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Optimization Analysis of Minimum Flat Curve Radius of High Speed Maglev Line with Design Speed of 500 km/h

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Abstract. Firstly, based on the traditional circuit design method, the theoretical calculation value of the minimum radius of the flat curve under the design speed of 500 km/h is calculated in this paper; Through the analysis of the structural characteristics of the TR08 high-speed maglev train and the degree of freedom of each component, a 129-DOF high-speed maglev vehicle-line dynamics model is established by using the multi-body dynamics software SIMPACK; And using the modle to simulate and analyze the influence of the radius of the flat curve on the dynamic performance of the vehicle. Finally, according to the simulation results, the theoretical calculation of the minimum radius of the flat curve is optimized and adjusted, and the minimum radius recommended value of the flat curve that satisfies the dynamic evaluation index is obtained. After the simulation optimization, the unbalanced lateral acceleration and the vertical acceleration dynamic response of the vehicle passing through the designed curve section are significantly reduced, and the ride comfort of the passengers is good.

1. Introduction

The traditional wheel-rail trains have reached the speed bottleneck of 400 km/h due to wheel-rail contact restrictions. If the speed is further increased, it will bring out a huge increase in operating costs. The high-speed maglev system has got rid of the wheel-rail contact restriction and obtained further speed-up space. For example, the German TR maglev train has achieved a test speed of 505 km/h, so the high-speed maglev system is considered to be the development direction of the next generation of rail transit The high-speed maglev transportation system includes vehicles, lines, traction power supply, operation control and other major parts [1], among which the line part is one of the most important parts of the high-speed maglev transportation system. The quality of line design is directly related to the operational safety, stability and ride comfort of the maglev train [2]. Traditionally, the line selection design is mostly based on the static method. The vehicle is regarded as a particle or a rigid body [3], and the theoretical calculation value of the minimum horizontal curve radius of the line is obtained on the basis of the unbalanced lateral acceleration limit value of the vehicle body. The method does not take into account the complex structure of the vehicle and the relative motion between the components is considered less. The calculated minimum radius of the flat curve may not meet the dynamic performance requirements of the high-speed maglev vehicle. Therefore, in order to ensure the safety of train operation and passenger ride comfort, it is particularly important to verify and optimize the value of the minimum radius parameters of the flat curve under the design speed of 500 km/h calculated by traditional circuit design method from the dynamic point of view. At the same time, it also has certain innovative significance in the design of high-speed maglev lines.

Theoretical Calculation of the Minimum Radius of the Flat Curve of High-Speed Maglev Line

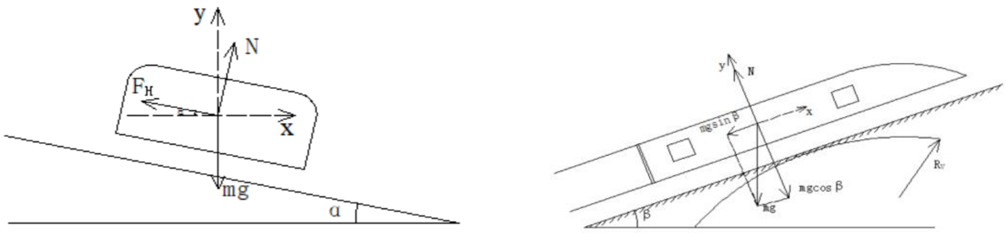
Simulation Model. The minimum radius of the flat curve is one of the main technical standards for line selection design. In addition to the comfort requirement, the minimum radius of flat curve of the traditional wheel-rail trains should also meet the safety requirement to prevent derailment and overturning accidents due to mismatched line design parameters. For the high-speed maglev system, the vehicle adopts the outsourced suspension frame structure, and the vehicle always surrounds the track, which greatly reduces the possibility of derailment and overturning of the vehicle [4]. Therefore, based on the structure characteristics and engineering technical requirements of high-speed maglev train, the main factors affecting the minimum radius of flat curve of high-speed maglev line are the vehicle structure requirements and passenger ride comfort requirements [5].

（1）Vehicle construction requirements

The structural characteristics of TR08 maglev train determine that the minimum curve radius of the train passing through the flat curve cannot be lower than 350m.

（2）Passenger ride comfort requirements

The force diagram of the maglev train running on the curve is shown in Fig.1.



(a) flat curve (b) vertical curve

Figure 1. Force analysis of high-speed maglev train running in curved section

When the train runs in the curve section, if the designed driving speed does not match the setting value of the cross-slope angle of the line, the train will generate a certain amount of centrifugal force, and the passengers in the train will bear the unbalanced lateral acceleration [6]. According to the passenger's ride comfort requirements, this unbalanced lateral acceleration cannot exceed a certain limit, that is:

$$a_y \le a_{max}. \quad (1)$$

In this equation：a_y ——unbalanced lateral acceleration (m/s²)

a_{max} ——limit value of unbalanced lateral acceleration (m/s²)

According to the force diagram of the train in Fig. 1, the unbalanced lateral acceleration in the horizontal direction can be expressed as follows:

$$a_y = \frac{F_H \cos\alpha - N \sin\alpha}{m}. \quad (2)$$

The centrifugal force F_H and suspension force N that the train receives during the running of the curved section can be expressed as follows:

$$F_H = m\frac{\left(\frac{V}{3.6}\cos\beta\right)^2}{R_H}. \quad (3)$$

$$\mathrm{N} = \mathrm{mg}\cos\beta - m\frac{(V/3.6)^2}{R_V}. \quad (4)$$

The reason why the number 3.6 appears in Eq.3 is because the speed (km/h) needs to be converted to the international unit speed (m/s). Bringing the Eq.3 and Eq.4 into the Eq.2 and transforming the Eq.2, the equation for calculating the radius of the flat curve can be expressed as follows:

$$R_H = \left|\frac{(V/3.6)^2\cos\alpha\cos^2\beta}{a_y + \left[g\cos\beta + m\frac{(V/3.6)^2}{-R_V}\right]\sin\alpha}\right|, a_y \le a_{max}. \quad (5)$$

In this equation：R_H——Flat curve radius(m);

R_V——Vertical curve radius（m）；

V——Train running speed（km/h）；

α ——the Angle of the cross slope（°）；

β ——Longitudinal gradient（‰）；

g——Gravity acceleration，9.81 m/s²；
In practical engineering, the order of circuit design is generally to firstly design a flat curve and then design a vertical curve. In the design of flat curve, the influence of longitudinal slope and the radius of vertical curve are generally not considered. Therefore, taking the longitudinal slope $\beta = 0$ and the vertical curve radius R_V=∞, the Eq.5 can be simplified to the following equation:

$$R_H = \left|\frac{(V/3.6)^2 \cos\alpha}{\alpha_y + g \times \sin\alpha}\right|, a_y \le a_{max}. \tag{6}$$

Regarding to the value of the cross slope angle α, referring to the relevant provisions of the Shanghai High Speed Maglev Demonstration Operation Line and the German Transrapid Line Selection Instruction: the maximum cross-slope angle of high-speed maglev line shall not exceed 12 degrees, and in extreme cases, the maximum 16 degrees cross-slope angle can be obtained after the technical and economic demonstration.
Therefore, with the values of each parameters substituted into the above equation, the calculated minimum radius of the flat curve of the high-speed maglev line that satisfies the ride comfort requirement under the design speed of 500 km/h can be calculated, as shown in Table 1.

Table 1. Calculated minimum radius of flat curve of high-speed maglev line at the speed of 500 km/h

Design Speed（km/h）	Minimum Radius of Flat Curve	
	General situation	Difficult situation
500	6400	5800

Note：1.The general situation in the table refers to the unbalanced lateral acceleration limit of 1.0 m/s² and 1.25 m/s² in difficult cases.
2.When calculating, the maximum cross slope angle is taken as 12 degrees.
Establishment of High Speed Maglev Vehicle-Line Dynamic Model
In order to verify and optimize the theoretical calculation value of the minimum radius of the flat curve under the designed driving speed of 500 km/h, a complete vehicle-line dynamic model must be established. By setting different simulation conditions, the law of influence of the change of the radius of the flat curve on the dynamic performance of the vehicle can be simulated and analyzed.
The research is based on the TR08 maglev train. One TR08 high-speed maglev vehicle contains one body, four levitation frame running mechanisms, 14 suspension electromagnets, 12 guide electromagnets, 2 brake electromagnets, 16 anti-roll bolsters, 16 pendulum and other major components [7]. When considering the influence of the change of the radius curve parameter on the dynamic performance of the vehicle, only the uniform operation conditions is considered, and the traction and braking conditions are not involved, and the longitudinal motion of the vehicle is not considered. Therefore, the guide electromagnet can be used to replace the position of the brake electromagnet and play the guiding function in the process of establishing the model. By analyzing the structural characteristics and connection relationships of each component of the vehicle, the degree of freedom of each component of a single vehicle can be obtained as shown in Table 2.

Table 2. Freedoms of Components of a Single Vehicle

Components	Transverse	Sinking	Rolling	Nodding	Shaking head
Car body	√	√	√	√	√
Suspension electromagnet	-	√	-	√	-
Guided electromagnet	√	-	-	-	√
Bolster	-	-	√	-	-
Pendulum	-	-	√	√	-

According to the degree of freedom of each component and based on the principle of multi-body dynamics, the models of each component can be established in SIMPACK software platform. The connection and force transmission relationships between components can be replaced by hinges, force elements and constraints, and the line model can be obtained by setting the line parameters in Track module [8]. Finally, a high-speed maglev vehicle-line dynamic model with 129 degrees of freedom is obtained through a series of steps, as shown in Fig. 2.

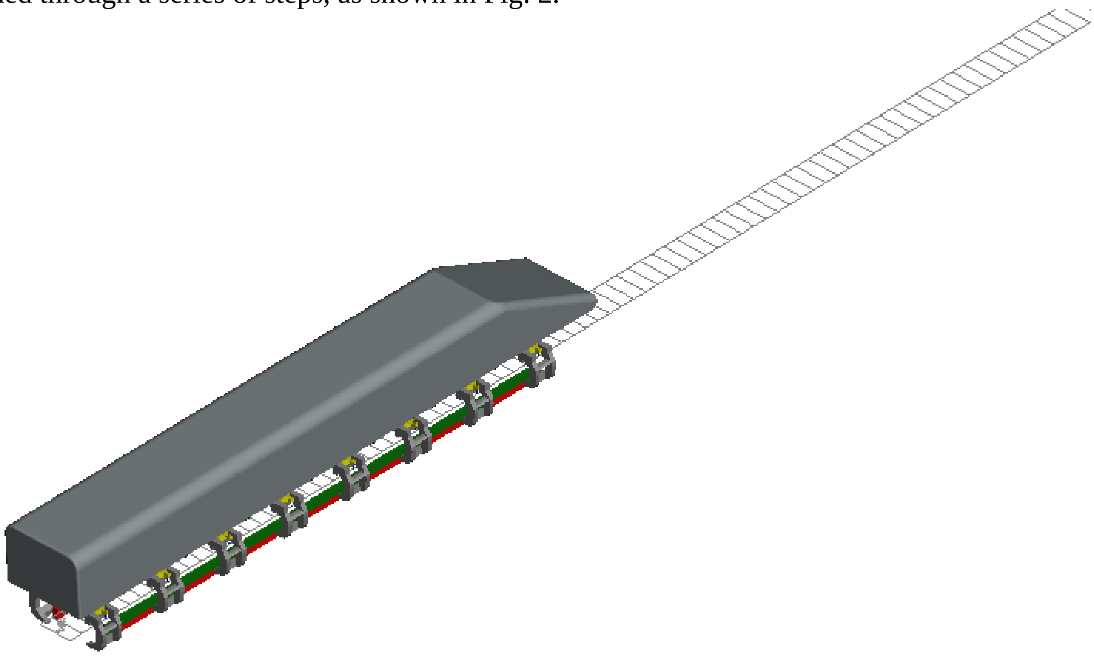


Figure 2. High Speed Maglev Vehicle-Line Dynamic Model

2. Model Simulation Analysis

Evaluation Index. When the maglev train runs on the curve, it will generate a certain amount of acceleration and vibration. The passengers on the train have a certain tolerance limit for the perceived acceleration and vibration. This limit must meet the requirements of dynamic performance. Up to now, the high-speed maglev transportation system has not yet formed a set of evaluation indicators to evaluate the dynamic performance of vehicles. Referring to the rail transit system, the ISO2631 standard is usually used to evaluate the relationship between passenger comfort and vehicle acceleration.

The ISO2631 standard is used to evaluate the human body's ability to withstand vibration. After extensive testing and demonstrations, it has become an international general evaluation standard applicable to various industries. In this study, the ISO2631 standard is used as an evaluation index for evaluating the dynamic performance of Maglev vehicles. Its standard is shown in Table 3

Table 3. ISO2631 Comfort Evaluation Index [9]

Acceleration Transmissibility （m/s²）	Comfort Condition	Comfort Level
＜0.315	Very comfortable	Level 1
0.315～0.63	Comfortable	Level 2
0.5～1.0	Fairly comfortable	Level 3
0.8～1.6	Discomfort	Level 4
1.25～2.5	Very uncomfortable	Level 5
＞2.5	Extremely uncomfortable	Level 6

When simulating the dynamic response of vehicle with the change of the radius of flat curve, the corresponding comfort level can be determined by comparing the unbalanced lateral acceleration and the vertical acceleration in the simulation results with the comfort evaluation standard in Table 3. The design requirements for high-speed maglev line selection are as follows: in the case of general curve sections, the passenger's ride comfort level is not less than level 2, that is, “comfortable”; in the case of difficult curve sections, it is not less than level 3, that is, “fairly comfortable”.

Simulation and Analysis of Vehicle Dynamic Performance with the Change of Radius Parameters of Flat Curve at the Speed of 500 km/h. Different working conditions are set up in SIMPACK simulation platform to simulate the influence of different flat curve radius on vehicle dynamic performance at 500 km/h speed. In the simulation, the unbalanced lateral acceleration and vertical acceleration dynamic response simulation results of vehicle body center are taken as the evaluation parameters to evaluate vehicle dynamic performance. After a series of simulation, the simulation results are shown in Table 4. The relationship between the lateral acceleration, the vertical acceleration and the radius of the flat curve is shown in Fig. 3

Table 4. simulation results of vehicle-line dynamic model under different radius of flat curve at the speed of 500 km/h

Radius of flat curve（m）	Unbalanced lateral acceleration （m/s²）	Vertical acceleration（m/s²）
5800	1.185	0.707
6000	1.077	0.683
6200	0.975	0.662
6400	0.881	0.641
6600	0.791	0.621
6800	0.708	0.602
7000	0.627	0.586
7200	0.552	0.570

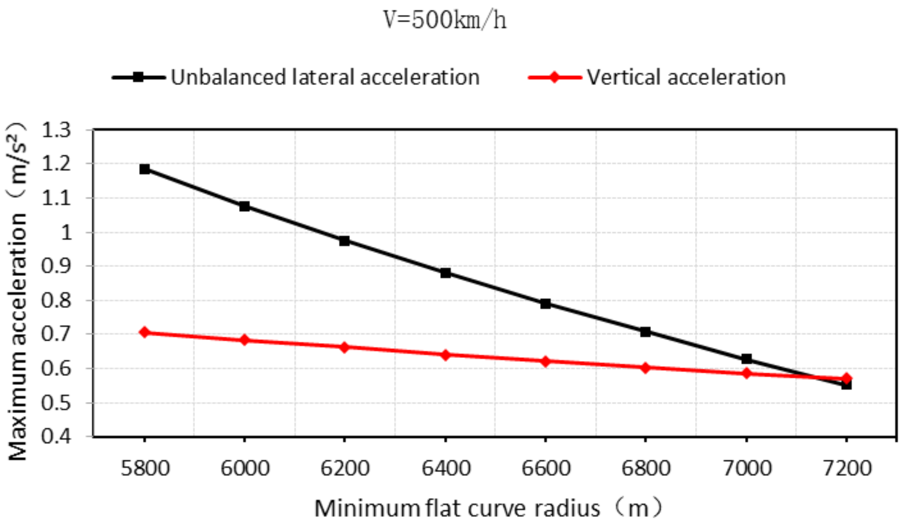


Figure 3. Relationship between the lateral, vertical acceleration and the flat curve radius

Observing the curve trend of Fig.3, we can see that the unbalanced lateral acceleration and vertical acceleration of the vehicle during the running of the curve section are all related to the radius of the flat curve, and both decrease with the increase of the radius of the curve. Careful observation of the trend of the curve slope shows that the radius of the slope of the shows that the radius of the flat curve has a greater impact on the lateral acceleration. The lateral acceleration first decreases rapidly with the increase of the radius of the flat curve. When the radius of the curve increases to a certain extent, the lateral acceleration decreases more slowly with the increase of the radius of the flat curve.

Combined with the data in Table 4, when the theoretical calculated radius of the flat curve is 5800m, the lateral acceleration is 1.185 m/s², and the vertical acceleration is 0.707 m/s² and the lateral comfort is level 4, the “uncomfortable” state, and the vertical comfort is level 3, that is “fairly comfortable”state, at this time, the lateral comfort does not meet the comfort requirements. When the radius of flat curve is 6400m, the lateral acceleration is 0.881 m/s², and the lateral comfort is level 4, which still does not meet the requirements of lateral comfort. When the radius of the flat curve increases to 6600m, the lateral acceleration is 0.791 m/s^2 and the lateral comfort is level 3, which is the "fairly comfortable" state, and the vertical acceleration is 0.621 m/s^2 and the vertical comfort is level 2, which is the "comfortable" state, so the lateral and vertical comfort meet the comfort requirements under difficult circumstances, and can be used as the minimum radius of the flat curve under difficult situation. When the radius of flat curve is further increased to 7000m, the value of lateral acceleration is 0.627 m/s^2 and the lateral comfort is level 2, which is “comfortable” state. And the value of vertical acceleration is 0.586 m/s^2 and the vertical comfort is level 2, the “comfortable” state. So the horizontal and vertical comfort meet the comfort requirement under general situations, and can be taken as the minimum radius of flat curve under general situations. Therefore, from the perspective of comfort requirement, the minimum radius of flat curve that satisfies passengers’ comfort requirement should be no less than 7000m under general situations and not less than 6600m under difficult situations.

In summary, the minimum radius of the flat curve of 6400m under general situations and 5800m under difficult situations calculated by traditional circuit design method cannot meet the passenger comfort requirements. After dynamic simulation optimization, its value should be adjusted to 7000m under general situations and 6600m under difficult situations, as shown in Table 5.

Table 5. Suggested values for the minimum radius of the flat curve of high-speed maglev line at the speed of 500 km/h

Designed Driving Speed（km/h）	Minimum Radius of Flat Curve（m）	
	General Situation	Difficult Situation
500	7000（6400）	6600（5800）

Note: The theoretical calculation value is in brackets, and the simulation optimization value is outside brackets.

After the optimization, when the high-speed maglev train with the maximum design speed of 500 km/h passes through the flat curve section under normal and difficult situations, the lateral and vertical comfort of the car body can meet the requirements, and the passengers' ride comfort is good. And through simulation and optimization, the lateral acceleration and vertical acceleration dynamic response of the car body passing through the curve section are reduced by 33.2% and 12.2% under general situations, and 28.8% and 8.6% under difficult situations, which better improves the ride comfort of passengers.

3. Conclusion

In this paper, by establishing the high-speed maglev vehicle-line dynamic model, the theoretical calculation value of the minimum radius of flat curve under the condition of speed 500 km/h obtained by the traditional circuit design method is simulated and optimized, and the ride comfort of passengers is taken as the evaluation index to evaluate the dynamic performance of maglev vehicle under different flat curve radius conditions. Finally, according to the simulation results, the theoretical calculation value of the minimum radius of the flat curve is optimized and adjusted, and the recommended value of the minimum radius of the flat curve of the high-speed maglev line with a design speed of 500 km/h that meeting the ride comfort of passengers is obtained. The optimization results show that:

（1）After the optimization, when the high-speed maglev train with the maximum design speed of 500 km/h passes through the flat curve section under normal and difficult situations, the lateral and vertical comfort of the car body can meet the requirements, and the passengers' ride comfort is good.

（2）Through simulation and optimization, the lateral acceleration and vertical acceleration dynamic response of the car body passing through the curve section are reduced by 33.2% and 12.2% under general situations, and 28.8% and 8.6% under difficult situations.

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