Research Article

Modeling of Lateral Stability of Tractor-Semitrailer on Combined Alignments of Freeway

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The objective of this research was to investigate the impact of roadway geometrics and speed on lateral stability of tractor-semitrailer on combined alignments of freeways since the current design guidelines of combined alignments are not available in China. A closed-loop vehicle dynamic simulation model was established using TruckSim multibody dynamics software. The maximum wheel side friction demand and lateral load transfer ratio were used to measure the skidding and rollover risks, and the variation laws of each indicator were determined by developing the controlled variable simulation scenarios. Based on the theory of statistical analysis, an orthogonal test was designed, and the effects of various impact factors on the lateral stability of the tractor-semitrailer were analyzed. The models for lateral stability indicators were developed by multiple linear regression analysis and applied to evaluate the driving risk of tractor-semitrailer on a wet road surface. The results showed that the radius and speed have significant effects on the lateral stability while the effect of the downgrade is of general significance. In addition, lower safe speed should be adopted on wet road surfaces of curved downgrade. This paper proposed a surrogate approach to road safety analysis and the models can be used for building the freeway driving security system.

1. Introduction

At present, tractor-semitrailer safety on combined alignments of freeways has been a serious concern in China due to the overloading and relatively poor vehicle performances. According to the survey of serious and major traffic accidents of national highways (2010 to 2014), on freeways of China, the tractor-semitrailer accounted for 38% of all accident vehicles, killing 1,520 people with a mortality rate of 32%. Rear-end collision, fixed-object accident, and rollover accident are the main accident types of tractor-semitrailer with the percentage of 73.17% [1]. In the current Chinese highway design standard, the tractor-semitrailer is the newly added design vehicle. No detailed specifications on the configurations of tractor-semitrailer were provided, which required being further studied [2]. Currently, the maximum allowable weight for six-axle tractor-semitrailer is 49000 kg, much higher than the medium truck used in existing highway design and other types of tractor-semitrailer [3]. Meanwhile, the Chinese highway design standard did not specify the

design criteria for the combined alignments of freeways [2, 4]. Compared with other truck types, the complex articulated structure, high center of gravity, and the heavy load of six-axle tractor-semitrailer can lead to more severe forms of losing lateral stability when cornering on combined alignments. Therefore, a study is needed to analyze the variation laws of lateral stability of six-axle tractor-semitrailer on combined alignments of freeways.

In previous road safety studies, the impact of road alignment parameters on vehicle safety is mainly based on the point-mass model and vehicle dynamics simulation. The side friction factor is commonly used as the indicator of skidding, and the lateral acceleration and lateral load transfer ratio are adopted to measure the risk of rollover. In AASHTO green book, the point-mass model mainly considers the effects of radius and speed on the side friction factor of vehicle on horizontal curves [5]. Since the effect of the longitudinal grade is negligible, Dunlap et al. (1978) developed the equation of side friction factor by analyzing the forces acting on a vehicle on combined grade and horizontal curvature [6]. Eck and

French (2002) introduced the wheelbase and wheel angles of tractor and semitrailer to the equation of side friction factor to estimate the required additional superelevation for the tractor-semitrailer at the low radius [7]. However, the principle of the point-mass model is based on the steady-state cornering performance of the rigid vehicle, ignoring the vehicle configuration and characteristics, such as the suspension system, which have a great effect on vehicle rollover as well as the distribution of forces acting on different tires, since friction can vary significantly between tires when cornering [8–10].

The vehicle dynamics model has the advantages of reflecting the real-time response of the vehicle to evaluate the vehicle operational characteristics under the specific road environments, and the multiple regression analysis was adopted to develop the mathematical models of lateral stability indicators. Kontaratos et al. (1994) developed an enriched bicycle model to study the effects of grade and speed on lateral stability of passenger cars. Since the tractive forces expend some of the lateral friction, the results revealed that the upgrade can have a significant effect on side friction supply and the minimum radius should be increased on upgrades at higher vehicle speeds [11]. Bonneson (2000) found that the downgrade depletes the margin of safety for heavy trucks traveling on downgrade horizontal curves owing to the great weight and high peak side friction demands of heavy trucks [12]. You and Sun (2013) developed the driver-vehicle-road closed-loop dynamic simulation model of a two-axle convention truck and found that the rollover is the main concern for trucks on horizontal curves, which is affected by the vertical curve, small radius, and steep slope [13]. Kordani et al. (2014, 2015) used CarSim and TruckSim to examine the effect of combined alignments on lateral stability of passenger cars and two-axle conventional trucks and presented a series of formulas based on the multiple regression analysis. They found that a higher maximum wheel side friction demand is produced on steep downgrades and the truck is more likely to roll over [14, 15]. Shin and Lee (2015) investigated the lateral stability of heavy trucks by TruckSim and the study suggested that the rollover is highly sensitive to vehicle speed and steering angle, whereas skidding is vulnerable to the change in tire-road friction coefficient [16]. Zhang et al. (2015) studied the lateral stability of passenger cars on horizontal curves by CarSim and developed the mathematical models of lateral stability with the consideration of curvature radius, longitudinal grade, speed, and brake pressure [17]. Wang et al. (2015) adopted the multiple linear regression models to analyze the effects of the combined alignments on the lateral acceleration of passenger cars [18].

By focusing on the dynamic performances of trucks, a series of researches were conducted to put forward the recommendations to the existing roadway design policies. Considering the driver comfort levels and necessity to maintain the vehicle safety, the effect of vertical alignment on minimum radius requirements was evaluated using computer simulation and multiple linear regression method was employed to calibrate the minimum radius requirements for combined alignments based on the AASHTO green book [19–21]. Torbic et al. (2014) used a combination of field data

and analytical and vehicle dynamics simulation models to evaluate geometric design criteria for sharp horizontal curves on steep grades and put forward the limit of maximum superelevation rate on a simple horizontal curve combined with vertical alignments [22]. Li and He (2016) demonstrated the safety margins of lateral tire forces for radius, operating speed, and superelevation rate on horizontal curves to guarantee good vehicle lateral reliability and ride comfort [23].

The previous studies mainly concentrated on lateral stability of passenger cars and two-axle conventional trucks according to the AASHTO roadway design policy but paid little attention to the lateral stability of six-axle tractor-semitrailer on combined alignments of freeways. To analyze and reveal the traffic accident mechanism of rollover and skidding of six-axle tractor-semitrailer, the present study is organized as follows. In Section 2, a driver-vehicle-road closed-loop model considering three-dimensional alignment was established by TruckSim. In Section 3, to demonstrate the effects of speed and roadway geometrics on lateral stability of the vehicle, the controlled variable method and orthogonal test method were used to develop the simulation scenarios, and the one-way analysis of variance was adopted to analyze the effects of various factors quantitatively. In Section 4, the simulation results were used to establish the models for lateral stability indicators and put forward a speed limit for six-axle tractor-semitrailer on the wet road surface.

2. Materials and Methods

TruckSim multibody vehicle dynamics software was used to establish the driver-vehicle-road dynamic simulation model. It consists of three essential components: the driver control model, the vehicle model, and the 3D road model. A typical six-axle tractor-semitrailer was used to evaluate the stability performance on different terrains at various speeds. The detailed parameter settings and establishment process of the model were described in this section. Based on force analysis of tractor-semitrailer on combined alignments, the evaluation indicators of lateral stability were determined to measure the risk of skidding and rollover.

2.1. Driver-Vehicle-Road Dynamic Simulation Model

2.1.1. Vehicle Model. The investigated tractor-semitrailers selected are Suzuki QL4250SKFZ three-axle tractor and Huajun ZCZ9390 three-axle semitrailer, which are commonly used in China. The drive type of the tractor is 6×4 . The gross vehicle weight is 49000 kg with a rated load of 33000 kg. The vehicle model includes four-wheel drive powertrain, air pressure braking system, Ackermann steering mechanism, solid axle suspensions of steering axle, drive axles, and trailer axles. According to the structural parameters of the investigated tractor-semitrailer and the field test to calibrate the vehicle model, the main parameters of tractor-semitrailer were determined, as shown in Table 1. The vehicle configuration interfaces in TruckSim are shown in Figure 1.

2.1.2. 3D Road Model. The 3D road model in TruckSim simulation software defines the geometric alignments and

FIGURE 1: Vehicle configuration interfaces in TruckSim.

TABLE 1: Main parameters of tractor and semitrailer.

Category	Parameter	Value
Size and weight of tractor	Gross vehicle weight (kg)	25000
	Unladen mass (kg)	7880
	Maximum towed mass (kg)	39600
	Length (mm)	6895
	Width (mm)	2465
	Height (mm)	3060
	Wheelbase (mm)	3400 + 1300
	Front track (mm)	2060
	Rear track (mm)	1855/1855
Size and weight of semitrailer	Length (mm)	13000
	Width (mm)	2500
	Wheelbase (mm)	6831 + 1310 + 1310
	Sprung mass (mm)	6250
Powertrain	Maximum load (kg)	33000
	Rated power/engine speed (kW/rpm)	265/2000
	Maximum torque (Nm/rpm)	1422/1400
Suspension	Compression ratio	17.5 : 1
	Unsprung mass (kg)	Steering axle: 570 Drive axles: 785 Trailer axles: 690
	Axle roll and yaw inertia (kg·m ²)	Steering axle: 335 Drive axles: 305 Trailer axles: 266
	Spring stiffness (N·mm ⁻¹)	Steering axle: 250 Drive axles: 700 Trailer axles: 2500
	Damping coefficient (N·s·mm ⁻¹)	Steering axle: 15 Drive axles: 30 Trailer axles: 30
	Brake torque	Steering axle (kN·m): 7.5 Drive axles (kN·m): 10 Trailer axles (kN·m): 10
Tires	Tire size	11.00R20
	Effective rolling radius (mm)	528
	Unloaded free radius (mm)	542
	Maximum allowed force (kN)	100

friction of the ground relative to a 3D reference line. The geometric alignments consist of the horizontal alignment, vertical alignment, and cross section. In TruckSim, the “X-Y coordinates of centerline” module defines the horizontal alignment of the road, using a table of X-Y coordinates of the investigated road segment calculated by multiquadric (MQ) interpolation method. For the vertical alignment design, the “centerline elevation: Z versus S” module is available for specifying the elevation for the reference line through inputting the elevation of the starting and ending points of the road segment. The superelevation rate of the cross section is set by modifying the elevations of both sides of the road segment at the feature points such as the straight-spiral point, spiral-curve point, curve-spiral point, and spiral-tangent point. For the dry asphalt pavement, the typical value of friction coefficient is 0.8 (Yu, 2011) [24]. Figure 2 shows an example of the detailed settings of 3D road model in TruckSim simulation.

2.1.3. Driver Control Model. The closed-loop driver control model contains four parts: speed control, brake control, gear-shifting control, and steering control. The vehicle travels at a constant target speed. Automatic gear-shifting control was adopted using the closed-loop shift control at all gears. For the downgrades, the step brake control was used to maintain the constant descending speed, and the values of braking force varied along with the simulation step size. In steering control, the key control parameters are the target path of the vehicle and the preview time. The vehicle travels along the road centerline as the target path with no offset. The preview control looks ahead a distance determined from the specified time and the current speed, to compare the current vehicle trajectory to the target path. A realistic value for the preview time is about 1.5 seconds, which can produce smoother steering to keep the vehicle on the target winding paths.

2.1.4. Experimental Validation. To further investigate the accuracy of the driver-vehicle-road dynamic simulation model, the field test was conducted on the Hunchun-Dunhua freeway, which is a segment of G12 National Highway, in Jilin province, China. The tractor-semitrailer was controlled by a driver with more than 10 years of experience. The speed and lateral acceleration were recorded by VBOX and gyroscope simultaneously, and the experimental setup and test instruments are shown in Figure 3. One typical segment with curve radius of 490 m and average gradient of 3.1% (−3.1% for downgrade) was selected, and the lengths of the spiral transition curve and circular curve section are 120 m and 305 m, respectively. In the process of field test, owing to the effect of real-time traffic status, the initial speeds for upgrade and downgrade were 86.3 km/h and 67.9 km/h, respectively. The comparisons of simulated and measured results on curved upgrade and downgrade are shown in Figure 4.

As shown in Figure 4(a), on the curved upgrade, with the increase of the length of longitudinal slope, the simulated speed and measured speed decrease gradually. The simulated and measured lateral acceleration reaches 0.11 g

at the spiral-curve point. On the circular curve section, the lateral acceleration decreases slowly; after entering the spiral transition curve, the lateral acceleration decreases rapidly with the decrease of curvature. As shown in Figure 4(b), on the curved downgrade, the simulated and measured speeds increase slightly with the increase of longitudinal grade. On the circular curve section, the lateral acceleration obtained from the simulation and field test increases slowly, reaching the maximum value of 0.08 g at the curve-spiral point. After entering the spiral transition curve, the values of lateral acceleration decrease rapidly. It can be concluded that the dynamic responses of the simulation model were in good agreement with those of field tests, indicating that the driver-vehicle-road dynamic simulation model was sufficiently accurate to analyze the lateral stability of the tractor-semitrailer.

2.2. Force Analysis of Combined Alignments. A three-dimensional reference system of the road was developed to analyze the force condition under the influence of cross slope and the longitudinal slope. The original reference system (X_0, Y_0, Z_0) is defined as the reference system of the horizontal curve without superelevation, where O is the coordinate origin fixed on the ground. Then, by rotating coordinators with the degree of θ around the Y_0 axis, the reference system on vertical alignment $(X_\theta, Y_\theta, Z_\theta)$ was developed, and θ is the angle of vertical slope. Finally, through rotating the coordinators with the degree of α (the angle of cross slope) around the X_0 axis, the three-dimensional reference system for combined horizontal and vertical alignments (X_r, Y_r, Z_r) was developed, as shown in Figure 5. The reference transformation formula from the original reference system (X_0, Y_0, Z_0) to the three-dimensional reference system (X_r, Y_r, Z_r) can be expressed as

$$\begin{bmatrix} X_r \\ Y_r \\ Z_r \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ \sin \alpha \sin \theta & \cos \alpha & -\sin \alpha \cos \theta \\ -\sin \theta \cos \alpha & \sin \alpha & \cos \alpha \cos \theta \end{bmatrix} \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}. \quad (1)$$

Figure 5 shows the three-dimensional reference system and the force analysis of tractor-semitrailer cornering on combined horizontal and vertical alignments.

In Figure 5, F is the centrifugal force (N), G is the vehicle gravity (N), F_y is the total lateral tire force (N), F_z is the total vertical tire force (N), F_{yLno} , F_{yLni} , F_{yRno} , and F_{yRni} are lateral forces of the outer and inner tires of the left and right n th axle (N), F_{zLno} , F_{zLni} , F_{zRno} , and F_{zRni} are vertical forces of the right n th axle (N), g is the gravity acceleration (m/s^2), V is the speed (km/h), R is the radius of curve (m), α is the angle of cross slope ($^\circ$), and θ is the angle of vertical slope ($^\circ$).

A general formula of lateral tire forces and vertical tire forces acting on six-axle tractor-semitrailer can be written as

$$\begin{aligned} F &= \frac{GV^2}{gR}, \\ F_y &= \sum_{n=1}^6 (F_{yLno} + F_{yLni} + F_{yRno} + F_{yRni}) \\ &= \frac{GV^2}{gR} \cos \alpha - G \cos \theta \sin \alpha, \end{aligned}$$

(a) Settings of horizontal alignment

(b) Settings of vertical alignment

(c) Settings of cross section

FIGURE 2: Settings of 3D road model in TruckSim simulation.

FIGURE 3: Experimental setup and test instruments.

(a) Speed and lateral acceleration on curved upgrades

(b) Speed and lateral acceleration on curved downgrades

FIGURE 4: Comparison of simulated and measured results of typical freeway section.

FIGURE 5: Force analysis of tractor-semitrailer cornering on combined alignments.

$$\begin{aligned}
 F_z &= \sum_{n=1}^6 (F_{zLno} + F_{zLni} + F_{zRno} + F_{zRni}) \\
 &= \frac{GV^2}{gR} \sin \alpha + G \cos \theta \cos \alpha.
 \end{aligned} \quad (2)$$

2.3. Evaluation Indicator of Lateral Stability. The skidding and rollover are the main hazardous situations of the six-axle tractor-semitrailer losing lateral stability on the curved upgrades and downgrades. The vehicle skids when the centrifugal force on the mass center of the vehicle exceeds the lateral forces between the tire and the pavement and rolls over when the centrifugal force moment exceeds the gravity moment. The high speed, heavy load, and decreased road friction coefficient are the primary cause of the skidding and rollover.

According to Figure 5, the maximum wheel side friction demand was selected as the evaluation indicator of skidding. The definition of maximum wheel side friction demand is the absolute value of the maximum ratio of total lateral forces to total vertical forces of each side of axle, denoted by f_D . It is also the maximum wheel side friction demand by the vehicle moving on the curved road without skidding, which can be given by [17]

$$f_D = \max \left(\left| \frac{F_{yLno} + F_{yLni}}{F_{zLno} + F_{zLni}} \right|, \left| \frac{F_{yRno} + F_{yRni}}{F_{zRno} + F_{zRni}} \right| \right) \quad (3)$$

$(n = 1, 2, 3, 4, 5, 6),$

where f_D denotes the maximum wheel side friction demand, F_{yLno} and F_{yLni} are lateral forces of the outer and inner tires of the left n th axle (N), F_{yRno} and F_{yRni} are lateral forces of the outer and inner tires of the right n th axle (N), F_{zLno} and

F_{zLni} are vertical forces of the left n th axle (N), and F_{zRno} and F_{zRni} are the vertical forces of the right n th axle (N). The vehicle will skid if the maximum wheel side friction demand f_D exceeds the supplied road friction coefficient ϕ , so the value of road friction coefficient ϕ is the safety threshold of maximum wheel side friction demand f_D .

The vehicle rollover is one of the most frequent single vehicle accidents, especially for six-axle tractor-semitrailers with a high gravity center. The truck experiences vertical load transfer from the tires on one side of the vehicle to those on the other side when traveling on curved road sections. The lateral load transfer ratio denoted by LTR is used to measure the risk of the rollover of the heavy truck [25, 26]. It is defined as the ratio of the difference between the sum of right wheel loads and the sum of left wheel loads to the sum of total wheel loads [27], as shown in

$$\text{LTR} = \frac{\sum_{n=1}^6 (F_{zLno} + F_{zLni}) - \sum_{n=1}^6 (F_{zRno} + F_{zRni})}{\sum_{n=1}^6 (F_{zLno} + F_{zLni}) + \sum_{n=1}^6 (F_{zRno} + F_{zRni})}, \quad (4)$$

where LTR denotes the lateral load transfer ratio, F_{zLno} and F_{zLni} are vertical forces of the left n th axle (N), and F_{zRno} and F_{zRni} are the vertical forces of the right n th axle (N).

Based on the research conducted by Fan et al. (2016), the risk level of LTR can be classified into three states [28]:

- (1) When $\text{LTR} \in [0.6, 0.8]$, the vehicle has a modest potentiality in occurrence of rollover, which is defined as the warning state of rollover.
- (2) When $\text{LTR} \in [0.8, 1]$, the vehicle has a definite potentiality in occurrence of rollover; this state is defined as dangerous state of rollover.
- (3) When $\text{LTR} = 1$, the wheels of one side leave the ground, and the vertical load of one side transfers to the wheels on the other side; this state is defined as "critical state of rollover."

FIGURE 6: Road geometric parameters of scenarios.

3. Simulation Process and Driving Dynamics Analysis

This section describes the criteria used for the selection of road alignments; a series of controlled variable simulation scenarios and orthogonal tests were designed. The variation laws of lateral stability indicators in controlled variable simulation scenarios and the ANOVA results of orthogonal tests regarding the roadway geometrics and speeds were presented.

3.1. Design of Controlled Variable Simulation Scenarios. To explore the variation laws of f_D and LTR along the stations under the influence of roadway geometrics and speeds, respectively, a series of controlled variable simulation scenarios were developed. For the determination of the road alignments, according to the Chinese standard *Technical Standard of Highway Engineering (JTGB01-2014)* [2] and *Design Specification for Highway Alignment (JTGD20-2006)* [4], the freeway with a design speed of 80 km/h was considered. For the horizontal alignment, the ultimate minimum radius is 250 m with a maximum superelevation rate of 8%. To compare the impact of the radius on the lateral stability, a control group with the radii of 450 m, 650 m, and 850 m were selected. The total length of the simulated segment is 800 m: the length of the approach and departure tangent is 100 m, the length of the spiral transition curve L_s is 200 m, and the length of the circular curve is 200 m. For the vertical alignment, the maximum allowable longitudinal grade of freeway with the design speed of 80 km/h is 6%, and therefore the upgrades of 3%, 4%, 5%, and 6% and downgrades of -3%, -4%, -5%, and -6% were selected. In the standard, the critical slope length increases with the decreasing longitudinal grade. To simplify the influence of the slope length, the longitudinal slope starts at the distance of 150 m and ends at the distance of 650 m with a total length of 500 m. The road alignment

parameters of scenarios are shown in Figure 6, and the detailed design of controlled variable simulation scenarios is presented in Table 2.

3.2. Simulation Results of Controlled Variable Simulation Scenarios. Figure 7 shows the simulation results of the variation laws of f_D and LTR on curved upgrades. It can be found that f_D and LTR present the same variation law. On the approach tangent (from 0 to 100 m), the values of f_D and LTR are approximate to 0. As the vehicle enters the spiral transition curve (from 100 m to 300 m), the centrifugal force increases as the curvature radius reduces gradually, and the values of f_D and LTR increase dramatically. As the length of longitudinal slope increases, the speed decreases on upgrades, and the values of f_D and LTR decrease slightly. On the circular curve (from 300 m to 500 m), owing to the smallest curvature radius, the constant maximum centrifugal force causes the maximum roll motion of the vehicle, and therefore f_D and LTR reach the peak values. However, the constant horizontal radius makes constant and limited contribution to the roll motion of the vehicle; due to the speed loss of the upgrades, the values of f_D and LTR decrease sharply. On the spiral transition curve (from 500 m to 700 m), as the curvature radius increases gradually and the ascending speed decreases, the centrifugal force on the truck slowly decreases. Therefore, the values of f_D and LTR show a dramatic reduction. After entering the departure tangent (from 700 to 800 m), the values of f_D and LTR are approximate to 0, without the influence of horizontal curve and upgrades. The variation laws reveal that the values of f_D and LTR are in direct proportion to the speed while being in inverse proportion to the radius and upgrade.

Figure 8 shows the simulation results of the variation laws of f_D and LTR on curved downgrades. The values of f_D and LTR on curved downgrades have a similar tendency to the curved upgrades except in the circular curve section

TABLE 2: Design of controlled variable simulation scenarios.

Road type	Scenarios	Radius (m)	Grade (%)	Speed (km/h)	Simulation purpose
Curved upgrades	1	250, 450, 650, 850	4	80	Study the effect of radius
	2	450	3, 4, 5, 6	80	Study the effect of grades
	3	450	4	60, 70, 80, 90	Study the effect of speeds
Curved downgrades	1	250, 450, 650, 850	-4	80	Study the effect of radius
	2	450	-3, -4, -5, -6	80	Study the effect of grades
	3	450	-4	60, 70, 80, 90	Study the effect of speeds

TABLE 3: Factors and corresponding levels.

Level	Radius (m)	Grade (%)	Speed (km/h)
1	250	3 (-3)	60
2	450	4 (-4)	70
3	650	5 (-5)	80
4	850	6 (-6)	90

(from 250 m to 450 m). Instead of the decreasing values of f_D and LTR on upgrades, f_D and LTR reach the peak values after entering the circular curve, as the braking forces act on the vehicle to maintain a constant speed, and there is no speed loss on downgrades; the values of f_D and LTR remain constant. Particularly, on the circular curve, there is an increase in values of f_D and LTR on downgrades of -5% and -6%, indicating that, on downgrades steeper than -4%, the descending speed still increases slightly though the braking maneuvers are applied. The variation laws reveal that, in braking cases, the values of f_D and LTR are in direct proportion to speed and downgrade while being in inverse proportion to the radius.

3.3. Design and ANOVA Results of Orthogonal Tests. The orthogonal test method is commonly used in experimental study of multilevel factors by effectively simplifying the design of experiment test. In this research, it can be used to quantitatively analyze the effects of multilevel factors on the lateral stability of six-axle tractor-semitrailer on curved upgrades and downgrades. The $L_{16}(4^5)$ orthogonal array was selected to analyze the three factors with four levels for curved upgrades and downgrades, respectively. Factors and corresponding levels are shown in Table 3. In the column of grade, the negative gradients in brackets denote the downgrades.

F -test was used for significance testing of factors in the variance analysis. The significance level α includes 0.01, 0.05, and 0.10 for F distribution. For the factor i , if $F_i \geq F_{0.01}$, the factor i has a high significant effect on the dependent variables; if $F_{0.05} \leq F_i < F_{0.01}$, the factor i has a significant effect on the dependent variables; if $F_{0.1} \leq F_i < F_{0.05}$, the factor i has a general significant effect on the dependent variables; if $F_i < F_{0.1}$, the factor i has no significant effect on the dependent variables.

Tables 4 and 5 show the variance analysis of factors influencing f_D and LTR on curved upgrades. It can be found that, on curved upgrades, the order of primary and secondary factors affecting f_D and LTR is radius, speed, and grade

according to the order of sum of squares. The F values of radius and speed are greater than the corresponding critical F values, and therefore the radius has a highly significant effect on the lateral stability of tractor-semitrailer, and speed has a significant effect whereas the effect of the grade is not significant.

Tables 6 and 7 show the variance analysis of factors influencing f_D and LTR on curved downgrades. It can be found that, on curved downgrades, the values of sum of squares decrease gradually from the radius to speed to grade, indicating that the order of primary and secondary factors affecting f_D and LTR is the radius, speed, and grade, respectively. The F values of the radius, speed, and grade are greater than the corresponding critical F values, and therefore the effect of the radius is of high significance, the effect of the speed is of significance, and the effect of the grade is of general significance. This is mainly due to the fact that the radius and speed can influence the roll motion of vehicle and centrifugal force directly when cornering on curves. The grade can change the component of force, as its value is relatively low, so the effect of the grade is less significant than radius and speed.

4. Results and Discussion

Following the consideration of the simulation results, the multiple linear regression analysis was conducted to develop new models of f_D and LTR for six-axle tractor-semitrailer by selecting the radius, longitudinal grade, and vehicle speed as the independent variables. Based on the models, the risk analysis of vehicle on the wet road surface was conducted and the safe speed limits were put forward.

4.1. Calibrated Mathematical Model. A total of 56 observations of curved upgrades and downgrades were used to calibrate the mathematical model. Many independent variables were examined, and the final models were calibrated based on the following criteria [29]:

- (1) The coefficient of determination R^2 must be significant at the 0.95 confidence level.
- (2) Each of the independent variables used in the model must have a coefficient that is significantly different from zero at the 0.95 confidence level.
- (3) The algebraic signs of the coefficients of the independent variables must have a logical explanation.

The final models of f_D and LTR on curved upgrades and downgrades were presented in (5)-(6).

FIGURE 7: Variation laws of f_D and LTR on curved upgrades.

(a) Variation laws of f_D and LTR of different curvature radii (b) Variation laws of f_D and LTR of different grades (c) Variation laws of f_D and LTR of different speedsFIGURE 8: Variation laws of f_D and LTR on curved downgrades.

TABLE 4: Variance analysis of factors influencing f_D on curved upgrades.

Source	Sum of squares	df	Mean square	F value	Critical F value
Corrected model	0.186	9	0.021	32.686	
Intercept	1.731	1	1.731	2731.354	
Radius	0.146	3	0.049	77.008	$F_{0.01}(3, 3) = 29.5$
Grade	0.001	3	0.000	0.414	$F_{0.1}(3, 3) = 5.39$
Speed	0.039	3	0.013	20.637	$F_{0.05}(3, 3) = 9.28$
Error	0.004	6	0.001		
Total	1.921	16			
Correct total	0.190	15			

TABLE 5: Variance analysis of factors influencing the LTR on curved upgrades.

Source	Sum of squares	df	Mean square	F value	Critical F value
Corrected model	0.243	9	0.027	34.915	
Intercept	3.042	1	3.042	3926.216	
Radius	0.178	3	0.059	76.416	$F_{0.01}(3, 3) = 29.5$
Grade	0.001	3	0.000	0.507	$F_{0.1}(3, 3) = 5.39$
Speed	0.065	3	0.022	27.821	$F_{0.05}(3, 3) = 9.28$
Error	0.005	6	0.001		
Total	3.291	16			
Correct total	0.248	15			

TABLE 6: Variance analysis of factors influencing f_D on curved downgrades.

Source	Sum of squares	Df	Mean square	F value	Critical F value
Corrected model	0.325	9	0.036	21.211	
Intercept	1.951	1	1.951	1146.316	
Radius	0.208	3	0.069	40.808	$F_{0.01}(3, 3) = 29.5$
Grade	0.035	3	0.012	6.873	$F_{0.1}(3, 3) = 5.39$
Speed	0.081	3	0.027	15.953	$F_{0.05}(3, 3) = 9.28$
Error	0.010	6	0.002		
Total	2.286	16			
Correct total	0.335	15			

TABLE 7: Variance analysis of factors influencing the LTR on downgrades.

Source	Sum of squares	df	Mean square	F value	Critical F value
Corrected model	0.480	9	0.053	23.119	
Intercept	4.197	1	4.197	1819.425	
Radius	0.301	3	0.100	43.538	$F_{0.01}(3, 3) = 29.5$
Grade	0.052	3	0.017	7.524	$F_{0.1}(3, 3) = 5.39$
Speed	0.127	3	0.042	18.294	$F_{0.05}(3, 3) = 9.28$
Error	0.014	6	0.002		
Total	4.691	16			
Correct total	0.494	15			

$$\text{Curved upgrades: } f_D = 0.015 \frac{V^2}{R} - 0.013i + 0.194 \quad (5)$$

$$\text{Curved downgrades: } f_D = 0.018 \frac{V^2}{R} - 0.02i + 0.022,$$

$$\text{Curved upgrades: LTR} = 0.017 \frac{V^2}{R} - 0.014i + 0.281$$

$$\begin{aligned} \text{Curved downgrades: LTR} \\ = 0.022 \frac{V^2}{R} - 0.025i + 0.112, \end{aligned} \quad (6)$$

where f_D is the maximum wheel side friction demand; R is the radius (m); i is the grade (%); V is the speed (km/h).

where LTR is the lateral load transfer ratio; R is the radius (m); i is the grade (%); V is the speed (km/h).

TABLE 8: Results of statistical analysis for f_D cornering on upgrades and downgrades.

Road type	Independent variable	B	t	P value
Curved upgrades	<i>Constant</i>	0.194	26.441	0.001
	V^2/R	0.015	63.064	0.001
	i	-0.013	-7.976	0.001
	$R^2 = 0.994$			
Curved downgrades	<i>Constant</i>	0.022	2.635	0.015
	V^2/R	0.018	68.886	0.001
	i	-0.020	-11.326	0.001
	$R^2 = 0.996$			

TABLE 9: Results of statistical analysis for LTR cornering on upgrades and downgrades.

Road type	Independent variable	B	t	P value
Curved upgrades	<i>Constant</i>	0.281	60.183	0.001
	V^2/R	0.017	113.230	0.001
	i	-0.014	-14.143	0.001
	$R^2 = 0.998$			
Curved downgrades	<i>Constant</i>	0.112	8.347	0.001
	V^2/R	0.022	50.799	0.001
	i	-0.025	-8.792	0.001
	$R^2 = 0.992$			

From Tables 8 and 9, the P value of all independent variables is significantly different from zero at the 95% confidence level, so (5)-(6) have logical explanations for the effect of each independent variable on dependent variables, f_D and LTR. The positive sign for the coefficient of V^2/R means that f_D and LTR increase with the increase in V^2/R . The negative sign for the coefficient of i means that, on curved upgrades, f_D and LTR decrease as grade i increases. On curved downgrades, f_D and LTR increase when downgrade i increases (as the signs for downgrades are negative).

4.2. Risk Analysis of Vehicle on Wet Road Surface. On wet road surface, the road friction coefficient is greatly decreased by rainwater. Meanwhile, the rainwater that accumulated in the tread pattern may lead to a decrease in the contact area between the tire and the pavement. As a result, brake failure and inflexible steering can greatly reduce the lateral stability of the vehicle, and the high speed can lead to the increase in centrifugal force, increasing the probability of traffic accidents. Therefore, by conducting the risk analysis of the vehicle on a wet road surface, the safe speed limit is put forward.

The supplied friction coefficient φ of wet road surface at different speeds V can be determined as follows (Wambold et al., 1984) [30]:

$$\varphi = 0.874e^{-0.00393V}. \quad (7)$$

The lateral stability of the vehicle on curved upgrades and downgrades can be analyzed by utilizing (5)-(6). By comparing the values of f_D and LTR with the available friction coefficient φ and the rollover risk level, respectively, the risk analysis on wet road surface was conducted. For the freeway

with the design speed of 80 km/h, the ultimate minimum horizontal curve radius of 250 m and general minimum horizontal curve radius of 400 m with the superelevation rate of 8% were selected as the evaluating section. The upgrade ranges from 3% to 6%, and the downgrade ranges from -3% to -6%. The six-axle tractor-semitrailer travels at the speed of 70 km/h to 90 km/h. The risk analyses of vehicle on upgrades and downgrades combined with the ultimate minimum horizontal curve radius and the general minimum horizontal curve radius were presented in Tables 10 and 11, respectively.

From Tables 10 and 11, the following can be concluded.

- (1) To avoid the skidding risk, the safe speed on the curved upgrade is higher than that on curved downgrades. For the radius of 250 m combined with upgrades of 3%, 4%, and 5%, the skidding occurs at 90 km/h. There is no skidding risk of tractor-semitrailer at 90 km/h on upgrade of 6%. On curved downgrades, the skidding occurs at 90 km/h on downgrades of -3% and -4% and 85 km/h on downgrades of -5% and -6%.
- (2) From the viewpoint of the rollover risk, the risk levels on the downgrades are higher than on upgrades. On curved upgrades, for the ultimate minimum radius of 250 m combined with upgrades of 3%, 4%, and 5%, at the speed of 70 km/h, the vehicle is in the safe status. However, when the speed reaches 75 km/h or more, the vehicle remains in the warning state of rollover. On the upgrade of 6%, the vehicle is in the warning state of rollover within a range from 80 km/h to 90 km/h. On curved downgrades of -3% and -4%, the vehicle is in the warning state of rollover within a

TABLE 10: Risk Analysis of Tractor-semitrailer on the Ultimate Minimum Horizontal Curve Radius Combined with Upgrades and Downgrades.

$i/\%$	$V/(km/h)$	φ	f_D	LTR	Risk status	$i/\%$	$V/(km/h)$	φ	f_D	LTR	Risk status
3	70	0.66	0.45	0.57	Safe		70	0.66	0.43	0.62	Warning state of rollover
	75	0.65	0.49	0.62	Warning state of rollover		75	0.65	0.49	0.68	Warning state of rollover
	80	0.64	0.54	0.67	Warning state of rollover	-3	80	0.64	0.54	0.75	Warning state of rollover
	85	0.63	0.59	0.73	Warning state of rollover		85	0.63	0.60	0.82	Dangerous state of rollover
	90	0.61	0.64	0.79	Skidding, warning state of rollover		90	0.61	0.67	0.90	Skidding, dangerous state of rollover
4	70	0.66	0.44	0.56	Safe		70	0.66	0.45	0.64	Warning state of rollover
	75	0.65	0.48	0.61	Warning state of rollover		75	0.65	0.51	0.71	Warning state of rollover
	80	0.64	0.53	0.66	Warning state of rollover	-4	80	0.64	0.56	0.78	Warning state of rollover
	85	0.63	0.58	0.72	Warning state of rollover		85	0.63	0.62	0.85	Dangerous state of rollover
	90	0.61	0.63	0.78	Skidding, warning state of rollover		90	0.61	0.69	0.92	Skidding, dangerous state of rollover
5	70	0.66	0.42	0.54	Safe		70	0.66	0.47	0.67	Warning state of rollover
	75	0.65	0.47	0.59	Warning state of rollover		75	0.65	0.53	0.73	Warning state of rollover
	80	0.64	0.51	0.65	Warning state of rollover	-5	80	0.64	0.58	0.80	Dangerous state of rollover
	85	0.63	0.56	0.70	Warning state of rollover		85	0.63	0.64	0.87	Skidding, dangerous state of rollover
	90	0.61	0.62	0.76	Skidding, warning state of rollover		90	0.61	0.71	0.95	Skidding, dangerous state of rollover
6	70	0.66	0.41	0.53	Safe		70	0.66	0.47	0.67	Warning state of rollover
	75	0.65	0.45	0.58	Safe		75	0.65	0.53	0.73	Warning state of rollover
	80	0.64	0.50	0.63	Warning state of rollover	-6	80	0.64	0.60	0.83	Dangerous state of rollover
	85	0.63	0.55	0.69	Warning state of rollover		85	0.63	0.66	0.90	Skidding, dangerous state of rollover
	90	0.61	0.60	0.75	Warning state of rollover		90	0.61	0.73	0.97	Skidding, dangerous state of rollover

TABLE 11: Risk analysis of tractor-semitrailer on the general minimum horizontal curve radius combined with upgrades and downgrades.

$i/\%$	V (km/h)	φ	f_D	LTR	Risk status	$i/\%$	V (km/h)	φ	f_D	LTR	Risk status
3	70	0.66	0.34	0.45	Safe	-3	70	0.66	0.30	0.46	Safe
	75	0.65	0.37	0.48	Safe		75	0.65	0.34	0.50	Safe
	80	0.64	0.40	0.51	Safe		80	0.64	0.37	0.54	Safe
	85	0.63	0.43	0.55	Safe		85	0.63	0.41	0.58	Safe
	90	0.61	0.46	0.58	Safe		90	0.61	0.45	0.63	Warning state of rollover
4	70	0.66	0.33	0.43	Safe	-4	70	0.66	0.32	0.48	Safe
	75	0.65	0.35	0.46	Safe		75	0.65	0.36	0.52	Safe
	80	0.64	0.38	0.50	Safe		80	0.64	0.39	0.56	Safe
	85	0.63	0.41	0.53	Safe		85	0.63	0.43	0.61	Warning state of rollover
	90	0.61	0.45	0.57	Safe		90	0.61	0.47	0.66	Warning state of rollover
5	70	0.66	0.31	0.42	Safe	-5	70	0.66	0.34	0.51	Safe
	75	0.65	0.34	0.45	Safe		75	0.65	0.38	0.55	Safe
	80	0.64	0.37	0.48	Safe		80	0.64	0.41	0.59	Safe
	85	0.63	0.40	0.52	Safe		85	0.63	0.45	0.63	Warning state of rollover
	90	0.61	0.43	0.56	Safe		90	0.61	0.49	0.68	Warning state of rollover
6	70	0.66	0.30	0.41	Safe	-6	70	0.66	0.36	0.53	Safe
	75	0.65	0.33	0.44	Safe		75	0.65	0.40	0.57	Safe
	80	0.64	0.36	0.47	Safe		80	0.64	0.43	0.61	Warning state of rollover
	85	0.63	0.39	0.50	Safe		85	0.63	0.47	0.66	Warning state of rollover
	90	0.61	0.42	0.54	Safe		90	0.61	0.51	0.71	Warning state of rollover

range from 70 km/h to 80 km/h and dangerous state of rollover within a range from 85 km/h to 90 km/h. On curved downgrades of -5% and -6% , the vehicle remains in the warning state of rollover within a range from 70 km/h to 75 km/h and dangerous state of rollover within a range from 80 km/h to 90 km/h.

- (3) The lateral stability of tractor-semitrailer improves markedly on the general minimum radius of 400 m. On upgrades, the values of f_D and LTR are much lower than the threshold values, so the six-axle tractor-semitrailer remains in safe status at the speed of 90 km/h. On downgrades of -3% , -4% , -5% , and -6% , the speed causing the warning state of rollover is 90 km/h, 85 km/h, 85 km/h, and 80 km/h, respectively. Therefore, the general minimum radius can basically satisfy the lateral stability requirements of six-axle tractor-semitrailer at the design speed of 80 km/h. Besides, it is necessary to limit the speed on the ultimate minimum horizontal curve radius combined with upgrades and downgrades.

5. Conclusions

To investigate the lateral stability of six-axle tractor-semitrailer on combined alignments of the freeway, the closed-loop vehicle dynamic simulation model using TruckSim multi-body software was established, and the following remarks are offered:

- (1) The variation laws of the maximum wheel side friction demand f_D and lateral load transfer ratio LTR on curved upgrades are consistent with the curved downgrades except in circular curve section due to the speed loss on curved upgrades. The steeper upgrade causes a reduction in f_D and LTR whereas the steeper downgrade can lead to an increase in f_D and LTR, showing that more side friction demand and roll motion are created on steep downgrades compared with upgrades and mild downgrades.
- (2) On both curved upgrades and downgrades, the order of primary and secondary factors affecting f_D and LTR is radius, speed, and grade. The effect of the horizontal radius is of high significance, and the effect of speed is of significance. On curved downgrades, the grade has the general significant effect on lateral stability of six-axle tractor-semitrailer. Therefore, more concerns should be attached to the safety issues of curved downgrades.
- (3) The horizontal radius, speed, and grade were introduced to calibrate the mathematical models of the lateral stability. Skidding and rollover risks were analyzed on the wet road surface of the curved upgrades and downgrades, respectively. This study recommends that, to ensure the lateral stability of six-axle tractor-semitrailer on the wet road surface, low speed should be adopted to ensure the lateral stability of tractor-semitrailer. From the comprehensive perspective of preventing the skidding risk and

rollover risk, for the ultimate minimum radius, the safe ascending speed and descending speed should better not exceed 75 km/h and 70 km/h, respectively; for the ultimate minimum radius of 400 m, a safe descending speed should better not exceed 80 km/h.

- (4) The results and recommendation models can provide guide for both combined alignments design and safety improvement of existing roads. However, this research only considered the lateral stability of six-axle tractor-semitrailer on the simple horizontal curves combined with vertical slopes. Therefore, the lateral stability related to more alignment combinations such as the compound horizontal curves and reverse horizontal curves on upgrades and downgrades should be investigated in further research.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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