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Studies on Track Irregularity Limit Values of Heavy Haul Railway Under Sensitive Wavelength

T. Xin, C. Kong, C. Li and L. Sun

**School of Civil Engineering, Beijing Jiaotong University
Beijing, China**

Abstract

The benefits of low cost of transportation, high efficiency, and big volume have led to the rapid development of heavy haul railway in China. However, given the features of heavy haul railway traffic, there are no dynamic management guidelines for track irregularity. Field testing and simulation analysis of the heavy haul test line are required, and the heavy haul freight train line's track irregularity management standard must be presented. This study establishes a rigid-flexible coupling dynamic simulation model of heavy haul freight train and validates the simulation model with real detection data of a specific line. The investigation focuses on the heavy-duty trains 's sensitive sensitivity for height and irregularities in track. The sensitive wavelength is determined to be 10 m based on the simulation findings and field measurements of the chord length, which are 10 m. The amplitude is adjusted in the sensitive wavelength analysis until the vehicle dynamic response approaches or surpasses the safety limit. The suggested value of the dynamic management IV speed restriction for track irregularity is put forth, taking into account the safety margin of 1 to 2 mm. For heavy haul railway lines, it offers a theoretical foundation for managing track irregularity, developing maintenance management guidelines, and formulating irregularity maintenance.

Keywords: heavy haul railway, track irregularity, sensitive wavelength, limit management, vehicle-track simulation model, maintenance

1 Introduction

Due in great part to its major advantages, which include low cost, high efficiency, and large capacity, heavy haul railways have grown quickly globally [1]. The transportation capacity of heavy haul railways has been effectively increased in recent years due to the growing demand for freight transportation in China. This has been accomplished by raising the axle load of heavy haul freight trains, increasing train formation, increasing the number of trains, and increasing traffic density [2]. The operation of heavy axle load freight trains causes the geometric state of the track to accelerate and deteriorate, the deformation of heavy haul railway track structure and rail wear to worsen, and an increase in the vertical and lateral dynamic interaction between wheel and rail. All of these factors have an impact on the safe and stable operation of freight trains.

Many studies on railway track irregularity have been conducted recently, both domestically and internationally. Based on the virtual work principle, Wu et al. [3] created a coupling model of heavy haul train-track-bridge interaction and examined the connection between wavelength and dynamic response. Yang and Xie [4] investigated the impact of irregularity wavelength shift on vehicle dynamic response by building a high-speed train-track coupling dynamic model of flexible body. They also discovered the association between the sensitive wavelength and the modal of vehicle. On the basis of the theory of vehicle-track coupling dynamics, Gao, Zhai, et al. [5] investigated the impact of wavelength variation on the dynamic response of high-speed vehicles under the excitation of track vertical profile, alignment, cross level, and twist irregularity. They also determined the sensitive wavelength range of track irregularity. Based on test results and the theory of vehicle-track coupling dynamics, Wang and Zhai [6] investigated the impact of the wavelength of track irregularity on the stability and comfort of train operation as well as its variation law. Xin and Wang et al. [7] computed and studied the sensitive wavelength and its control limit of long-wave track irregularity at 250–500 km/h speed. They also built a vehicle-track coupling analysis model based on a self-compiled program. C. F. Hung and W. L. Hsu [8] examined the link between vehicle vibration and bridge vibration, track irregularity wavelength, and train speed using the three-dimensional finite element (FE) transient dynamic analysis approach. By conducting coherence and spectrum analyses between track irregularity and train body acceleration, Lian [9] examined the dynamic responses of passenger and freight trains to irregularity excitation. From these analyses, he was able to determine the unfavorable wavelength that significantly affects these vehicles' dynamic responses. The EU [10] separated irregularity management into three levels: warning, intervention, and emergency repair in their research of track irregularity management. Lei [11] established the vertical dynamic model of the high-speed train-track coupling system and used the cross iteration approach to examine the effects of four different types of irregularities, including random and short wave, on the vibration response of the train and track.

The track structure, load form, and irregularity development characteristics of heavy haul railways are clearly different from those of ordinary speed railways due to the continuous increase in axle load, total weight, and train density. Additionally, the mileage of heavy haul railways is increasing, leading to the formation of a specific scale. There is an increasing need for track irregularity management and detection technologies appropriate for large load railroads. Currently, the general speed comprehensive inspection train or the track inspection vehicle are the primary means by which the domestic heavy freight railway conducts daily infrastructure inspections. However, it is impossible to actually detect equal working conditions because the axle load of the track inspection vehicle cannot match the actual weight of the heavy haul railway. Specifically, there are no pertinent test results to confirm if the heavy haul railway's track irregularity varies depending on whether the freight train or the comprehensive inspection train operates on it. However, as of right now, the general speed repair requirements from 2006 or 2019 are still used to guide the application of China's heavy haul railway track inspection standards. The passenger train's dynamic performance index and the general speed railway's track irregularity characteristics are the two that determine the track dynamic irregularity management value. Regarding economy and safety, there isn't a meaningful demonstration to support its suitability for huge axle load scenarios on heavy haul lines. As a result, there are currently no dynamic management guidelines for track irregularity that take into account the features of freight trains on heavy haul railroads. The heavy haul freight train line's track irregularity management standard and the heavy haul test line's actual vehicle test must be implemented in order to address the aforementioned issues. Consequently, the sensitive wavelength of heavy haul freight train irregularity is obtained, and a rigid-flexible coupling dynamic simulation model of heavy haul freight trains is established in this article. The study examines the amplitude management limit of track irregularity in conjunction with the line detection method and various operating conditions.

2 Vehicle-track system dynamics simulation model

2.1 Simulation model

The foundation for examining how the train and the track interact is the vehicle model. Usually, it is emulated as a multi-rigid-body system moving at a set speed on the track framework. UM multi-body dynamics software is used in this study to construct the dynamic simulation model of the C80 haul vehicle. One train body, two bolsters, four side frames, and four wheelsets make up the discretized vehicle model. The dynamic response of the vehicle system is solved using the numerical integration algorithm, the modal superposition concept, and the multi-degree-of-freedom system vibration theory. The vehicle as a whole is taken into account in the model, and the body's component parts are regarded as rigid bodies. There are five different ways the train body can move: it can sink, roll, move laterally, shake its head, and nod. The left and right side frames, a bolster, and two wheelsets make up the freight train bogie. Four degrees of lateral movement, sinking and floating, side rolling, and rocking head are taken into consideration by the bolster; five degrees of longitudinal movement, lateral movement, sinking and floating, nodding, and rocking head are taken into consideration by the side frame; and four degrees of lateral movement, sinking and floating, side rolling, and rocking head are taken into consideration by the wheelset. There are 49 degrees of freedom in total throughout the entire train. As a result, the modeling takes into account the system's degree of freedom and nonlinear linkages in great detail.

The center plate connection between the bolster and the train body is simplified in the train design to a rotating friction pair. Between the side frame and the bolster, the vertical, lateral, and longitudinal stiffness of the bolster spring is taken into account, and the friction wedge is taken into account as a two-way friction pair. A spring-damping element with clearance simulates the axle box's longitudinal and transverse suspension, while a friction pair simulates its vertical suspension. Table 1 displays the vehicle's primary specifications. Figure 1 displays the bogie's schematic diagram. The 70 kg rail's geometric size is adopted by the rail section, and the LM wheel tread is chosen. Figure 2 displays the developed wheel tread model and rail profile. Figure 3 displays the C80 train's topology, and Figure 4 displays the C80 train's final dynamic simulation model.

Train parameter	Numerical value
Vehicle spacing/m	8.20
Wheelsets spacing/m	1.83
Axle load/t	20
Rolling radius/m	0.42
Wheel tread	LM

Table 1: Train parameter.

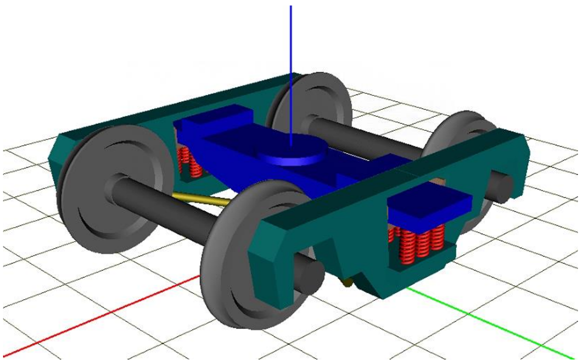
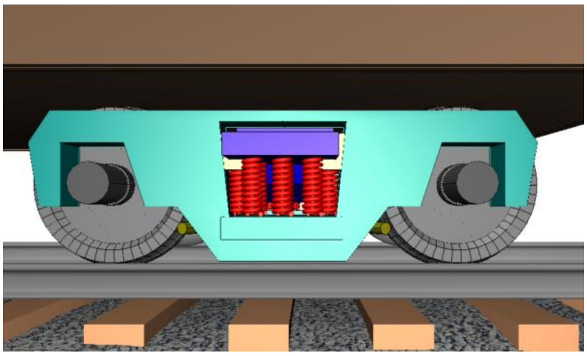
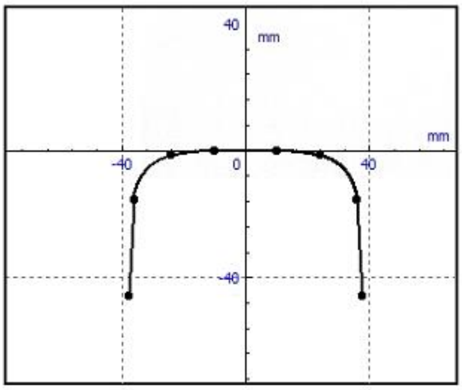
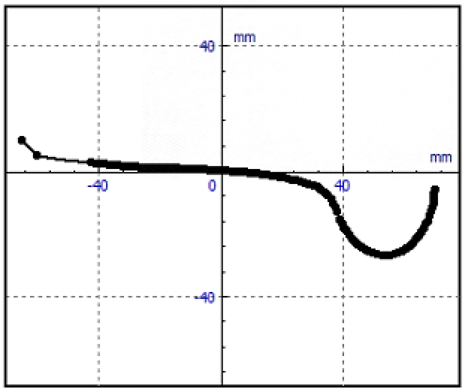


Figure 1: The bogie's diagram



(a) Wheel-rail contact simulation





(b) Rail profile (c)Wheel tread

Figure 2: Wheel-rail

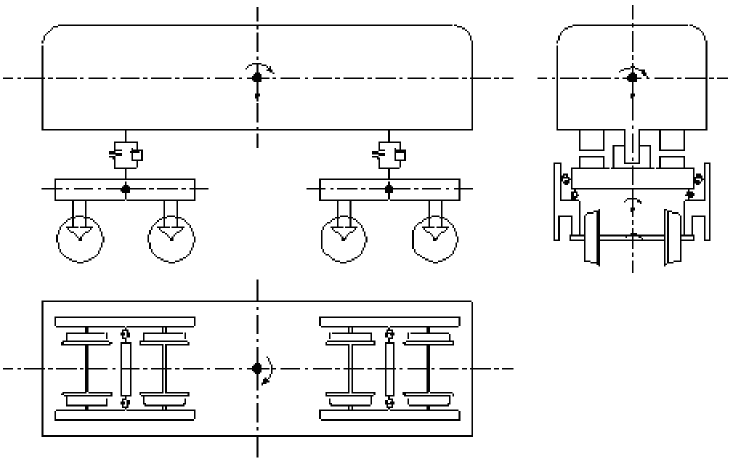


Figure 3: Topological structure of C80 heavy haul train

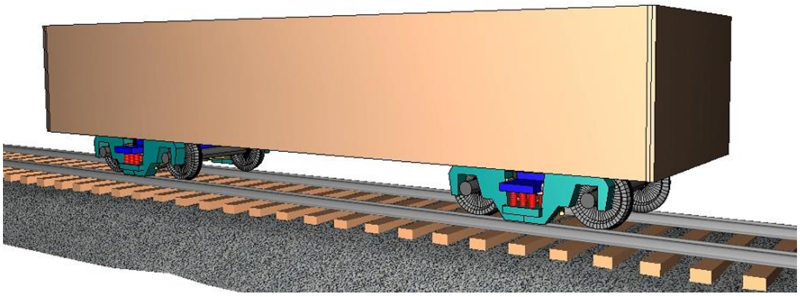
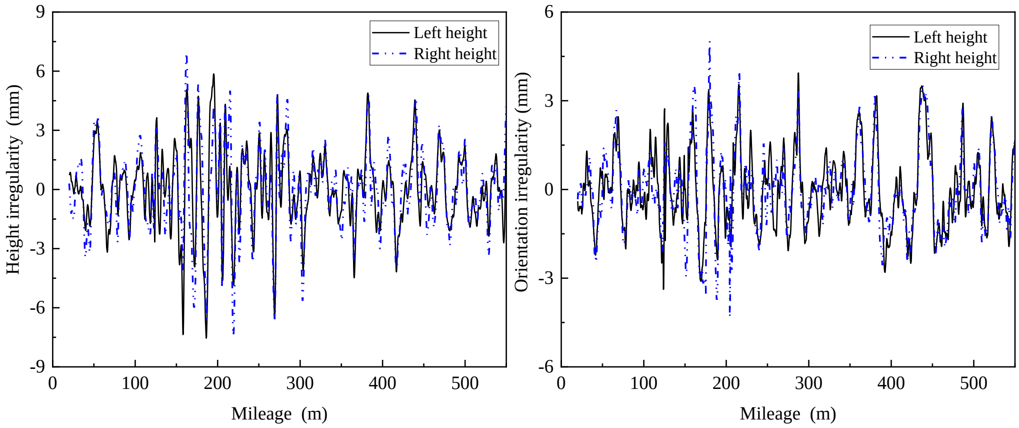


Figure 4: C80 heavy haul train simulation model

2.2 Model Verification

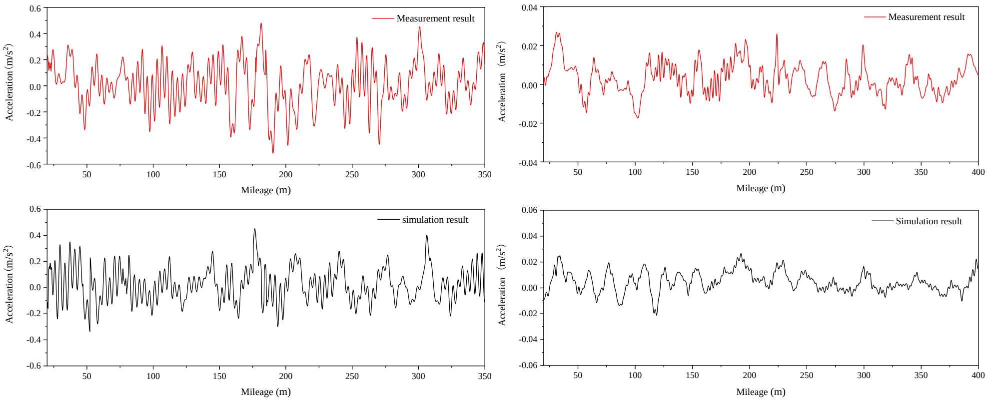
As seen in Figure 5, the accuracy of the established model is confirmed by contrasting the simulation results of the model with the real behavior of the vehicle under the action of the measured track irregularity of a specific segment of the heavy haul railway. The train body's lateral and vertical accelerations under excitation serve as the comparison index.



(a) Height irregularity (b) Orientation irregularity

Figure 5: Measured irregularity data

Figure 6 presents a time domain comparative analysis of the recorded vertical and lateral acceleration of the comprehensive detection train and the vertical acceleration of the train body as determined by the simulation calculation.



(a) Vertical acceleration (b) Lateral acceleration

Figure 6: Comparison of vehicle acceleration

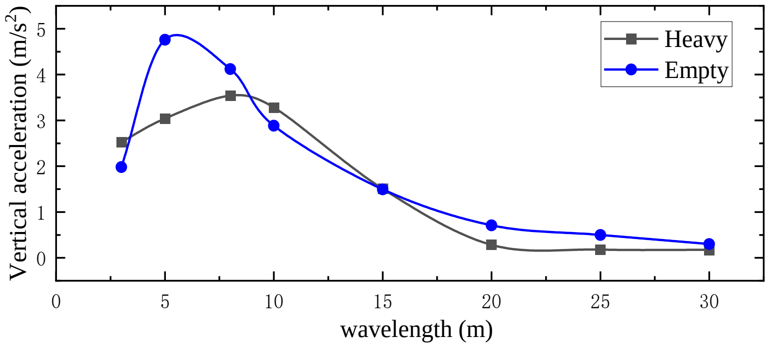
The model simulation's vertical and horizontal vehicle acceleration calculation results are comparatively smaller than the measured data, as can be observed from the comparison results of Figure 6. The measured data are influenced by a variety of external factors, and the simulation only reflects the influence of the geometric irregularity state of the track, so there is a certain difference between the two. This is because the measured data are the dynamic data collected by the comprehensive detection train, and the detected vehicle parameters and the vehicle parameters used in the simulation model cannot be completely corresponding.

3 Track irregularity-sensitive wavelengths

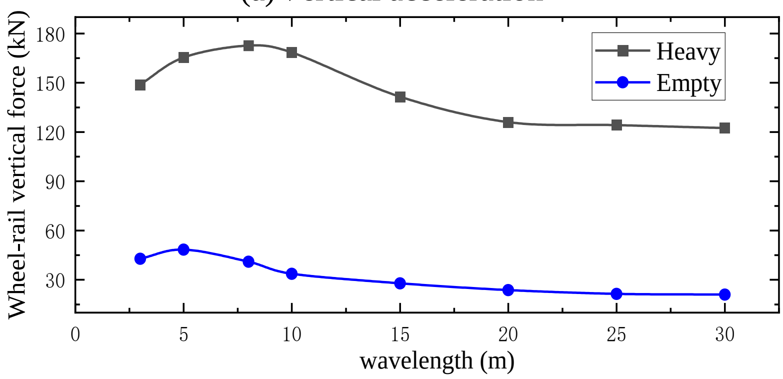
3.1 Sensitive wavelength of the vertical profile irregularity

The primary cause of line vertical profile irregularity excitation is the vehicle's floating and nodding movement, which modifies the wheel load variations and the vertical acceleration of the vehicle's body as well as the vertical force applied to the wheels and rails.

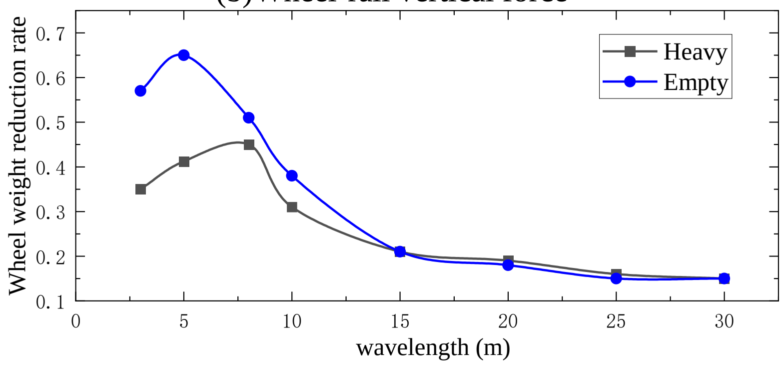
To determine the wavelength of the vehicle with the maximum response under vertical profile irregularity, the cosine function is selected for simulation. The wavelength range is 3~30m, and the amplitude of irregularity is 20mm. The irregularity excitation is adjusted by varying the wavelength size. This allows for an investigation of the relationship between the vertical profile irregularity of the C80 heavy haul train and the vehicle's dynamic response under both empty and heavy vehicle conditions. It is established how big the sensitive wavelength is. Based on computation and model, the wavelength of vertical profile irregularity is determined to have a major impact on the vehicle body's vertical acceleration, the wheel-rail's vertical force, and the wheel-weight reduction rate, as shown in Figure 7.



(a) Vertical acceleration



(b)Wheel-rail vertical force



(c) Wheel weight reduction rate

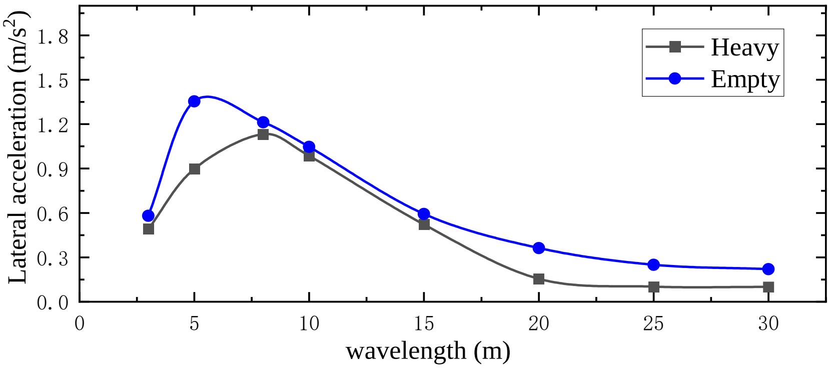
Figure 7: Vehicle dynamic response at different heights of irregularity.

The wheel-weight reduction rate, wheel-body vertical acceleration, and wheel-rail vertical force of the C80 empty and heavy vehicles have wavelengths of 5~10m, as can be observed in Figure 7. It is known that the sensitive wavelength of the empty train is approximately 5 meters when the wavelength is 5 meters; similarly, the body vertical acceleration and wheel load shedding rate of the heavy train (C80) have the largest response when the wavelength is 8 meters, and it is known that the sensitive wavelength of the heavy train is approximately 8 meters. To be more in line with the actual working conditions at the site, the sensitive wavelength is calculated with 10m when calculating the dynamic response of the wheel and rail with different amplitudes, even though the measurement is done at the site with a 10m chord length.

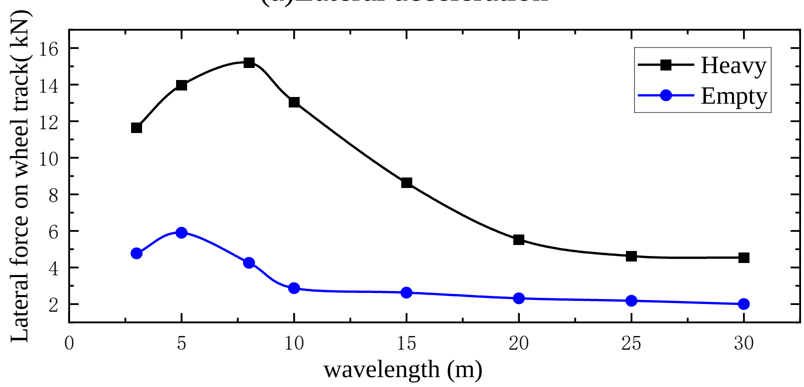
3.2 Sensitive wavelength of the track alignment irregularity

The main cause of the uneven line rail alignment is the vehicle's shaking head and side roll movement, which alters the transverse acceleration and force of the wheels and rails as well as the vehicle body. This leads to an increase in the gauge and lateral movement of the rail, and rail tilt to the outside increases the derailment coefficient. This increases the risk of a train derailment, which compromises the vehicle's ability to operate safely. In order to determine the rail irregularity of the vehicle response to the maximum size of the wavelength that is the sensitive wavelength, the analysis and calculation of the sensitive wavelength of the rail to the irregularity used a multi-wave cosine function simulation. The rail to the irregularity of the amplitude of the value of 10mm was determined by changing the wavelength size to alter the excitation's irregularity. Heavy-duty trains C80 were examined in empty trains, and the conditions of the heavy train's dynamic response to the irregularity of the vehicle under correspondence. Through the calculation and simulation, it is found that the wavelength of rail alignment irregularity has a significant effect on the lateral acceleration of the vehicle body, the lateral force of the wheel and rail, and the derailment coefficient, as shown in Figure 8.

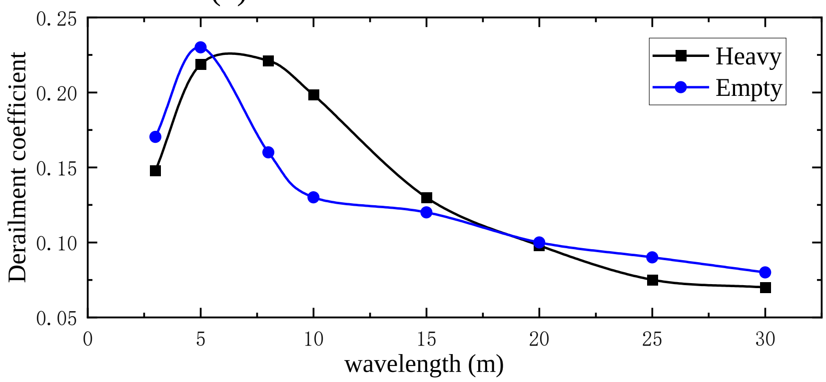
It is evident from Figure 8 that the C80 empty and heavy haul trains' body vertical acceleration, wheel-rail lateral force, and derailment coefficient peak at a wavelength of 5–10 m. The body lateral acceleration and derailment coefficient response of the C80 empty train is largest at a wavelength of 5 m, and it is known that this is also the sensitive wavelength for the empty train; the body lateral acceleration and derailment coefficient response of the C80 heavy train is largest at a wavelength of 8 m, and it is known that this is also the sensitive wavelength for the heavy train. Also, to be more in line with the actual working conditions at the site, the sensitive wavelength is calculated with 10m when calculating the dynamic response of the wheel and rail with different amplitudes, even though the measurement is done at the site with a 10m chord length.



(a)Lateral acceleration



(b) Lateral force on wheel track



(c) Derailment coefficient

Figure 8: Vehicle dynamic response under track irregularity.

4 Determination of track irregularity management values

4.1 Dynamic indicators

The safety limits are determined by applying the data in the following Table 2, where g is the gravitational acceleration constant, and the following derailment coefficients, wheel weight reduction rate, acceleration, and other safety indexes. These are adopted as the evaluation standard, taking the most recent version of China's "Specification for the Evaluation and Test Identification of the Dynamic Performance of Rolling Stock" (GB/T5599-2019) as reference.

No.	Dynamics Indicator	Numerical value
1	Wheel Weight Reduction Rate	0.65
2	Vertical acceleration of train body /(m/s^2)	6.86
3	Lateral acceleration of train body/(m/s^2)	4.90
4	Derailment coefficient	1.00
5	Lateral force on wheel track/ kN	98.00
6	Vertical force on wheel track/ kN	212.50

Table 2: Safety limits.

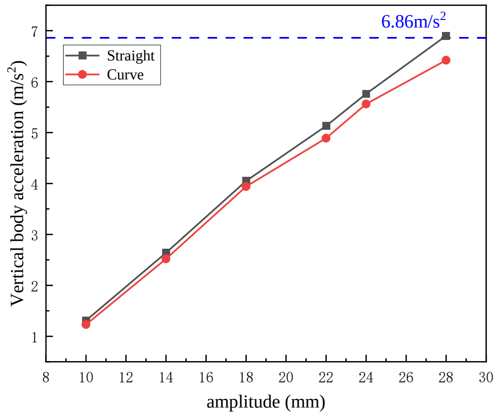
4.2 Track Irregularity Management Values

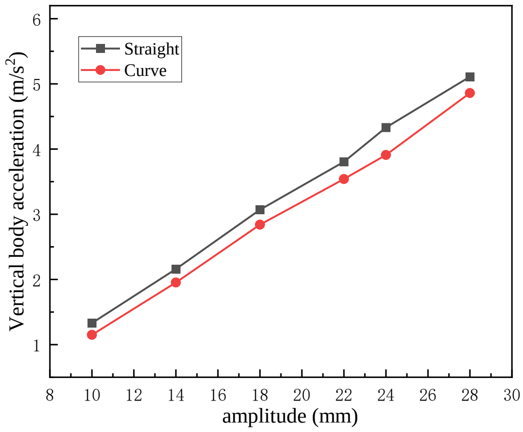
For the set cosine irregularity excitation, as per the 10m sensitive wavelength explored in Section 3, gradually adjust the magnitude size without altering the wavelength until the vehicle dynamic response surpasses or approaches the safety limit value. Take into account the safety margin of approximately 1-2 mm and propose the corresponding proposed value of the dynamic management of track irregularity in heavy load lines with class IV speed limit.

Take the exploration of high and low irregularity as an example.

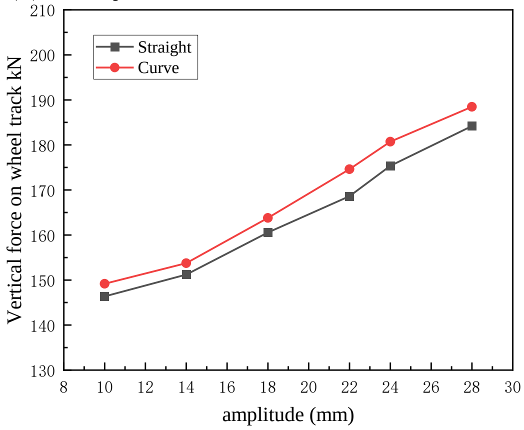
In the two strands of steel rail, a single wave harmonic excitation displacement input function simulated by different amplitudes of rail irregularity, C80 heavy trains and empty trains in a straight line, curves in the two conditions of the magnitude of the high and low irregularity of the vertical acceleration of the train, the reduction of the rate of the vertical forces and wheel and rail, and so on. Take the high and low irregularity sensitive wavelength of 10m and calculate the speed for the maximum operating speed of 100km/h. Figure 9 shows the relationship between the vertical dynamic response of the train body and the magnitude of high and low irregularity when the C80 heavy train and empty train reach the safety limit.

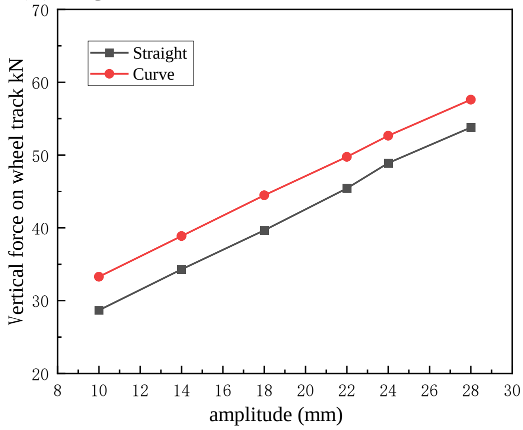
For the C80 heavy vehicle, it can be found from Figure 9 that the calculated results of body vertical acceleration, wheel-rail vertical force and wheel-weight derailment rate for the straight curve are increasing with the change of amplitude. While the wheel-rail transverse force, derailment coefficient and train body transverse addition change slightly, but the change is very small. It can be concluded that the amplitude change has a greater influence on the wheel load shedding rate, train body vertical acceleration and wheel rail vertical force. When the amplitude of C80 heavy train track height is 28mm, the load shedding rate on the straight line and curve is 0.536 and 0.506 respectively, which is within the limit of 0.65 of the safety judgement index and has a big difference with the safety limit of 0.65; the vertical acceleration of the train body on the straight curve is $6.9m/s^2$ and $6.42m/s^2$, which is up to or closer to the safety limit of $6.86m/s^2$, while the other calculation results are far from reaching the safety limit. At this time, the other calculation results are far from reaching the safety limit, which can be seen that the body vertical acceleration of the C80 heavy train high and low irregularity play a controlling role, and from Figure 9 can be found that the irregularity amplitude and the body vertical acceleration of the relationship between the linear growth.



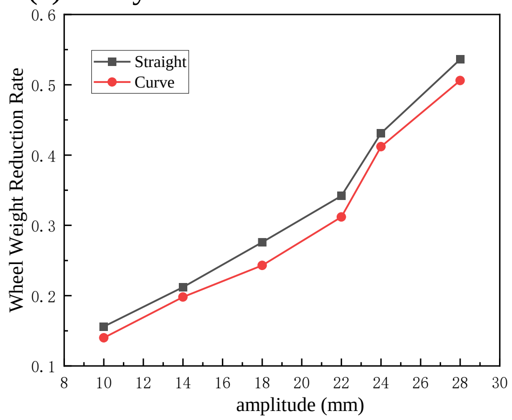


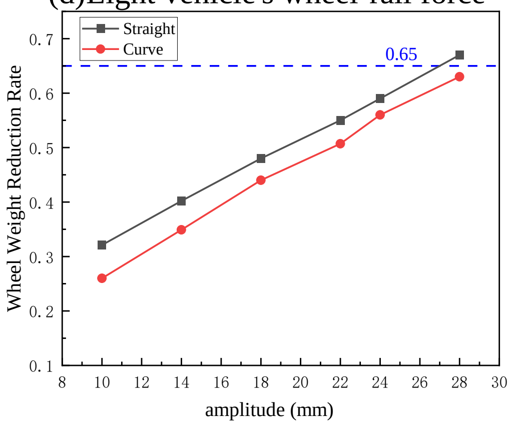
(a) Heavy vehicle's vertical acceleration (b) Light vehicle's vertical acceleration





(c) Heavy vehicle's wheel-rail force (d) Light vehicle's wheel-rail force





(e) Heavy vehicle's wheel weight reduction rate (f) Light vehicle's wheel weight reduction rate

Figure 9: Vehicle Dynamic Response with Changing High and Low Irregularity Amplitude.

For the C80 empty train, it can be found from Figure 9 that with the change of magnitude, it is still the body vertical acceleration, wheel weight reduction rate and wheel-rail transverse force that change more. When the magnitude increases from 10mm to 28mm, the body vertical acceleration increases by 3.78m/s^2, 3.71m/s^2 respectively; the wheel weight reduction rate increases by 0.35, 0.37 respectively; the wheel-rail vertical force increases by 25kN, 24kN respectively; all of them have a large increase. Comparative analysis of the C80 heavy train calculation data can be found, the three changes in the amount of empty train wheel load shedding rate relative to the heavy train is larger, while the body of the vertical acceleration and the wheel-rail vertical force is relatively small, and in the amplitude of 28mm, the straight curve of the wheel load shedding rate of 0.67, 0.63, at this time, the curve of the wheel load shedding rate has reached the safety limit of 0.65, and the train body of the vertical acceleration maximum value of only 5.11m/s^2, less than the safety limit value of 6.86m/s^2.

It can be seen that the control factors of heavy vehicle and empty vehicle are not consistent, the wheel load shedding rate plays a controlling role in the high and low irregularity of C80 empty vehicle, and the graph can be found that the amplitude of the irregularity and the wheel load shedding rate is basically a linear relationship between.

For rail alignment, level, twist, gauge after the same analysis, and finally came to the conclusion of the relevant management restrictions as shown in Table 3 below.

Track irregularity	Track profile	Track alignment	Track cross level	Twisted	Gauge
Recommended speed limit for class IV	24mm	20mm	21mm	18mm	-12/18mm

Table 3: Recommended Speed Limit Values for Track Irregularity Dynamic Management Level IV

5 Conclusions and Contributions

This paper establishes a dynamic simulation model of heavy haul freight trains based on UM multi-body dynamics software, investigates the relationship between the dynamic response of C80 heavy haul vehicles and the wavelength and amplitude of irregularity, and determines the sensitive wavelength of irregularity of heavy haul freight trains. The amplitude management standard of track irregularity is examined on this premise, together with the line detection method and various operating situations. This has some reference relevance for the heavy haul railway engineering department's irregularity management and optimization. The following are the primary conclusions:

(1) Based on dynamic simulation, the heavy haul freight train's sensitive wavelength for height and rail irregularity is around 5–10 m. The dynamic response of the wheel and rail with varying amplitudes is computed, taking into account that

the field is recorded at a chord length of 10 m. To accommodate the more realistic working conditions on location, the sensitive wavelength is determined to be 10 m.

(2) Analyse and adjust the amplitude size based on the wavelength that is sensitive, until the vehicle dynamic reaction reaches or above the safety limit. The recommended IV speed limit for dynamic track irregularity management is 24 mm for height, 20 mm for rail alignment, 21 mm for level, 18 mm for triangle pit, and 12 / 18 mm for gauge, taking into account a safety margin of 1 ~ 2 mm.

Acknowledgements

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References

[1] Zhang J, Yang H, Wei Y, Shang P. The empty wagons adjustment algorithm of Chinese heavy-haul railway. Chaos, Solitons & Fractals 2016;89:91-9.

[2] Li Z, Li Z, Huang W, Xu Z, Zhang W, Chen K. Tunnel Bottom Cavity Laws of Heavy-Haul Railway Tunnel under Train Load and Groundwater in Weak Surrounding Rock Condition. KSCE J Civ Eng 2022;26:1451-64.

[3] Wu N, Yang H, Afsar H, Wang B, Fan J. Analysis of Train–Track–Bridge Coupling Vibration Characteristics for Heavy-Haul Railway Based on Virtual Work Principle. Sensors (Basel) 2023;23:8550.

[4] Yang J, Xie Y, Pang L, Jiang P, Ling L. Sensitive Wavelength Analysis on Track Geometric Irregularities of 400 km/h High-speed Railway. High Speed Railway Technology 2021;12:50-5.

[5] Gao J, Zhai W, Wang K. Study on Sensitive Wavelengths of Track Irregularities in High-speed Operation. Journal of the China Railway Society 2012;34:83-8.

[6] Wang K, Zhai W, Liu J, Feng Q, Cai C. Effect of rail irregularity wavelength on lateral running comfort of speed raised train. Journal of Traffic and Transportation Engineering 2007;7:1-5.

[7] Xin T, Wang P, Ding Y. Effect of Long-Wavelength Track Irregularities on Vehicle Dynamic Responses. Shock Vib 2019;2019:1-11.

[8] Hung C F, Hsu W L. Influence of long-wavelength track irregularities on the motion of a high-speed train[J]. VEHICLE SYSTEM DYNAMICS, 2018,56(1): 95-112.

[9] Lian S, Huang J. Study of the Detrimental Wavelengths of Track Irregularities for Railways with Passenger and Freight Traffic. Journal of the China Railway Society 2004;26:111-5.

[10] European Committee For Standardization. BS EN 13848-5 Railway Applications-track-track Geometry Quality-part5: Geometric Quality Levels[S]. London: British Standards Institution,2010.

[11] Lei X. Analysis of the influence of the track vertical profile irregularity on the vibration of the vehicle and the track under high speed moving train[J]. Transportmetrica. (Abingdon, Oxfordshire, UK), 2023,11(1): 896-911.