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Bridge vehicle load model on different grades of roads in China based on Weigh-in-Motion (WIM) data

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ABSTRACT

Bridge vehicle load is an important parameter that is relevant to the construction and maintenance stages of a bridge. In recent years, a large number of orthotropic steel deck bridges have been built in China, and it is urgent to establish a fatigue load model that reflects the actual traffic conditions of the bridges. This study has investigated the variation of vehicles over time on four grades of road (expressway, first-class highway, second-class highway and urban main road) according to the weight-in-motion (WIM) data. Subsequently, the statistical model was established in terms of speed, axle weight, and gross weight of vehicle (GVW) acting on the four grades of road. Finally, a fatigue load model of vehicles on the four grades of road was established based on a two-stage method. The results show that (1) the speed of vehicle on the four grades of road obeys the unimodal distribution; (2) the GVW of two- and three-axle vehicles on the four grades of road belongs to the *t*-distribution and the log-normal distribution, respectively; (3) the GVW of four- and five-axle vehicles on expressways is a finite mixed distribution, whereas the GVW of four- and five-axle vehicles on the remain three grades of road obeys the log-logistic and log-normal distribution respectively; (4) the GVW of six- and above axle vehicles on expressways and second-class highways obeys a finite mixed distribution with two variables, whereas that on first-class and urban main roads obeys the log-normal distribution; (5) the axle weight of standard fatigue vehicles differs remarkably on different grades of roads, which is difficult to describe the fatigue damage in a uniform standard fatigue vehicle.

1. Introduction

Vehicle load is one of the important parameters that affect the construction and the maintenance management of modern traffic infrastructures. It not only relates to the design of the bridge structure, but also affects the assessment, maintenance and reliability verification of in-service bridges. Due to the randomness, time-variability and regionalism of vehicle load, researches on the vehicle load have attracted much attention. Baliey et al. [1] have described the proportion of different types of vehicles based on the measured vehicle data and selected 14 representative vehicle types that occupied 99% of the traffic flow for the analysis of probability distribution. Buckland [2] has analyzed and compared the vehicle loads introduced in bridge design codes from America, Canada and UK, and discussed the influence of multi-lane load on the vehicle design load. Crespo-Minguillón and Casas [3] have established an overall load model for bridge security evaluation, considering the uncertainty of main vehicle load variables. A Chinese research group of vehicle load for highway bridges [4] has laid the foundation for vehicle load determination of the Chinese bridge design code according to the analysis and arrangement of data of over 60,000 vehicles from 4 measuring points. Recently, with the application of a Weigh-in-Motion (WIM) system or a structural health monitoring (SHM) system [5–9], the statistics analysis of vehicle load has been widely conducted based on the observed vehicle data. Chen et al. [10–12] have established a variety of probability models according to the observed vehicle load. Apart from the analysis of vehicle load, researchers have conducted a series of work on the probabilistic modeling of vehicle load. Nowak et al. [13–15] have proposed probabilistic models of vehicle load and conducted extensive studies on the estimation method of model parameters, according to the compliance of the vehicle load to the multimodal distribution.

With the development of economy, steel bridges have been extensively constructed in China [16,17]. The establishment of a reliable fatigue load model for steel bridges would provide an important

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reference for the anti-fatigue design and operational fatigue evaluation of the bridges, which has academic and practical values. Researches have made great efforts to build fatigue vehicle load models. Schilling et al. [18] and Raju et al. [19] have pointed out that the overall weight of the fatigue vehicle load should be adjusted based on the traffic load acting on specific locations and the axle load should be adjusted according to the proportion of the accuracy of a fatigue vehicle load model. Laman and Nowak [20] have picked up 5 steel bridges to collect vehicle data by using WIM systems and analyzed the time-history strain of the steel component obtained from a structural health monitoring system to establish a steel fatigue load model with respect to standard fatigue vehicles. The result indicated that there existed significant differences between the vehicle load and the stress spectrum among different components in different locations. They suggested that three-axle vehicles would fit for the fatigue vehicle load model in the conventional regions while four-axle vehicles would fit for the model if there existed ten-axle vehicles or eleven-axle vehicles in the region. The result was validated by measured data and adopted in the American AASHTO code [21]. Similarly, Gagarin et al. [22], Chotickai and Bowman [23] have established fatigue vehicle load models and verified the models based on the data observed from a WIM system. The British BS5400 specification [24], European Eurocode1 [25] and American AASHTO code [26] have provided fatigue vehicle load models for the design of steel bridges. *The Highway Steel Bridge Design Code of China* (JTG D64-2015) [27] has provided the fatigue vehicle load model for steel bridges in China, but there remain shortcomings: (1) Most of the vehicle load data acquisition time used in fatigue load models is short, usually a few days. However, the daily traffic is random and the parameters of the vehicle load are difficult to be described by vehicle load data that is observed within a short time period; (2) China is large in territory, economic conditions, resources and the industrialization varies from area to area. Moreover, the traffic type on different grades of roads is different, and an unique fatigue load model cannot properly reflect such complicated traffic conditions.

Zhejiang province, developed in economy, locates in the coast of southeast China with its transportation industry ranking the forefront in China. In recent years, steel bridges with orthotropic deck plates have been massively constructed in Zhejiang province. However, there exist few vehicle load models that can be used for simulating the actual traffic conditions. Fatigue load models representing the traffic conditions in Zhejiang province are needed for evaluating the condition of orthotropic steel deck plates. This paper adopts data observed from WIM systems on different grades of roads (expressway, first-class highway, second-class highway and urban main road) and conducts a systematical study on the features of vehicle loads. Firstly, the vehicle type and traffic flow variation over time on different grades of roads in Zhejiang Province are discussed. Subsequently, probability models reflecting vehicle parameters on different grades of roads, such as vehicle speed, axle weight, GVW, are established by means of a nonlinear least square estimation, and a hypothesis testing. Finally, methods for establishing the fatigue load model of orthotropic steel deck plates are discussed based on the analysis of the influence of the vehicle load parameters on the fatigue damage of the deck plates. The fatigue load model on different grades of roads in Zhejiang province is proposed.

2. Vehicle loads measured from WIM systems

Considering the difference of vehicle load among different grades of roads, this paper firsly observed WIM data from expressways, first-class highways, second-class highways and urban main roads. Locations of measuring points are listed in Table 1. The duration of each measurement is approximately two years with more than 50 million vehicle data. Every measurement contains the information of crossing time, overall weight, axle weight, the number of axles, the set of axles, wheelbase, vehicle type, lane position, vehicle speed, vehicle acceleration, license plate number, license plate type, etc.

Table 1
Measurements of vehicle load.

Grades of road	Measuring sites
Expressway	Hangzhou Bay Bridge, Jiashao Bridge
First-class highway	Taizhou, Qujiang, Jinyun, Longyou
Second-class Highway	Fenghua village, Lishui
Urban main road	Shixiang Road, Fuxing Bridge, Hangzhou

2.1. Data preprocessing

The WIM system is inevitably affected by many uncertainties, such as electromagnetic interference, extreme weather and human, which would lead to data distortion. Moreover, the WIM system has errors in the collection of vehicle information. For instance, if two vehicles pass by a road slowly and closely, the system might consider them as one vehicle while a super long vehicle might be considered as two vehicles. To improve the accuracy of vehicle samples and the reliability of analysis, the potential false vehicle data should be eliminated firstly by the analysis of the original data.

2.2. The constitution of traffic type

The constitution of traffic type is an important index reflecting traffic conditions. The Chinese specification of Inspection and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2011) [28] introduces the mix ratio of large vehicles in the vehicle flow considering the actual bridge locations for modifications of standard live loads. The vehicle flow on the expressway, first-class highway, second-class highway and urban main road is classified by the number of axles and the proportion of traffic. Vehicles with different axles have been obtained and listed in Table 2. It shows that two-axle vehicle occupies the main proportion of over 64% on four kinds of roads. The highest proportion of trucks with more than three axles is on first-class highway. In the urban main road, the proportion of two-axle vehicles is 97.33% which indicates the majority of the vehicles are limousine and other types are quite tiny.

Further analysis of the percentage of the vehicles with different weights in the traffic flow is shown in Table 3. It indicates that vehicles less than 3 tons are dominant for the vehicle flows on the expressway, second-class highway and urban main road. Among them, this feature is mostly distinct on urban main road with a proportion of over 83.59%. Also, the proportion decreases with the increase of vehicle weight.

3. Statistical models of vehicle loads

Vehicle load is the main variable load of highway bridges, which significantly affects the security and duration of bridges. It varies considerablely with time, which is featured as a random variable. In order to understand the vehicle load condition on different roads in Zhejiang province, in this paper, the vehicle loads on different types of roads are analyzed and the statistical model is established.

3.1. Statistical models of parameters

A previous study [29] as well as the preliminary analysis of this

Table 2
Flowrates of vehicles with different axles on different grades of roads (%).

Number of axis	2	3	4	5	6
Expressway	80.25	5.02	4.31	2.03	8.39
First-class highway	64.72	4.28	9.00	8.03	13.98
Second-class Highway	84.24	6.42	3.78	0.53	5.03
Urban main road	97.33	1.48	0.89	0.09	0.21