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Research on the horizontal curve's radius under coupling effects of uneven adhesion coefficient and crosswind

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ABSTRACT

In order to study the effects of uneven adhesion coefficient and crosswind on alignment design indexes, a six-axle semi-trailer is selected as the typical vehicle model to investigate the effects of uneven adhesion coefficient caused by superelevation under the condition of rainfall on the truck's lateral stability, quantifying the crosswind using TruckSim. Based on the basic theory of vehicle dynamics, vehicle safety driving model is established. Also, the minimum radius is calculated with the consideration of uneven adhesion coefficient and crosswind. The results show that the effects of uneven adhesion coefficient and crosswind on the truck's lateral stability increase with the increasing of the truck's speed. Truck's lateral slide instability begins to appear when crosswind grade grows up to 9 or above. According to sensitive analysis, speed, rainfall, crosswind, and the interaction of the speed and rainfall have significant influences on the truck's lateral stability. The results quantify the effects of uneven adhesion coefficient and crosswind on truck's lateral stability. The advised index for horizontal curve design control is proposed, which provides a good reference for road safety design and safety protective measures. It can also provide theoretical basis and guidelines for highway safe operation in the windy and rainy areas.

1. Introduction

The traditional design standard of highway engineering only takes safety, economy, easy manipulation, and comfort factors into consideration for the lateral force coefficient, while ignoring the influence of crosswind and uneven road adhesion coefficient caused by rainfall on truck's lateral instability. Recent years, as the global environment deterioration, extreme weather events like strong winds and heavy rain are very frequent. The low technical standards of mountain roads in China and poor stability of trucks can easily lead to truck skidding, rollover, and other severe accidents under the conditions of strong winds and heavy rain. Moreover, the road traffic capacity and service level are greatly reduced (Baker, 1991, 1994; Coleman and Baker, 1992; Pang et al., 2006; Schlosser, 1977).

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The importance to understand the performance of crosswind and rainfall in the truck's lateral stability has become apparent. As early as 1990, Hight et al. (1990) and Pei et al. (1998) studied the stress distribution of the tire at different speeds and thicknesses of water film, then put forward the cause of the high accident rate for friction and water skiing on the rainy day. Peters (1993) and Start et al. (1998) carried out a wind tunnel test which chose vehicles' model ratio from 1:1 to 1:6 and the wind heading from 0° to 90°. Moreover, he put forward the changing rule of the aerodynamic force and the corresponding torque. Ryan and Dominy (1998) and Amundsen and Ranes (2000) obtained the passenger car model's aerodynamic force value with rollover in the wind heading of about 30°. Fang (2000) set up a vehicle dynamics simulation and high-speed aerodynamic characteristics model, and analyzed the speeding, side wind effects on vehicle handling stability. Maruyama and Yamazaki (2006) and Snæbjörnsson et al. (2007) came up with an accident risk method based on the vehicle weight, tire load, aerodynamic force and driving behavior, including the strong subjectivity driving behavior and other factors which were difficult to quantify. Wu (2011) studied the highway safety which affected by the typhoon weather, and developed a cars skid model. He also calculated the safety driving speed of the car under the different grades of typhoon weather, but didn't give a quantitative reaction of wind in the paper. Rodriguez et al. (2014) used a driving simulator to quantify the crosswind influence on driver behavior and vehicle lateral displacement, and proposed a calculation model based on the cross culture power, driver behavior, and the vehicle lateral displacement. Xu et al. (2014) and Ueckermann et al. (2015) studied the effect of crosswind on alignment design indexes by wind tunnel test, but his article did not consider the influence of the aerodynamic torque caused by wind and uneven coefficient on trucks lateral stability. Therefore, this article focuses on uneven adhesion coefficient and crosswind to study truck's lateral stability. Wind force on trucks in simulated uniform wind field is obtained by TruckSim simulation software. Based on vehicle dynamics principle, a vehicle stability driving model is established. Also, the radius of the road is calculated with the consideration of crosswind and uneven adhesion coefficient. Moreover, the research can provide technical reference for road safety design in the future.

2. Research method

2.1. TruckSim simulation test

TruckSim is a vehicle dynamics simulation software package developed by the Transportation Research Institute at University of Michigan, which has engaged in vehicle dynamics simulation research for more than 20 years (Song et al., 2010). Due to use of the parametric modeling method and the characteristic of module parameter accurate setting, this software can be used to analyze the response of roads, environment, driving behavior, and the vehicle itself parameter input. Therefore, the software has been widely used. At present, scholars have started to use this software for vehicle dynamics simulation study in China. Li et al. (2009) and Kwon et al. (2011) imported a driver model by using the software TruckSim, and changed the parameters such as wind speed, wind heading, and speed of truck. It analyzed the effect of crosswind on handling and stability of truck driving in a straight-line. Zhang and Ding (2012) and Wang et al. (2014) used TruckSim software to study the stability of a tractor semi-trailer in crosswind. Digital simulations were carried out at different wind headings, wind speeds, and vehicle speeds with step steering input to analyze different vehicle responses of roll angle, yaw rate, and hitch angle, and then obtain the critical vehicle speed and critical wind speed for the tractor semi-trailer with stability driving. Therefore, it is worthwhile to use TruckSim simulation software to quantify crosswind effect on truck.

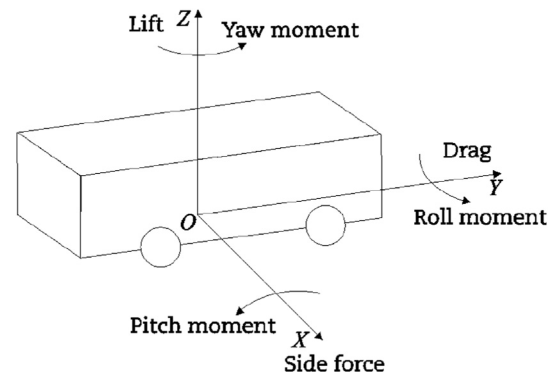

Fig. 1 – Wind force distribution on vehicle.

2.1.1. *Analysis of automotive aerodynamics*

According to the principle of aerodynamics, three directions of the aerodynamic force will act on wind pressure center of the truck where there is no pneumatic torque, but the wind pressure center and the vehicle mass center are always not at the same point (Rhonda and Joel, 2007). In order to facilitate the analysis of stress and kinematics equation, the vehicle mass center, which can add three pneumatic torques, is often used. This article uses the TruckSim software which transforms the reference point to the vehicle mass center automatically to reflect the influence of aerodynamics on vehicle dynamics in time. Under the action of crosswind, the vehicles' aerodynamic force is shown in Fig. 1.

2.1.2. *Calculation of the aerodynamic force*

In order to quantify the effects of crosswind on truck, a six-axle semi-trailer (Fig. 2) with no-load weight 14 t, center of

Fig. 2 – Test model.

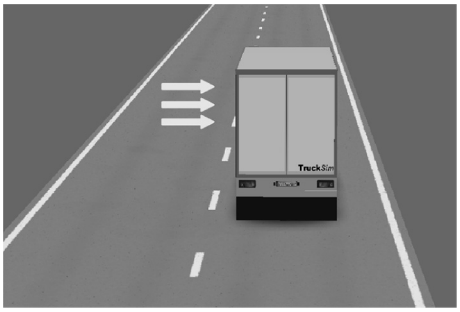

Fig. 3 – Vertical wind act on 6-semi-trailer axle box type profile.

mass's height 1.6 m, and wheelbase 2.0 m is selected as the typical vehicle model. The test is conducted under the condition of open loop. The steering is fixed as well. The truck drives on a straight and level road and the crosswind acts on the side of the vehicle vertically (Fig. 3). It is easy to obtain aerodynamic force by changing the speed of wind as shown in Table 1. With the increasing of wind scale, the aerodynamic force has also increased, as can be seen in Fig. 4.

2.2. *Uneven adhesion coefficient analysis under the condition of rainfall*

Water flow is changed due to the effect of road cross-sectional slope. The water film depth is different on the same road cross section. Therefore, the adhesion coefficient of each point on the same road cross section is also different. The car driving on different thicknesses of water film road when it is raining will cause the car side slipping and the occurrence of accident. Anderson (1995) and Ji (2004) obtained the relationship between rainfall intensity and water film depth where the text conducted on the section was paved with the mixture asphalt of SMA-13 as follow

$$h = 0.0609 l^{0.6134} \alpha^{-0.3133} q^{1.4483} \quad (1)$$

where h is water film depth, l is slope length, α is superelevation, q is rainfall intensity. The relationship between adhesion coefficient and water film depth is

$$\varphi = 1.3280 - 0.0078v - 0.017h \quad (2)$$

where φ is adhesion coefficient, v is the speed of truck.

Summing up Eqs. (1) and (2) we can get the following result

$$\varphi = 1.3280 - 0.0078v - 0.00104 l^{0.6134} \alpha^{-0.3133} q^{1.4483} \quad (3)$$

Usually, the classic formula of the relationship between road adhesion coefficient φ and the longitudinal adhesion coefficient φ' is $\varphi' = 0.6\varphi - 0.7\varphi$ (Chen and Williams, 2014). The primary objective of this part is to investigate the road of 4 lanes with each lane width of 3.5 m, where the superelevations of 6%, 8%, 10% are considered. The truck drives on the middle of the outer lane when the experiment has been done. The left and the right wheels' lateral adhesion coefficients $\varphi_L^{'}$, $\varphi_R^{'}$ are shown in Tables 2–4.

3. Research works and findings

3.1. *Analysis for truck's lateral stability*

Vehicle's lateral stability is that the vehicle can keep normal running, direction, and not out of control such as sliding, rollover and so on under the action of external factors. When the truck drives on a horizontal curve, truck's lateral stability is analyzed based on the basic theory of mechanical balance principle. The force analysis of truck is shown in Fig. 5.

The aerodynamic force, centrifugal force, and gravity can be decomposed into X (which is paralleled to the road) and Y (which is perpendicular to the road) directions.

$$X = F_X + mv^2 \cos(\alpha)/R - G \sin(\alpha) \quad (4)$$

$$Y = mv^2 \sin(\alpha)/R + G \cos(\alpha) \quad (5)$$

where X is aerodynamic force, Y is centrifugal force, m is the mass of the vehicle whose unloaded weight is 14 t in this paper, R is minimum radius of horizontal curve, G is gravity, the gravity acceleration is 10 N/kg in this paper.

Because α is always small, it is assumed that $\sin(\alpha) \approx \tan(\alpha) = i$, $\cos(\alpha) \approx 1$, where i is superelevation.

$$X = F_X + mv^2/R - Gi \quad (6)$$

Table 1 – Aerodynamic force on vehicle under wind.

Wind grade	Wind speed (m/s)	F_X(N)	F_Y(N)	F_Z(N)	M_X(N·m)	M_Y(N·m)	M_Z(N·m)
5	8.0	2042.0	190.7	18.2	287.3	690.4	582.3
	10.7	3653.0	341.2	32.6	514.0	1235.1	1041.7
6	10.8	3721.6	347.6	33.2	523.6	1258.3	1061.3
	13.8	6076.2	567.5	54.3	855.0	2054.4	1732.7
7	13.9	6164.6	575.7	55.1	867.4	2084.3	1757.9
	17.1	9329.7	871.3	83.3	1312.7	3154.4	2660.5
8	17.2	9439.2	881.6	84.3	1328.1	3191.4	2691.7
	20.7	13,671.5	1276.8	122.1	1923.7	4622.4	3898.7
9	20.8	13,803.9	1289.2	123.3	1942.3	4667.2	3936.4
	24.4	18,995.7	1774.1	169.7	2672.8	6422.5	5416.9
10	24.5	19,151.8	1788.7	171.1	2694.7	6475.3	5461.4
	28.4	25,734.3	2403.4	229.9	3621.0	8700.9	7338.6
11	28.5	25,915.9	2420.4	231.5	3646.5	8762.7	7390.3
	32.6	33,908.7	3266.9	302.9	4771.1	11,464.8	9669.6
12–13	32.7	34,117.1	3186.3	304.7	4800.4	11,535.1	9729.0
	41.4	54,686.1	5107.4	488.4	7694.6	18,489.6	15,594.6

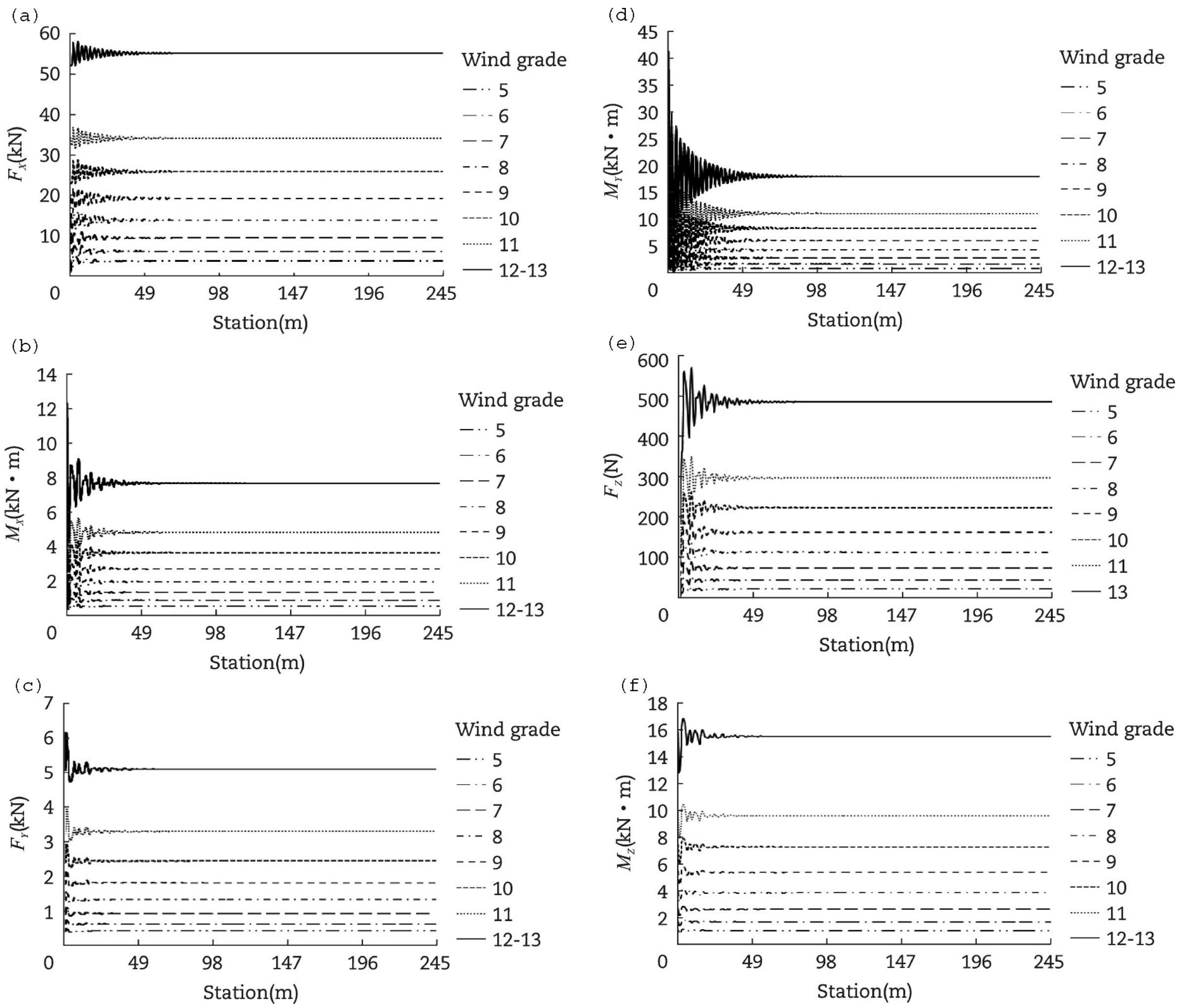

Fig. 4 – Biggest aerodynamic force under different grades of wind. (a) Side force F_X. (b) Pitch moment M_X. (c) Drag F_Y. (d) Roll moment M_Y. (e) Lift F_Z. (f) Yaw moment M_Z.

The left and right wheel's vertical reactions of the road can be obtained according to D'Alembert's principle under the condition of the vehicle in a stable state.

$$F_R b + M_Y + (F_X + mv^2/R)h_g = 1/2Gb + Gh_g i + 1/2mv^2/R\cdot bi \quad (7)$$

$$F_L b + Gh_g i = 1/2Gb + M_Y + 1/2mv^2/R\cdot bi + (F_X + mv^2/R)h_g \quad (8)$$

where F_L and F_R are the left and right wheel's vertical reactions of the road, b is wheelbase which is 2.0 m, h_g is center of mass's height which is 1.6 m.

In order to avoid the vehicle's skidding, X should be less than or equal to the lateral friction. The inequality can be listed as follow

$$X \le F_R\varphi'_R + F_L\varphi'_L \quad (9)$$

Table 2 – Vehicle's lateral adhesion coefficients under the condition of rainfall and the superelevation of 6%.

Design speed (km/h)	Rainfall intensity (mm/min)	φ'_L	φ'_R
40	5	0.572	0.562
	10	0.507	0.479
	15	0.425	0.375
60	5	0.478	0.468
	10	0.413	0.386
	15	0.331	0.282
80	5	0.385	0.375
	10	0.320	0.292
	15	0.238	0.188

Table 3 – Vehicle's lateral adhesion coefficients under the condition of rainfall and the superelevation of 8%.

Design speed (km/h)	Rainfall intensity (mm/min)	φ'_L	φ'_R
40	5	0.575	0.566
	10	0.516	0.491
	15	0.441	0.396
60	5	0.482	0.472
	10	0.422	0.397
	15	0.347	0.302
80	5	0.388	0.379
	10	0.329	0.303
	15	0.253	0.208

Table 4 – Vehicle's lateral adhesion coefficients under the condition of rainfall and the superelevation of 10%.

Design speed (km/h)	Rainfall intensity (mm/min)	φ'_L	φ'_R
40	5	0.578	0.569
	10	0.522	0.499
	15	0.452	0.410
60	5	0.484	0.475
	10	0.428	0.405
	15	0.359	0.316
80	5	0.390	0.382
	10	0.335	0.311
	15	0.265	0.223

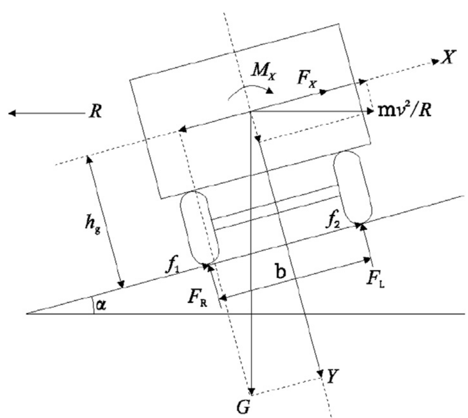

Fig. 5 – Force analysis of vehicle driving on horizontally curved section.

To use Eqs. (4), (6–8) correctly, a helpful equation can be obtained as follow

$$R \geq \frac{mv^2\left[1+h_g/b\cdot(\varphi'_R-\varphi'_L)-1/2\cdot i\cdot(\varphi'_R+\varphi'_L)\right]}{1/2\cdot G(\varphi'_R+\varphi'_L)+\left(Gih_g/b-M_Y/b-F_Xh_g/b\right)(\varphi'_R-\varphi'_L)-F_X+Gi} \tag{10}$$

3.2. *Minimum radius under the condition of uneven adhesion coefficient and crosswind*

According to "Technical Standard of Highway Engineering (JTG B01—2014)" (short for "standard"), MOT (2014), the traditional concept of the limit minimum radius is removed and the minimum radius of horizontal curve is listed under the superelevation of 4%, 6%, 8% and 10%. Because of the restriction of paper length, the minimum radius is only calculated under the superelevation of 6%, 8% and 10% in this study. The truck's rollover stability is also checked. The results shown in Tables 5–7 meet the requirements.

From the analysis of the data in Tables 5–7, it can be seen that

(1) The minimum radius of horizontal curve in "standard", which is close to those under the conditions of ice and snow, is smaller than the calculation in this paper. In addition, the minimum radius under the effects of uneven adhesion coefficient and crosswind is greater than that ignoring crosswind.
(2) Because the superelevation can speed up road drainage, the adhesion coefficient will increase with the superelevation's increasing at a certain range. In addition, the component of gravity along the direction of superelevation can offset a part of centrifugal force. Therefore, the greater the superelevation is, the more stable the truck will be. It also can be seen in Table 5 when superelevation is 6%, there are 2 dangerous points where accidents easily happen, one point at 8% and no point at 10%.
(3) The effects of crosswind and rain on the lateral stability of the truck are more obvious when the speed is higher. Calculating radii begins to exceed the specified value in the "standards" when the wind reaches grade 9 or above.

3.3. *Sensitivity analysis for truck's lateral stability*

The minimum radius of horizontal curve can reflect the influence of vehicle speed (v), rainfall intensity (q), wind grade (k), and superelevation (i) to truck's lateral stability. In this paper, v, q, k, i, and the interactions between each 2 factors ($v \times q$), ($v \times k$), ($v \times i$) are considered. The results are shown in Tables 8 and 9.

According to the sensitive analysis, the results show that the significance of factors to truck's lateral stability can be ranked as follows, vehicle speed, rainfall intensity, wind grade, the interaction between vehicle speed and rainfall intensity, superelevation, the interaction between vehicle speed and wind grade, and the interaction between vehicle speed and superelevation. Furthermore, the significance of the above factors can be verified by F-statistic. The result can be shown as follows, $F(v)>F_{0.05}(2, 6)$, $F(q)>F_{0.05}(2, 6)$, $F(k)>F_{0.05}(2, 6)$, $F(i)<F_{0.05}(2, 6)$, $F(v \times q)>F_{0.05}(4, 6)$, $F(v \times k)<F_{0.05}(4, 6)$, $F(v \times i)$

Table 5 – Minimum radius of horizontal curve under the conditions of rainfall, wind and the superelevation of 6%.

Design speed (km/h)	Rainfall intensity (mm/min)	Wind grade									Value of "standard" (m)
		0	5	6	7	8	9	10	11	12–13	
40	5	19	20	21	22	23	25	27	31	50	60
	10	22	23	24	25	26	29	32	38	70	
	15	26	27	28	30	32	36	42	52	137	
60	5	51	54	56	59	63	67	78	93	188	135
	10	59	63	65	69	75	83	97	122	348	
	15	73	79	83	89	99	114	141	200	Dangerous	
80	5	111	118	123	131	143	160	190	245	927	270
	10	133	143	150	161	179	208	260	375	Dangerous	

Table 6 – Minimum radius of horizontal curve under the conditions of rainfall, wind and the superelevation of 8%.

Design speed (km/h)	Rainfall intensity (mm/min)	Wind grade									Value of “standard” (m)
		0	5	6	7	8	9	10	11	12–13	
40	5	18	19	20	20	22	23	26	29	45	60
	10	20	21	22	23	24	26	29	34	59	
	15	24	25	26	27	29	32	37	44	96	
60	5	49	51	53	55	59	64	72	85	159	125
	10	55	58	60	64	68	76	87	108	252	
	15	66	71	74	79	86	98	118	156	948	
80	5	105	111	116	122	132	148	173	218	640	250
	10	122	130	137	146	161	183	223	304	3544	
	15	155	169	179	195	222	268	362	627	Dangerous	

Table 7 – Minimum radius of horizontal curve under the conditions of rainfall, wind and the superelevation of 10%.

Design speed (km/h)	Rainfall intensity (mm/min)	Wind grade									Value in “standard” (m)
		0	5	6	7	8	9	10	11	12–13	
60	5	46	48	50	52	56	60	68	79	140	115
	10	52	55	56	59	64	70	80	96	201	
	15	61	65	67	71	78	87	102	131	442	
80	5	99	105	109	115	124	137	159	196	492	220
	10	114	121	126	134	147	166	178	259	1209	

Table 8 – Factors and levels.

Level	Vehicle speed (km/h)	Rainfall intensity (mm/min)	Wind grade	Superelevation (%)
1	40	5	0	6
2	60	10	6	8
3	80	15	8	10

$<F_{0.05}(4, 6)$. Therefore, vehicle speed, rainfall intensity, wind grade, and the interaction between vehicle speed and rainfall intensity have significant influences on truck's lateral stability.

4. Conclusions

(1) In order to study the effects of crosswind on truck's lateral stability, crosswind was quantified by TruckSim in this article.

(2) Based on the basic theory of vehicle dynamics, a vehicle safety driving model was established. Also, the minimum radius was calculated with the consideration of uneven adhesion coefficient and crosswind.

(3) The calculated minimum radius can provide a good reference for road safety design in the areas of eastern coastal ports, bridges, pass, and tunnel exit, where the storm weather is very frequent. In order to take safety protective measures in time, crosswind and rainfall detection devices should be installed along the roadside.

(4) Due to some restrictions, this paper only considers the conditions under the rainfall and uneven adhesion coefficient. Therefore, the future research about truck's lateral stability could focus on the condition of snow, ice, or ice water mixture.

(5) With the development of the global economy, more and more types of trucks appear. Only one type of truck was investigated in this paper, other types of trucks could be considered in future research.

Table 9 – Result of deviation and variance analysis based on the minimum radius of horizontal curve.

Factor	Mean square deviation	DOF	Value of F statistic	Significance	Critical value
v	38,239.4	2	159.13	Significant	$F_{0.05}(2, 6) = 5.14$
q	2841.4	2	11.82	Significant	$F_{0.05}(2, 6) = 5.14$
k	1319.2	2	5.49	Significant	$F_{0.05}(2, 6) = 5.14$
i	692.2	2	2.88	Not significant	$F_{0.05}(2, 6) = 5.14$
$v \times q$	1097.5	4	4.57	Significant	$F_{0.05}(4, 6) = 4.53$
$v \times k$	610.2	4	2.54	Not significant	$F_{0.05}(4, 6) = 4.53$
$v \times i$	370.0	4	1.54	Not significant	$F_{0.05}(4, 6) = 4.53$
Error	240.3	6			

Note: the significant level is 0.05.

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