Acta Mech. Sin. (2016) 32(2):206–214
DOI 10.1007/s10409-015-0471-0

RESEARCH PAPER

Dynamic simulation and safety evaluation of high-speed trains meeting in open air

Songyan Li[1] · Zhijun Zheng[1] · Jilin Yu[1] · Chunqiang Qian[1]

Received: 24 September 2014 / Revised: 28 December 2014 / Accepted: 3 May 2015 / Published online: 15 August 2015

Abstract Dynamic responses of a carriage under excitation with the German high-speed low-interference track spectrum together with the air pressure pulse generated as high-speed trains passing each other are investigated with a multi-body dynamics method. The variations of degrees of freedom (DOFs: horizontal movement, roll angle, and yaw angle), the lateral wheel-rail force, the derailment coefficient, and the rate of wheel load reduction with time when two carriages meet in open air are obtained and compared with the results of a single train travelling at specified speeds. Results show that the rate of wheel load reduction increases with the increase of train speed and meets some safety standard at a certain speed, but exceeding the value of the rate of wheel load reduction does not necessarily mean derailment. The evaluation standard of the rate of wheel load reduction is somewhat conservative and may be loosened. The pressure pulse has significant effects on the train DOFs, and the evaluations of these safety indexes are strongly suggested in practice. The pressure pulse has a limited effect on the derailment coefficient and the lateral wheel-rail force, and, thus, their further evaluations may be not necessary.

Keywords High-speed train · Pressure pulse · Derailment · Dynamics simulation · Safety standard

✉ Zhijun Zheng
zjzheng@ustc.edu.cn

1 CAS Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, Hefei 230026, China

1 Introduction

Aerodynamics problems and structural safety involved in modern high-speed trains have gained much attention [1]. When two trains pass each other, an air pressure pulse generates and sweeps through car bodies, which is a type of transient load. A typical feature of a pressure pulse is that the value of pressure fluctuation alternates positively and negatively [2], which is caused by the fore-/after-body of one train passing the other train. The spatial interval between the positive- and the negative-peak pressure values is constant and the peak value of the air pressure pulse is proportional to the square of the relative speed of trains [3]. For example, Xiong and Liang [4] measured the pressure pulse generated in the meeting of China Railways CRH2 Electric Multiple Unit (EMU) trains and presented a fitting function of the pressure amplitude versus meeting speeds. In addition, Tian and He [5] simulated the three-dimensional flow field with a fluid dynamics method to obtain the pressure pulse. Furthermore, Cui and Zhang [6] employed fluid dynamics and train multibody system dynamics methods, analyzed the dynamics response of a train traveling under a crosswind, and evaluated the safety indexes under a crosswind environment. Also, Lai et al. [7] indicated that strong transient loads generated by high-speed trains meeting have significant effects on horizontal movement, roll angle, and yaw angle of trains. When subjected to a pressure pulse, a train is more likely to have snaking motion, overturn, and derail. Lateral wheel-rail force [8], derailment coefficient [9], and rate of wheel load reduction [10] are key indexes to evaluate the safety of running vehicle. A track irregularity has a significant effect on the running safety of trains. An investigation by Choi et al. [11] showed the irregularities of cross level, vertical profile, and gauge to understand their influence on the safety indexes of trains. Wheel-rail unsymmetrical contact caused by wheel profile wear of high-speed trains may lead to lateral instability and a large derailment coefficient [12]. In another study, Bocciolone et al. [13] studied the crosswind action on rail vehicles. Meanwhile, Li et al. [14] investigated the characteristics of a pressure wave induced by high-speed trains meeting in open air. A new method for numerical simulation was found by Zhao and Sun [15] for two trains passing each other at the same speed. In another study, Liu et al. [16] studied the influence factors and developed a regularity for an air pressure pulse as trains pass by each other. Also, Qian et al. [17] simulated a dynamic response for side windows of high-speed trains subjected to crossing air pressure pulse.

A multi-body dynamics method is employed herein to analyze the dynamic response of a middle car of China Railways CRH3 EMU, whose geometric and kinetic parameters are the same as the actual vehicle. The air pressure measured from high-speed trains on the Zhengzhou–Xi'an railway passenger dedicated line by China Academy of Railway Sciences is adopted, and excitation with the German high-speed low-interference track spectrum is applied to the running train model. The vibrations of degrees of freedom (DOFs: horizontal movement, roll angle, and yaw angle), the lateral wheel-rail force, the derailment coefficient, and the rate of wheel load reduction of two trains meeting in open air are compared with the results of a single train traveling at certain speeds. The influences of air pressure applying to traveling trains on all safety indexes are obtained.

2 Numerical model

2.1 Multi-body dynamics model

A China Railways CRH3 EMU has eight carriages. The first and the last carriages are cabs, and the other carriages are passenger areas. One of the passenger carriages is simplified and shown in Fig. 1. Its dynamic responses are carried out by using a multi-body dynamics simulation method in the commercial software SIMPACK. A simplified model of bogies is shown in Fig. 2. The model is established as follows:

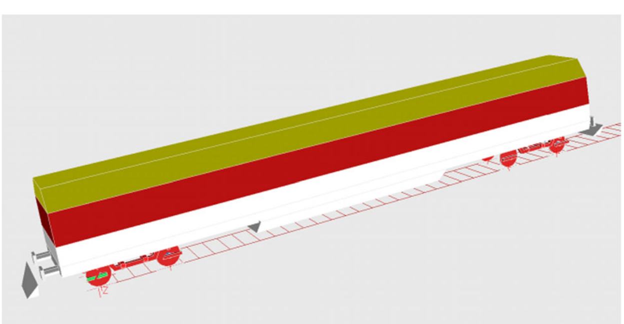

Fig. 1 Model of a car body

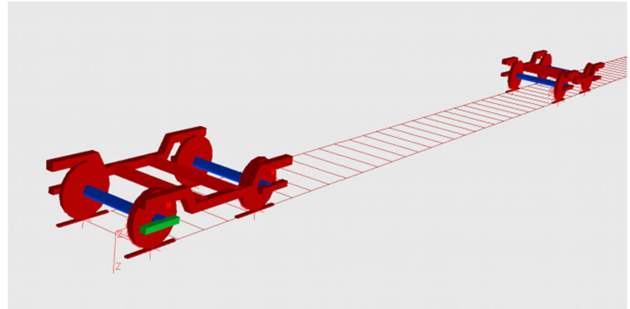

Fig. 2 Models of bogies

(1) The models including one car body, two bogies, four wheelsets, and eight rotating arms are assumed to be rigid. Each rotating arm has one DOF, and any of the other free rigid bodies has three translational DOFs and three rotational DOFs. Thus, there are in total 42 independent DOFs and eight constrained DOFs.
(2) The total mass and the rotational inertias of a carriage, and the parameters of bogies are consistent with those of an actual carriage.
(3) Some tiny structures, such as door handles and power boxes, are not included in the car body model.
(4) The air pressure generated by the first cab is considered, and the peak value of the air pressure is taken to be constant in the vertical direction of a carriage.

2.2 Nonlinear details

The nonlinear parts of the model mainly include the wheel rail contact nonlinear geometry relationship, wheel rail creep, free transverse momentum of the wheel set, and nonlinear suspension system. In this study, the wheel tread of the train is S1002GH and the rail outline is Rail_60H [18]. The wheel-rail relationship is shown in Fig. 3. The nonlinear factors of the suspension system mainly include the vertical dampers of primary suspension and secondary suspension, the lateral damper of secondary suspension, anti-snake movement damper, and the lateral stopping block. The force–displacement curve of a lateral stopping block is shown in Fig. 4.

2.3 Simplification and loading of pressure pulse

Consider a typical pressure pulse generated by trains passing each other in open air applyied to a passenger carriage. Two trains travel at the same speed, denoted as V. When they pass each other, the pressure pulse relative to a train moves with speed v, which is twice the meeting speed of trains, written as

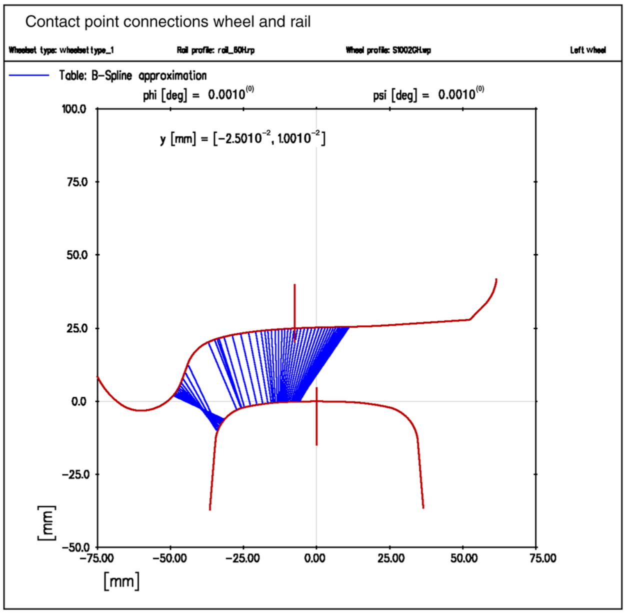

Fig. 3 Spatial wheel/rail contact geometry relationship

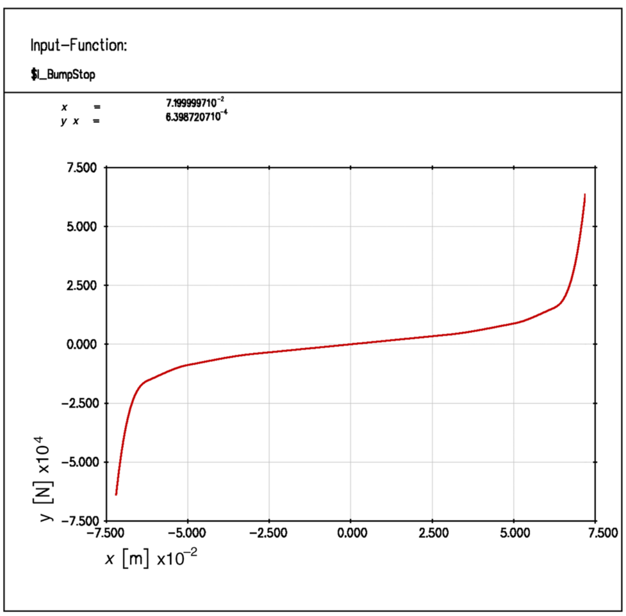

Fig. 4 The force–displacement curve of a lateral stop

$$v = 2V. \tag{1}$$

An example of the pressure pulse measured is given in Fig. 5. The waveform of the central compartment point was measured, when the CRHA380 trains passed each other in open air in the line of Zhengzhou–Xi'an in September, 2010. When the heads of the trains meet each other, the amplitude of the pressure wave generated is much higher than that when the tails of the trains meet each other. Here, only the waveform of the pressure pulse when the heads of the trains

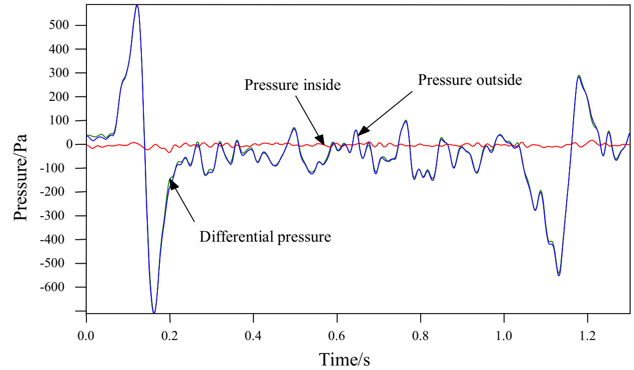

Fig. 5 The pressure pulse was measured from the middle point of the passenger carriage by China Academy of Railway Sciences when two CRHA380 trains passed each other in open air on the Zhengzhou–Xi'an railway at 350 km/h in September, 2010

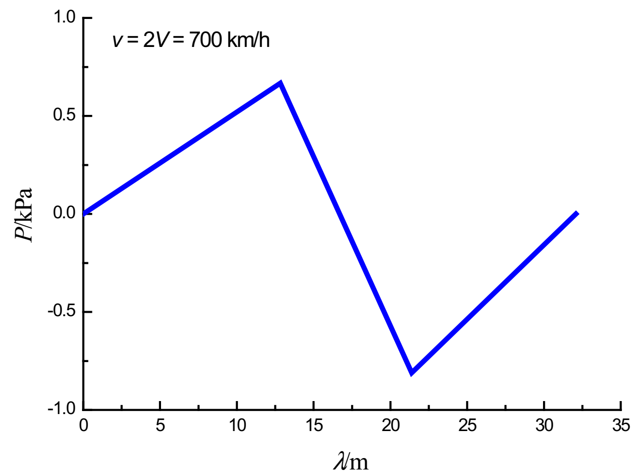

Fig. 6 Simplified pressure pulse of CRH3 when two trains pass each other at 350 km/h

meet each other is taken into consideration. The simplified waveform when two trains pass each other at the same speed of $V = 350$ km/h is shown in Fig. 6, and the wavelength of the pressure pulse does not vary with the change of the meeting speed.

Applying the pressure pulse sweeping through the carriage to the centroid of the train (the pressure pulse in the vertical direction is uniformly distributed) and using the interaction method, we get the force perpendicular to the side of the carriage F_y, the shaking moment M_z, and the overturning moment M_x. The expressions are given by

$$\begin{aligned} F_y(t) &= \int_{vt-L}^{vt} P(x)h\,\mathrm{d}\,x, \\ M_z(t) &= \int_{vt-L}^{vt} (x - x_c)P(x)h\,\mathrm{d}\,x, \\ M_x(t) &= F_y(t)D, \end{aligned} \tag{2}$$

where L is the length of a single carriage, h the effective height of train, D the height difference between the geometric center and the centroid of carriage, $P(x)$ the spatial

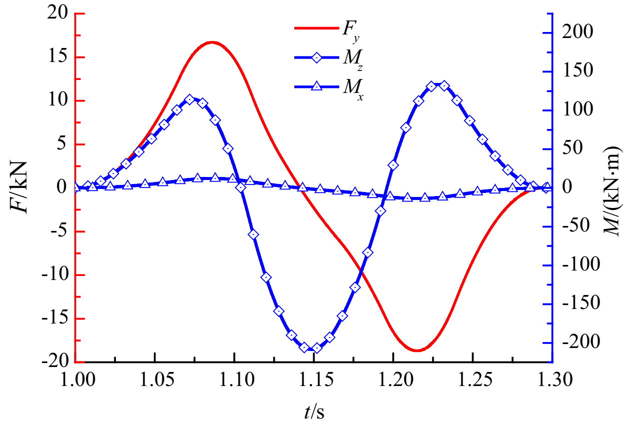

Fig. 7 The force and moments of CRH3 when two trains pass each other at 350 km/h

distribution function of the pressure pulse, and x_c the location of the centroid of carriage. The force and moments applying to the carriage when two trains pass each other in open air at 350 km/h are shown in Fig. 7. According to the rule that the amplitude of the pressure pulse is in proportion to the square of the meeting speed, we have

$$p = 0.012V^2, \tag{3}$$

where p is the absolute value of the difference between the positive and the negative amplitude of the pressure pulse, whose unit is kPa, and V the meeting speed of trains, whose unit is km/h. Furthermore, we can get the force, F_y, and the two moments, M_z and M_x, at different meeting speeds.

2.4 Working conditions

The rails of railway are not in the ideal straight and flat situation. They have several types of irregularity, including alignment irregularity, cross level irregularity, vertical profile irregularity, and gauge irregularity. These geometric irregularities make the wheel have much interaction with the rail, cause rail surface abrasion and track geometry changes, and make the rail have random and imbalanced conditions [11]. The faster a train travels, the larger frequency range of the track irregularity effects. This increases the disturbance and decreases the stability of traveling. The international standard of the German high-speed low-disturbance spectrum [11] is applied in the present simulation. For the comparability of results, the track spectrum is used at different traveling speeds of trains and different track irregularities.

The working conditions for the multi-body dynamics simulation in this study are:

(1) Transient pressure pulses are generated under the condition of trains meeting at constant speeds of 250, 300, 350, 400, 450, and 500 km/h.

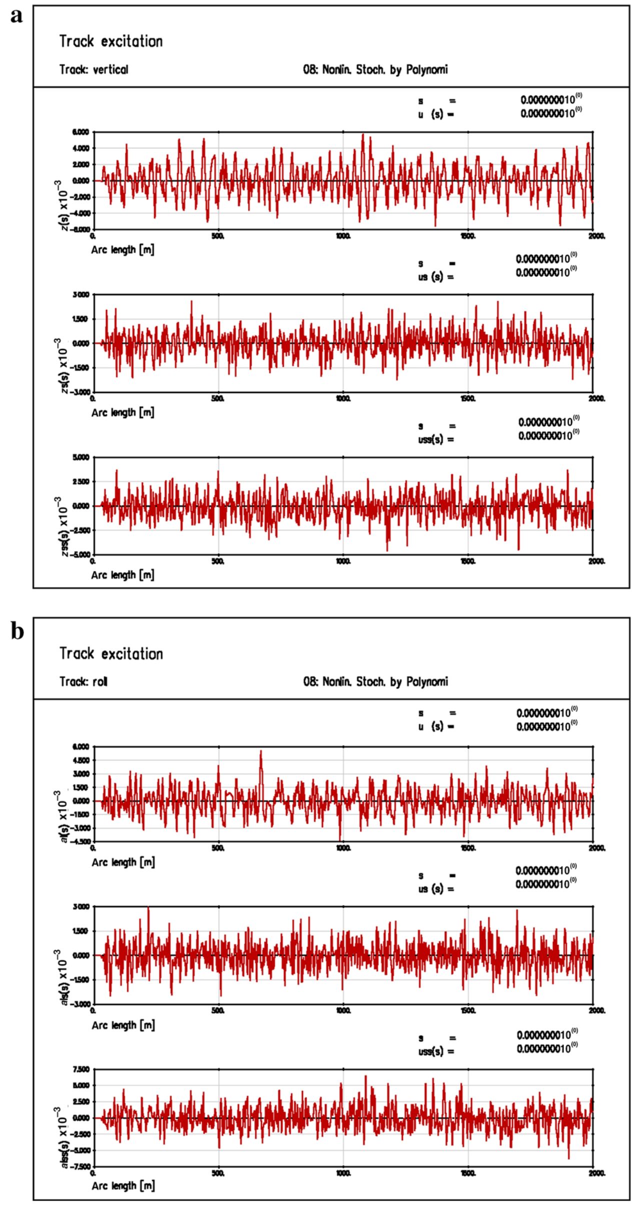

Fig. 8 Irregularities of the German high-speed low-disturbance spectrum. **a** Vertical profile irregularity and alignment irregularity. **b** Cross level irregularity (The data are from the commercial software SIMPACK.)

(2) The track excitation is the German high-speed low-disturbance spectrum[19], including vertical profile, cross level and alignment irregularities, see Fig. 8.

3 Results and discussion

3.1 Dynamic response of train DOFs

When a high-speed train moves on irregular tracks, it has small vibration responses. The maximum amplitude that the

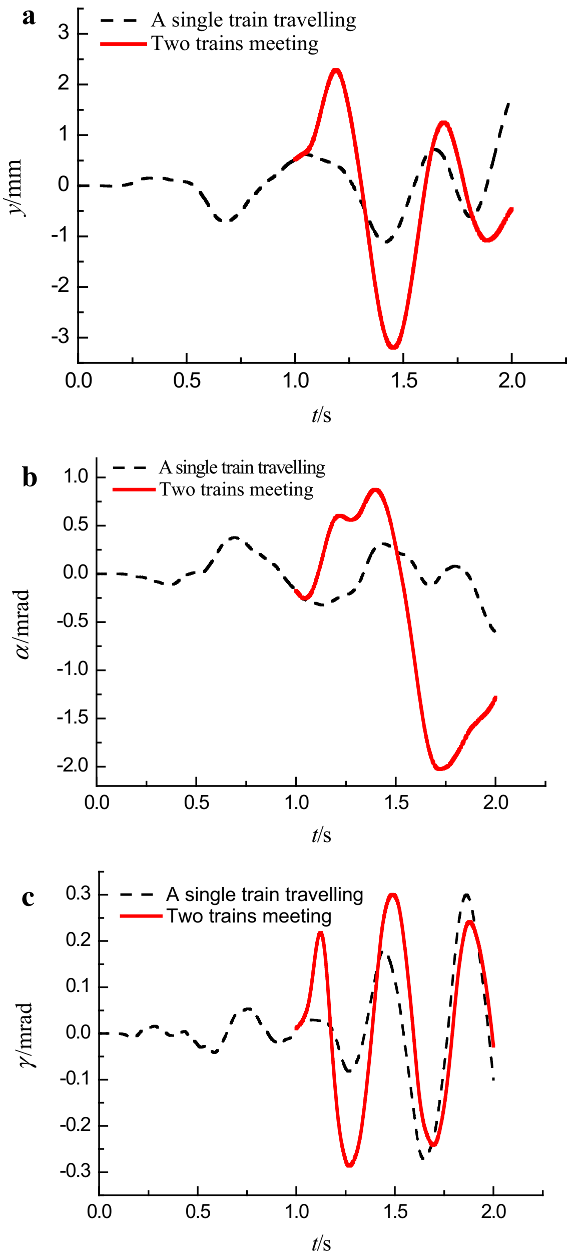

Fig. 9 Comparison of vibrations between two trains passing each other and a single train traveling at 400 km/h. **a** Horizontal movement. **b** Roll angle. **c** Yaw angle

vibration responses can reach is an important condition for measuring the operation's stability. When two trains pass each other, the swings of the trains may be much evident. The variations of horizontal movement, roll angle, and yaw angle when two trains pass each other in open air at 400 km/h, and when a train travels alone are shown in Fig. 9. Vibrations in all directions are significantly increased with the increase of time. The maximum values of vibrations are given in Table 1. It is found that the pressure wave when two trains pass each other in open air has significant effects on the vibrations of train DOFs. The horizontal movement and the yaw angle of the meeting trains vary more strongly than those of a single traveling train. The severe vibrations may increase the likelihood of capsizing and serpentine locomotion of trains, and decrease the train operation stability and the passenger comfort.

Table 1 The maximums of vibration when two trains pass each other and when a single train travels at 400 km/h

	Single train traveling	Trains meeting	Relative increase (%)
Horizontal movement/mm	0.62	2.29	269.4
Roll angle/μrad	321.25	603.62	87.9
Yaw angle/μrad	81.30	284.22	249.6

3.2 Lateral wheel-rail force

The lateral wheel-rail force is the transverse component of the force between track and wheel, whose maximum value is used to judge whether the train will lead to gauge widening or produce some severe deformation on the line. The first and the second limit values of the lateral wheel-rail force are given by [8]

$$H \leqslant 10 + (P_{\mathrm{st1}} + P_{\mathrm{st2}})/2, \\ H \leqslant 0.85\,[10 + (P_{\mathrm{st1}} + P_{\mathrm{st2}})/3], \tag{4}$$

where H is the maximum of the lateral wheel-rail force with the unit of kN, and P_{st1} and P_{st2} the static loads of the left- and right-side wheels, respectively, with the unit of kN. In general, the lateral wheel-rail force requires meeting a tougher second limit. In the other words, it has certain standards for a safety margin. According to the railway vehicles–specification for evaluation, the dynamic performance, and accreditation test [8], the weight of the locomotive axle load studied in this study is 116.35 kN, and the second standard in Eq. (4) gives $H \leqslant 41.47$ kN. The lateral wheel-rail forces of the four wheelsets versus train speeds are shown in Fig. 10. It shows that the lateral wheel-rail force of each wheelset is increased with the increase of the meeting speed. When the meeting speed is under 500 km/h, all the lateral wheel-rail forces are less than the critical value 41.47 kN. The lateral wheel-rail force is affected by both the rail random excitation and the air pressure pulse. The lateral wheel-rail force at 250 km/h could be slightly greater than that at 300 km/h in some wheelsets.

3.3 Derailment coefficient

Derailment means that the geometric relationship between wheel and rail is broken. This possibility of derailment is measured by the derailment coefficient, which is defined as the ratio of wheel lateral (Q_{w}) to vertical (P_{w}) forces

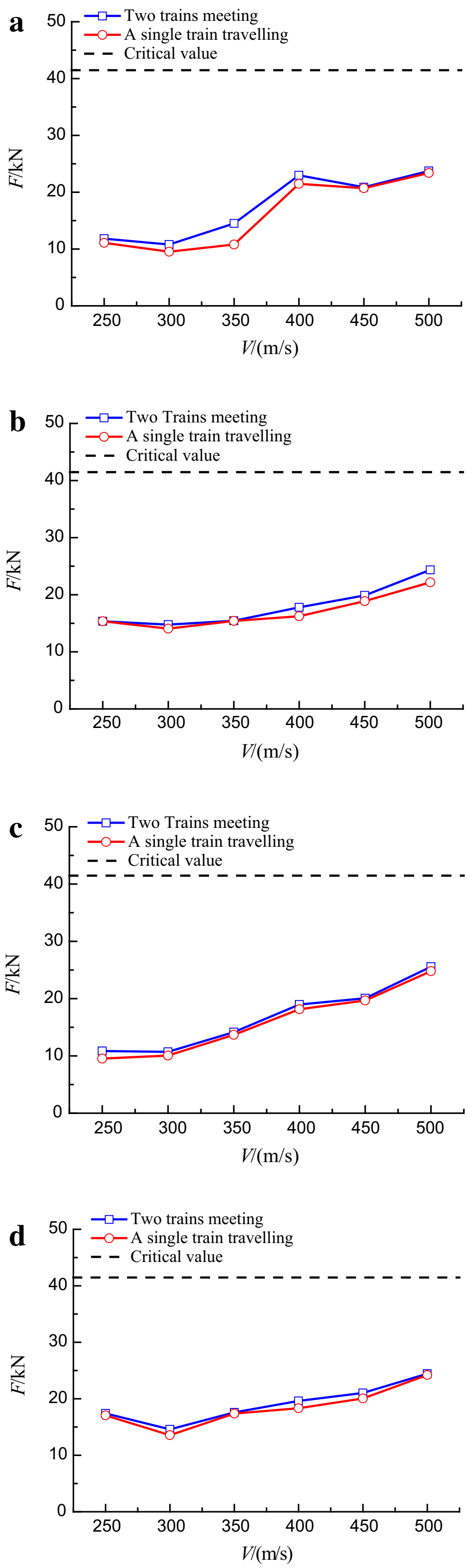

Fig. 10 The lateral wheel-rail force versus train speed. **a** Wheelset 1. **b** Wheelset 2. **c** Wheelset 3. **d** Wheelset 4

Table 2 Evaluation criteria for the derailment coefficient [8]

Derailment coefficient	<0.6	<0.8	<0.9
Safety level	Excellent	Good	Passed

at the flange-railhead contact surface. The Chinese derailment coefficient standard is shown in Table 2. According to the code for design of a high-speed railway (for trial implementation) promulgated in 2009, the value of the derailment coefficient is $Q_\mathrm{w}/P_\mathrm{w} \leqslant 0.8$.

The vehicle model used in this study has four axles. Each axle has two wheels, and there are eight wheels in total. The calculation of the derailment coefficient is for two working conditions: a single train travels on tracks and two trains pass each other on tracks. The train speeds for the two working conditions are 250, 300, 350, 400, 450, and 500 km/h. The derailment coefficients for the eight wheels at 400 km/h are shown in Table 3. The derailment coefficient of each wheel when the trains pass each other is slightly larger than that of a single traveling train. The derailment coefficient of the fourth right wheel is larger than that of others. The derailment coefficients of the fourth right wheel at different traveling speeds are shown in Fig. 11. At a low traveling speed (<400 km/h), the pressure pulse does not have obvious effects on the derailment coefficient. At a high traveling speed (>400 km/h), the pressure pulse makes the derailment coefficient obviously increase. For example, at 500 km/h, the derailment coefficient increases from 0.248 to 0.289, 16.54 % higher. It is found that all the derailment coefficients are far lower than 0.6 and, thus, the levels of evaluation are all in the excellent range.

3.4 Rate of wheel load reduction

The rate of wheel load reduction is another important index to evaluate the safety of a running train. It is defined as the ratio of the load reduction of the wheel vertical force $-\Delta P_\mathrm{w}$ to the average of the left and the right wheel vertical forces P_w, i.e., $-\Delta P_\mathrm{w}/P_\mathrm{w}$. The rate of wheel load reduction plays a supporting and complementary role to the derailment coefficient. The wheel load reduction evaluation standards of China are shown in Table 4. The wheel load reductions at 400 km/h are presented in Table 5. The rates of wheel load reduction for the four wheelsets when traveling at different speeds are shown in Fig. 12. Far below 400 km/h, the rates of wheel load reduction when a train travels alone or two trains passing each other in open air are less than 0.65, which is the first-level standard of China; above 400 km/h, the values exceed 0.65 and are close to 1 at 500 km/h.

Table 3 Derailment coefficients of two trains passing each other and a single train traveling at 400 km/h

Wheel	1R	1L	2R	2L	3R	3L	4R	4L
Single train	0.177	0.155	0.176	0.169	0.172	0.145	0.201	0.172
Meeting trains	0.198	0.172	0.180	0.170	0.190	0.166	0.212	0.184

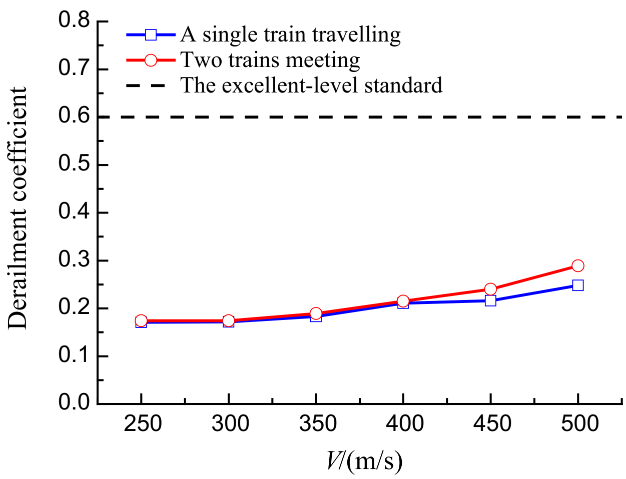

Fig. 11 The derailment coefficient of wheelset 4 right versus train speed

Table 4 Evaluation criteria for the rate of wheel load reduction [9]

$-\Delta P_w/P_w$	<0.65	<0.60
Safety level	First level	Second level

Table 5 The rate of wheel load reduction of two trains passing each other and a single train traveling at 400 km/h

	Wheelset 1	Wheelset 2	Wheelset 3	Wheelset 4
Single train	0.731	0.661	0.655	0.671
Meeting trains	0.748	0.680	0.669	0.680

There is a special explanation needed for the contradiction that the rate of wheel load reduction and the derailment coefficient sometimes does appear in the EMU test. Sometimes the derailment coefficient is not too large, but the rate of wheel load reduction could exceed the standard. In the EMU speed test of the "Pioneer" and "China Star", even if the rate of wheel load reduction standard is relaxed to 0.8, there are some situations where the standard is exceeded. Some European scholars [3] think that the dynamic rate of wheel load reduction is not necessary. Some North American scholars [9] relax the standard to 0.9. The rate of wheel load reduction in the dynamic conditions have a relationship with both magnitude and direction of lateral wheel-rail force. If the lateral wheel-rail force is not conducive to derailment, the derailment coefficient will not be too large and a train will not derail. Japanese scholars [9] even allow the rate of wheel load reduction larger than 1.0, but the duration can not exceed 0.015 s. Therefore, the derailment coefficient is a main standard while the rate of wheel load reduction is an auxiliary standard. If the derailment coefficient and the rate of wheel load reduction both exceed the maximum values allowed, the rate of wheel load reduction is the main factor causing the derailment. If the derailment coefficient is not large but the rate of wheel load reduction is exceeded, we should analyze and examine the cause.

From the comparison in Fig. 11, the rate of wheel load reduction when trains pass each other in open air is larger than that when a single train is traveling. Especially at a high speed (>400 km/h), the increase of the rate of wheel load reduction is much more obvious, for which one should be pay much attention.

4 Conclusions

A carriage model under excitation with the German high-speed low-interference track spectrum and action with a pressure pulse is proposed with a multi-body dynamics simulation method in the commercial software SIMPACK. The carriage model is applied with the pressure pulse generated by trains passing each other at different speeds to simulate various conditions. It is focused on understanding the effects of the pressure pulse on the safety of trains meeting in open air. The investigations of the vibrations of DOFs (horizontal movement, roll angle, and yaw angle), the lateral wheel-rail force, the derailment coefficient, and the rate of wheel load reduction are carried out.

(1) When the train speed is not less than 400 km/h, all safety indexes calculated meet the requirements for the two cases of a single train traveling and two trains meeting in open air. When the train speed is higher than 450 km/h, the rate of wheel load reduction exceeds 0.65. According to the safety standard for the rate of wheel load reduction in Europe and United States, the derailment coefficient plays the most important role in derailment, while the rate of wheel load reduction is a complementary role to the derailment, so exceeding the value of the rate of wheel load reduction does not necessarily mean derailment. It is suggested that the evaluation standard in China is too conservative, which may be loosened to 1 with limiting the exceeding duration.

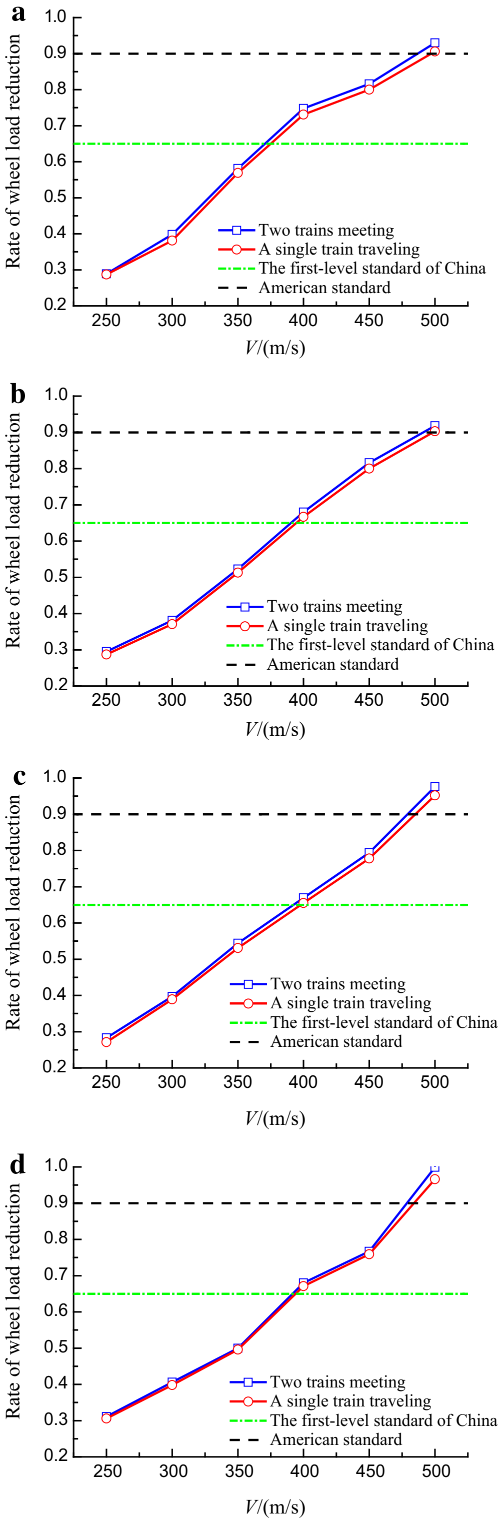

Fig. 12 The rate of wheel load reduction versus train speed. **a** Wheelset 1 **b** Wheelset 2 **c** Wheelset 3 **d** Wheelset 4

(2) The variations of train DOFs (horizontal movement, roll angle, and yaw angle), the lateral wheel-rail force, the derailment coefficient, and the rate of wheel load reduction with time when trains pass each other in open air are larger than those when a single train is traveling, which means that, the pressure generated by trains meeting, significantly affects the dynamic response of high-speed trains. The horizontal movement and the yaw angle apparently change much. Thus, these two indexes should be evaluated in practice. The evaluation of the roll angle is also necessary.

(3) The results show that the pressure pulse has a limited effect on the derailment coefficient and the lateral wheel-rail force. Even if two trains pass each other in open air at a high speed above 400 km/h, the values of the derailment coefficients and the lateral wheel-rail forces are much less than the safety standard values. The further evaluations of the derailment coefficient and the lateral wheel-rail force may be not necessary in practice.

Acknowledgments The financial supports from the National Basic Research Program of China (973 program, Grant 2011CB711100), the National Natural Science Foundation of China (Project No. 11372307) and the Chinese Academy of Sciences (Grant KJCX2-EW-L03) are acknowledged.

References

1. Baker, C.: The flow around high speed trains. J. Wind Eng. Ind. Aerodyn. **98**, 277–298 (2010)
2. Komatsu, N., Yamada, F.: The Reduction of the Train Draft Pressure in Passing by Each Other. Proceedings of World Congrence Railway Research, Tokyo (1999)
3. Raghunathan, R.S., Kim, H.D., Setoguchi, T.: Aerodynamics of high-speed railway train. Prog. Aerosp. Sci. **38**, 469–514 (2002)
4. Xiong, X.H., Liang, X.F.: Analysis of air pressure pulses in meeting of CRH2 EMU trains. Tiedao Xuebao/J. China Railw. Soc. **31**, 15–20 (2009). (in Chinese)
5. Tian, H.Q., He, D.X.: 3-D Numerical calculation of the air pressure pulse from two trains passing by each other. Tiedao Xuebao/J. China Railw. Soc. **23**, 18–22 (2001). (in Chinese)
6. Cui, T., Zhang, W.H.: A new studying method for safety of a train with attitude changing in side wind. Zhendong yu Chongji/J. Vib. Shock **30**, 143–146 (2011). (in Chinese)
7. Lai, J., Zeng, X.H., Sun, Z.X., et al.: The dynamic responses of high-speed trains passing tunnel, passing by each other on open track and inside tunnel. Proc. Twenty-First Natl. Conf. Struct. Eng. **II**, 222–225 (2012)
8. GB/T 5599–1985. Railway vehicles-Specification for evaluation the dynamic performance and accreditation test. (1985)
9. Zeng, Y.Q., Wang, W.D., Shu, X.G., et al.: Dynamic limits for derailment safety evaluation. J. China Acad. Railw. Sci. **20**, 70–77 (1999)
10. Zhang, H., Yang, G.Z.: Derailment and wheel unloading of passenger car bogies. J. Rolling Stock **43**, 10–16 (2005). (in Chinese)
11. Choi, I.Y., Um, J.H., Lee, J.S., et al.: The influence of track irregularities on the running behavior of high-speed trains. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit **227**, 94–102 (2013)
12. Liu, W., Ma, S.H., Luo, S.H., et al.: Wheel/Rail unsymmetrical contact of a high-speed train due to wheel wear. Zhendong yu Chongji/J. Vib. Shock **32**, 107–107 (2013). (in Chinese)
13. Bocciolone, M., Cheli, F., Corradi, R., et al.: Crosswind action on rail vehicles: wind tunnel experimental analyses. J. Wind Eng. Ind. Aerodyn. **96**, 584–610 (2008)

14. Li, X.J., Liu, C.H., Yang, G.W.: Characteristics of pressure wave induced by high speed trains meeting in open air. J. Sci. Technol. Eng. **12**, 3689–3694 (2012). (in Chinese)
15. Zhao, X., Sun, Z.: A new method for numerical simulation of two trains passing by each other at the same speed. J. Hydrodyn. **22**, 697–702 (2010)
16. Liu, J., Li, R.X., Qi, Z.D.: The influence factors and developing regularity of air pressure pulse as trains passing through each other. Third International Conference on Transportation Engineering (ICTE), 2707–2713. Chengdu, China 2011
17. Qian, C.Q., Zheng, Z.J., Yu, J.L., et al.: Dynamics response of side windows of high-speed trains subjected to crossing air pressure pulse. J. Mech. Eng. **49**, 30–36 (2013). (in Chinese)
18. Railway Industrial Standard TB/T 449-2003: Profiles of wheel flange tread for locomotives and cars. Ministry of railway of the People's Republic of China (2003). (in Chinese)
19. Zhao, Y., Zhang, Y.H., Lin, J.H.: Summary on the pseudo-excitation method for vehicle random vibration PSD analysis. Appl. Math. Mech. **34**, 107–117 (2013). (in Chinese)