Comprehensive benefit analysis of reinforced concrete bridge under different axle load limits

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Abstract. Limiting the vehicle load crossing the bridge can improve the safety of the bridge, but the transportation efficiency might be reduced. In order to reasonably evaluate the comprehensive impact of vehicle load limit on bridges, a comprehensive benefit evaluation factor $K$ was defined to analyze the comprehensive benefits of highway bridge transportation under different axle load limits. Firstly, based on WIM data, the random distribution function of total vehicle weight and axle load was fitted, and the loss ratio of transportation benefit before and after limiting the axle load was defined and calculated based on the principle of invariable total vehicle weight. Combined with the random distribution function of the total weight and axle load, Monte-Carlo method was used to simulate the random traffic flow under different load limit levels and calculate the time-varying reliability of typical bridges under different load limit levels. Finally, the evaluation factor $K$ was introduced to evaluate the influence of axle load limit on the comprehensive benefit of highway reinforced concrete bridges, and reasonable axle load limit suggestions were put forward.

1. Introduction

With the continuous growth of freight demand, truck overload has become a common problem through the world. In China, due to the increasingly fierce competition in the road transportation market, the phenomenon of vehicle overload is becoming more and more serious[1]. Although overload vehicles can increase the freight transportation efficiency, it will accelerate the degradation of bearing capacity of bridge components and cause high maintenance costs as well. According to statistics, the economic loss of roads and bridges caused by overload trucks in Hebei Province of China was up to 400 million yuan per year, and the maintenance cost of bridges caused by overload trucks in Tianjin of China from 2003 to 2007 was up to 320 million yuan.

At present, scholars have carried out many researches on the problem of bridge vehicle weight limit. Vrouwenvelder et al.[2] controlled the vehicle density and speed through the random simulation of vehicle traffic flow, and analysed the influence of vehicle load on the bridge. Asantey et al.[3] studied the distribution law of vehicle weight and the influence of overload on the structural safety of simply supported beam bridge under different violation rates of trucks. Ghosn[4] analysed the rationality of the bridge formula for vehicle weight limit in the US based on structural reliability theory and proposed a bridge formula for vehicle weight limit to achieve the target reliability index in AASHTO code. Fortowsky et al.[5] proposed an economic vehicle load limit evaluation method combining with the dynamic weighing data of Maine in the United States, and comprehensively considered the damage of vehicle weight, vehicle driving route and transportation benefits.
The studies above provide a theoretical basis for the study of vehicle load limit on regional comprehensive economic benefits, and the reasonable evaluation of bridge limit also has its potential economic value. Based on the measured WIM data, this paper uses Monte-Carlo method to generate random traffic flow, analyses the reliability of a typical reinforced concrete simple beam bridge under different axle load limits, and calculated the transportation benefit loss ratio of the bridge under different axle load limits under the condition that the total transport volume is constant. Finally, the comprehensive benefit evaluation factor K was defined to analyse the relationship between the axle load limit and the comprehensive benefit of the highway bridge.

2. Calculation of bridge transportation benefit

2.1. Treatment method for overload vehicles
In order to simplify the calculation process of bridge structural damage, this paper has established a random traffic flow model based on the statistical results of measured WIM data, and determined the representative axle load split ratio and mean axle spacing of each axle type vehicle.

To ensure that the logistics traffic volume in the region is not affected by the load limiting, and then control the transportation profit is constant after limiting the load, this study assumes that the total freight weight in the transportation network remains unchanged before and after limiting the load, and the weight of the overload part is transported by the new standard vehicles, and the axle load split ratio and mean axle spacing of the vehicle model are consistent with the new standard vehicles. As for the vehicle after limiting the load, the axle load limit is selected the value of its heaviest axle load. After limiting the load, the axle load distribution function of different models should be recalculated and fitted. Taking the 3-axle vehicle as an example, first the out of limit parts of each 3-axle vehicle is cut off according to the axle limit value. Then, the axle load values of all out of limit 3-axle vehicles will be adjusted in equal proportion through their original axle weight ratio and axle limit value. Finally, the out of limit parts of all vehicles will be accumulated and borne by the load limit standard vehicle.

2.2. Time varying reliability of bridge
Due to the reciprocating action of vehicle load, the reliability and service life of the bridge will be reduced, while the load limit can change the vehicle load effect on the bridge. Therefore, the influence of vehicle axle limit on bridge safety can be analysed from the perspective of reliability.

Considering the influence of traffic load increase and resistance attenuation caused by external environment, the reliability of bridge structure will change with time. Under the influence of environment and load factors, the probability of bridge failure in service life is as follows[6]:

\[
P_i(t) = P\{Z(t) = R(t) - S(t) < 0 \} \quad t \in [t_0, T_s]
\]

The time-varying reliability index of the structure is expressed as:

\[
\beta(t) = \Phi^{-1}(1 - P_i(t))
\]

Where, \( t_0 \) is the analysis time of bridge structure; \( T_s \) is the design service time of bridge, the value is 100; \( Z(t) \) is the function of bridge structure at time of \( t \); \( R(t) \) and \( S(t) \) are the resistance random process and load effect random process of \( t \) time of bridge structure; \( \Phi^{-1} \) is the inverse function of standard normal distribution function.

Vehicle load limit will change the load effect of vehicles crossing the bridge and affect the time-varying reliability of the bridge structure. The attenuation factor \( \alpha_i \) is defined to evaluate the influence of axle limit value on time-varying reliability of bridge, which can be expressed as follows:

\[
\alpha_i(t) = \frac{\beta_i(t) - \beta_0(t)}{\beta_0(t)}
\]

Where, \( \beta_i(t) \) is the reliability of the bridge under the \( i \)-th axle load limit; \( \beta_0(t) \) is the time-varying reliability of the bridge without limiting the vehicle load.
2.3. Economic profit of bridge transportation
As this paper has assumed that the total freight weight is constant after limiting the load, in order to meet the economic benefits of transportation, the method of increasing transportation times after the load limit is adopted for each transportation model, and the transportation is carried out in batches. Therefore, although the transportation profit of vehicles remains the same, the increase of freight times leads to the increase of total transportation cost. The transportation profit loss rate is defined to evaluate the transportation profit under different load limits, and its expression is as follows:

\[ \varphi_i = \frac{A - B_i}{A - B_0} \]  

(4)

Where, \( A \) is the transportation profit generated by the truck crossing the bridge; \( B_i \) is the transportation cost under the \( i \)-th axle load limit; \( B_0 \) is the transportation profit without limiting the vehicle load.

Assuming that the vehicle transportation cost is directly proportional to the number of vehicle transportation, the proportion of vehicle transportation cost before and after limiting the vehicle load can be obtained by counting the number of truck transportation before and after the load limit. Set \( \lambda_i = B_i / B_0 \) to express the vehicle transportation cost after limiting the vehicle load. The Freight transport efficiency is set as \( \eta = A / B_0 \), because the transportation profit will be different due to the inconsistency of transportation goods. Meanwhile, \( \eta \) can represent the proportion of transportation profit and transportation cost when trucks convey different types of goods. \( \lambda_i \) and \( \eta \) are used to replace \( A \), \( B_i \) and \( B_0 \) in equation (4), and equation (4) can be converted into the following equation:

\[ \varphi_i = \frac{\eta - 1}{\eta - \lambda_i} \]  

(5)

2.4. Economic profit of bridge transportation
When the axle load limit is set for the vehicles crossing the bridge, the vehicle load generated by the traffic flow after the limit load will reduce the loss to the bridge compared with that before the limit load, but the increased transport frequency after the limit load will increase the transport cost. In order to comprehensively evaluate the impact of load limit on comprehensive transportation benefit, a comprehensive benefit evaluation factor \( K \) is proposed, which not only considers the safety change rate caused by load limit, but also considers the impact on economic benefit. Its definition is as follows:

\[ K = \alpha / \varphi_i \]  

(6)

Where, the symbolic meaning is the same as above.

3. Case study
3.1. WIM data processing
With reference to Limits of Dimensions, Axle Load and Masses for Motor Vehicles, Trailers and Combination Vehicles (GB 1589-2016) in China, this paper selects 8, 10, 12, 14, 16 and 22 t as axle load limits for analysis. In this paper, the measured WIM data from a highway in China was collected and the truck models were divided into five types according to the number of axles. The vehicle model of each type is shown in Table 1. In this paper, after considering the axle weight distribution under different axle load limits, the final total weight was obtained by adding the axle weight of each vehicle after distribution, and the total weight distribution function is fitted, in which the fitting diagram of the total weight distribution of four axle vehicle is taken as an example, as shown in Figure 1. It should be noted that since the maximum vehicle axle load value obtained from the measured WIM data is 27.08t, the setting of condition without limiting the vehicle load is equivalent to the setting of the axle load limit with 28t.
| Type    | Axle load split ratio and mean axle spacing / cm |
|---------|-----------------------------------------------|
| Two-axle| 34% 400 66%                                   |
| Three-axle| 26% 400 23% 51%                         |
| Four-axle| 21% 350 20% 700 30% 150 29%             |
| Five-axle| 19% 300 25% 150 20% 750 19% 150 17%        |
| Six-axle| 15% 300 16% 150 19% 550 18% 150 17% 15%    |

Figure 1. Fitting line of total weight function (4-axle truck as an example).

3.2. Comprehensive benefit analysis
The basic design data of the bridge selected in this paper are as follows[7]: the standard span of the bridge is 20 m, the width of the carriageway is 7 m, the width of the sidewalks on both sides is 1.0 m, and the main beam material is C40 concrete and HRB335 reinforcement. The cross section of the bridge checked is shown in Figure 2.

According to the bridge design data, the statistical parameters of bridge resistance, dead load and vehicle load effect are calculated respectively, and in combination with equation (2), the time-varying reliability indexes of bridges under different axle limit values are calculated by direct sampling method, and the calculation results are shown in Figure 3.
It can be seen from Figure 3 that under different axle limit constraints, the reliability index of bridge structure decreases with the increase of axle limit, which shows that the limit load can effectively slow down the decline rate of the reliability index of bridge structure. In addition, when the axle load limit is less than 10t, the reliability index of bridge will be at a high level in the design service life of 100 years. When the axle load limit is more than 14 t, the reliability index of the bridge might decrease obviously. Limiting vehicle load might also change the freight transportation efficiency and cause the freight transportation loss. According to formula (5), the influence of the axle load limit on the transportation benefit loss ratio can be calculated. Considering that the freight transportation efficiency will also affect the transportation benefit loss ratio, the freight transportation efficiency $\eta$ is set as 1.2-1.5, and the transportation benefit loss ratio value under different axle load limits is calculated, as shown in Figure 4. It should be noted that since the subsequent analysis is to consider the impact of axle load limit on the comprehensive benefit of bridge, the calculation process does not consider the axle load limit of 28t, which represents the case of no limiting load.

![Figure 3](image3.png)  
Figure 3. Time-varying reliability index of bridge under different axle load limits.

![Figure 4](image4.png)  
Figure 4. The influence trend of the transportation benefit loss ratio.

It can be seen from Figure 4 that with the increase of the axle load limit value, the transportation benefit loss ratio shows a non-linear downward trend, especially when the limit value is set to 8t, the transportation benefit loss ratio is large. In addition, freight transportation efficiency has a great influence on the transportation benefit loss ratio, especially when the axle load limit value is small.

According to the above calculation results, combined with equation (8), the change of comprehensive benefit evaluation factor $K$ with the change of axle limit value and bridge service time under different freight transportation efficiency could be further calculated (Figure 5).

![Figure 5](image5.png)  
Figure 5. Comprehensive benefit factors under different freight transportation efficiency.
According to the Figure 5, the comprehensive benefit evaluation factor fluctuates violently with the change of the load limit value, and there is a trend of rising first and then decreasing with the same service life, which shows that the formulation of a reasonable limit load value can maximize the comprehensive benefit index of bridge transportation, and the axle load limit corresponding to the maximum value of the comprehensive benefit evaluation factor is the optimal axle load limit value. With the increase of service life of the bridge, the optimal axle load limit value will be reduced, because when the service life of the bridge is longer, the damage rate of the bridge increases rapidly under the same load. At this time, a stricter load limit value scheme should be formulated. When the freight transportation efficiency increases, the optimal axle load limit value tends to decrease. Under the smaller axle limit value, the transportation efficiency has a significant effect on the comprehensive benefit evaluation factor.

4. Conclusions
A new indicator, the comprehensive benefit evaluation factor ($K$), was proposed to evaluate the effect of load limitation on the comprehensive benefit of bridge. The calculation results show that a reasonable axle load limit value could be effectively obtained based on the index to maximize the comprehensive benefit. When the bridge is used for a long time, the corresponding comprehensive benefit is the largest when a small load limit is established. However, when the freight transportation efficiency is small, a strict load limit scheme will result in a large loss of economic benefits, so it should be considered comprehensively in the formulation of axle load limit value.

Acknowledgments
This work was supported by Hunan Provincial Innovation Foundation For Postgraduate (CX2018B159).

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