Safety evaluation on rollover speed of on-ramp vehicles in complex coastal environment

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ABSTRACT: Driving safety assessment of on-ramp vehicles is one of the complicate problems in the current traffic field, and also a hot topic in the research of vehicle-road collaborative safety monitoring. In this paper, the safety of vehicles driving in the coastal ramp section is studied in the context of practical engineering. Due to the characteristics of large mass and high center of mass, and considering the influence of strong wind and adverse weather conditions, hazardous chemical vehicle is prone to rollover accident when driving on the ramp of coastal Bridges. In order to ensure the safety of vehicle transportation, this paper uses numerical simulation software to establish a safety speed threshold model, and analyzes the influence degree of wind speed, road adhesion coefficient and longitudinal slope on rollover accidents of hazardous chemical vehicles. By simulating the actual ramp traffic conditions, and the lateral load transfer rate was used as the rollover index to obtain the vehicle speed threshold under the rollover critical state. Compared with the ramp speed limit standard, the validity of the model is verified. The results show that the decreasing trend of safety speed is more significant when the wind speed is higher. The influence of the lower slope on the safety speed of the small radius curve is greater; When the ramp encounters rain and snow and other bad weather, the road adhesion coefficient is 0.18 and the wind speed is 50km/h, the safe speed threshold is 41km/h, 2.5% higher than the speed limit standard of 40km/h, and the threshold is reasonable.

KEY WORDS: Safety evaluation; Speed threshold; Numerical simulation; Coastal ramp.

1 INTRODUCTION

With the increasing mileage of road transportation of hazardous chemicals, vehicle accidents of hazardous chemicals have become an important safety risk of road transportation in coastal areas [1-3]. In recent years, highway ramps have become accident prone areas. The most typical case is the LPG tank truck explosion near the ramp of G15 Shenhai Expressway in Wenling, Zhejiang province on June 13, 2020, which resulted in 20 deaths and 175 injuries and had a huge impact on the society [4]. The wind speed in coastal areas is strong. For example, there are 3-5 typhoons registered in Zhejiang province every year, and the winter monsoon can reach level 11 or more, and the strong wind period is long in a year. In addition, there are more foggy days in coastal areas, low visibility, frequent rainstorms and fog, and the safety risks of hazardous chemical vehicles driving on the ramp section of coastal Bridges are more prominent, with a higher probability of accidents and greater damage to the environment after accidents [5]. Therefore, the study of the safety speed of hazardous chemical vehicles on ramp section of sea-crossing bridge can provide a certain reference value for driving safety on sharp curves.

In the aspect of road transportation safety research, there are two main methods: real vehicle test and numerical simulation. In terms of real vehicle tests, Gao [6] used VBOX series equipment to build a semi-trailer train running stability detection system, and carried out road tests of steady-state steering and cornering braking on real vehicles respectively, and analyzed the mechanism and reason of semi-trailer train turning braking causing instability. Cheng et al. [7] developed an optimal trailer steering control system by combining the trajectory error in the turning process of the semi-trailer with the lateral acceleration of the vehicle's center of gravity, and carried out real vehicle tests on the semi-trailer to verify the effectiveness of the control system. Xu et al. [8] obtained the lateral driving characteristics of passenger cars in ramp environment based on the driving data of real cars. Real vehicle testing has certain risks, which cannot ensure the safety of drivers and vehicles. At the same time, it will consume a lot of manpower and material resources, and the test cost is high. With the continuous improvement of computer performance, more and more domestic and foreign scholars choose to use numerical simulation to study vehicle driving safety. Simulation generally obtains simulation vehicle model by establishing kinematic differential equation of vehicle, and compares the influence of different environmental factors and driver model on vehicle safety. Kim and Choi [9] studied the influence of geometric conditions of different roads on drivers' speed changes and established a vehicle running speed model of multi-lane expressway. Kordani et al. [10] studied the influence of three-dimensional horizontal curves under different lateral friction coefficients and longitudinal slopes on driving safety, and carried out a series of simulation tests using CarSim and TruckSim simulation software packages. Wang et al. [11] studied the influence of different loading conditions and road conditions on the safe speed threshold of curved sections. Xu et al. [12] used vehicle simulation software to analyze the influence of vehicle speed and circular curve radius on driving safety in sharp curves. Pan et al. [13] established the sideslip speed model of trucks under curves based on Trucksim simulation, and compared the influence of different radii on sideslip speed. Qu et al. [14] based on the Monte Carlo reliability analysis theory, constructed the function of system failure in the case of multi-mode vehicles, providing theoretical basis for the safety and road design of heavy-duty vehicles running downhill in curves.

Most domestic and foreign scholars study the road safety analysis of small buses and single trucks, and the research results provide theoretical support for the safety of passenger and truck transportation on conventional roads [15-17]. However, the traffic conditions in coastal areas are complicated (frequent rain, snow, fog and many curves), and semi-trailer trains transporting hazardous chemicals are prone to rollover, rear-end collision and other accidents in ramp sections due to their large load weight and high center of mass [18, 19]. In addition, the ramp section is usually semi-closed with few lanes, so it is difficult to rescue hazardous chemical vehicle leakage accident timely, which will cause serious harm to the surrounding vehicles and ecological environment [20, 21].

In this paper, TruckSim software is used to establish a safety driving speed threshold model. Meanwhile, based on the impact of strong wind monitoring data in coastal areas and the actual ramp radius on the hazardous chemical tank semi-trailer transport vehicle, a speed threshold model is established with safety speed as the dependent variable and wind speed and road adhesion coefficient as the independent variable. The influence of different wind speed, ramp slope and road adhesion coefficient on safe speed threshold is discussed. Finally, the real ramp section is taken as an example for simulation analysis, and the safe speed threshold under different conditions is obtained.

2 SIMULATION MODEL OF TANK SEMI-TRAILER BASED ON TRUCKSIM

2.1 Simulation model of tank semi-trailer

In this paper, tank semi-trailer as the research object, the actual transport vehicle models are Beiqi Foton tractor (BJ4257SMFJB-S2), tank semi-trailer (THT9401GHY). Trucksim simulation software was used to build vehicle models, and different test conditions were set according to test requirements. The tractor body length is 7135mm, the height and width are 3800 and 2490mm respectively, the load mass is 4455kg, the height of the body's center of mass is 1020mm, the number of shafts is 3, the front wheelbase is 3300mm, the rear wheelbase is 1350mm, the tire specifications are 315/80, and the tire radius is 225mm. Since the transportation of dangerous chemicals needs to consider economic and safety factors, the vehicle load is set as full load in the simulation test in this paper, namely 25t, and the centroid height of the tank semi-trailer is constant under this condition.

The structural parameters and system parameters of the tank semi-trailer are shown in Table 1.

Table 1. Parameter of simulation vehicle.

Parameter	Value
length of car /mm	11651
width of car /mm	2481
height of car /mm	1771
Loading quality /kg	25000
Tire specification	315/80 R22.5
Front wheelbase /mm	6500
Medium and rear wheelbase /mm	1350

2.2 Road simulation model

The road simulation model considers the influence of ramp radius, road adhesion coefficient and longitudinal slope degree on the safe speed threshold of coastal ramp section. According to the plane geometry characteristics of the selected ramp section, an S-shaped ramp curve with radius of 82m and 150m connected was constructed, with a superelevation of 4% [22]. According to the weather conditions in coastal areas, the road adhesion coefficient is set as 0.18 (rain and snow weather), 0.5 (wet road surface on rainy day), 0.7 (dry road surface on sunny day) for three typical working conditions.

2.3 Driver simulation model

The driver model in TruckSim controls driving strategies such as driving speed, braking, shifting and steering. In this paper, the main research is speed related simulation, in the speed control is mainly used is a continuous change of fixed speed, to determine the vehicle safety speed threshold. The influence of braking on the safety speed threshold is not within the scope of this study, so the braking control strategy is open loop control without braking. For the direction control in the driver behavior model, this paper adopts the open-loop control mode. The driver was in good driving condition and ability and proceeded along the centerline of the ramp in normal behavior, shifting gears through the automatic clutch.

2.4 Selection of safety evaluation indexes for rollover

Most of the types of hazardous chemical transport accidents on ramp are vehicle rollover and collision, and the ramp is generally set a certain high on the outside of the curve to avoid the occurrence of the rollover accident of tank semi-trailer. General vehicle rollover is divided into two kinds: one is the lateral slip occurs when the vehicle is driving, and the obstacle on the road side collision and rollover occurs; The other is that when the lateral acceleration exceeds the threshold, the vertical reaction of the inner wheel is zero, causing rollover accidents.

At present, common rollover indicators of vehicles include lateral acceleration, roll Angle, static stability coefficient, lateral load transfer rate, etc. [23] Because the lateral load transfer rate can be used for rollover analysis of different types of semi-trailers and the calculation method is simple, the lateral load transfer rate is selected as the vehicle rollover safety evaluation index in this paper. The lateral load transfer ratio of the vehicle is the ratio of the difference between the axial loads on both sides and the sum of the axial loads on both sides, which can dynamically reflect the stability of the vehicle during driving, as shown in Equation (1). Generally, rollover occurs when one of the wheels is off the ground, and the lateral load transfer rate tends to be 1.

$$LTR = \sum_{i=1}^{n} \left| F_{Li} - F_{Ri} \right| \Big/ \sum_{i=1}^{n} \left(F_{Li} + F_{Ri} \right) \tag{1}$$

Where, F_{Li} and F_{Ri} are the vertical reaction forces of the left and right tires of the *i* axis respectively; *n* is the number of axles; $LTR \in [0,\ 1]$.

According to Formula (1), the vertical reaction of tires on both sides of the vehicle is close when the vehicle runs in a straight line, which LTR is approximately equal to 0. When the vehicle is fast cornering, the vertical reaction of one side of the tire decreases and LTR gradually increases, and the vehicle may be in danger of rolling over. As the rollover accident of the hazardous chemical tanker is more dangerous than that of ordinary vehicles, the vehicle is in the state of rollover instability when LTR is greater than 0.9.

3 THE INFLUENCE OF ENVIRONMENTAL FACTORS ON SAFETY SPEED

Ramp speed limit 40km/h, roadbed width 10.5m, ramp longitudinal slope 4%. The adhesion coefficient of road surface is about 0.7 in clear weather, it drops to about 0.5 in rainy and foggy days, and is about 0.18 in snow and ice. As the ramp section is in a semi-closed environment, the wind Angle is set at 90° side wind.

The experiment judged whether the vehicle entered the rollover critical state by observing whether the lateral load transfer rate was greater than 0.9 when the vehicle turned. If the vehicle does not enter the critical state of rollover, the vehicle speed is increased and the above steps are repeated until the peak value of lateral load transfer rate reaches 0.9, so as to obtain the safe speed threshold of vehicle passing the ramp under the critical state of rollover.

The vehicle loading mass was set at 25t, the road adhesion coefficient was set at 0.7, and the simulation test was carried out at a constant speed of 40km/h. When the vehicle passed through a preset curve, the curve was shown in Figure 1.

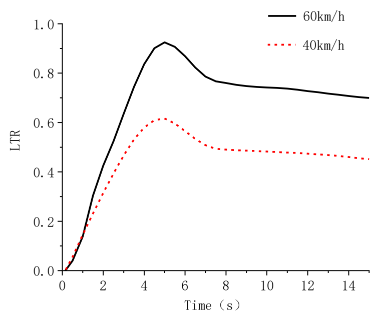


Fig.1 Lateral load transfer rate

Gradually increase the speed and observe the change of lateral load transfer rate curve. When the constant speed increases to 60km/h, the LTR peak value reaches 0.9, and the speed at this time is judged to be the safe speed threshold for the critical state of vehicle rolling over.

3.1 Influence of wind speed

The wind speed in coastal areas varies greatly and is in the gust environment of random change all year round. The wind speed has the characteristics of mutability, gradual and randomness. When the wind speed is too high, for safety reasons, dangerous chemical tank trucks are generally not allowed on the road. Therefore, part of wind speed was selected as the wind speed range of the study. The wind Angle is 90°, which is the most unfavorable condition for vehicle driving.

Several common wind speeds on the ramp are selected for comparative simulation tests to observe the lateral load transfer rate curve changes of tank semi-trailer at different wind speeds. Changes the size of wind speed to carry out simulation test, and obtain the safe speed threshold under each wind speed. Draw the scatter diagram of wind speed and safe speed threshold according to the simulation results, and fit it, as shown in Figure 2.

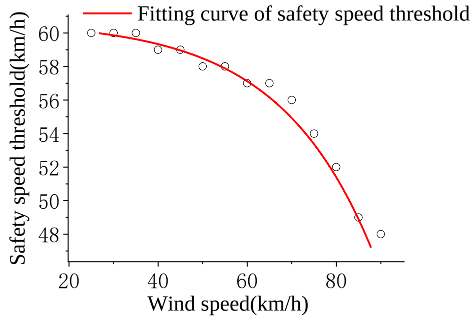


Fig.2 The relationship between wind speed and vehicle safety speed threshold

As can be seen from Figure 2, the safe speed threshold of tank semi-trailer passing ramp decreases with the increase of wind speed, and the two are roughly in a power function relationship. With the increasing wind speed, the road transportation risk of hazardous chemical vehicles is also increasing gradually. When the wind speed exceeds 60km/h, the rollover critical speed of vehicles decreases rapidly.

3.2 Influence of road adhesion coefficient

In order to analyze the influence of road adhesion coefficient on safety speed threshold of ramp section, the road adhesion coefficient was set as 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0, and a total of 10 groups of experimental data were simulated.

Set vehicle loading mass 25T, fixed wind speed 40km/h, wind direction Angle 90°. The tank semi-trailer was driven along the center line of the experimental road at a low constant speed, and the curve of lateral load transfer rate was observed. The constant speed was gradually increased until the vehicle reached the critical state of rollover, and the safe speed threshold under different road adhesion coefficients was obtained.

According to the simulation results, the scatter diagram of ramp road adhesion coefficient and safe speed threshold is drawn and fitted, as shown in Figure 3.

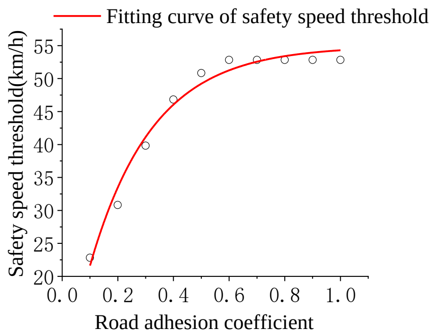


Fig.3 The relationship between road adhesion coefficient and vehicle safety speed threshold

As can be seen from Figure 3, the relationship between road adhesion coefficient and safe speed threshold basically presents a power function. When the road adhesion coefficient is in the range of 0.1~0.6, the ramp safety speed threshold increases gradually with the increase of the road adhesion coefficient. When the road adhesion coefficient is in the range of 0.6~1.0, the safe speed threshold is almost unchanged.

3.3 Slope and ramp radius

In order to analyze the influence of ramp slope and circular curve radius on safe speed threshold, a safe speed threshold model under different working conditions was established. Simulation tests were carried out with slope size and bend radius as variables, and the safety speed thresholds of 2%, 4%, 6% and 8% of longitudinal slope were compared, and the results were analyzed.

Experimental common wind speed of 50 km/h wind speed in coastal areas, from turning direction lateral blowing wind, vehicle loading quantity as the deadline of 25 t, tire-road friction coefficient is 0.7, ramp choosing different radius size, tank semi-trailer begins with a low constant speed simulation experiment, comparing LTR maximum value is greater than 0.9 to determine whether a vehicle rollover or sideslip. If the lateral load transfer rate does not reach 0.9, continue to increase the constant speed and repeat the above steps until the tank semi reaches the critical state of rollover.

According to the simulation results, scatter diagrams of off-ramp radius and safe speed threshold of different slopes were drawn and fitted, as shown in Figure 4.

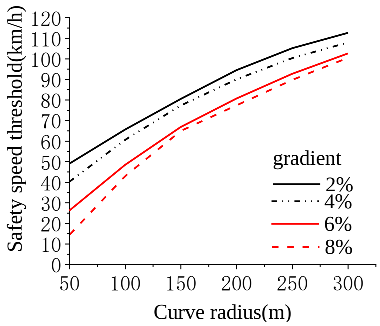


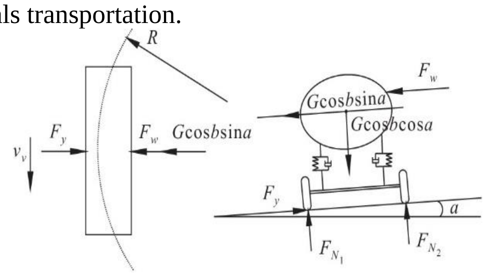
Fig.4 The relationship between road adhesion coefficient and vehicle safety speed threshold

As can be seen from Figure 4, in gentle slope section, the safe speed threshold of small radius curves is large. With the increase of longitudinal slope, the safe speed threshold decreases greatly. For the road with larger bend radius, the slope has little influence on the safe speed threshold. Ramp radius is usually small, tank semi - trailer overspeed is easy to rollover and other accidents. As can be seen from Figure 4, in gentle slope section, the safe speed threshold of small radius curves is large. With the increase of longitudinal slope, the safe speed threshold decreases greatly. For the road with larger bend radius, the slope has little influence on the safe speed threshold. Ramp radius is usually small, tank semi-trailer overspeed is easy to rollover and other accidents.

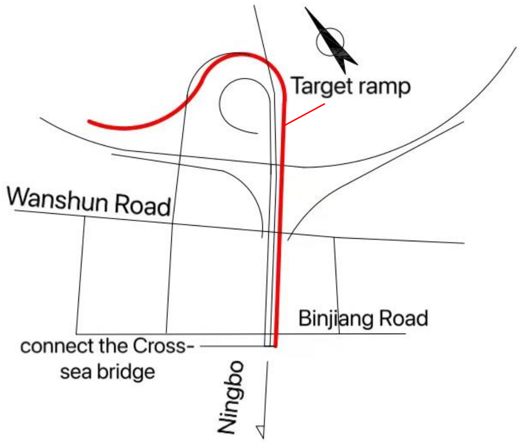
4 SIMULATION RESULTS AND ANALYSIS

4.1 Establishment of safety speed model

In this paper, the safety of vehicles driving in the coastal ramp section is studied in the context of practical engineering. The target ramp connects the Cross-sea bridge with the development zone, and it is the main road hub project of the island. During the driving process of the hazardous chemical tank semi-trailer, its force is shown in Figure 5a. When the adhesion provided by the road surface cannot balance the lateral force generated by the combined action of the vehicle's gravity, strong lateral wind force and inertial force, the vehicle will slip or even roll over. The plane line bitmap of this section is shown in Figure 5b. Given the bridge's location and the complex weather conditions, the wind speed is much more variable than measured by the adjacent weather station. Therefore, the establishment of a fast and accurate wind speed monitoring system is the key to ensure the safety of hazardous chemicals transportation.



(a) Dynamics model of hazardous chemical vehicles



(b) Plane line bitmap of actual project

Fig.5 Engineering background of hazardous chemicals vehicle driving

Simulation is carried out for the transport process of tank semi-trailer in the actual project, and the safety speed threshold of vehicle passing the ramp section under the influence of different wind speed and road adhesion coefficient is obtained, as shown in Table 2.

Table2 Safe speed threshold of vehicle under complex circumstances

wind	coefficient of road adhesion									
speed	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0	43	50	55	58.5	62	63	63	63.5	63.5	63.5
10	42	49	54	58	62	63	63	63.5	63.5	63.5
20	40	48	53	57	61	62	62	62.5	62.5	63
30	38	47	51	56	60	62	62	62.5	62.5	62.5
40	35	45	49	54	59	61	61	61.5	61.5	62
50	32	41	47	52	57	60	60	60.5	60.5	61
60	27	36	42	48	53	56	57	58	58	59
70	20	27	34	40	46	50	52	53	54	55

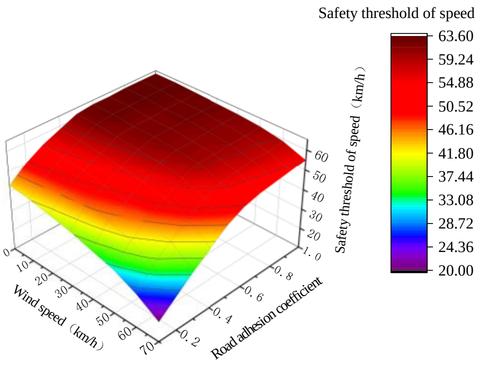


Fig.6 Three-dimensional surface diagram of safe speed threshold under complex conditions

According to the results of Table 2, draw the safety speed threshold of vehicle passing ramp under complex conditions, as shown in Figure 6. The least square method is used to fit the safety speed threshold of vehicle passing ramp under the influence of two factors, and the fitting results are shown in Formula (2).

$$v = 31.70 - 50.73\mu^2 + 83.08\mu - 0.004{v_f}^2 + 0.09v_f \tag{2}$$

The determination coefficient of Equation (2) is 0.958, the fitting error is within a reasonable range, and the fitting state is successful. It can be seen from Figure 6 that when the road adhesion coefficient is in the range of 0.6~1.0, the road adhesion coefficient has little influence on the safe speed threshold of vehicles. Therefore, the fitting range of road adhesion coefficient 0.6~1.0 is taken as the adjusted range. The fitting surface diagram is shown in Figure 7, and the fitting result is shown in Equation (3).

$$v = 57.99 - 2.68\mu^2 + 8.16\mu - 0.003{v_f}^2 + 0.09v_f \tag{3}$$

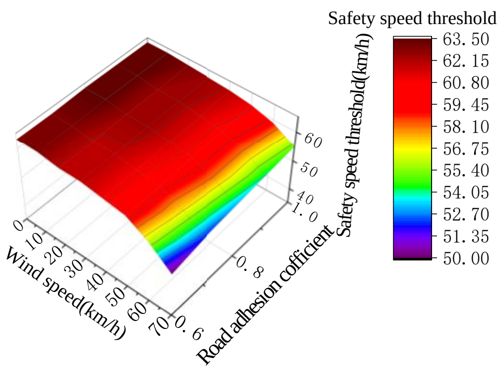


Fig.7 Three-dimensional surface diagram of safety speed threshold after adjustment

The determination coefficient of Equation (3) is 0.968, and the fitting error is small. According to the adjusted fitting formula, the safe speed of hazardous chemical vehicle on ramp under normal weather environment can be obtained, which provides a certain theoretical basis for the safety of ramp driving in coastal areas and achieves safe travel.

4.2 Model validity analysis

Considering the applicability of the model, real ramp section in the coastal area as a background, observation tank semi-trailer safe speed under different weather conditions, the tire-road friction coefficient is 0.18, 0.5, 0.7, respectively, safe speed threshold model curve drawing, will get the speed threshold model compared with the ramp speed limit standard, verify the validity of the model in this paper.

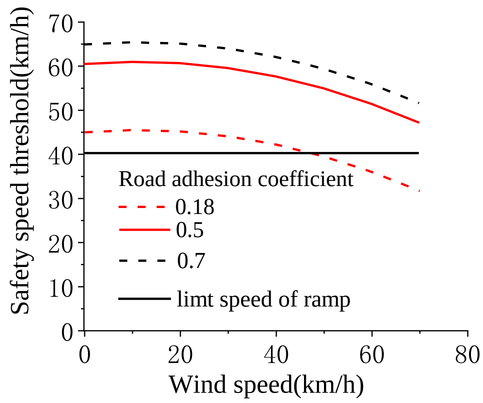


Fig.8 Comparison diagram of safe speed threshold model

It can be seen from Figure 8 that the safety speed model is basically effective. In sunny days and most rainy and snowy days, as long as the tank semi-trailer complies with the speed limit requirements on the ramp, rollover and other accidents can be greatly avoided. When the wind speed is more than 50km/h and the road adhesion coefficient is 0.18, the safety speed threshold is lower than the speed limit value of the ramp, and the dangerous driving risk of hazardous chemical vehicles is great.

4.3 Classification of dangerous grade for safety speed of hazardous chemical vehicle under bad weather

For wind speed levels above 50km/h, a 90° wind Angle and different road adhesion coefficients were selected to compare the safety speed threshold of hazardous chemical road transport vehicles obtained from the model with the ramp speed limit standard. Danger levels [20] were classified according to the safety speed threshold of vehicles and corresponding preventive measures were formulated, as shown in Table 3.

Table3 Classification of hazardous vehicle speed in inclement weather environment

Wind speed （km/h）	coefficient of road adhesion	Safe speed threshold （km/h）	danger level
50	0.7	60	I
50	0.5	57	I
50	0.18	40.1	II
60	0.7	57	I
60	0.5	53	I
60	0.18	36	III
70	0.7	52	I
70	0.5	46	II
70	0.18	31.7	III

Under the condition of grade I danger level, the vehicle can pass on the ramp at normal speed; In the II danger level, the ramp is more dangerous, usually accompanied by strong wind and rain and snow, wet road, poor visibility on the road, drivers should slow down, pay attention to avoid other vehicles; In III levels of dangerous situation, tank semi-trailer in sharp ramp rollover accident happens easily, such cases should be banned for transport vehicles, the ramp section can release information to ahead for vehicle change transport routes or suspend the transport plan of the route, minimize the possibility of accident.

5 CONCLUSIONS

(1) Based on TruckSim software, a simulation model of hazardous chemical vehicles was used to simulate real ramp road surface and environmental conditions. The safety speed threshold of rollover accident of hazardous chemical vehicle was simulated under different wind speed, slope, ramp radius and road adhesion coefficient, and the optimal safety speed threshold of rollover accident was obtained.

(2) Based on the actual engineering background, the driving safety of tank semi-trailer on the ramp is analyzed. In bad weather conditions, the speed limit of ramp cannot completely avoid rollover accidents. The test proves that when the wind speed is 50km/h and the road adhesion coefficient is 0.2, once the speed exceeds 41km/h, there will be the risk of rollover accident. The safety threshold of the speed is close to the speed limit standard of the ramp. In bad weather, hazardous chemical vehicles will roll over when driving at low speed, and the safe speed is far below the speed limit standard, which is prone to accidents.

(3) The coastal ramp section has complex meteorological conditions, and the wind speed and road adhesion coefficient change greatly, which is the area with high incidence of vehicle rollover accidents. The safety speed threshold of dangerous chemical vehicle has obvious difference in different environment. In bad weather, vehicles should slow down to ensure the safety of dangerous chemical road transportation. The management department can close the road in time for extreme weather to prevent serious traffic accidents.

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