Influence of overloaded vehicles on pavement life based on WIM data

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Abstract. In this paper, the weight distribution characteristics of overloaded vehicles and the influence of overloaded vehicles on pavement service life are studied based on WIM data. Based on the vehicle weight data collected from weight in motion station, the vehicle weight distribution function of different axle type trucks and the weight overload ratio distribution function of different axle types are obtained by fitting. Equivalent single axle loads of the pavement under different weight limits are calculated based on the vehicle weight distribution function, and finally the pavement life growth factors under different weight limits are determined. The calculation results show that: the maximum overload ratio of two-axle vehicle can reach 340%; the number of six-axle overloaded vehicle accounts for more than 50% of the total number of overloaded vehicles, which is the largest proportion. Pavement life can be improved effectively by limiting load, and the road life growth factor shows a quadratic parabolic trend to increase with the decrease of load limit value. For two axle trucks with serious overload, the pavement life can be increased by more than 15 times with a strict load limit value.

1. Introduction
Overloading will reduce the reliability of pavement and shorten the service life of pavement. Therefore, it is of great significance to limit the load for the pavement life. At present, there have been many researches on the influence of overloading on pavement.

Deshpande [1] put forward pavement optimization suggestions by the study of pavement damage caused by overload. Celso [2] evaluated the changes in the life cycle of the pavement, and conducted an economic evaluation of the 30-year life cycle cost analysis, which verified the necessity of increasing inspections of overloaded vehicles. Dawid [3] studied the fatigue damage of mixed traffic on asphalt pavement based on the dynamic weighing data from eight stations, and proposed a load equivalent factor model based on axle load distribution and overload percentage. Overloading would reduce the reliability of pavement and shorten the service life of pavement. Therefore, it is of great significance to limit the load for the pavement life. At present, there have been many researches on the influence of overloading on pavement.

Based on the phenomenon that the pavement cannot reach the expected service life due to vehicle overload, the relationship between different load limits and pavement life is established, and its life is evaluated effectively in this paper.
2. WIM data

Weighing the vehicle can monitor the vehicle load effectively and limit the vehicle weight accordingly. The traditional weighing method is mainly static, and the vehicle enters the weighing station for weighing. This is a weighing method with high measurement accuracy, but it takes a long time and has low efficiency. With the rapid development of the existing dynamic weighing technology, the weighing accuracy has reached more than 90%, and it has high weighing efficiency. Therefore, it is widely used in the management of highway infrastructure and one of the main tools of pavement management. Monitor traffic flow conditions by using WIM technology can minimize overload problems.

In this paper, WIM data measured for one month on a freeway in Hunan province of China are analyzed. The basic parameters, such as the number of axles and the total weight, are used to fit the vehicle weight distribution function of different axle types. Based on the number of axles, trucks are divided into 5 categories and the percentages of different types are counted. According to the statistical results of the literature [4], the percentage of the average axle weight of each type in the vehicle weight is listed in Table 1.

| The axle type | The percentage of each axle type vehicle in total vehicle (%) | The percentage of average axle load of each vehicle type in total vehicle weight (%) |
|---------------|---------------------------------------------------------------|----------------------------------------------------------------------------------|
| Two-axle      | 41.92                                                         | 34 66 - - - -                                                                      |
| Three-axle    | 7.58                                                          | 26 23 51 - - -                                                                      |
| Four-axle     | 11.61                                                         | 21 20 30 29 - -                                                                       |
| Five-axle     | 1.32                                                          | 19 25 20 19 17 -                                                                     |
| Six-axle      | 37.57                                                         | 15 16 19 18 17 15                                                                   |

It can be seen from Table 1 that two-axle vehicles account for the largest proportion of total traffic flow, two-axle vehicles account for 41.92% of total traffic flow, followed by six-axle vehicles, accounting for 37.57% of total traffic flow, but the five-axle vehicles account for the least proportion of total traffic flow, only 1.32%. Therefore, more attention should be paid to the overload situation of two-axle and six-axle vehicles in engineering. In order to further calculate the pavement damage caused by truck flow with different axle types, it is necessary to fit the vehicle weight distribution function of different vehicle types. In reference [5], it is indicated that the vehicle weight distribution function mainly follows the multimodal normal distribution, and the bimodal normal distribution function is shown in Formula 1.

\[
y = y_0 + \frac{A_1}{\sqrt{2\pi \sigma_1}} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + \frac{A_2}{\sqrt{2\pi \sigma_2}} e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}}
\]  

(1)

The vehicle frequency is counted by different vehicle weight intervals, and different vehicle weight frequency points are drawn. The distribution function is obtained by fitting the vehicle weight frequency points of different axle type vehicles, and the accuracy of fitting is judged by goodness of fit (R^2). The fitting result is shown in Figure 1.

According to Figure 1, the weights of each axle type obey the multimodal normal distribution well, and the goodness of fit of the distribution function is higher than 0.9, which further verifies the accuracy of the fitting. Except for the weight of the 6-axle vehicles which obeys the bimodal normal distribution, the weight of the other axle vehicle obeys the unimodal normal distribution. The vehicle weight of 6-axle vehicles is mainly concentrated near the first peak (43t), the peak value of 2-axle vehicles is mainly concentrated near 8t, the peak of 3-axle vehicle is mainly concentrated near 15t, and the peaks of 4-axle and 5-axle vehicles are mainly concentrated at around 20t. The characteristic parameters of the vehicle weight distribution function of each axle types are listed in Table 2.
According to the Chinese code Limits of Dimensions, Axle Load and Masses for Motor Vehicles, Trailers and Combination Vehicles (GB 1589-2016), and 18, 25, 31, 43, 49 t are specified as the total weight limit values of each axle types truck. Comparing the data shown in Table 1, except for 6-axle vehicle, the peak values of other type vehicles are not near the limit values. But the overload condition is closely related to the discreteness of distribution function and extreme overload. To further study the overload situation, the overload ratios of different axle types are statistically analyzed and the probability density distribution functions are fitted as shown in Figure 2. The fitting formula for the probability density distribution function is as formula (2-4).

\[ y = y_0 + C \left( \coth \left( \frac{x-x_C}{s} \right) - \frac{s}{x-x_C} \right) \]  

(2)

\[ \coth(z) = \frac{e^z + e^{-z}}{e^z - e^{-z}} \]  

(3)

\[ z = \frac{x-x_C}{s} \]  

(4)

According to the fitting formula and Figure 2, it could be seen that the highly nonlinear variation trend is shown for the overload ratio of different axle types. The maximum probability of overload proportion of 2-axle vehicles; 3-axle vehicles and 5-axles vehicle is about 5%, and the maximum probability of 4-axle and 6-vehicles is 10%. The overload ratio of two-axle vehicles is mainly concentrated within 75%; three-axle vehicles and six-axle vehicles are concentrated within 130%; four-axle vehicles are more serious, mainly concentrated within 210%, and five-axle vehicles are concentrated within 125%.

Except for four-axle vehicles, as the overload ratio increases, the probability of its occurrence decreases rapidly. In the initial stage, the overload ratio of four axle vehicle decreases slowly. When the overload ratio is more than 150%, the probability of overload begins to decline continuously. When the overload ratio increases to a certain inflection point, its downward trend gradually slows down, which shows that the probability of extreme loads is not very high, but it is still a common phenomenon. The maximum overload value of two-axle vehicles reached 344%, and six-axle vehicles reached 269%.
characteristic parameters of the vehicle weight overload ratio distribution function are listed in Table 3.

|                     | Two-axle vehicle | Three-axle vehicle | Four-axle vehicle | Five-axle vehicle | Six-axle vehicle |
|---------------------|------------------|--------------------|-------------------|-------------------|------------------|
| $y_0$               | 310.51           | 211.70             | 2.03              | 219.19            | 8.96             |
| $x_c$               | -1.90            | -8.84              | 198.64            | 3.50              | 83.53            |
| $C$                 | 311.86           | 212.37             | 2.14              | -212.54           | 10.08            |
| $s$                 | -0.80            | -1.42              | -7.77             | 0.98              | -12.33           |

The ratio of the number of overloaded vehicles with different axle types to the total number of overloaded vehicles indicates which type vehicle has the most common overload situation; the ratio of the weight of overloaded vehicles with different axle types to the total weight of overloaded vehicles indicates which type vehicle has the most serious overload situation. Both of these are of great significance for the setting of the load limit values. According to the statistical analysis of the data, the pie chart of the proportion of the overloaded vehicles of each axle type to the total overloaded vehicles is shown in Figure 3; the pie chart of the proportion of the overloaded weight of each axle type to the total overloaded weight is shown in Figure 4.

According to Figure 3, six-axle overloaded vehicles accounted for the largest proportion of the total number of overloaded vehicles, which accounted for more than 50% of the total number of overloaded vehicles; the number of overloaded vehicles for two-axle vehicles and four-axle vehicles accounted for a larger proportion of the total number of overloaded vehicles, both are about 20%. Therefore, these three type vehicles have accounted for more than 90% of the total overloaded vehicles; the number of three-axle overloaded vehicles and the number of five-axle overloaded vehicles accounted for a small proportion of the total overloaded vehicles.

Figure 4 shows that the overload weight of six axle vehicles accounts for the largest proportion of the total overload weight, which has exceeded 60%. The overload weight of four axle vehicles accounts for a large proportion of the total overload weight, which is nearly 30%; the rest of the other axle type vehicles accounted for a small proportion of the total overload weight, all below 5%. Combined with Figure 3, it can be seen that the six-axle vehicle has the largest number of overloaded vehicles, and the overloaded weight is also the largest. The number of overloaded vehicles and the overloaded weight of five-axle vehicles are both small. Except for two-axle vehicles, there is a positive correlation between the number of overloaded vehicles of various types and their overloaded weight. It is worth noting that two-axle vehicles have a large number of overloads, but they account for a small proportion of the total overload weight. Because the overload ratio of two-axle vehicles is mainly concentrated within 5%, and the overload weight of most overloaded two-axle vehicles is not very large. Therefore, when considering the impact of overload on the pavement, the six-axle overloaded vehicle has the greatest impact on the road. Although there are more two-axle overloaded vehicles, its impact on the road is relatively small. Five-axle overloaded vehicles have the least impact on the pavement.
3. Pavement life analysis

Overloading of vehicles will cause road surface cracking and other diseases, reducing the service life of the pavement. At present, the main basis for predicting pavement life is based on the damage of pavement material under the cyclic load, which is mainly derived from the test data under the standard load. Since the distribution function of vehicle weight is obtained based on WIM data, it is necessary to determine the relationship between the vehicle weight distribution function under different load limit values and the standard axle load, and then determine the impact of different load limit levels on the pavement life.

First of all, the weight distribution function should be determined after the load limit. It is assumed that the enforcement is strict, and many studies directly cut off the tail of the distribution function exceeding the load limit after the load limit. However, a part of the transportation weight will be lost in this operation, which can improve the pavement life, but also reduce the transportation efficiency. Therefore, based on the principle of constant total weight, it is assumed that the form of the vehicle weight distribution function remains unchanged before and after the load limit, and the censored weight after the load limit is added to the non-overloaded distribution function in accordance with the same distribution. The formula for calculating the total weight based on the weight of the vehicle is as Equation 5 formula, \( x \) is the vehicle weight, \( f_i(x) \) is the vehicle distribution function of the \( i \)-axle vehicle, \( x_{\text{max}} \) is the observed maximum vehicle weight, and \( x_{\text{min}} \) is the observed minimum vehicle weight.

\[
\text{GVW}_i = \int_{x_{\text{min}}}^{x_{\text{max}}} x f_i(x) dx
\]  

(5)

The axle load distribution function \( f(x) \) can be obtained by multiplying the vehicle weight distribution function by the proportional coefficient of each axle weight in Table 1. According to the standard axle load \( x_p \) (BZ-100kN), the actual axle load \( x \) can be converted into equivalent standard axis order \( e(x) \), through the equivalent standard axis order \( e(x) \) and the axle load distribution function \( f(x) \), the equivalent standard axle load (ESAL) can be calculated. Based on the axle load distribution function, the calculation process of the equivalent standard axle load with different axle type vehicle is as follows (6-7).

\[
e(x) = (x/x_p)^n
\]  

(6)

\[
\text{ESAL} = \int_{x_{\text{min}}}^{x_{\text{max}}} e(x) f(x) dx
\]  

(7)

In the formula 6, \( n \) is the axle load conversion factor; when \( x_p \) is 100 kN, for high-grade asphalt pavement, \( n \) is 4.

According to the calculation of equivalent standard axle load, the damage degree \( \alpha \) of the pavement under different traffic conditions can be calculated (Equation 8), and a new index pavement life growth factor \( \beta \) is proposed, which is defined as the pavement damage degree (Equation 9). The pavement life growth factor is the ratio of the equivalent standard axle load under overload to the equivalent standard axle load after the limit load, that is, how many times the pavement life can be increased under the condition of limited load compared with the unlimited load.

\[
\alpha_i = \frac{\text{ESAL}_i}{\text{ESAL}_0}
\]

(8)

\[
\beta_i = \frac{\alpha_{i0}}{\alpha_{iL}} = \frac{\text{ESAL}_{i0}}{\text{ESAL}_{iL}}
\]

(9)

In the formula, ESAL\(_i\) is equivalent standard axle load under different axle types, which can be calculated by Equation 7. ESAL\(_0\) is design total cumulative equivalent standard axle load, which is related to the statistical traffic flow as designing pavement thickness. It is subdivided With the calculation of pavement life growth factor \( \beta \).

The load limit value specified by the code is the center point, and the interval is 2\( t \), and 8\( t \) is set as the load limit boundary before and after the center point. According to Equation 9, the pavement life growth factors under different load limit values are calculated, and the calculation results are plotted in Figure 5.
Figure 5. Variation trend of pavement life growth factor under different load limits

By fitting, it is seen from figure 5 that the $\beta$ of different type vehicles present quadratic parabola nonlinear growth with the decrease of load limit value, and the goodness of fit is all greater than 0.95. When the load limit is set to 8t, the pavement life growth factor can be increased to 150, and the pavement life growth factor of three axle vehicle is the least sensitive to the change of load limit value.

4. Conclusions
Based on weight in motion data, this paper studies the impact of overloaded vehicles on pavement life. The following conclusions can be drawn:

1) The method of evaluating pavement life based on WIM data is feasible. If WIM data is combined with early traffic data, it can provide a reference for pavement life prediction and reinforcement maintenance plan.

2) Fitting the vehicle weight distribution based on WIM data, the vehicle weight of each type obeys a normal distribution, the ratio of number and weight of six-axle overloaded vehicles are all the highest. Six-axle vehicles should be subject to key restrictions. It provides a reference for the formulation of load limit regulations.

3) A new index is proposed, which is the pavement life growth factor. When the limit load is reduced, the pavement life growth factor increases in the form of quadratic parabola, and the growth rate of two axle vehicle is the fastest. So, a strict load limit can greatly improve the pavement life.

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