An Improved Load Spectrum Extrapolation Method of Railway Vehicle Bogie Frame

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Abstract. This article is aimed to seek for a precise extrapolation method on railway vehicle bogie frame load spectrum based on real engineering problem in China Standard EMU and Beijing Subway vehicle. The most common used methods, exceeding probability and standard load spectrum with cumulative frequency, are discussed. An improved method that excludes trivial load amplitude while calculating cumulative frequency is proposed. The three methods are deployed with real measured data and then compared with the ground truth. The comparison result shows that the improved method introduced in this article has the minimum error of the estimated load maxima and least deviation from ground truth load spectrum.

Keywords: Railway Vehicle; Load Spectrum Extrapolation; Bogie Frame; Standard Load Spectrum; Cumulative Frequency.

1. Introduction
The bogie is one of the most important part of the railway vehicle. According to the observation in railway transportation operation, there are many cases that the bogie is damaged to different extent due to mechanical fatigue. The Fig. 1 shows the cracks on the bogie of one Beijing subway line 2 vehicle, which is not the single case in their fleet even though all vehicles are produced strictly according to the national and industrial standard.

Figure 1. Bogie damage of Beijing subway line 2 vehicle
Vehicle load spectrum is thus introduced to analyze and deal with above problems. The concept is first brought by German scientist Gasser, E [1] and widely used in various fields, e.g. automotive, farm machinery, aviation as well as railway transportation [2-6]. North American Rail Alliance has established the standard load spectrum AAR for freight trains. The load spectrum has also been considered in multiple railway vehicle design standard, such as UIC615-4 [7], EN13740 [8], JIS E4507 [9].

However, the bogie damage and cracks still happen occasionally which threaten the human and freight transportation safety. It proves the necessity to improve the load spectrum research method and, moreover, to derive a load spectrum according to Chinese practice.

2. Load Spectrum Extrapolation

The most significant difficulty while generating load spectrum is that the measurement data samples are often limited which might not reflect the life time behavior and, especially, might not include the maximum amplitude in the load spectrum. A classical and fundamental assumption regarding load spectrum is that the maximum mechanical load appears once in every $10^6$ amplitude cycles and this maxima can be considered as the maximum amplitude in the full life cycle [10]. Therefore, the common load spectrum is applied with extrapolation method up to $10^6$ amplitude cycles. The longer load spectrum than $10^6$ amplitude cycles can be considered as the repeated behavior. This assumption is the basis of all discussions in this article.

The commonly used approaches to apply the load spectrum extrapolation are the followings:

1) Exceeding probability method, combined with parametric estimation (EPPE) or non-parametric estimation (EPNPE) [11-13];
2) Extrapolation of standardized load spectrum with cumulative frequency (ESLS);
3) Extreme value distribution method, including block-based extreme value method and Peak over Threshold method (POT) [14].

Since the extreme value distribution method is applied in the time domain, huge amount of measured data needs to be processed, which brings more complexity to engineering practice than statistical accumulation. For EPNPE, more computation effort is needed on the kernel calculation and not widely used in engineering practice.

Thus, EPPE and ESLS is studied and compared in this article. Specifically, an improved ESLS (IESLS) is proposed where an amplitude gate/threshold is defined while pre-processing the samples to exclude the trivial amplitude which has no impact on the mechanical structure. The methods are then deployed and verified using the measured floating load data from railway vehicle bogie frame of Chinese Standard EMU and Beijing Subway line 2.

The common steps of load spectrum extrapolation can be summarized as the followings:

1) Build or choose a mathematic model;
2) Apply the measured data to estimate the maxima in a $10^6$ amplitude cycle;
3) Calculate the extrapolated load spectrum by using the mathematic model and the estimated maxima.

2.1. Exceeding Probability Method combined with Parametric Estimation.

The basic assumption of EPPE is that the amplitude probability distribution could be modeled as a normal distribution, a Weibull distribution, or a logarithmic normal distribution [13]. The parameter used in EPPE is meant to be the parameter in the mathematic probability distribution model.

The probability of load maxima could be assumed as $1/N$, where $N$ is the target amount of amplitude cycle after extrapolation, usually $N=10^6$ [15].

The estimated load maxima $\hat{\delta}_{\text{max}}$ can be expressed as:

$$F(\hat{\delta}_{\text{max}}) = 1 - \frac{1}{N}$$ (1)
max \hat{s}_s is the assumed amplitude probability distribution function at \hat{s}_s. See the probability density function in Fig. 2, \( F(s) \) is the cumulative probability up to \( s \).

![Figure 2. An example of exceeding probability of Weibull distribution](image)

2.2. Extrapolation of Standardized Load Spectrum with Cumulative Frequency.

Standardized load spectrum with cumulative frequency is a widely used statistical method raised by European WGs in 1970s [16, 17]. The mathematical model is:

\[
H(s) = H_0 \left( \frac{s}{s_{\text{max}}} \right)^v
\]

Where \( s \) is the load amplitude value; \( s_{\text{max}} \) is the maximum load amplitude; \( H_0 \) is the total occurrence of all load amplitude; \( H(s) \) is the cumulative occurrence of load amplitude \( s \), where accumulation starts from \( s_{\text{max}} \) and ends at minimum amplitude value \( s_{\text{min}} \). \( H(s_{\text{min}})=H_0 \); \( v \) is the characteristic parameter.

In [18], an extrapolation method based on Eq. 2 is proposed. Suppose the current load spectrum with less measurements is curve a. The total number of measurement samples is \( H_0 \). Target number of samples after extrapolation is \( H_{02} \).

![Figure 3. The sketch map of ESLS](image)

As shown in Fig. 3, the extrapolation steps are:
1) Translational lift the curve a up. Result in curve b.
2) Draw the tangent of curve b at the intersection p.
3) Generate curve c as a straight line or curve based on 2.

The estimated amplitude maxima is thus represented by the intersection point q. The extrapolated load spectrum is curve b + curve c.

According to Eq. 2,
\[
\frac{d(\ln H(s))}{ds} = -v \ln H_0 \frac{1}{s_{\max}} \left( \frac{s}{s_{\max}} \right)^{v-1}
\]

(3)

The slope of tangent at p in step 2) is
\[
\left( \frac{ds}{d \ln H(s)} \right)_{s=s_{\max}} = -\frac{s_{\max}}{v \ln H_0}
\]

(4)

The coordinate of point p is \((s_{\max}, \ln(H_0/02))\)

Assuming straight line of curve c, the expression of \(H(s)\) when \(s > s_{\max}\) is
\[
s = s_{\max} \left[ 1 - \frac{1}{v \ln H_0} \left( \ln H(s) - \ln H_0 / 02 \right) \right]
\]

(5)

The estimated maxima of the extrapolated load spectrum is
\[
\hat{s}_{\max} = s_{\max} \left[ 1 + \frac{\ln(H_0 / 02)}{v \ln H_0} \right]
\]

(6)

3. Improved Extrapolation Method based on ESLS.
Since in the engineering practice, the impact of low amplitude load on mechanical structure is trivial, the exclusion of those amplitude from ESLS is first proposed in this article. The exclusion is realized by a gate \(s_{\text{gate}}\). The approach is similar as in above. However, the x-axis is changed in Fig. 4.

![Figure 4. The sketch map of IESLS](image)

The estimated maxima of the extrapolated load spectrum is
\[
\hat{s}_{\max} = s_{\max} - s_{\text{gate}} \left[ 1 + \frac{\ln(H_0 / 02)}{v \ln H_0} \right] + s_{\text{gate}}
\]

(7)

4. Example and Result Comparison
The key performance indicators of a load spectrum extrapolation method are
1) Error of estimated load maxima;
2) Goodness of fit of the extrapolated load spectrum (reflected by R-Square or RMSE), comparing with the ground truth data.

5. Measurement Data.
The measurement data is obtained on two real bogie frames of Chinese Standard EMU and Beijing Subway line 2 for identifying the vertical bouncing load of each frame. The sensors are placed at the ends of side beams shown in Fig. 5.
Figure 5. The load identification positions on these two bogie frames

The measurement sampling frequency is 1000Hz. The measurement length of Chinese Standard EMU is 7000s, during which the maximum operation speed is 300km/h; the measurement length of Beijing Subway line 2 is 57550s, during which the maximum operation speed is 75km/h. The detail measurement setup and data pre-processing (e.g. noise reduction) is the same as explained in [11]. The obtained load amplitude data is shown in Fig. 6.

Figure 6. Load time histories of the two measured vertical bouncing loads

In the following verification, short (1890s for Chinese Standard EMU and 2676s for Beijing Subway) measurement data is randomly selected and used for extrapolation. The full length of measurement data is served as the target length of the extrapolated load spectrum. The final result comparison is between extrapolated load spectrum using short measurement with ground truth load spectrum directly calculated by full measurement.

The characteristic parameter $v$ calculated by IESLS and ESLS is shown in Table 1. All the $v$ values of ESLS are slightly larger than that of IESLS. Table 2 shows the comparison of estimated load maxima of different extrapolation methods, all the estimated load maxima calculated by EPPE is smaller than the maxima of the ground truth with the minimum error 9.92%. For the EMU Load, the error of the estimated maxima from ESLS is 2.40% smaller than the error from IESLS, however, for the subway load, the error value of ESLS is 8.19% larger than the error of IESLS. The performance of estimating load maxima is thus comparative by using ESLS and IESLS.

Table 1. Comparison of the parameters calculated by IESLS with ESLS

| Parameter | ESLS on EMU | IESLS on EMU | ESLS on Subway | IESLS on Subway |
|-----------|-------------|--------------|----------------|-----------------|
| $v$       | 1.23        | 0.97         | 1.01           | 0.74            |
Table 2. Comparison of estimated load maxima of different extrapolation methods

| Extrapolation Method       | EMU Load (kN) | Error   | Subway Load (kN) | Error   |
|---------------------------|---------------|---------|------------------|---------|
| Ground Truth              | 5.24          | 11.47   | 2.78             | 75.76%  |
| Normal Distribution       | 2.33          | 55.53%  | 2.78             | 75.76%  |
| Weibull distribution      | 2.77          | 47.14%  | 3.74             | 67.39%  |
| Log-normal Distribution   | 4.72          | 9.92%   | 7.34             | 36.01%  |
| ESLS                      | 5.44          | 3.74%   | 10.27            | 10.72%  |
| IESLS                     | 5.52          | 5.34%   | 11.18            | 2.53%   |

Table 3. Goodness of fit statistics

|                      | Before extrapolation | After extrapolation | Before extrapolation | After extrapolation |
|----------------------|----------------------|---------------------|----------------------|---------------------|
|                      | IESLS                | ESLS                | IESLS                | ESLS                | IESLS                | ESLS                | IESLS                | ESLS                |
| RMSE                 | 358                  | 2567                | 282                  | 2557                | 611                  | 5825                | 3143                  | 7338                |
| R-square             | 0.9990               | 0.9309              | 0.9994               | 0.9317              | 0.9982               | 0.8487              | 0.9847               | 0.9091              |

Fig. 7 gives the intuitively comparison of IESLS with ESLS. The estimated load spectrum has the same length with ground truth. It is extrapolated from the modelled load spectrum (black solid line) which has shorter length. The modelled load spectrum is the obtained by the curve fitting with the original short length load spectrum (randomly selected from full length measurement) by using Eq. 2.

The result shows that by using IESLS the estimated load spectrum is more likely fits the ground truth than using ESLS, especially in the middle 1/3 part of the curves.

Table 3 provides the quantitative evidence of the above intuitive feeling. Before extrapolation, RMSE and R-square is calculated between original short length load spectrum and modelled short length load spectrum. After extrapolation, RMSE and R-square is calculated between estimated full length load spectrum and the full length ground truth. Firstly, before the extrapolation, IESLS provides better spectrum modelling goodness than ESLS. Secondly and most importantly, IESLS provides a more precise extrapolation result which is closer to the ground truth than ESLS.

![Figure 7. Comparison of extrapolation results of IESLS with ESLS](image)

6. Conclusion

The extrapolation method IESLS is proposed in this article and the precision of extrapolation is proved using real measurement data from both low-speed and high-speed railway vehicle. The method could
be contributed to multiple engineering practice to compensate the short length of measurement data. However, in order to reach a certain performance, the minimum required measurement data length used for IESLS extrapolation is still not clear. More verifications could be made in the future by applying the IESLS using various length of measurement data.

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