Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 5910463, 13 pages
https://doi.org/10.1155/2019/5910463

Research Article

Effects of Revised Toll-by-Weight Policy on Truck Overloading Behavior and Bridge Infrastructure Damage Using Weigh-in-Motion Data: A Comparative Study in China

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Received 30 October 2018; Accepted 14 January 2019; Published 4 February 2019

Academic Editor: Mario D'Aniello

Since 2000, overloaded trucks have caused more than 50 bridges to collapse in China. In an effort to ensure the structural safety and extend the service life of the highway infrastructure, the Chinese government has proposed a series of policies in the past decade to mitigate truck overloading. This study aimed at investigating the effects of China's recently revised toll-by-weight policy on truck overloading behavior and bridge infrastructure damage using weigh-in-motion data that spanned seven years (January 2011 to March 2018) and two successive toll-by-weight policies (with the new one implemented from August 2016), wherein truck data were measured from a typical national freeway segment. We first compared truck traffic volumes, compositions, and weight distributions under the initial and revised toll-by-weight policies. Next, we compared bridge infrastructure performance with respect to safety and fatigue based on the overloaded truck traffic observed under the initial and revised toll-by-weight policies. The results indicated that the revised toll-by-weight policy, which uses a stepwise incremental fee structure based on vehicle weight, was more effective at controlling truck overloading behavior and reducing bridge infrastructure damage than the initial toll-by-weight policy. Under the current policy, average daily truck volumes, overloaded truck proportions, and maximum truck weights decreased significantly. Concurrently, extreme and equivalent load effects for safety and fatigue assessments, respectively, decreased by an average of 20% for small- to medium-span bridges. Despite these noted improvements, overloaded truck traffic persisted, with loads often exceeding bridge design levels. This study's findings can support future efforts by the Chinese government to further refine their toll-by-weight policies and subsequently ensure a safe and viable transportation network.

1. Introduction

Beginning in the late 1980s, the Chinese government recognized the importance of a comprehensive national transportation network in promoting rapid economic development and thus focused significant resources on infrastructure construction. Table 1 presents the highway infrastructure development and concurrent traffic trends during the most recent decade in China [1]. In 2010, the cumulative highway mileage in China was 4.01×10^8 km, which included 3.05×10^4 km of highway bridges. In 2017, the cumulative highway mileage increased to 4.77×10^8 km and included 5.23×10^4 km of highway bridges. This rapid development of transportation infrastructure spurred concurrent and diversified vehicle industry development. The daily traffic volumes per highway increased from 1.82×10^4 veh/d in 2010 to 2.63×10^4 veh/d in 2017. The average truck weights increased substantially from 5.71 t to 8.60 t during the same time. Many of these trucks were hauling construction materials, mineral materials, and other heavy goods. The increase in average truck weights combined with the concurrent increase in the number of highway bridges (from 6.58×10^5 to 8.33×10^5) raises serious concerns regarding truck overloading behavior and bridge infrastructure damage in China.

Table 1: China's highway infrastructure development and concurrent traffic trends in 2010–2017 [1].

Year	2010	2011	2012	2013	2014	2015	2016	2017
Cumulative highway mileage ($\times 10^8$ km)	4.01	4.11	4.24	4.36	4.46	4.58	4.70	4.77
Number of highway bridges ($\times 10^5$)	6.58	6.89	7.13	7.35	7.57	7.79	8.05	8.33
Total length of highway bridges ($\times 10^4$ km)	3.05	3.35	3.66	3.98	4.26	4.59	4.92	5.23
Daily traffic volume per highway ($\times 10^4$ veh/d)	1.82	1.94	2.13	2.10	2.20	2.23	2.45	2.63
Average loaded weight per truck (t/veh)	5.71	6.16	6.43	6.78	7.08	7.46	8.01	8.60

Overloaded trucks cause significant damage to highway infrastructures (e.g., pavements, subgrades, and bridges) and substantially reduce their service lives [2–4]. Overloaded trucks also present a serious safety risk. Since 2000, overloaded trucks have caused more than 50 bridges to collapse in China [5–7]. In an incident in 2012, four heavy trucks with gross weights of 18.625 t, 153.29 t, 163.59 t, and 149.68 t caused a highway ramp to collapse in the Heilongjiang Province, killing three and injuring five persons [6]. More recently, in an incident in 2015, four overloaded trucks with gross weights of 117.7 t, 111.4 t, 78.7 t, and 116.7 t caused an interchange ramp to collapse in the Guangdong Province, killing one and injuring four persons [7]. Controlling truck overloading behavior is therefore essential in minimizing structural damage to highway infrastructures and preventing the associated catastrophic failures that threaten public safety.

For trucks, the question of how much weight is too much weight is not definitive. However, the safety and service life of highway infrastructures is related to their bearing loads, and weight limits have historically been determined by the reduction in a highway's service life attributable to large trucks. As one example, Ghosn [8] developed truck weight limits based on bridge safety using reliability analysis. In China, the legal truck weight limits have changed based on transportation industry developments. The most recent national standard [9] and regulation [10] specify both gross and axle weight limits for trucks based on their associated reduction in a highway's service life and the most frequently used vehicle types in China.

Regulatory truck weight limits are often challenging to enforce. Conventional truck weight enforcement efforts rely on identifying trucks exceeding the specified weight limits and punishing the responsible parties with penalties or through other means according to relevant administrative rules [11, 12]. Commercial technologies are not widely available to support fully automatic weight enforcement, and human resources struggle to manage the expansive highway infrastructure in China. As an alternative to conventional truck weight enforcement efforts, truck tolling is a comprehensive scheme that not only raises additional revenue to fund the construction and maintenance of transportation infrastructure but also mitigates the structural damage caused by heavy trucks [13]. The fee structure requires truck drivers/owners to balance the potential profit from overloading against the increased toll amount. All vehicles must be charged equitably based on their actual highway usage [14]; heavy trucks must be charged based on their actual damage to the highway infrastructure to properly control overloading behavior [15]. Such toll-by-weight schemes are currently used worldwide.

China first introduced a toll-by-weight policy in 2001. The policy has since been lauded by China's Ministry of Transport and is currently implemented along nearly 90% of the nation's highways. China's toll-by-weight policy can be implemented in three phases:

(i) In Phase 1, toll rates are determined based on vehicle types and their corresponding rated load capacities. For instance, trucks with rated load capacities of (0~2] t, (2~5] t, (5~10] t, (10~15] t, and [15~) t are tolled 0.50, 1.00, 1.50, 1.75, and 2.25 CNY/(veh-km) for many freeways at this time (for more details, refer Table 1 in [16]). In this implementation phase, the distinction between legal and overloaded truck toll rates is slight, which may encourage truck overloading behavior based on freight transportation profit stimulation.

(ii) In Phase 2, toll rates are determined based on each truck type's weight and associated damage to the highway infrastructure. Trucks that exceed legal weight limits are charged a higher toll. However, this higher toll is often only 1–3 times the base toll rate and may be offset by the benefits of overloading in some regions [17]. Thus, in this implementation phase, severe overloading behavior may be controlled but still persist.

(iii) In Phase 3, a more precise stepwise incremental fee structure is used. Advanced technologies, such as weigh-in-motion (WIM) systems, are used to accurately and effectively classify and weigh vehicles. Additional WIM/detection systems are recommended for installation at highway entrances to restrict access for overloaded trucks [10].

Each subsequent implementation phase of China's toll-by-weight policy is intended to enhance control of truck overloading behavior. In addition, the Chinese government continues to refine its overall toll-by-weight policy over time.

The objective of this study was to investigate the effects of China's recently revised toll-by-weight policy on truck overloading behavior and bridge infrastructure damage using weigh-in-motion data that spanned seven years (January 2011 to March 2018) and two successive toll-by-weight policies (with the new one implemented from August 2016), in which truck data were measured in the context of a typical national freeway segment. We first compared truck traffic volumes, compositions, and weight distributions under the initial and revised toll-by-weight policies. Next, we compared bridge infrastructure performance with respect to safety and fatigue based on the overloaded truck traffic observed under the initial and revised toll-by-weight policies. This study's findings can support future efforts by the Chinese government to further refine their toll-by-weight policies and subsequently ensure a safe and viable transportation network.

2. Methods

2.1. Traffic Data Collection. To support this investigation, we collected traffic data using WIM technology from an important exit located in the Guangdong Province of the national north-south artery—the Beijing–Hong Kong–Macao Expressway. Traffic and transportation conditions along this highway were representative of most industrialized regio.ns in China. This highway opened to traffic in November 2003, and an initial toll-by-weight policy was implemented in December 2009. Because the initial policy did not effectively control severe truck overloading behavior, a revised toll-by-weight policy was implemented along this highway in August 2016. Traffic data that spanned seven years (January 2011 to March 2018) and these two successive toll-by-weight policies were collected in this study.

Note that WIM systems were not yet installed at this highway's entrances to restrict access for overloaded trucks. Instead, WIM systems were installed at all highway exits, which included toll stations. Figure 1 shows the WIM system configuration on the measured freeway exit, which included a vehicle separator, weighing pad, axle identifier, induction coil sensors, video camera, and data processor. Passing vehicles were identified or separated via infrared scanning. Vehicle axles were identified as single, tandem, or tridem and weighed on the weigh pad. The induction coil sensors were used to record each passing vehicle's speed and determine its axle spacings. Finally, the video camera was used to capture each vehicle's license plate number. Data for each passing vehicle were computer processed to determine a toll rate based on the toll fee structure. The WIM system offered a high level of accuracy with a relative gross vehicle weight (GVW) error of ≤2%.

Traffic data were initially filtered to identify unreliable, incorrect, or suspect values. Using a prescribed set of criteria, data were assumed robust if a vehicle had the following criteria:

(i) Between 2 and 6 axles
(ii) A GVW ≥3.5 t
(iii) Individual axle weights between 0.2 and 30 t
(iv) Individual axle spacings between 0.6 and 20 m
(v) Axle weights that summed to the equivalent measured GVW
(vi) Axle numbers and spacings consistent with the identified vehicle type

After the filtering process was completed, the dataset for this study comprised records for 4,484,328 trucks captured over 1,516 valid days between January 2011 and December 2015 (before the policy revision) and 877,968 trucks captured over 402 valid days between January 2017 and March 2018 (after the policy revision). Note that all light vehicles (GVW < 3.5 t) such as passenger cars were filtered from the dataset because of their negligible loading impact on highway infrastructures.

2.2. Toll-by-Weight Policy Review. To accurately interpret the observed differences in truck traffic volumes, compositions, and weight distributions under the initial and revised toll-by-weight policies and the associated effects on specifically the bridge infrastructure damage, we needed to comprehensively understand the policy differences. As such, we conducted a thorough review on the initial and revised toll-by-weight policies. The initial toll-by-weight policy—in effect from December 2009 to August 2016—reduced but did not eliminate severely overloaded trucks in the traffic stream. In the beginning of August 2016, the government revised the initial toll-by-weight policy to include increased penalties for truck overloading behavior [9, 10].

Table 2 summarizes the toll fee structure for the initial toll-by-weight policy based on four distinct truck loading scenarios: (1) a legally loaded truck weighs less than or equal to the standard weight of light-carriage trucks ($W_{\text{legal}} \leq W_{\text{light}}$), (2) a legally loaded truck weighs more than the standard weight of light-carriage trucks ($W_{\text{legal}} > W_{\text{light}}$), (3) an overloaded truck weighs less than or equal to 1.3 times the truck's legal GVW limit ($W_{\text{excess}} \leq 0.3W_{\text{limit}}$), and (4) an overloaded truck weighs more than 1.3 times the truck's legal GVW limit ($W_{\text{excess}} > 0.3W_{\text{limit}}$). Based on these four weight scenarios, unique fee rates (R) were determined as a function of the vehicle type (i), the measured GVW (G), the fee rate coefficient for vehicle type i (r_i), and the base fee rate (b), which was 0.45 CNY/km for four-lane freeways and 0.60 CNY/km for ≥6-lane freeways. Table 3 lists r_j and W_{light} values for five different vehicle types. Separate fee rates were applied for the legal (W_{legal}) and overloaded (W_{excess}) proportions of each truck's GVW.

Note that, under this initial toll-by-weight policy, a constant fee rate was applied for all trucks—legal and overloaded—weighing up to 1.3 times the truck's legal GVW limit. This constant fee rate did not adequately reflect the relationship between applied vehicle loads and highway infrastructure damage and provided little incentive for truck drivers/owners to comply with legal weight limits.

Comparatively, Table 4 summarizes the toll fee structure for the revised toll-by-weight policy. In the revised policy, the number of weight scenarios was expanded from four to nine and a greater focus was placed on the relationship between applied vehicle loads and highway infrastructure damage. Similar to the initial policy, separate fee rates are applied for the legal (W_{legal}) and overloaded (W_{excess}) proportions of each truck's GVW. In the revised policy, however, the fee rate directly and consistently increases as a truck's GVW increases. Furthermore, the fee rate for severe truck overloading behavior is exceedingly high, providing a stiff penalty for trucks that may cause catastrophic infrastructure failure. The base fee rate (b) was also changed under this policy from 0.45 and 0.60 CNY/km to 0.09 and 0.12 CNY/t-km for 4- and ≥6-lane freeways, respectively.

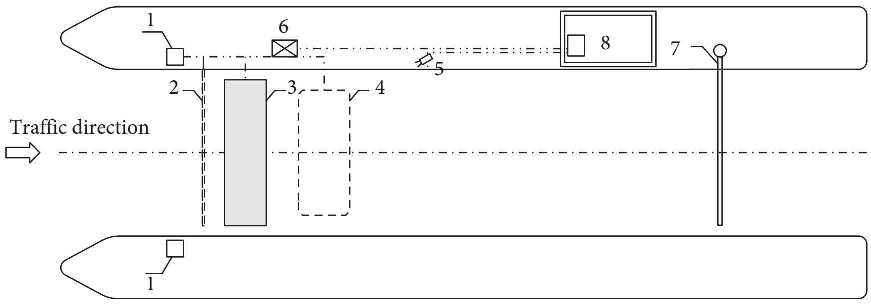

Figure 1: Weigh-in-motion (WIM) system configuration along a toll station exit of the considered expressway. 1: vehicle separator; 2: axle identifier; 3: weighing pad; 4: induction coil sensors; 5: video camera; 6: data processor; 7: stop rail; 8: toll booth.

Table 2: Toll fee structure for the initial toll-by-weight policy.

Weight type	Weight scenario	Fee rate (CNY/km)
W_{legal}	$W_{\text{legal}} \leq W_{\text{light}}$	$R = r_i \times b$ $(i \leq 3)$ or $r_{i-1} \times b$ $(i > 3)$
	$W_{\text{legal}} > W_{\text{light}}$	$R = r_i \times b$
W_{excess}	$W_{\text{excess}} \leq 0.3W_{\text{limit}}$	$R = r_i \times b$
	$W_{\text{excess}} > 0.3W_{\text{limit}}$	$R = [4 \times (G - 1.3W_{\text{limit}})/W_{\text{limit}} + 1] \times r_i \times b$

Table 3: Fee rate coefficients and standard light-carriage weight W_{light} for various vehicle types (i) used to determine tolls under the initial toll-by-weight policy.

Vehicle type, i	Number of axles	Number of wheels	Fee rate coefficient, r_i	Standard light-carriage weight, W_{light} (t)
Type 1	2	2–4	1.0	N/A
Type 2	2	4	1.5	13.8
Type 3	2	6	2.0	16.8
Type 4	3	6–10	3.0	18.7
Type 5	>3	>10	3.5	21.3

Table 4: Toll fee structure for the revised toll-by-weight policy.

Weight type	Weight scenario	Fee rate (CNY/km)
W_{legal}	$W_{\text{legal}} \leq 5$ t	$R_{\text{legal}} = 5 \times b$
	$5\text{ t} < W_{\text{legal}} \leq 10$ t	$R_{\text{legal}} = 1.25 \times W_{\text{legal}} \times b$
	$10\text{ t} < W_{\text{legal}} \leq 20$ t	$R_{\text{legal}} = [1.1 \times 10 + (W_{\text{legal}} - 10) \times (7/6 - W_{\text{legal}}/60)] \times b$
	$20\text{ t} < W_{\text{legal}} \leq 40$ t	$R_{\text{legal}} = [10 + (W_{\text{legal}} - 10) \times (370/300 - 7 \times W_{\text{legal}}/300)] \times b$
	$W_{\text{legal}} > 40$ t	$R_{\text{legal}} = [10 + (W_{\text{legal}} - 10) \times 0.3] \times b$
W_{excess}	$W_{\text{excess}} \leq 0.3W_{\text{limit}}$	$R = R_{\text{legal}} + (G - W_{\text{limit}}) \times 0.4 \times b$
	$0.3W_{\text{limit}} < W_{\text{excess}} \leq 0.5W_{\text{limit}}$	$R = R_{\text{legal}} + [0.3W_{\text{limit}} \times 0.4 + (G - 1.3W_{\text{limit}}) \times 4] \times b$
	$0.5W_{\text{limit}} < W_{\text{excess}} \leq 0.8W_{\text{limit}}$	$R = R_{\text{legal}} + [0.3W_{\text{limit}} \times 0.4 + 0.2W_{\text{limit}} \times 4 + (G - 1.5W_{\text{limit}}) \times 5] \times b$
	$W_{\text{excess}} > 0.8W_{\text{limit}}$	$R = R_{\text{legal}} + [0.3W_{\text{limit}} \times 0.4 + 0.2W_{\text{limit}} \times 4 + 0.3W_{\text{limit}} \times 5 + (G - 1.8W_{\text{limit}}) \times 6] \times b$

To better understand the differences between the two toll-by-weight policies, we calculated toll fees for various truck configurations (2 ≥ 6-axle trucks) along a typical ≥6-lane freeway under both the initial and revised toll-by-weight policies. Figure 2 illustrates these comparative results.

In general, drivers/owners of slightly overloaded trucks pay a lower toll under the current revised policy than they would have under the initial policy. Conversely, drivers/owners of heavily overloaded trucks pay a much higher toll under the current revised policy than they would have under the initial policy. For example, a driver/owner of a 6-axle truck weighing 100 t would have paid 8.32 CNY/km under the initial policy. The same driver/owner would pay 25.33 CNY/km—more than 3 times the prior toll amount—under the current revised policy. This substantial increase in the toll rate based on GVW could make it cost-prohibitive for drivers/owners to overload their vehicles, reducing both the number of overloaded trucks and the weight overages per truck.

In this study, we used field data from a WIM system to confirm these predicted effects of the recently revised toll-by-weight policy on truck overloading behavior and bridge infrastructure damage.

2.3. Comparative Analysis. The objective of this study was to investigate the effects of China's recently revised toll-by-weight policy on truck overloading behavior and bridge infrastructure damage. We first compared truck traffic volumes, compositions, and weight distributions under the initial and revised toll-by-weight policies. Next, we compared bridge infrastructure performance with respect to safety and fatigue based on the overloaded truck traffic observed under the initial and revised toll-by-weight policies. A description of the comparative analysis methods used in this study, including descriptive statistics, statistical modeling, and bridge safety, and fatigue assessments is given below.

2.3.1. Descriptive Statistics. Descriptive statistics were used to compare truck traffic volumes, compositions, and weight distributions under the initial and revised toll-by-weight policies. Results were presented in both graphical and tabular forms.

2.3.2. Statistical Modeling. Before proceeding with the bridge safety and fatigue assessments, we first had to reconcile the different durations of data that corresponded to the initial and revised toll-by-weight policies considered in

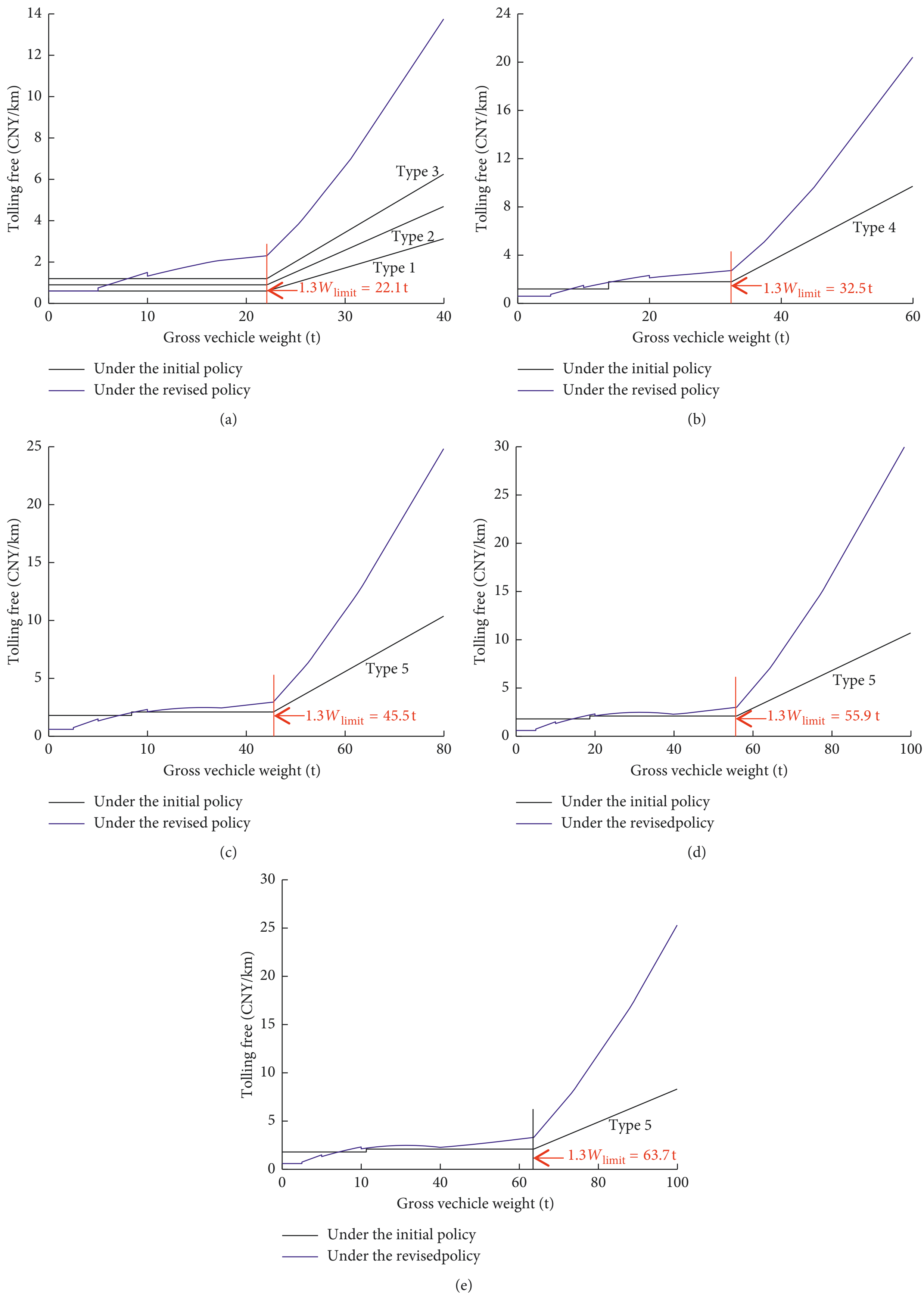

FIGURE 2: Toll fees under the initial and revised toll-by-weight policies. (a) Two-axle trucks. (b) Three-axle trucks. (c) Four-axle trucks. (d) Five-axle trucks. (e) Six or more-axle trucks. Note: W_{limit}, GVW limit.

this study. We used statistical modeling methods to simulate random truck loading for an equivalent comparison. Random truck load modeling has been widely used to estimate load effects on bridges based on site-specific data [18–21]. This methodology includes (1) developing statistical models for hourly truck volume, truck composition, GVW, axle weight, and axle spacing; (2) generating truck load sequences based on a truck arrival model with randomly assigned vehicle types, GVWs, axle weights, and axle spacings; and (3) progressing the truck load sequences across the bridge and evaluating bridge performance based on influence lines and historical load effects. For more details on the simulation methodology, refer [18]. For truck loading on single-lane ramp bridges considered in this work, it is critical to model gross truck weight, axle weights, and axle spacings.

Gross Weight Modeling. A methodology based on a mixed Gaussian distribution is commonly used to estimate GVW [18, 21]. O'Brien et al. [19] noted, however, that the use of a mixed Gaussian model to estimate truck weight yielded satisfactory results across much of the GVW range, but significantly underestimated probabilities in the upper tail. Instead, they used a semiparametric modeling method, which used a measured histogram in the lower GVW range where there were sufficient data and estimated the upper tail with a parametric model using the tail of a Gaussian distribution.

Based on this work, we used a semiparametric modeling method with a measured histogram and generalized Pareto distribution (GPD) to model the truck weights in this study. The peaks-over-threshold- (POT-) based GPD theory is more optimal for modeling extreme events [22] and is more accurate when estimating the upper GVW range. Using this methodology, truck weights were regarded as a sequence of observations (X_i, where $i = 1, 2, \ldots, n$). According to extreme value theory, the excesses ($Y = X - u$) over a certain high threshold (u) were approximated by a GPD [$G(.)$] as follows:

$$
\begin{aligned}
G(x; u, \sigma, \xi) &= 1 - \left(1 + \xi \frac{x-u}{\sigma}\right)^{-1/\xi}, \\
1 + \xi \frac{(x-u)}{\sigma} &> 0,
\end{aligned}
\tag{1}
$$

where u, σ, and ξ are the location, scale, and shape parameters of the GPD model. The Kolmogorov–Smirnov test and maximum likelihood methods were used to determine the GPD model parameters.

Using a measured histogram in the lower GVW range, the full distribution function of truck weights [$F(.)$] was formulated as follows:

$$
F(x) = \begin{cases} H(x), & x < u, \\ [1 - F(u)]G(x) + F(u), & x \geq u, \end{cases}
\tag{2}
$$

where $H(.)$ is the empirical distribution function of the measured histogram in the lower GVW range. These estimated extreme load events within the truck traffic weight distributions formed the basis of the bridge safety assessments performed in this study.

Axle Weight Modeling. Axle weight distributions should be strongly dependent on truck type and correlated with GVW. In this study, we identified an optimal copula function (t-copula) that describes the multivariate correlation between axle group weights and GVW. Note that the relationships among axle group weights and GVW were consistent under this study's initial and revised toll-by-weight policies. As such, these before-after data were combined when identifying appropriate statistical functions.

Table 5 details the performance of the t-copula function in describing this correlation. The squared Euclidean distance is the cumulative sum of squares of deviations between the fitting copula function and empirical copula function [23]. Therefore, a smaller deviation of the rank correlation coefficient between estimation and raw data and a smaller squared Euclidean distance indicate a better fitting result. After trying several copula functions, it is found the t-copula function produces the proximal rank correlation coefficient and the least squared Euclidean distance, and therefore, it is used in the paper. To illustrate the performance of the t-copula function, Figure 3 shows an example of the comparison of the correlation between the tandem axle weight (G2) and GVW (G) of the T15 truck type as determined using the raw data and t-copula function. The axle group weight was highly correlated with the GVW, and the t-copula function described this correlation effectively. This correlation should not be ignored; estimating axle group weights independently will cause errors.

Axle Spacings Modeling. Commonly, axle spacings of a certain vehicle type were regressed as constant values, which neglected their inherit randomness. In the study, the distribution of vehicle axle spacings is fitted by normal distributions, and Table 6 lists the estimated model parameters of the normal distribution for each truck type, including mean and standard deviation values.

2.3.3. Bridge Safety and Fatigue Assessments. After modeling truck loading on bridges, we next compared bridge infrastructure performance with respect to safety and fatigue based on the overloaded truck traffic observed under the initial and revised toll-by-weight policies. Specifically, we considered extreme and equivalent load effects for safety and fatigue assessments, respectively, on simply supported highway ramp bridges with a single lane and span lengths of 5–40 m. Similar bridge types and span lengths have been used in previous studies [24, 25] to investigate bridge effects under realistic traffic loading.

Safety Assessments. To support bridge safety assessments, an extrapolation method was used to estimate extreme load events based on simulated random truck loading effects. To reduce variation among the estimated extreme loads, 3000-day (10-year) truck loads were simulated. The midspan girder bending moment and girder shear force near the bearing were determined.

The standard load effects, determined using D60 [26], were compared to this study's results to illustrate the

Table 5: T-copula performance in describing axle group weight and GVW correlation.

Truck type	Axle group configuration	Raw data rank correlation coefficient	T-copula function: Kendall's rank correlation coefficient	T-copula function: Degrees of freedom	Squared euclidean distance
T12	G-G2	0.89	0.88	11.55	2.87
T15	G-G2	0.86	0.85	34.78	1.21
T112	G–G2, G–G3, G2-G3	0.58, 0.82, 0.42	0.58, 0.81, 0.42	11.10	4.89
T115	G–G2, G–G3, G2-G3	0.55, 0.84, 0.40	0.54, 0.84, 0.40	6.71	13.08
T125	G–G2, G–G3, G2-G3	0.66, 0.85, 0.55	0.65, 0.85, 0.54	6.49	10.72
T129	G–G2, G–G3, G2-G3	0.49, 0.80, 0.31	0.44, 0.75, 0.22	5.81	12.41
T155	G–G2, G–G3, G2-G3	0.74, 0.84, 0.60	0.75, 0.85, 0.64	3.19	3.10
T159	G–G2, G–G3, G2-G3	0.70, 0.80, 0.52	0.70, 0.80, 0.52	3.80	12.25
T1129	G–G2, G–G3, G–G4, G2-G3,G2–G4,	0.38, 0.59, 0.80, 0.28, 0.28, 0.42	0.36, 0.60, 0.79, 0.27, 0.26, 0.43	4.48	18.15

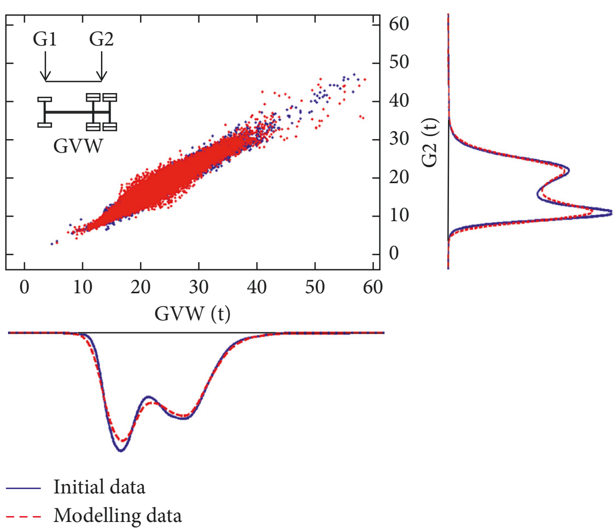

Figure 3: Comparison of correlation between the tandem axle weight (G2) and GVW (G) for the T15 truck type as determined using the raw data and t-copula function.

safety-related load effects attributable to truck overloading behavior. The JTG D60-2015 design traffic load model used for bridge safety assessments includes a uniformly distributed line load (q_k), that is, 10.5 kN/m for freeway bridges, and a concentrated point load (P_k) that varies linearly from 270 to 360 kN as span lengths increase from 5 to 50 m. A dynamic factor is not included in the JTG D60-2015 design traffic load model. The multilane factor for a single lane is 1.2. To assess bridge safety, the line and point loads are placed at locations along the bridge that elicit the most adverse responses. The traffic load return period specified in the JTG D60-2015 design load model is 1,950 years; results from this study were extrapolated to the same return period to support equivalent comparisons.

Using the 3000-day (10-year) truck load simulation, the POT-based GPD model was subsequently applied to estimate extreme load effects. The daily maxima were first extracted, and a high threshold value was then used to further extract the peaks-over-threshold events. Then, the GPD was fitted to these POTs using the Kolmogorov–Smirnov test and maximum likelihood methods, and the distribution model could be regarded as the yearly maximal load effects. Finally, the characteristic extreme load effects in a 1,950-year return period were formulated based on the GPD fitting model as follows:

$$x_{1950} = \overline{u} + \frac{\overline{\sigma}}{\overline{\xi}}\left(1950^{\overline{\xi}} - 1\right), \tag{3}$$

where $\overline{\xi}$, $\overline{u}$, and $\overline{\sigma}$ are the shape, location, and scale parameters of the GPD model, which is regarded as the distribution of yearly maximum load effects.

Fatigue Assessments. Unlike bridge safety, structural fatigue in bridges is affected by cumulative rather than maximum truck loading. For a simply supported girder bridge, longitudinal steel bars located at the bottom of the girder section are subjected to significant stress under truck loading, which may lead to fatigue failure. In this study, we used the equivalent bending moment amplitude to represent the fatigue performance of these steel bars. Empirically, the complete bending moment amplitude curve stabilizes after a certain period of truck loading. As such, a more limited random truck loading simulation was performed; 300-day (1-year) truck loads were simulated for this aspect of the investigation.

The standard load effects determined using the JTG D60-2015 [26] were again compared to this study's results to illustrate the fatigue-related load effects attributable to truck overloading behavior. JTG D60-2015 includes three traffic load models that can be used for bridge fatigue assessments. Models I and II correspond to infinite and finite fatigue life design, respectively, and are both intended for global component and connection design. Model III is intended for the design of local components directly exposed to vehicle wheels (e.g., orthotropic bridge decks or cross beams). In this study, Model II was most applicable. Model II considers two identical trucks separated by a ≥40 m gap. Figure 4 depicts the truck's configuration and axle group weights in Model II. When comparing this study's results to those of JTG D60-2015 Model II, the dynamic load and multilane factors were not considered because they are factors in the fatigue assessment equation rather than the model itself.

The stress of the steel bar is monotonically related to the bending moment. Thus, the equivalent bending moment

Table 6: Estimated axle spacing model parameters for each truck type (mean, standard deviation).

Truck type		Axle spacing 1	2	3	4	5
2 axles	T12	(4.24, 1.12)	N/A	N/A	N/A	N/A
3 axles	T15	(3.05, 0.82)	(1.33, 0.02)	N/A	N/A	N/A
	T112		(4.83, 1.59)	N/A	N/A	N/A
4 axles	T115	(3.61, 1.59)	(7.53, 0.21)	(1.30, 0.10)	N/A	N/A
	T125		(5.50, 0.77)			
5 axles	T129	(2.89, 0.55)	(6.61, 0.08)	(1.04, 0.23)	(1.26, 0.08)	N/A
	T155		(1.19, 0.10)	(5.68, 1.36)		
6 axles	T159	(2.34, 0.66)	(1.04, 0.10)	(2.92, 0.57)	(1.35, 0.06)	(1.25, 0.11)
	T1129		(2.40, 0.75)			

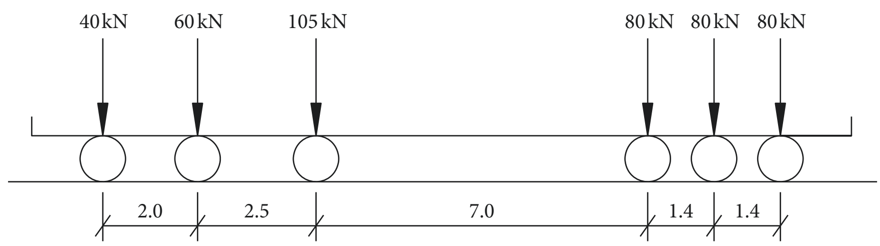

Figure 4: Truck configuration used in Fatigue Load Model II from D60 [26].

amplitude directly reflects the cumulative fatigue effects of the steel bar. Palmgren–Miner linear cumulative and rainflow counting methods were used to determine the equivalent bending moment amplitude (ΔM) under truck loading as follows:

$$\Delta M = \left[\frac{\sum n_i (\Delta M_i)^m}{\sum n_i} \right]^{1/m}, \tag{4}$$

where ΔM_i is the i^{th} bending moment amplitude, n_i is the corresponding number of stress cycles, and m is the fatigue limit coefficient (m = 5) based on the stress-number of stress cycles (S-N) curve.

3. Results

Based on the previously described methodology, we determined the effects of China's recently revised toll-by-weight policy on truck overloading behavior and bridge infrastructure damage. Specific results related to differences in truck traffic volumes, compositions, and weight distributions as well as bridge infrastructure performance with respect to safety and fatigue under the initial and revised toll-by-weight policies are shown below.

3.1. Truck Overloading Behavior

3.1.1. Truck Traffic Volumes. The average daily truck volumes decreased from 2,958 to 2,184 veh/d under the initial and revised toll-by-weight policies, respectively. Weekday and weekend truck volumes were similar under both the initial (coefficient of variance = 0.0387) and revised (coefficient of variance = 0.0347) policies. The decreased truck volumes under the revised toll-by-weight policy may suggest that truck drivers/owners were either discouraged from making select trips altogether or chose alternate routes with lower or no associated tolls.

When considering the hourly truck volume distribution throughout the day, marked differences were observed between the initial and revised toll-by-weight policies. Figure 5 illustrates these differences. Under the initial policy, hourly truck volumes were relatively constant throughout the day and night, but the hourly overloaded truck volume in the nighttime is significantly higher than that in the daytime. Under the revised policy, two daytime peaks in hourly truck volumes emerged: one in the morning around 10 a.m. and a second in the afternoon between 3 and 5 p.m., and meanwhile, the hourly overloaded truck volumes are constant and low throughout a day. This phenomenon may be explained that overloaded trucks trend to use freeways at nighttime under the initial policy to avoid detection. However, the revised weight limit policy increased the penalties for overloaded trucks, which make the overloaded truck drivers/owners chose other routes with lower tolls, especially at nighttime.

3.1.2. Truck Traffic Compositions. Nine primary truck types were identified along the Beijing–Hong Kong–Macao Expressway. Table 7 details the weight and configuration characteristics of each of these truck types and their relative proportions in the truck traffic stream under the initial and revised toll-by-weight policies. Under both policies, 6-axle trucks (V159 and V1129) made up more than 70% of the truck traffic, indicating the importance of this route for heavy freight transportation. Under the revised policy, the proportion of 2-axle trucks (T12) increased while the proportion of select 4- and 5- axle trucks (T115 and T129) decreased. The measured GVW for each truck type

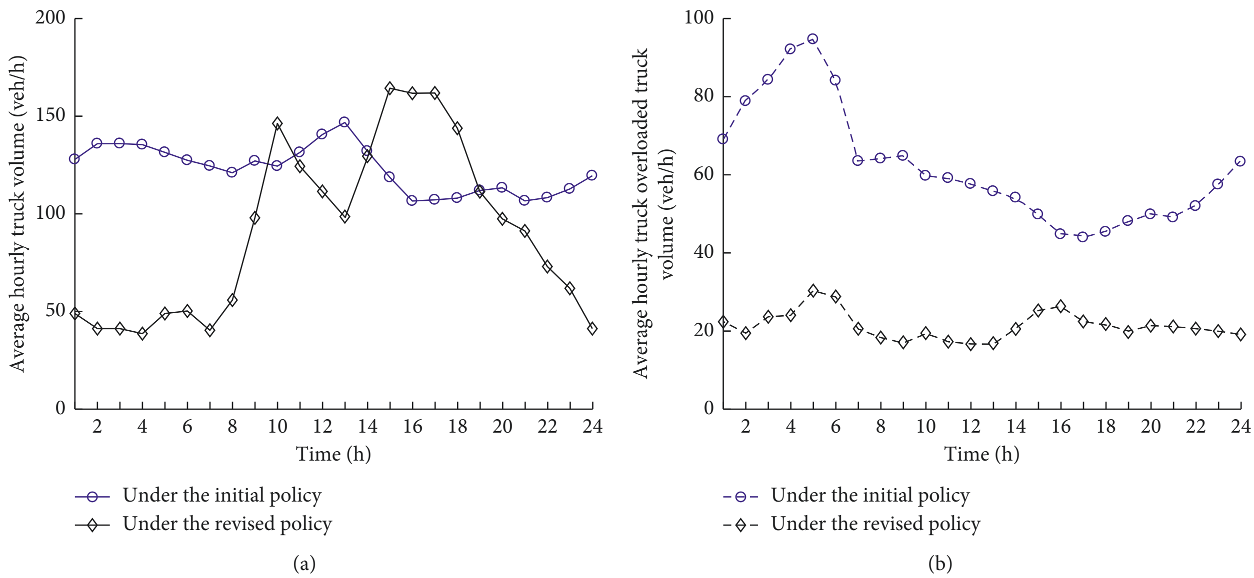

Figure 5: Truck volume distribution throughout the day under the initial and revised toll-by-weight policies with (a) hourly truck volume and (b) hourly overloaded truck volume.

Table 7: Truck traffic characteristics and composition under the initial and revised toll-by-weight policies.

Truck type		Configuration	GVW limit (t)	Initial policy		Revised policy	
				Proportion (%)	Mean GVW (t)	Proportion (%)	Mean GVW (t)
2 axles	T12		17	7.71	11.84	17.29	7.65
3 axles	T15		25	0.56	23.29	0.72	18.93
	T112		25	4.01	21.34	3.57	17.90
4 axles	T115		31	11.24	34.19	3.35	25.78
	T125		31	1.19	30.49	0.61	23.20
5 axles	T129		43	4.48	40.96	0.72	26.28
	T155		43	0.35	36.01	0.28	20.28
6 axles	T159		49	55.60	49.17	70.79	41.85
	T1129		49	14.87	47.91	2.67	32.01

decreased by an average of 25% under the revised policy, demonstrating its effectiveness in controlling truck overloading behavior. Despite these improvements, the average measured GVW of the most commonly used 6-axle truck (T159) remained high (41.85 t) under the revised policy and should be of concern.

3.1.3. Truck Traffic Weight Distributions. Truck traffic weight distributions under both the initial and revised toll-by-weight policies were examined to determine the frequency and extent of overloading activity. Table 8 summarizes the proportion of overloaded trucks, the mean GVW overage relative to legal limits, and the maximum measured GVW by truck type. Under the initial policy, the proportion of overloaded trucks was high across all truck types, ranging from 13.23% (T12) to 64.39% (T115). Under the revised policy, the proportion of overloaded trucks decreased, ranging from 1.43% (T155) to 39.61% (T125). Concurrently, the mean GVW overage across all truck types was approximately 4 t and 2 t under the initial and revised policies, respectively. Finally, the maximum GVW across all truck types totaled 117.30 t under the initial policy but only 61.43 t under the revised policy. Based on these results, the revised toll-by-weight policy appears effective in reducing but not eliminating truck overloading activity.

In addition to the descriptive statistics presented previously, we applied statistical modeling methods—namely,

Table 8: Frequency and extent of truck overloading under the initial and revised toll-by-weight policies.

Truck type	Initial policy			Revised policy		
	Proportion (%)	Mean over- limit GVW (t)	Maximum GVW (t)	Proportion (%)	Mean over- limit GVW (t)	Maximum GVW (t)
T12	13.23	1.30	39.25	1.49	0.45	21.01
T15	41.14	4.13	62.38	5.49	2.13	32.42
T112	20.01	2.60	56.82	9.93	1.03	31.49
T115	64.39	4.11	94.54	21.85	2.26	48.17
T125	50.52	4.55	76.57	39.61	2.10	47.97
T129	42.61	5.26	91.30	3.33	2.36	53.38
T155	26.20	3.60	107.20	1.43	1.63	43.63
T159	52.85	5.54	117.30	3.97	0.58	61.43
T1129	45.62	4.70	108.80	1.79	1.43	55.24

the semiparametric model with tailed GPD and measured histogram—to estimate the truck traffic weight distributions. Figure 6 shows the application of this model to GVW data of T159 under the revised toll-by-weight policy. Based on this example, the POT-based GPD model effectively represents the distribution's tail characteristics. Table 9 summarizes the location (u), scale (σ), and shape (ξ) parameters of the GPD used to model GVW tail by truck type under the initial and revised toll-by-weight policies. Again, significant differences are revealed that truck overloading behavior is clearly restricted but not eliminated.

3.2. Bridge Infrastructure Damage. In addition to investigating the effects of the revised toll-by-weight policy on truck overloading behavior, a second focus of this investigation related to bridge infrastructure damage is attributable to overloaded trucks. We performed both safety assessments based on extreme load effects and fatigue assessments based on equivalent load effects in this study.

3.2.1. Safety Assessments Based on Extreme Load Effects. To assess the safety-related load effects attributable to truck overloading behavior, we first estimated extreme load effects using a POT-based GPD model and compared this study's associated results to the standard load effects [26].

As an example, Figure 7 shows the extreme extrapolation of bending moments for a 20 m bridge under the initial and revised toll-by-weight policies. Table 10 summarizes the characteristic load effects (S_r) of bending moment and shear force under the initial and revised toll-by-weight policies and their relative values to load effects (S_d) calculated by the JTG D60-2015 load design model. Bridge span lengths of 5–40 m were considered.

Under both the initial and revised toll-by-weight policies, the characteristic load effects estimated in this study exceeded design levels ($S_r/S_d > 1$) across all bridge span lengths indicating a potential risk of strength failure. Under the initial policy, characteristic values ranged from 1.49 to 1.84 and 1.54 to 1.98 times the design level for bending moment and shear force, respectively. Under the revised policy, characteristic values decreased to 1.17–1.57 and 1.21–1.57 times the design level for bending moment and shear force, respectively, reflecting a 20.3% average reduction.

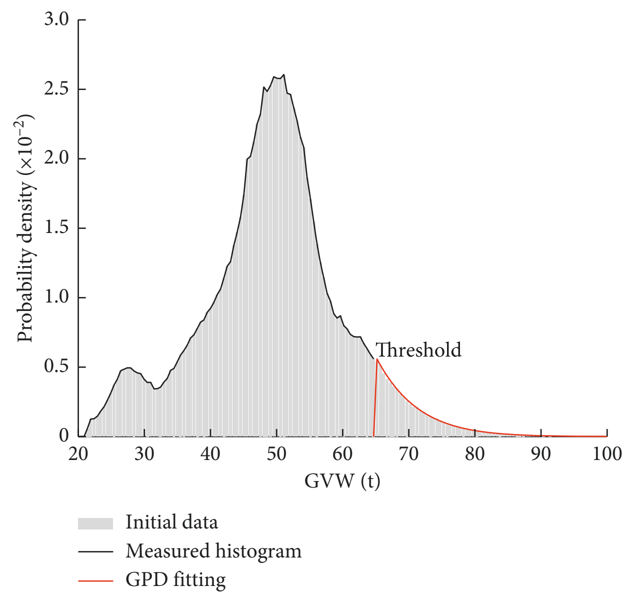

Figure 6: Semiparametric model fitting on GVW data of T159 under the revised toll-by-weight policy.

Based on these results, the revised toll-by-weight policy was estimated to reduce load effects on bridges by approximately 20% over their design life. However, the current policy does not fully eliminate overloaded truck traffic and characteristic load effects still exceeded design levels. Administrative penalties should be increased to further reduce truck overloading behavior, and bridge infrastructure maintenance should be closely monitored.

3.2.2. Fatigue Assessments Based on Equivalent Load Effects. To assess the cumulative truck loading effects on structural fatigue in bridges, we used the equivalent bending moment amplitude to represent the fatigue performance of the longitudinal steel bars at the bottom of a simply supported girder bridge section. This study's results were again compared to the standard load effects determined using JTG D60-2015 Model II [26] to distinguish the fatigue-related load effects attributable to truck overloading behavior. As an example, Figure 8 shows the bending moment amplitude versus the number of stress cycles for a bridge with a 20 m span length.

Table 9: Location (u), scale (σ), and shape (ξ) parameters of the GPD used to model GVW tail by truck type under the initial and revised toll-by-weight policies.

Truck type	Initial policy				Revised policy			
	u	$F(u)$	ξ	σ	u	$F(u)$	ξ	σ
T12	26.03	0.9977	−0.3015	4.65	15.74	0.9454	−0.1508	1.12
T15	30.19	0.8467	0.1252	2.96	24.60	0.8137	−0.2362	2.11
T112	31.31	0.9703	0.1077	2.18	23.37	0.8270	−0.2744	2.68
T115	57.70	0.9858	−0.2413	9.81	28.40	0.8128	−0.1578	4.03
T125	42.24	0.9639	0.1906	2.42	31.58	0.8104	−0.3032	8.65
T129	53.38	0.9298	0.0092	3.49	41.98	0.9500	−0.3740	3.19
T155	46.52	0.8676	0.0943	2.94	39.19	0.9571	−0.2915	4.74
T159	64.83	0.9326	−0.0549	5.10	48.79	0.9468	0.2086	1.12
T1129	63.09	0.9573	0.0071	4.06	44.33	0.8771	−0.1745	2.49

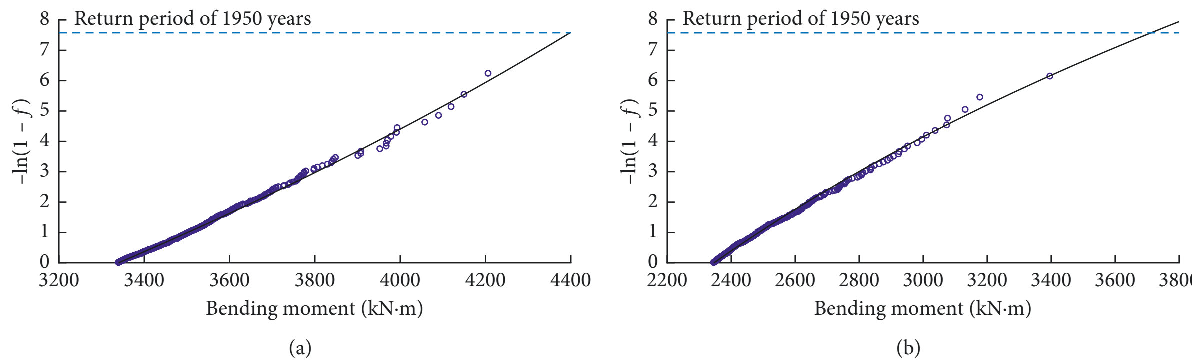

Figure 7: Extreme extrapolation of bending moment for a 20 m bridge under (a) initial toll-by-weight policy and (b) revised toll-by-weight policy.

Table 10: Characteristic load effects (S_r) under the initial and revised toll-by-weight policies and their relative values to load effects (S_d) calculated using the design load model.

Policy	Estimated parameter		Bridge span (m)							
			5	10	15	20	25	30	35	40
Initial policy	Bending moment	u (kN·m)	483	1248	2267	3340	4569	5680	6896	8051
		ξ ($\times10^{-3}$)	−181	22	−19	−47	−59	−61	−72	−77
		Σ (kN·m)	43	66	112	166	210	263	315	374
		S_r (kN·m)	660	1792	3057	4398	5852	7275	8735	10197
		S_r/S_d	**1.49**	**1.80**	**1.84**	**1.81**	**1.77**	**1.69**	**1.61**	**1.55**
	Shear force	u (kN·m)	456	610	712	761	803	817	855	911
		ξ ($\times10^{-3}$)	16	15	−48	−57	−60	−102	−95	−104
		Σ (kN·m)	35	39	42	43	42	46	45	44
		S_r (kN·m)	738	923	979	1026	1058	1059	1098	1142
		S_r/S_d	**1.76**	**1.98**	**1.91**	**1.84**	**1.75**	**1.63**	**1.58**	**1.54**
Revised policy	Bending moment	u (kN·m)	422	1067	1626	2346	3023	3726	4418	5164
		ξ ($\times10^{-3}$)	−201	−80	64	73	37	62	41	48
		Σ (kN·m)	47	66	101	135	179	198	252	279
		S_r (kN·m)	605	1552	2611	3712	4588	5641	6657	7385
		S_r/S_d	**1.36**	**1.56**	**1.57**	**1.53**	**1.39**	**1.31**	**1.23**	**1.17**
	Shear force	u (kN·m)	426	476	500	515	526	531	572	623
		ξ ($\times10^{-3}$)	−17	32	49	53	41	82	96	102
		Σ (kN·m)	31	30	29	28	29	27	25	24
		S_r (kN·m)	646	733	766	776	784	815	850	897
		S_r/S_d	**1.54**	**1.57**	**1.50**	**1.39**	**1.30**	**1.25**	**1.22**	**1.21**

Table 11 compares the equivalent bending moment amplitudes determined using JTG D60-2015 Model II [26] and this study's methods under the initial and revised toll-by-weight policies for bridge span lengths of 5–40 m. For bridges <30 m in length, equivalent bending moment amplitudes exceeded design levels by 57% and 14% under initial

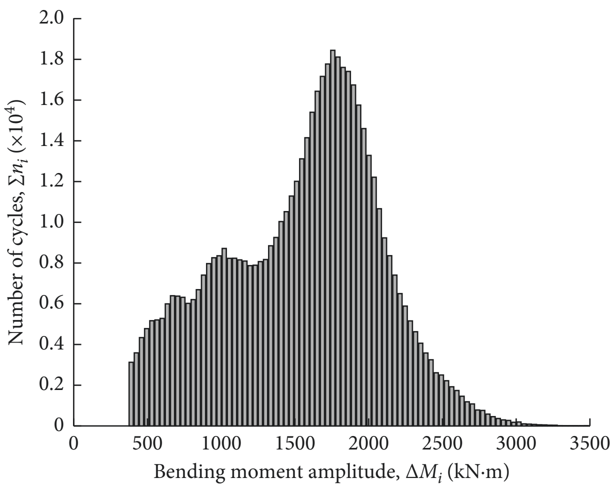

Figure 8: Bending moment amplitude versus the number of stress cycles for a 20 m bridge and traffic loading under the initial toll-by-weight policy.

Table 11: Equivalent bending moment amplitudes determined using D60 Model II [26] and this study's methods under the initial and revised toll-by-weight policies.

Bridge span (m)	Design model II	Initial policy		Revised policy	
	$\triangle M_p$ (kN·m)	$\triangle M$ (kN·m)	$\sum n_i$ ($\times 10^6$)	$\triangle M$ (kN·m)	$\sum n_i$ ($\times 10^6$)
5	188.0	**223.9**	56.1	**193.9**	34.1
10	488.0	**656.1**	57.7	**559.2**	36.8
15	788.0	**1237.9**	56.6	**897.0**	38.0
20	1208.5	**1849.3**	56.9	**1336.6**	38.1
25	1805.8	**2386.6**	55.8	**1889.3**	37.7
30	2579.7	**2782.2**	52.7	2366.2	36.3
35	3392.2	3113.8	47.7	2811.1	32.3
40	4212.7	3479.8	39.4	3108.4	28.1

and revised policies, respectively. The number of stress cycles for the equivalent bending moment amplitudes was also substantially higher (by a factor of nearly 2) under the initial policy. For bridges >30 m in length, equivalent bending moment amplitudes fell below design levels under both initial and revised policies. For bridges 30 m in length, equivalent bending moment amplitudes exceeded design levels under the initial policy but fell below design levels under the revised policy.

Based on these results, the revised toll-by-weight policy reduced equivalent bending moment amplitudes and associated bridge fatigue damage overall. However, equivalent bending moment amplitudes and associated cumulative load effects for fatigue assessment still exceeded design levels for short-span bridges (<30 m in length).

4. Conclusions

The objective of this study was to investigate the effects of China's recently revised toll-by-weight policy on truck overloading behavior and bridge infrastructure damage using weigh-in-motion data that spanned seven years (January 2011 to March 2018) and two successive toll-by-weight policies. Along a typical national freeway segment in China, an initial toll-by-weight policy was in effect from December 2009 to August 2016; a revised toll-by-weight policy was implemented in August 2016.

We first compared truck traffic volumes, compositions, and weight distributions under the initial and revised toll-by-weight policies. Next, we compared bridge infrastructure performance with respect to safety and fatigue based on the overloaded truck traffic observed under the initial and revised toll-by-weight policies.

The results indicated that the revised toll-by-weight policy, which uses a stepwise incremental fee structure based on vehicle weight (rather than type), was more effective at controlling truck overloading behavior and reducing bridge infrastructure damage than the initial toll-by-weight policy. The revised policy charges trucks more equitably based on their damage to highway infrastructures.

Under the current policy, average daily truck volumes, overloaded truck proportions, and maximum truck weights decreased significantly, suggesting its effectiveness in controlling truck overloading behavior. However, overloaded truck traffic persisted, with select trucks weighing up to 61 t or 25.4% over their legal GVW limit.

Concurrently, extreme and equivalent load effects for safety and fatigue assessments, respectively, decreased by an average of 20% for small- to medium-span bridges under the revised policy. Despite these noted improvements, overloaded truck traffic again persisted, with loads often exceeding bridge design levels. As a result, bridge infrastructure maintenance should be closely monitored.

The recent revisions to the toll-by-weight policy proved effective in reducing truck volumes, overloaded truck proportions, overloaded truck weights, and infrastructure failure risks but proved ineffective at eliminating overloaded truck traffic. This study's findings can support future efforts by the Chinese government to further refine their toll-by-weight policies and subsequently ensure a safe and viable transportation network. For example, administrative penalties maybe increased to further control truck overloading behavior or WIM systems and detection technology should be installed at freeway entrances to prevent access by severely overloaded trucks.

Data Availability

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

Conflicts of Interest

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

Acknowledgments

This study was funded by the National Nature Science Foundation of China (grant nos. 51808148 and 51278134); the Science and Technology Program of Guangzhou, China;

and the Science and Technology Program of the Transportation Department of Guangdong (grant no. 201402022).

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