Research on the evolution law of dynamic performance of CR400BF EMU train based on stochastic dynamics simulation

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Abstract
Purpose – This paper aims to obtain the evolution law of dynamic performance of CR400BF electric multiple unit (EMU).
Design/methodology/approach – Using the dynamic simulation based on field test, stiffness of rotary arm nodes and damping coefficient of anti-hunting dampers were tested. Stiffness, damping coefficient, friction coefficient, track gauge were taken as random variables, the stochastic dynamics simulation method was constructed and applied to research the evolution law with running mileage of dynamic index of CR400BF EMU.
Findings – The results showed that stiffness and damping coefficient subjected to normal distribution, the mean and variance were computed and the evolution law of stiffness and damping coefficient with running mileage was obtained.
Originality/value – Firstly, based on the field test we found that stiffness of rotary arm nodes and damping coefficient of anti-hunting dampers subjected to normal distribution, and the evolution law of stiffness and damping coefficient with running mileage was proposed. Secondly stiffness, damping coefficient, friction coefficient, track gauge were taken as random variables, the stochastic dynamics simulation method was constructed and applied to the research to the evolution law with running mileage of dynamic index of CR400BF EMU.

Keywords Vehicle system dynamics, Stiffness of rotary arm nodes, Anti-snaking damper damping, Random variable

Paper type Research paper

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1. Introduction

The basic prerequisite for the normal operation of high-speed electric multiple unit (EMU) is the safe operation of trains, among which the key suspension components of the running gear that have a significant impact on the stability of the high-speed EMUs will not malfunction or completely fail during service.

The actual situation is that even if the key suspension components of the running gear do not malfunction during the service of the high-speed EMU, the dynamic parameters of the key suspension components of the bogie will also change during the service of the high-speed EMU, usually with significant differences from the design values, which may bring about operational stability issues of the service high-speed EMU.

Hu, Hou, Guo, Fan, and Luo (2019) mentions that the radial stiffness range of the CRH380B EMU's rotary arm node, which operates for 1.2 million kilometers, is between 74.5 and 163.18 MN/m, which is significantly different from the nominal value of the CRH380B EMU's axle box rotary arm node radial stiffness of 120 MN/m. This leads to a decrease in the critical hunting speed of the CRH380B EMU. Wu (2018) conducted practical tests, and the results showed that the damping of the anti-hunting damper of the CRH380B EMU during the fourth level repair was significantly lower than that during the third level repair, and the fullness of the indicator diagram decreased, indicating a significant decrease in the anti-hunting damper's ability to resist snake motion. In addition, during the operation of the high-speed EMU, the wheel and rail profile will also change accordingly. Studies have shown that the wheel rail profile has a significant impact on the dynamics of the high-speed EMU. For example, the study of Sun, Li, Hu, Chang, Cheng, and Zhou, (2020) shows that with the increase of the running mileage after wheel turning, the critical speed of vehicle hunting generally shows a downward trend. Yang, Cheng, Song, Zhou, and Zhou (2021) used simulation methods to study the impact of deviation changes in the 60N rail profile on the operational performance of high-speed EMUs, and proposed a tolerance for the 60N rail profile.

Many scholars studied the impact of dynamics parameters of suspension component, wheel and rail profiles on the dynamics of high-speed EMU by choosing one parameter or several combinations of those parameters (Bai, Zeng, Shi, & Wu, 2020; Mădălina & Dragos, 2020; Hou, Hu, Zong, Guo, Luo, & Fan, 2021). These studies had yielded many meaningful results, but they only consider simple combinations of maximum and minimum values for a small number of parameters, without considering these parameters as random variables then systematically studying the distribution range and form of vehicle dynamics index when those parameters undergo random changes simultaneously. The application of stochastic dynamics simulation mainly comes from the sensitivity analysis of dynamic parameters (Kassa & Nielsen, 2008; Mazzola & Bruni, 2012; Kraft, Puel, Aubry, & Funfschilling, 2013; Bigoni, True, & Engsig-karup, 2014) Subsequently, some scholars have applied this method to vehicle dynamics, such as Funfscilling (Funfschilling, Perrin, & Kraft, 2012), which randomly combines typical concerned parameters according to probability distribution values to obtain calculation conditions and obtain the distribution of dynamic index.

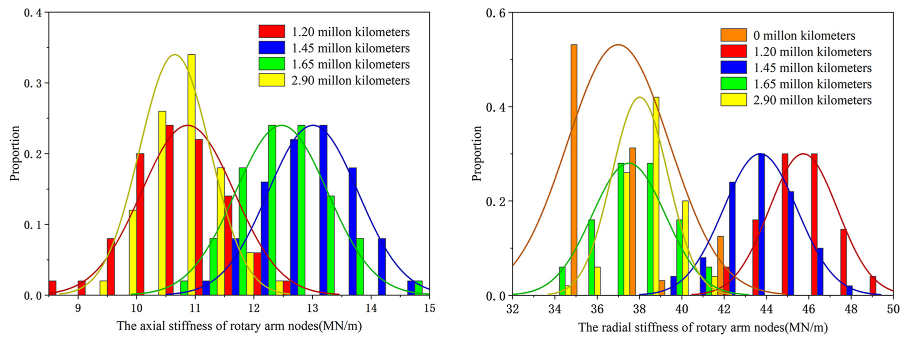
Some scholars in China has also carried out an amount of research work in this area. Luo Ren considered the randomness of stiffness and damping of suspension, wheel rail interface parameters, track irregularity and axle load, then studied the stochastic statistical characteristics of dynamic performance of high-speed EMU (Luo, Li, Hu, & Peng, 2015). These scholars use the Monte Carlo method to sample the values of random parameters and the disadvantage of the Monte Carlo method is that the sampling of random variables is random, which causes a large number of simulation to obtain satisfactory results. When there are many random variables, the simulation calculation cost is too high to implement. In order to resolve this problem, Teng, Luo, and Shi (2019) used Latin hypercube sampling method to obtain suspension parameters and wheel rail geometric parameters, and studied the dynamic performance of high-speed EMU running at environment of −40 °C. However, the research results have little guiding significance for high-speed EMU under non low-temperature operating conditions. Li Shuang used Latin hypercube sampling to simulate random changes in parameters and studied the sensitivity of various suspension random parameters to changes in running smooth index, but did not conduct research on the stability and safety of high-speed EMU operation (Li, Yu, Chen, & Li, 2015).

The research mentioned above is the range of dynamic index under various random parameter changes in a specific operating mileage. But currently there is limited research on the evolution of dynamic parameters of suspension components of high-speed EMU bogies with operating mileage through testing and statistics, and it is also impossible to systematically obtain the variation law of dynamic index with operating mileage. Therefore, this article tested the stiffness of the rotary arm node and the damping of the anti-hunting damper of the CR400BF high-speed EMU from 0 to 2.9 million kilometers, and obtained those evolution law with the operating mileage. Based on test data, combined with the random changes in wheel profile, wheel rail friction coefficient, and wheel rail geometric dimensions, the operational stability, safety, and stability of the CR400BF high-speed EMU unit will be studied as a function of the operating mileage.

2. Evolution law of stiffness of rotary arm nodes and damping of anti-hunting dampers

2.1 Stiffness of rotary arm nodes

The measured data of the axial and radial stiffness of the rotary arm nodes of the CR400BF high-speed EMU bogies with service mileage of 0 million, 1.2 million, 1.45 million, 1.65 million, and 2.9 million kilometers are shown in Figure 1. From Figure 1, it can be seen that the radial stiffness of the 0 million kilometers rotary arm node does not follow a normal distribution, with a distribution range of 35–43 MN/m and an average of 37 MN/m, and at other mileage the distribution of the axial and radial stiffness of the rotary arm nodes can be roughly regarded as normal distribution. The distribution range, mean, and variance at different mileage are shown in Table 1. From Table 1, it can be seen that in terms of axial stiffness, the mean increased by 19.58% at from 1.2 million kilometers to 1.45 million kilometers, and decreased by 18.14% at from 1.45 million kilometers to 2.9 million kilometers, and the variance of the normal distribution decreases with the increase of service mileage, a decrease of 43.75% compared to 1.2 million kilometers and 2.9 million kilometers. In terms of radial stiffness, the



axial stiffness
(a)

radial stiffness
(b)

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Figure 1.
Comparison histogram of stiffness of rotary arm nodes in operating mileage

Table 1.
Statistical values of stiffness of rotary arm nodes MN/m

Direction	Statistical items	1.2 million kilometers	1.45 million kilometers	1.65 million kilometers	2.9 million kilometers
Axial	Distribution range	8.5~13	11~15	10.5~15	9~12.5
	Mean	10.88	13.01	12.47	10.65
	Variance	0.64	0.62	0.60	0.36
Radial	Distribution range	41.5~50	39~48.5	33~42	33~42
	Mean	45.74	43.69	37.49	38.04
	Variance	2.59	3.02	3.13	1.55

Source(s): Authors' own work

mean of the normal distribution decreased by 18.04% at from 1.2 million kilometers to 1.65 million kilometers, and increased by 1.47% at from 1.65 million kilometers to 2.9 million kilometers; The variance of the normal distribution increased by 20.85% at from 1.2 million kilometers to 1.65 million kilometers, and decreased by 50.48% at from 1.65 million kilometers to 2.9 million kilometers.

2.2 Anti-hunting damper damping

The measured data of anti-hunting dampers for the CR400BF high-speed EMU bogies with a service life of 1.2 million and 1.45 million kilometers are shown in Figure 2. From Figure 2, it can be seen that the distribution of the damping coefficient of the anti-hunting damper at each mileage is roughly regarded as a normal distribution, and the distribution range, mean, and variance at different mileage are shown in Table 2.

From Table 2, it can be seen that as the service mileage increases the mean of the normal distribution decreases for the damping coefficient for velocity of 0.02 m/s, Specifically decreases by 4.46% at velocity of +0.02 m/s, and decreases by 6.63% at velocity of −0.02 m/s. As the service mileage increases the variance of the normal distribution increases s for the damping coefficient, Specifically increases by 5.57% at velocity of +0.02 m/s, and decreases by 34.78% at velocity of −0.02 m/s. With the increase of service mileage, the mean and variance of the normal distribution of damping coefficient increase for velocity of 0.01 m/s, while the mean and variance at the velocity of +0.01 m/s damping coefficient increase by 3.34% and 106.4%, respectively; The mean damping coefficient increases by 4.1% at velocity of −0.01 m/s, and the variance increases by 94.29%.

3. Vehicle dynamics model

Taking into account the wheel rail contact relationship and nonlinear factors of key suspension parameters, a single CR400BF EMU trailer model was established using SIMPACK, the model is shown in Figure 3. The CR400BF EMU dynamic simulation model mainly includes the vehicle body, bogie, wheelset, axle box, suspension device, etc. The wheelset is connected to the bogie through rotary arm nodes of axle box, primary vertical dampers, and primary springs. The bogie is connected to the vehicle body through central suspension devices such as traction rod, air springs, lateral dampers, and anti-hunting dampers.

The vehicle body and bogie are both rigid bodies, fully considering the six degrees of freedom of the vehicle body, frame, and wheelset, including telescoping, lateral sway,

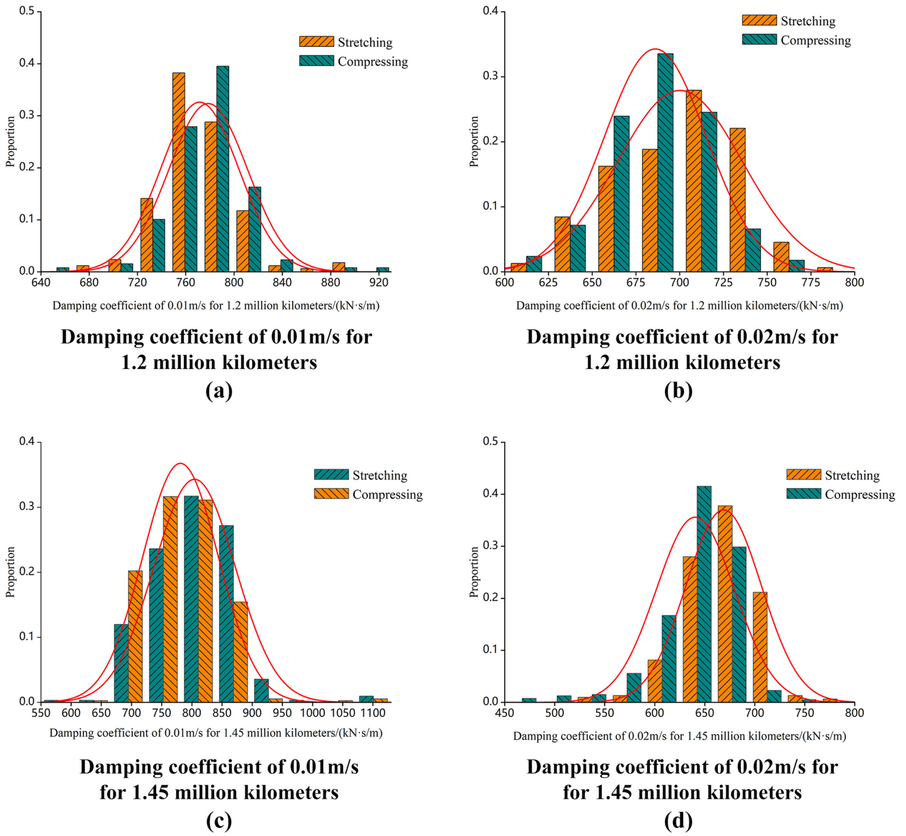

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Figure 2. Damping coefficient test results of anti-hunting dampers

Table 2. Statistical values of damping coefficient for anti-hunting dampers kN●s/m

Mileage	Statistical items	−0.02 m/s	+0.02 m/s	−0.01 m/s	+0.01 m/s
1.2 million kilometers	Distribution range	600~775	600~800	670~900	640~920
	Mean	686.09	700.17	750.50	778.59
	Variance	29.10	35.75	32.40	32.68
1.45 million kilometers	Distribution range	450~760	525~800	600~1,130	550~1,130
	Mean	640.62	668.95	781.25	804.57
	Variance	39.22	37.74	62.95	67.45

Source(s): Authors' own work

heaving, rolling, pitching, and yaw. The axle box only considers pitching degrees of freedom. Therefore, the CR400BF EMU trailer dynamics model includes a total of 50 degrees of freedom. The vehicle system topology diagram is shown in Figure 4, and the correctness of the dynamics simulation model of CR400BF EMU had been verified in literature (Yao *et al.*, 2019).

4. Stochastic dynamics simulation method

4.1 Random factors

One important aspect of vehicle system dynamics research is the wheel rail rolling contact behavior, which directly affects the dynamic performance of vehicles. With the increase of operating mileage, wheel wear continues to increase, and the relevant parameters of the line are also constantly changing. The rail profile changes slowly compared to the wheel profile, therefore, in this article, the 60N standard rail profile is selected, without considering the changes in the rail profile.

(1) Stiffness of rotary arm nodes and damping of anti-hunting dampers

The stiffness of the 1.2 and 1.45 million kilometer rotary arm nodes and the damping of the anti-hunting dampers are matched according to the operating mileage. The axial stiffness of the 0 million kilometer rotary arm node and the damping force of the 0, 1.65, and 2.9 million

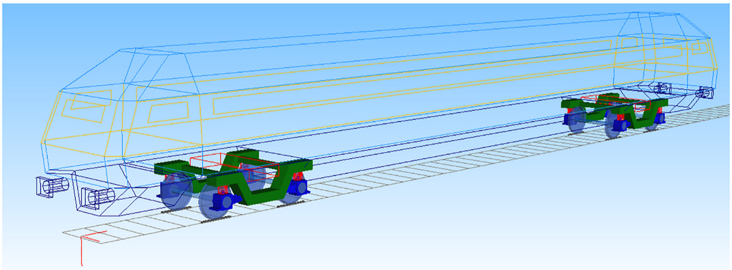

Figure 3.
Vehicle multi body dynamics model figure

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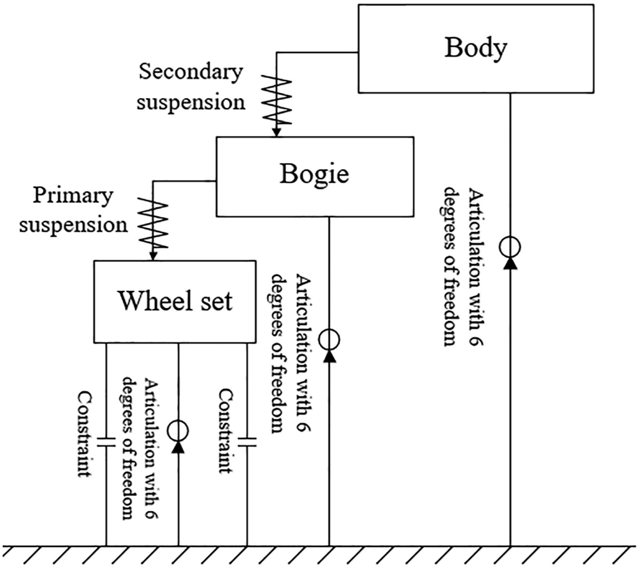

Figure 4.
Schematic diagram of vehicle topology structure

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kilometer anti-hunting dampers are taken according to the standard value specified in the usage requirements within an error range of ±15% due to the lack of measured data.

(2) Wheel profile

In order to fully simulate the actual operating conditions of the CR400BF high-speed EMU, the initial wheel tread of LMB10 is used as the standard, and predict wheel wear in 0~300 thousand kilometers period (Yao *et al.*, 2019). With a limit of every 50 thousand kilometers, and the worn tread of 0–300,000 kilometers of vehicles is input into the model. The nominal equivalent conicity of the wheel profile of different wear mileage matching with 60N rail profile is shown in Table 3.

(3) Wheel rail interface and geometric parameters

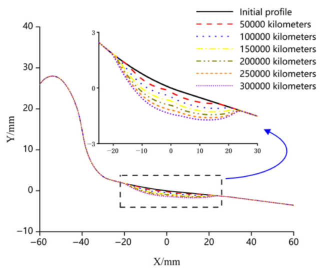
The geometric parameters of the track include track gauge and rail bottom slope, assuming they also follow a normal distribution. The range of values is obtained based on standard specifications and experimental literature. Wheel rail interface and geometric parameters are shown in Table 4.

4.2 Simulated line settings

The radius, Super-elevation, and operating speed of the line used in this paper are shown in Table 5.

4.3 Implementation procedure

This article conducts Latin hypercube sampling with number of samples specified based on the distribution of random variables and randomly combines them to modify the parameter

Wheel profile	Nominal Equivalent conicity	Outline drawing of wheel tread
LMB10	Standard	
LMB10_5wkm	0.163	
LMB10_10wkm	0.181	
LMB10_15wkm	0.256	
LMB10_20wkm	0.344	
LMB10_25wkm	0.420	
LMB10_30wkm	0.528	

Source(s): Authors' own work

Table 3. Wheel tread profile for different mileages

Parameters	Mean	Minimum	Maximum
Wheel rail friction coefficient	0.350	0.150	0.550
Track gauge/m	1.435	1.432	1.438
Rail bottom slope	40	30	50

Source(s): Authors' own work

Table 4. Wheel rail interface and geometric parameters

values of the simulation model file of CR400BF high-speed EMU constructed in SIMPACK. Then, the program calls the SIMPACK solver to simulate the modified models. Extract the time domain data of the required dynamic index from the SIMPACK result file through the result extraction program. According to the GB/T 5599—2019 Dynamic Performance Evaluation and Test Specification, write a program to calculate the relevant index and obtain the safety, stability, and running smooth index values of CR400BF. The simulation method flowchart is shown in Figure 5.

5. Simulation result

This section selects four representative index, namely lateral acceleration of the bogie, derailment coefficient, and wheelset lateral forces, to analyze stability, running smooth, and safety of CR400BF high-speed EMU with service mileage of 0 million, 1.45 million, 1.65 million, and 2.9 million kilometers.

5.1 Safety

The derailment coefficient and wheelset lateral forces for each service mileage are shown in Figures 6 and 7. From Figures 6 and 7, it can be seen that the distribution of derailment coefficient and wheelset lateral forces at each mileage can be roughly regarded as a normal distribution, and the mean and variance at different mileage are shown in Table 6. From Table 6, it can be seen that the average derailment coefficient decreased by 2.35% from 0 to 1.45 million kilometers, and increased by 0.69% from 1.45 million to 2.9 million kilometers; The variance of the derailment coefficient decreased by 3.70% from 0 to 2.9 million kilometers. The average wheelset lateral force decreased by 0.35% from 0 to 1.65 million

Table 5.
Simulation line settings

Number	Radius (m)	Super-elevation (mm)	Speed (km/h)
1	5,500	175	330
2	9,000	140	350
3	Straight line	–	350

Source(s): Authors' own work

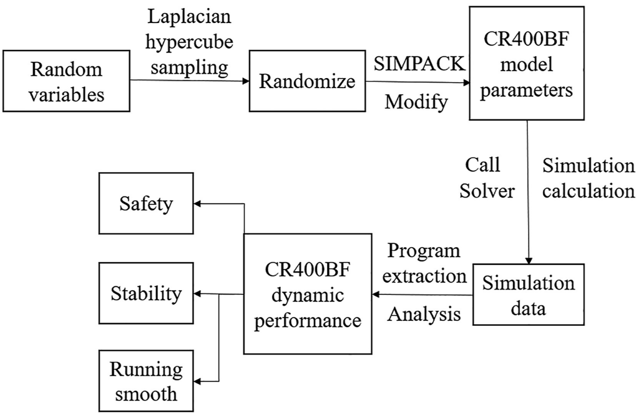


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Figure 5.
Simulation method flowchart

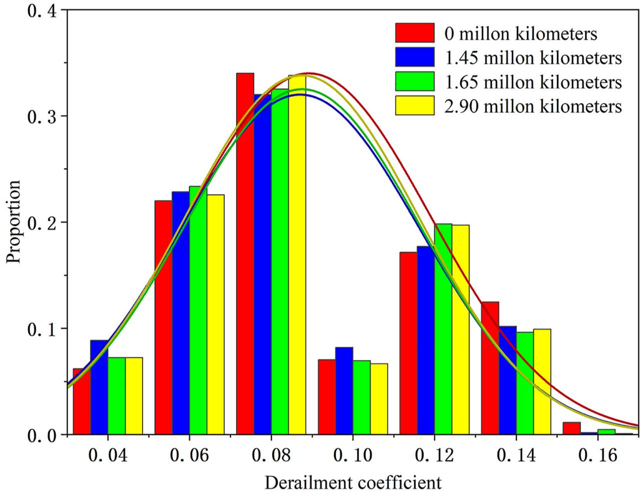

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Figure 6. Statistical histogram of derailment coefficient

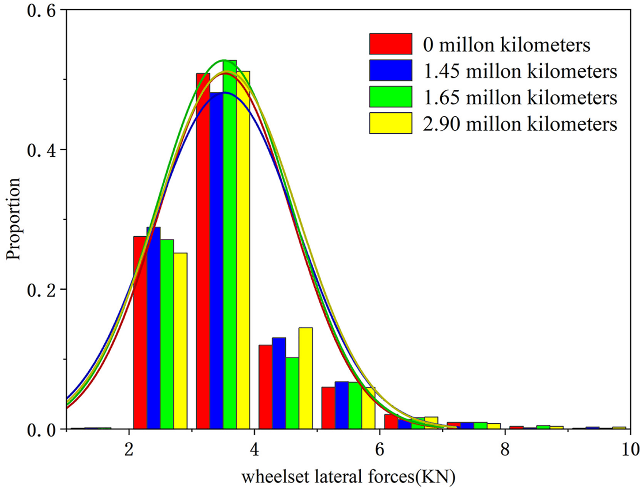

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Figure 7. Histogram of wheelset lateral forces

Safety index	Statistical items	0 million kilometers	1.45 million kilometers	1.65 million kilometers	2.9 million kilometers
Derailment coefficient	Mean	0.0892	0.0871	0.0876	0.0877
	Variance	0.0297	0.0292	0.0288	0.0286
Wheelset lateral forces	Mean	3.5281	3.5277	3.5158	3.5611
	Variance	1.0602	1.1514	1.1247	1.1232

Source(s): Authors' own work

Table 6. Statistical values of safety index

kilometers, and increased by 1.29% from 1.65 million to 2.9 million kilometers; the variance of wheelset lateral force increased by 8.6% from 0 to 1.45 million kilometers, and decreased by 2.45% from 1.45 million to 2.9 million kilometers.

5.2 Stability

The maximum lateral acceleration of the bogie for each service mileage is shown in Figure 8. From Figure 8, it can be seen that the distribution of the maximum lateral acceleration of the bogie at each mileage can be roughly regarded as a normal distribution, and the mean and variance at different mileage are shown in Table 7. From Table 7, it can be seen that the average maximum lateral acceleration of the bogie decreased by 1.33% from 0 to 1.45 million kilometers, and increased by 0.69% from 1.45 million to 2.9 million kilometers; The variance of the maximum lateral acceleration of the bogie increased by 0.23% from 0 to 1.65 million kilometers, and decreased by 0.38% from 1.65 million to 2.9 million kilometers.

5.3 Running smooth

The lateral running smooth index of the bogie for each service mileage is shown in Figure 9. From Figure 9, it can be seen that the distribution of the lateral running smooth index at each mileage is roughly regarded as a normal distribution, and the mean and variance of different mileage are shown in Table 8. From Table 8, it can be seen that the mean value of the lateral running smooth index decreased by 0.24% from 0 to 2.9 million kilometers; the variance of the

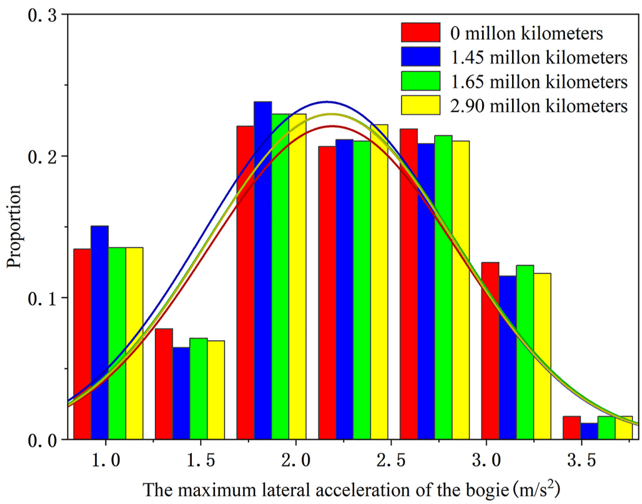

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Figure 8. Statistical histogram of maximum lateral acceleration of the bogie

Table 7. Statistical values of stability index

Stability index	Statistical items	0 million kilometers	1.45 million kilometers	1.65 million kilometers	2.9 million kilometers
Lateral acceleration of the bogie	Mean	2.1906	2.1615	2.1859	2.1868
	Variance	0.6546	0.6547	0.6561	0.6507

Source(s): Authors' own work

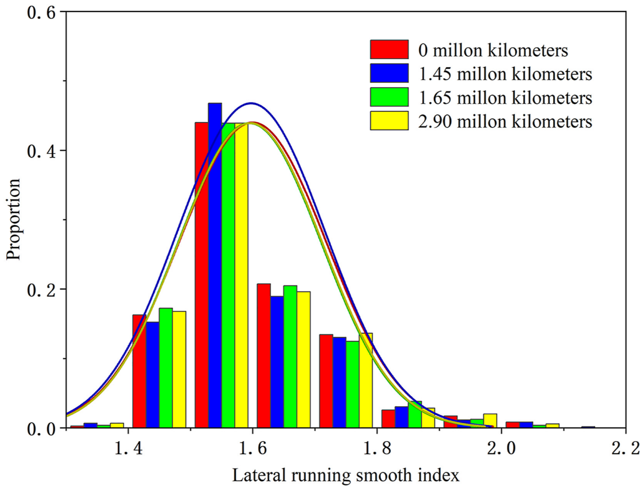

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Figure 9. Histogram of lateral running smooth index

Table 8. Statistical values of running smooth index

Running smooth index	Statistical items	0 million kilometers	1.45 million kilometers	1.65 million kilometers	2.9 million kilometers
Lateral running smooth index	Mean	1.5999	1.5974	1.5962	1.5961
	Variance	0.1187	0.1184	0.1154	0.1159

Source(s): Authors' own work

lateral running smooth index decreased by 2.78% from 0 to 1.65 million kilometers, and increased by 0.43% from 1.65 million to 2.9 million kilometers.

In summary, the dynamic index which subject to normal distribution of vehicles with different service mileage have similar contours, and the fitting curves of the histograms of the dynamic index of vehicles with different service mileage roughly overlap. As the mileage increases, the mean and variance of various dynamic index fluctuate, but the changes are not significant, indicating that the vehicle's dynamic performance still maintains good performance with the increase of service mileage.

6. Conclusion

(1) The mean of the normal distribution of axial stiffness of the rotary arm node increased by 19.58% from 1.2 million kilometers to 1.45 million kilometers, and decreased by 18.14% from 1.45 million kilometers to 2.9 million kilometers; the variance of the normal distribution decreases with the increase of service mileage, a decrease of 43.75% compared to 1.2 million kilometers and 2.9 million kilometers. The mean radial stiffness normal distribution of the rotary arm node decreased by 18.04% from 1.2 million kilometers to 1.65 million kilometers, and increased by 1.47% from 1.65 million kilometers to 2.9 million kilometers; The variance of the normal distribution increased by 20.85% from 1.2 million kilometers to 1.65 million kilometers, and decreased by 50.48% from 1.65 million kilometers to 2.9 million

kilometers. The damping coefficient of the anti-hunting damper at 0.02 m/s decreases with the increase of service mileage, the mean of the normal distribution decreases, the damping coefficient at +0.02 m/s decreases by 4.46%, and the damping coefficient at −0.02 m/s decreases by 6.63%; The variance of the normal distribution increases, the damping coefficient increases by 5.57% at +0.02 m/s, and the damping coefficient increases by 34.78% at −0.02 m/s. The damping coefficient of the anti-hunting damper at 0.01m/s increases with the increase of service mileage, and both the mean and variance of the normal distribution increase. The mean damping coefficient at +0.01 m/s increases by 3.34%, and the variance increases by 106.4%. The mean damping coefficient increases by 4.1% at 0.01 m/s, and the variance increases by 94.29%.

(2) Through simulation, it was found that the average derailment coefficient of CR400BF EMU decreased by 2.35% from 0 to 1.45 million kilometers, and increased by 0.69% from 1.45 million to 2.9 million kilometers; The variance of the derailment coefficient decreased by 3.70% from 0 to 2.9 million kilometers. The average wheelset lateral forces decreased by 0.35% from 0 to 1.65 million kilometers, and increased by 1.29% from 1.65 million to 2.9 million kilometers; the variance of wheelset lateral forces increased by 8.6% from 0 to 1.45 million kilometers, and decreased by 2.45% from 1.45 million to 2.9 million kilometers. The average maximum lateral acceleration of the bogie decreased by 1.33% from 0 to 1.45 million kilometers, and increased by 0.69% from 1.45 million to 2.9 million kilometers; the variance of the maximum lateral acceleration of the bogie increased by 0.23% from 0 to 1.65 million kilometers, and decreased by 0.38% from 1.65 million to 2.9 million kilometers. The average lateral running smooth index decreased by 0.24% from 0 to 2.9 million kilometers; the variance of the lateral running smooth index decreased by 2.78% from 0 to 1.65 million kilometers, and increased by 0.43% from 1.65 million to 2.9 million kilometers.

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Further reading

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