Determination of Instability Critical Speed of Articulated Vehicle on Ramp Section Based on Response Surface Method

CAO Xingju*
Xinjiang Vocational & Technical College of Communications, Urumqi, Xinjiang, China
email:xjjiaotong@126.com

Abstract: In order to improve the driving safety of vehicles on the ramp section, aiming at the lateral instability problems such as sideslip and rollover in the corner driving of semi-trailer trains, the six-axis articulated vehicle, which is the representative model of current highway freight transportation in China, is selected as the research object. The TruckSim simulation software is used to establish the vehicle dynamic model of nonlinear articulated vehicle, and the orthogonal simulation test of different loading quality and different road adhesion coefficient is designed. The vertical reaction force and lateral displacement of the wheel are taken as the evaluation indexes of vehicle sideslip and rollover, and the critical speed of instability under various road conditions is obtained. On the basis of surface function fitting, combined with the simulation experimental data, the response surface mathematical model of instability critical speed, road adhesion coefficient and loading quality is established. The comparison calculation shows that only 2.23% of the calculation error of the mathematical model reduces the error of the traditional model and improves the calculation accuracy of the model. The results show that the critical speed threshold of instability decreases with the increase of loading mass. With the increase of road adhesion coefficient, the threshold of instability critical speed increases. When the road adhesion coefficient reaches 0.6, the change of instability critical speed threshold tends to be steady. The research results can provide a reference for the evaluation of rollover and sideslip during the turning of articulated vehicle and the determination of anti-instability warning speed of articulated vehicle crossing the ramp section safely.

1. Introduction
Ramp section as a complex curved section, is a traffic accident-prone section, which has a high probability of occurrence and high severity. As the main vehicle in the highway transportation industry, articulated trains have complex physical characteristics such as high center of mass, long body length, large load, and mutual coupling between semi-trailer towing vehicle and semi-trailer. As a result, the probability of rollover on the ramp section at high speed is much higher than that of ordinary vehicles. Therefore, the study of the speed problem of the anti-instability warning of the articulated vehicle on the ramp section is of great significance for protecting the safety of the occupants and improving the efficiency of road transportation.

Domestic and foreign scholars have done a lot of research on the safety of road transport vehicles running on ramp sections. Wang Chuanlian used TruckSim simulation software to establish a complete vehicle dynamics model of a large vehicle, and analyzed the influencing factors and the extent of the vehicle sideslip and rollover on curved road sections. Tang Geteng applied TruckSim simulation software to establish a vehicle dynamics model, and conducted orthogonal simulation experiments with different curve radii and traffic speeds, and obtained safe vehicle speed thresholds for vehicles under different curve radii. Li Changcheng reviewed the main speed limit methods at home and abroad,
combined with the actual conditions of domestic roads, and analyzed the use conditions of various methods and their respective advantages and disadvantages.

In this paper, the six-axle articulated vehicle is taken as the research object. The orthogonal simulation experiment is carried out by combining different loading quality and road adhesion coefficient. The polynomial function model is established with the critical speed as the dependent variable and the loading quality and adhesion coefficient as the independent variable. The surface fitting processing is realized by Matlab programming, and it is verified. The influence of loading quality and road adhesion coefficient on the threshold of unstable critical speed is analyzed, which provides technical support for vehicle safety.

2. Vehicle dynamic model of articulated vehicle

In this paper, six-axle articulated vehicle is selected as the research object, and the whole vehicle dynamics module of TruckSim simulation software is used to establish a simulation experiment model composed of 6×4 tractor and 3-axle van semi-trailer, as shown in Figure 1. The vehicle dynamic model includes nine parts: vehicle system, aerodynamic system, power transmission system, braking system, steering system, suspension system, wheel system, and traction connection mechanism.

![Vehicle dynamics model](image)

Figure 1 Vehicle dynamics model

The basic main parameter settings are shown in Table 1 and Table 2.

### Table 1 Basic parameters of 6×4 tractor

| Denomination                                   | Value  |
|-----------------------------------------------|--------|
| Axle distance of semi-trailer tractor/mm      | 3105   |
| Distance of towing attachment in front of rear of vehicle/mm | 1035   |

Continued

| Denomination                                    | Value   |
|------------------------------------------------|---------|
| Distance between centroid and front axle of tractor/mm | 2412    |
| Centroid height of tractor/mm                   | 945     |
| Height of traction seat from ground/mm          | 1170    |
| Sprung mass of tractor/kg                       | 4770    |

### Table 2 Basic parameters of 3-axle van semitrailer

| Denomination                                  | Value |
|-----------------------------------------------|-------|
| semitrailer wheel base/mm                     | 7227  |
| Semi-trailer load/kg                          | 27000 |
| Distance between centroid and traction pin/mm | 4203  |
| Load centroid height/mm                       | 1140  |
| Height of traction seat from ground/mm        | 1.2-1.4 |
| Sprung mass of Semitrailer/kg                 | 5500  |
2.1. Scene model of ramp section
The scene model of ramp section is constructed by comprehensively considering the main influencing factors such as the geometric characteristics of the road, the road adhesion coefficient, and the surrounding environment of the road. In order to reveal the coupling relationship between different loading quality, different road adhesion coefficient and the instability speed of the semi-trailer train ramp section, based on the plane geometry characteristics of the ramp section, this paper constructs a curved section combining a straight line and a circular curve with a certain bending radius. According to the difference of road adhesion coefficient such as dry, snow and ice, the friction coefficient between tire and road is set.

![Figure 2 Scene model of ramp section](image)

2.2. Driver control strategy model
Driver control strategy model mainly includes speed control, steering control, braking control, shift control, etc. The speed control adopts the constant target speed control strategy to determine the unstable speed when driving on the bend. The steering control adopts path following control strategy; The braking control adopts the open-loop control strategy without braking; The shift control adopts the control strategy of automatic clutch shift according to the speed value, so as to construct the driver control strategy model of articulated train.

3. Determination of critical speed threshold for instability based on orthogonal simulation test
After the establishment of the vehicle dynamics model, the corresponding road environment and simulation test settings are added to carry out the test simulation under various road models of the vehicle. There are many factors that affect the instability of the ramp section of the semi-trailer train. In this paper, the loading quality and road adhesion coefficient are taken as the main factors, and TruckSim simulation software is used to simulate the semi-trailer train. The orthogonal experimental design method is used to design the critical speed of the instability of the ramp section.

3.1. Orthogonal simulation experiment design
In order to analyze the influence of loading quality and road adhesion coefficient on the critical speed threshold of ramp instability, the ramp section of the simulation test in this paper adopts a straight line and a curve, and the radius of the curve is set to 120m. To study the critical speed of semi speed of semi-trailer train on the ramp section, the interactive combination parameter input of loading quality and road adhesion coefficient was used to start the simulation test at an appropriate constant speed. Ten groups of different vehicles loading quality (4,8,12,16,20,24,28,32,36,39) and seven groups of different road friction coefficient (0.2,0.3,0.5,0.6,0.7,0.8,0.9) were set up.

After the simulation analysis, by observing whether the vertical counter-forces of the wheels when the vehicle is driving on the ramp section is 0 and whether the lateral displacement of the center of mass of the vehicle is 0, it is judged whether the vehicle enters the critical state of rollover or sideslip. If the vehicle does not enter the critical state, the driving speed of the vehicle is increased, and the above steps are repeated until the critical state of rollover or sideslip occurs, so as to solve the critical speed of
instability of the vehicle through the ramp under a certain load mass and a certain road adhesion coefficient.

By observing the change curves of figure 3 and figure 4, the critical state of the vehicle’s rollover or sideslip can be judged, and the corresponding critical vehicle speed of the ramp section can be obtained. The change in vertical counter-forces of the wheels when a semi-trailer train rolls over, as shown in Figure 3; the change in the lateral displacement of the center of mass of the vehicle when a semi-trailer train has a sideslip condition, as shown in Figure 4.

3.2. Determination of instability critical speed threshold
There are many factors that affect the critical speed threshold of the instability of the semi-trailer train on the ramp section. In this paper, the TruckSim simulation software is used to calculate the critical speed threshold of the instability of the semi-trailer train on the ramp section under the influence of different loading quality and different road adhesion coefficients, as shown in Table 3. With the increase of loading mass, the critical speed threshold of instability decreases. With the increase of road adhesion coefficient, the threshold of instability critical speed increases; When the road adhesion coefficient reaches 0.6, the change of instability critical speed threshold tends to be gentle.

| Loading mass/t | 0.2 | 0.3 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| 4             | 67  | 80  | 83  | 84  | 85  | 85  | 85.5|
| 8             | 66  | 78  | 82  | 82  | 82  | 82.5| 84  |
| 12            | 66  | 77  | 81  | 81  | 81.5| 82  | 82  |
| 16            | 65.5| 75  | 77  | 77.5| 78  | 79  | 80.5|
3.3. Mathematical model fitting based on response surface method

According to the orthogonal simulation test data in Table 3, the interpolation method is used, and the loading quality and road adhesion coefficient are used as independent variables to obtain the instability critical speed threshold of the semi-trailer train passing the ramp section for fitting, and the fitted three-dimensional surface graph, as shown in Figure 5.

The quadratic response surface tool of MATLAB is used to perform polynomial function fitting processing, and finally the response surface mathematical model of the critical speed of the semitrailer train instability, the road adhesion coefficient, and the loading quality is obtained. The fitting result is shown in formula (1).

\[ v \leq 65.49 + 47.33 \cdot \Phi -0.3376 \cdot m - 23.42 \cdot \Phi^2 - 0.2408 \cdot \Phi \cdot m - 0.0003996 \cdot m^2 \]  

Its certainty coefficient (representing the accuracy of the model measurement) R-square is 0.928.

4. Instability critical speed calculation model test

Due to the limitation of test equipment and dangerous test process, this paper still uses the vehicle model established by the above TruckSim simulation software to verify the accuracy of the calculation model of ramp instability critical speed. The road adhesion coefficient is set to 0.5, 0.6, 0.7, 0.8, and the loading mass is 25t. The simulation conditions and steps are consistent with the above. Through the change curve of vertical counter-forces, the critical instability speed of the vehicle at rollover can be obtained, which is compared with the results of the mathematical model, as shown in Table 4.

| Pavement friction coefficient | TruckSim simulation results critical speed/(km/h) | Model calculation results critical speed/(km/h) |
|------------------------------|-----------------------------------------------|-----------------------------------------------|
| 0.5                          | 71                                            | 71.60                                         |
| 0.6                          | 72.5                                          | 73.15                                         |
| 0.7                          | 73                                            | 74.24                                         |
| 0.8                          | 74                                            | 74.85                                         |

Table 4 Comparison of simulation results and model calculation results
According to the above four groups of verification test results, there are 2.23%, 1.88%, 0.91% and 1.17% calculation errors in the mathematical model, respectively. Because the control threshold of the curve speed early warning control system is mostly about 80% of the critical speed, there is nearly 20% fault tolerance rate. Therefore, the mathematical model can ensure the safety of vehicles passing through ramp sections, and the model is reasonable. Compared with the simplified model used at present, the calculation accuracy is significantly improved, and the calculation scheme of the critical speed of instability is optimized.

5. Conclusion
In this paper, through the orthogonal simulation test of the articulated vehicle in the ramp section, the response surface mathematical model of the critical speed of instability and the road adhesion coefficient and the load quality is established, and the critical threshold of the semi-trailer train in the ramp section is determined. With the increase of loading mass, the critical speed threshold of instability decreases. With the increase of road adhesion coefficient, the threshold of instability critical speed increases; When the road adhesion coefficient reaches 0.6, the change of instability critical speed threshold tends to be gentle. The research results can be used for the development of active safety warning of articulated vehicle.

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