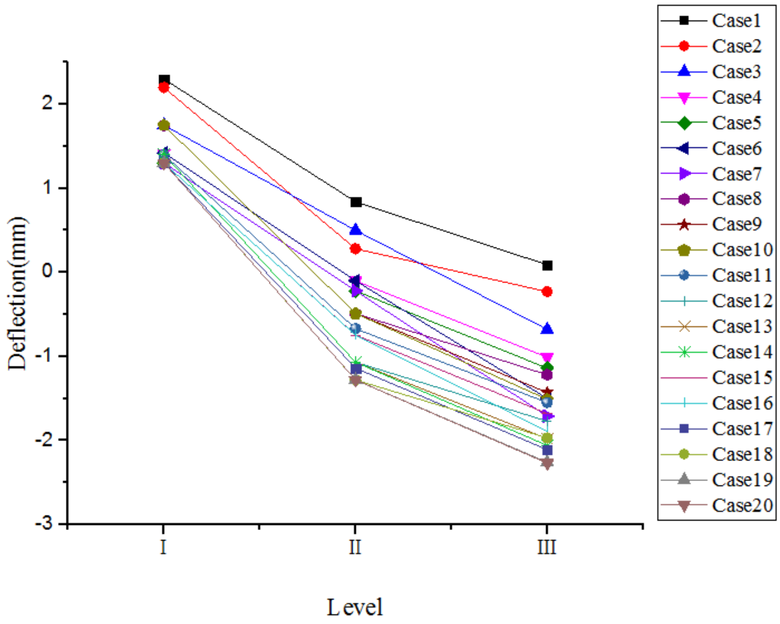


Figure 11 The maximum deflections of 7 girders in 20 loading cases

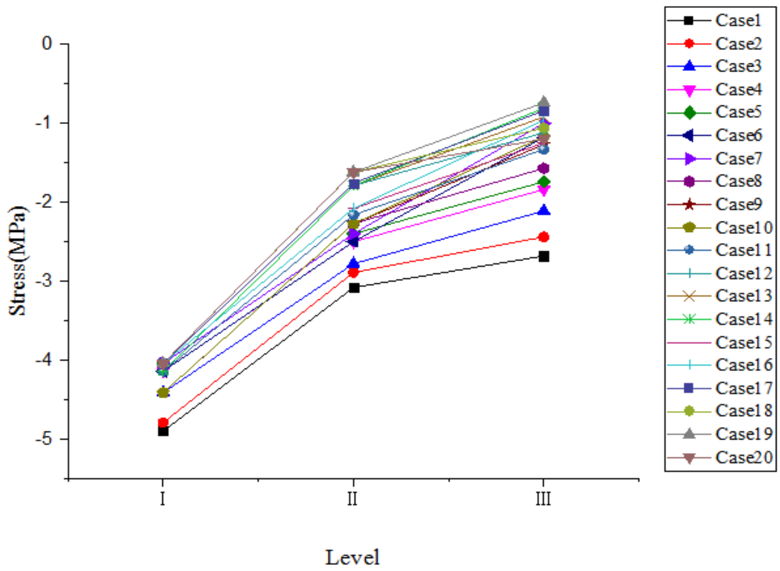


Figure 12 The maximum stresses of 7 girders in 20 loading cases

CONCLUSION

In this paper, the definition of heavy truck based on the severest of load effect is firstly proposed, and then the characteristics of heavy traffic are studied using WIM data from 6 heavy sites in China, furthermore, heavy truck models are developed and their impacts on the small- to medium- span bridge are researched. The following conclusions are drawn from this study.

1. The characteristics of the heavy trucks are significantly different from those of normal trucks for gross vehicle weight, speed, axle load and axle spacing, and 5-axle trucks are the dominant group representing typical industrial semi-trailer or trailer appearing on the bridges concerned.

2. Compared with the specified standard truck model, the proposed heavy truck models have shorter axle spacing and their axle weight varies significantly along the truck length; thus, the distribution of the gross vehicle weight is relatively intensive embodying by several concentrated loads acting on a small bridge span.

3. According to the 20 loading cases, the maximum bending moment induced by the loading level III is 1.6 times the value of the standard truck model, which may affect the loading capacity and safety of the bridge, on the other hand, the eccentric loading of a very heavy vehicle moving on a single lane has obviously impact on the bridge.

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