

RESEARCH ON THE ROAD LINEAR OPTIMIZATION DESIGN OF BRIDGE AND TUNNEL CONNECTING SEGMENT IN THE CANYON

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Abstract:

It is easy to skid and roll by centrifugal force and wind, which affects the safety of the vehicle. At the same time, the special location of bridge and tunnel connecting segment in the canyon will accelerate the wind, and make the transverse wind play a more important role in driving vehicles. Based on the acceleration effect of canyons on wind, the vehicle model is simulated by Carsim software, and the road and wind models are established. It is studied that the vehicle has different radius of circular curve under different wind levels, corresponding to different superelevation. The lateral acceleration, lateral deflection and transverse force coefficient are selected as the running state of the vehicle at different speeds to research the linear optimization design of bridge and tunnel connecting segment in the canyon. The result shows that when the wind force exceeds the fifth grade, it is possible for the vehicle to overturn under the limit minimum radius required by the standard value. In order to ensure the stability and safety of the vehicle, this paper considers the geographical position of bridge and tunnel connecting segment in the canyon and the relationship between the radius of the superelevation and circular curve. What's more, it puts forward the optimal limit minimum radius of the circular curve with different wind grades of 5-9 grades. At the same time, when the road alignment cannot be optimized under the condition, this paper puts forward the speed limit that the vehicle safety can be guaranteed under different wind speed conditions. The speed limit can provide reference for traffic management and safety guarantee of mountain expressway.

Keywords: traffic engineering, curved road design, simulation experiment, limit minimum radius of circular curve, bridge and tunnel connecting segment in the canyon, traffic safety

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1. Introduction

Safety is one of the six main aspects of the negative impact of transport. Attention should be drawn to the need to improve transport systems in terms of improving safety (Urbańczyk, 2017). Vehicles driving in curved road section are prone to lateral flip and sideslip under strong wind (Baker & Reynolds, 1992; Baker, 1994; Coleman & Baker, 1994). According to the existing research, the special geographic location of the canyon bridge-tunnel junction will cause the acceleration effect of the canyon wind. From the author's simulation of canyon wind (Wang & Chen, 2012; Wang, 2012), it is known that the speed of canyon wind in the general bridge-tunnel junction can be increased by about 30% compared with the incoming wind because of the acceleration effect. It is equivalent to improving wind level invisibly, which has an impact on the safety of driving vehicles. Base on the technology of virtual machine, researcher Hai *et al.* (2016) point out that the crosswind effect directly affects the safety of vehicle driving. By analyzing the driving state of vehicles in curved road section based on wind tunnel test, and establishing a stable driving model of vehicles considering the influence of crosswind, Xu *et al.* (2014) calculates the limit value and general value of minimum radius of flat curve under different wind speed and running speed. Moreover, the radius of the plane curve in "Design Specification for Highway Route" is not suitable for the safety radius required by the plane curve in windy area, and there are potential safety hazards when the standard value is adopted. At present, in road design, bridges are mainly subordinate to road alignment. In mountainous expressways, horizontal curves have to be adopted because of terrain limitations, which sometimes have to adopt the limit values prescribed by the norms. For inexperienced drivers, traffic accidents are easy to occur in these places (Huang, 2017). Especially under strong wind, it difficult for the driver to judge the exact driving direction because of the force of the car, so that the car deviates from the original driving direction, affects the driver's psychological quality, and is more prone to traffic accidents (Tian *et al.*, 2013; Wu *et al.*, 2017). Tian, Xu and Zhang (2015) used wind tunnel test to simulate the impact of strong wind on the safety of trucks, established the safety speed model of rollover and sideslip of trucks in curved sections by using MATLAB simulation software, and put forward the speed limit standard

of trucks in complex sections under crosswind. Xia *et al.* (2016) proposed the calculation model of the maximum safe running speed of large bus at the horizontal curves based on the current calculation model of radius of horizontal curve. Zhang (2015) used dynamics simulation software Trucksim and Carsim to construct the vehicle model of the big car and the small car respectively, and then carried out a large number of simulation experiments and analysis to determine the safe driving speed values of vehicles under different wind speeds. Batista and Perkovič (2014) constructed a static model of vehicle stability under crosswind conditions, and studied and proposed the critical wind speed values of three traffic accident modes including sideslip, rollover and rotation. Fuller *et al.* (2013) simulated the driver's response state and the vehicle offset of five dynamic and aerodynamic instability conditions under normal wind and extreme gust respectively.

In the current research results, more attention has been paid to the relationship between road alignment index and vehicle lateral stability, but fewer researchers have synthetically studied wind environment, road alignment and driving safety. And the special structure of bridge-tunnel junction is not considered in current studies, that is, the acceleration effect of the canyon wind is not considered. Meanwhile, this paper also takes superelevation as a variable to study the optimal alignment design of canyon bridge-tunnel junction, considering the interaction between superelevation and the corresponding radius of circular curve.

Based on the acceleration effect of the canyon wind, Carsim simulation software is used to simulate driving state of vehicles in different radius of circular curve, corresponding superelevation and at different running speed under different wind level, in which the minimum radius of circular curve stipulated in "Design Specification for Highway Route" (JTG D20-2017) (hereinafter referred to as "Standard") is used. And according to the sideslip and unsteady steering of wheel caused by aerodynamic lateral force under strong wind, the value of curve radius of mountainous expressways is studied to propose a more suitable curve radius.

2. Model building

The researcher is using the Carsim software to build 3-D numerical models, including the vehicle model, road model and wind model, to simulate the effect

of crosswind in tunnel and bridges. In the simulation procedure, because the speed and the total length of the road under different conditions are different, so in order to facilitate data comparison, the simulation running stops at a specified station to control the simulation time.

2.1. Vehicle model setting up

In order to accurately simulate the running state of vehicles in windy weather, the appropriate vehicle types are selected in the vehicle model database of Carsim software, and then the vehicle parameters are set up, so as to meet the conditions that the selected vehicles and the mountain expressway driving environment under the actual wind environment as much as possible. The main vehicle types in the vehicle model database of Carsim software are mainly divided into four categories, including A, B, C, and D four-level standard vehicles, which are consistent with the market type of vehicles. On mountainous expressways, small vehicles usually travel at a higher speed, and the effect of crosswind is more significant because of the smaller quality of small vehicles. At the same time, based on the fact that the vehicles are mainly small cars in actual vehicle running environment, the vehicle type matching with the parameters of the small car is selected. Then taking the C grade standard model car in the vehicle model database of Carsim software as the research object, and some vehicle parameters are corrected. Figure 1 is the standard model vehicle, and this model vehicle's detail data are as table 1.



Fig. 1. Class C standard model vehicle

2.2. Road model setting up

This research chooses 3-dimensional road to reflect the influence of driving at different location of radius curve on vehicle's lateral stability, and the road is simulated by inputting or importing the flat, vertical and horizontal indicators of the road. The boundary conditions are mainly controlled by refining the road model. The horizontal alignment is controlled by setting the X, Y coordinate values of the road centerline. Then the lane width and curb width from the road centerline to the left and right sides respectively are set; finally, set the cross-section alignment to reflect the superelevation value of the road. The road longitudinal grade is set as 0 because the research focuses on horizontal curve road. This model uses a combination of a 200 m straight line and a circular curve with different radius of 90° to simulate the case where the vehicle turns in a straight line due to linear control. Taking a radius of 250 m as an example, Table 2 is the horizontal alignment parameter of road model, and Figure 2 is the horizontal alignment of road model.

Table 1. Main parameters of vehicle

Parameter	Length (mm)	Width (mm)	Height (mm)	Wheel base (mm)	Front overhang (mm)	Height of center of mass (mm)	Sprung mass (kg)
Number	4501	1704	1469	2604	1540	540	1140

Tab.2 The horizontal alignment parameters of the road model

X-coordinate (m)	0	40	80	120	160	200	239.1086	277.2542
Y-coordinate (m)	0	0	0	0	0	0	3.0779	12.2359
Stake number (m)	0	40	80	120	160	200	239.2654225	278.5308449
X-coordinate (m)	313.4976	346.9463	376.7767	402.2542	422.7516	437.7641	446.9221	450.0000
Y-coordinate (m)	27.2484	47.7458	73.2233	103.0537	136.5024	172.7458	210.8914	250.0000
Stake number (m)	317.7963	357.0617	396.3271	435.5925	474.8580	514.1234	553.3888	592.6542

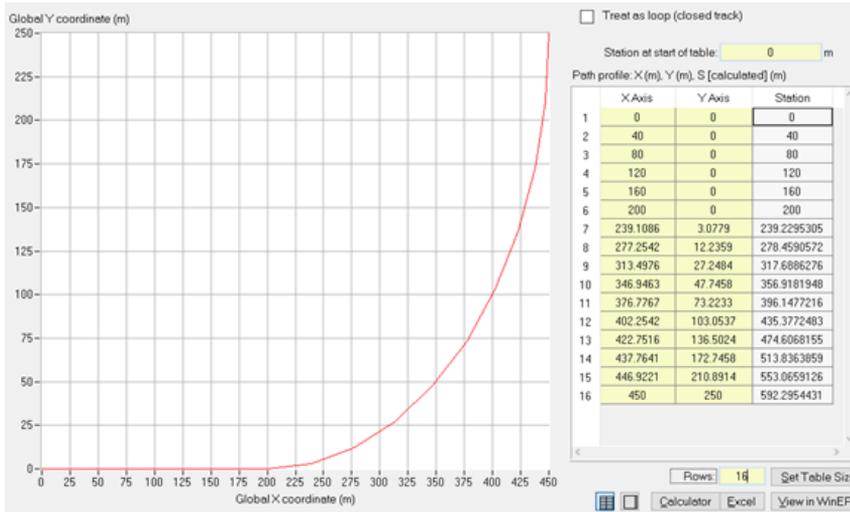


Fig. 2. Plane alignment of road model

Because this model doesn't take into account the influence of road slope on driving stability, this research does not set the vertical parameters of road's linear section. Meanwhile, this research chooses the horizontal slope of 8 degrees frequently used in mountainous highway and 6 degrees used in snow and ice areas to build up the model.

2.3. Wind model setting up

Base on the same wind speed and mountain environment, the canyon has increased the wind speed at the central position of the bridge. However, due to the blockage effect on the entrance of tunnel, the wind speed is not accelerated. Therefore, this paper chooses the minimum data of the wind speed at the entrance of tunnel as the best. On the other hand, it used an acceleration ratio as parameter of wind at the central position of the bridge. As a conclusion, the separation distance is smaller, the speedup effect of wind is greater. when the canyon separation distance is 20 meters, 30 meters or 50 meters, the wind speedup effect is 33.5%, 30.7% and 27.5% respectively. In order to analyze the driving stability affected by crosswind at connecting segment of tunnel and bridge, this article chose the typical case which has 20 meters separation distance between tunnels to simulate speedup effect of wind.

In these tests, the windward area sets 5 m², the crosswind influence point sets 1.226 m. Then entering the data of wind direction and wind speed which

takes a linear interpolation and extrapolation. The setting interface is as Figure 3 shows. In order to analyze the influence of wind direction change on driving stability, three groups of constant wind direction angles are set in each simulation, which are 0, 30, and 90, respectively.

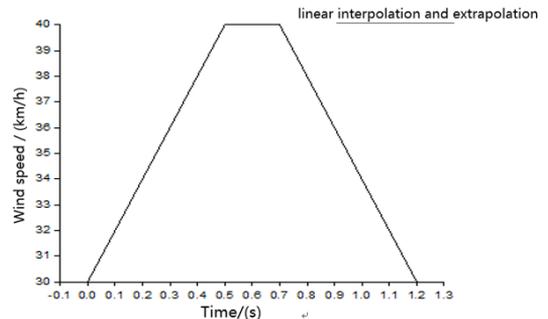


Fig. 3. Wind speed data setting interface

3. Evaluation index

Vehicles in the canyon bridge-tunnel junction are greatly affected by the wind because of the acceleration effect of the canyon wind. When the vehicles are driving at a high speed, the influence of crosswind is more significant. The aerodynamic lateral force will cause the vehicle sideslip and unsteady steering, which is likely to create the risk of sideslip and overturning. Therefore, considering the risk of

sideslip and overturning, the lateral acceleration, lateral offset and lateral force coefficient of vehicle under Canyon wind are selected as evaluation indexes.

3.1. Lateral acceleration

When vehicle is driving on a curve, the lateral acceleration will be generated by the effect of lateral force. If the combined force of the longitudinal force and the lateral force exceeds the maximum adhesion between the tire and the ground, the vehicle will sideslip. The equilibrium equation is as below:

$$(mg\mu)^2 = F_x^2 + F_y^2 \quad (1)$$

$$F_y = ma_y \quad (2)$$

Where m is the mass of the vehicle, μ is the adhesion coefficient of the road, F_x and F_y are the longitudinal and lateral forces respectively of the vehicle, and a_y is the lateral acceleration.

In the canyon bridge-tunnel junction, the lateral acceleration will be greater due to the intensification of crosswind, which will increase the risk of sideslip. Therefore, it is necessary to study the lateral acceleration of the vehicle. According to the national standard, the lateral acceleration of ordinary vehicles should not exceed 0.4g, otherwise, it is not good for the safety and stability of driving. In this paper, 0.4g is used as the safety threshold.

3.2. Lateral offset

When driving at the mountainous expressways, the vehicle can't keep driving along the middle of the lane all the time, and the lateral offset of the vehicle is more obvious under strong wind. Generally, the lane width of highway is 3.75 m, and the car width of most vehicles is 2 m, so the maximum acceptable offset of the vehicle on one side is 0.875 m. Therefore, in order to ensure the safety of vehicles, it is necessary to investigate the lateral offset. Based on the research of relevant scholars, and considering the psychological safety distance between driver and vehicle in adjacent lanes, this paper chooses 0.5 m as the safety threshold of lateral offset.

3.3. Lateral force coefficient

Lateral force is the unstable factor of vehicle driving, and the degree of vehicle stability is generally measured by the lateral force coefficient, which means the lateral force the vehicle received by unit:

$$f = \frac{v^2}{gR} - i_h \quad (3)$$

Where R is the radius of the circular curve, f is the transverse force coefficient, v is the vehicle traveling speed, and i_h is the lateral superelevation.

The bigger the lateral force coefficient f is, the worse the stability of the vehicle driving on the circular curve is, and the more likely it is to overturn and side slip. Therefore, to study the linear safety of the canyon bridge and tunnel junction under the crosswind, the lateral force coefficient must be considered. According to the research, when $f > 0.4$, the vehicle is very unstable when turning and there is a risk of lateral flip^[3]. Therefore, this paper takes the lateral force coefficient f as 0.4 as the threshold of lateral flip. When f is 0.10-0.17, it is safe for driving vehicles. If $f > 0.17$, there is a risk of lateral slip, so the lateral force coefficient is taken as 0.17 as threshold of sideslip.

4. Results and analysis

4.1. Study on safety of vehicle driving safety with level 5 incoming wind as object of wind speed

Firstly, the level 5 incoming wind which is often encountered is taken as the research object of wind speed to consider the acceleration effect of canyon wind. The entrance wind speed is set at 30 km/h, and the time required for vehicles to cross a 20m bridge at 60 km/h (about 16.7 m/s) is about 1.2 s. Since the acceleration effect is most obvious near the central position of the bridge, which can reach 33.5%, the wind speed is set at 40 km/h in 0.3 s-0.9 s and restored to 30 km/h at 1.2 s. Similarly, when the vehicle travels through a 50m bridge, it takes about 3.0 seconds, the acceleration effect near the central position of the bridge can reach 27.5%, the wind speed can accelerate to 38.25 km/h, and the wind speed can recover to 30 km/h at the entrance of the tunnel.

Considering the relationship between the superelevation and the radius of circular curve, the superelevation is analyzed by using the value of 8% in the mountain area of the Standard and 6% in the ice and snow area of the north as variables. Six kinds of working conditions are analyzed (as shown in Table 3), which are common in the alignment of mountain expressways.

Table 3. Common working conditions of Highway alignment in Mountain area under different speeds

Velocity (km/h)	80	80	100	100	120	120
Superelevation (%)	8	6	8	6	8	6

4.1.1. Study on vehicle driving stability with lateral acceleration as evaluation index

Figure 4 and Figure 5 show the lateral acceleration of a vehicle at a speed of 80 km/h on bridge-tunnel junction where the radius of a circular curve is 250m and the superelevation is 8%. Since the lateral acceleration is an instantaneous amount, the faster the wind acceleration is, the more disadvantageous it is. Therefore, the lateral acceleration occurs when the wind speed acts on the length of 20m, that is, the short distance (20 m) is the lateral acceleration index.

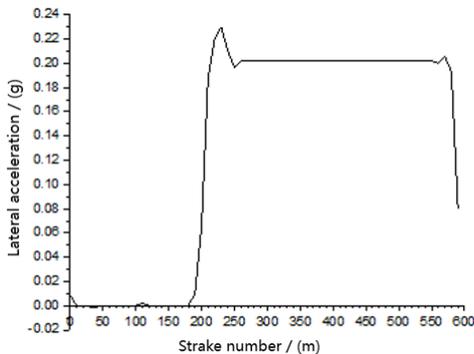


Fig. 4. Lateral acceleration of vehicles without crosswind

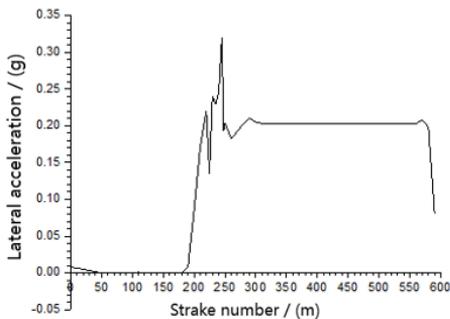


Fig. 5. Lateral acceleration of vehicles under crosswind

It can be seen from figure 4 and figure 5 that the two trends are consistent in a certain range. Before 180 m, the lateral acceleration was almost zero, indicating that the vehicle was moving at a uniform speed in a straight line. Within 180 m and 250 m, the vehicle moves to the circular curve, where the acceleration of the vehicle increases, and the vehicle starts to change direction. Between 250 m and 580 m, the acceleration of the vehicle tends to be stable and the car turn at a uniform speed. Beyond 580 m, the lateral acceleration gradually changes to zero, which indicates that the vehicle is gradually returning to straight driving. Although the two figures have the same trend in the comparison of loading and unloading crosswind effect, when the vehicle suddenly changes its direction (between 180 m and 250 m), the peak values of the two figures are quite different. In Figure 4, the peak lateral acceleration of the vehicle is about 0.23g, while in Figure 5, the lateral acceleration of the vehicle reaches 0.32g, an increase of about 39%, due to the effect of the crosswind. It can be seen that the crosswind with low speed commonly encountered in mountainous areas has already had a certain impact on the acceleration stability of vehicles. Although the lateral acceleration value of the vehicle under level 5 wind does not exceed 0.4g which causes the lateral flip of the vehicle and does not pose a threat to the safety of the vehicle temporarily, the discomfort caused by the unstable dynamic performance of the vehicle will cause certain mental pressure and fatigue to the driver driving on the mountainous expressways.

The trend is the same under the six conditions. The extreme values of lateral acceleration under the level 5 crosswind are summarized as shown in Table 4.

Analysis of the data in Table 4 shows that at the same speed, the subtle change of the superelevation value has little effect on the peak lateral acceleration of the vehicle running on the circular curve. Compared with the influence of crosswind on driving stability, it can be seen that the influence of external force on vehicle is more significant than that of internal force component. When the radius of circular curve is taken as the limit value in "Standard", although it has the acceleration effect of canyon wind, the lateral acceleration value of vehicle driving at the bridge-tunnel junction under level 5 wind not exceed the threshold of 0.4g.

Table 4. The extreme value of lateral acceleration under the action of level 5 crosswind under various conditions

circular curve radius (m)		250	300	350	400	450	550	650
velocity (km/h) (km/h) / superelevation (%)	80 (8)	0.32						
	80 (6)	0.32						
	100 (8)	0.41	0.37	0.34	0.22			
	100 (6)	0.41	0.37	0.34	0.32			
	120 (8)			0.4		0.36	0.32	0.27
	120 (6)			-		0.37	0.32	0.28

4.1.2. Study on vehicle driving stability with lateral offset as evaluation index

Figure 6 and figure 7 show the lateral offset of the vehicle when the vehicle travels at a speed of 80 km/h on the bridge-tunnel junction with a radius of 250m and 8% of the superelevation, under the condition of no crosswind and crosswind respectively. As the lateral offset is a cumulant, the longer the bridge-tunnel junction is, the more disadvantageous it is to drive.

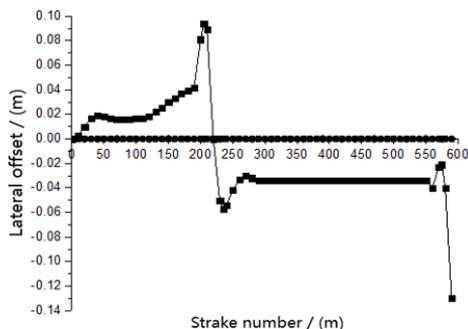


Fig. 6 Lateral offset of vehicles without crosswind

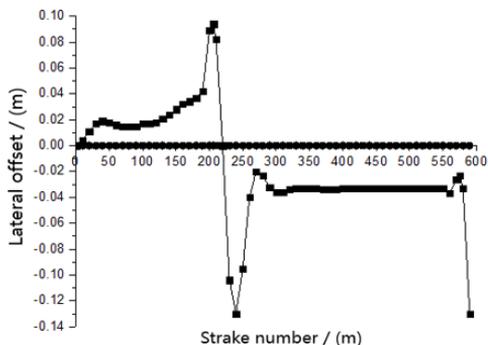


Fig. 7 Lateral offsets of vehicle under crosswind

According to figure 6 and figure 7, it can be seen that the two trends are consistent within a certain range. From 0 to 180 m, the vehicle travels in the straight line, and the lateral offset value is very small. From 180m to 250m, the vehicle transits from straight line to circular curve, and the driving direction will be deviated greatly. The gradual increase of vehicle lateral offset indicates that drivers need to constantly adjust the wheel track offset to adapt to the change of curve.

The positive and negative values of the lateral offset in figure 6 and figure 7 represent the left and right offset of the vehicle trajectory relative to the middle line of the road, in which the positive values are the right-side offset of the middle line (the direction of the crosswind action), and the negative values are the left-side offset of the middle line (the opposite direction of the cross-wind action). Comparing the positive and negative side of the lateral offset with the direction of the crosswind, it is known that the right-side offset at the beginning of the vehicle is caused by the increased centrifugal force and the crosswind effects encountered by the vehicle after entering the circular curve. Subsequently, the vehicle shifts to the left, the reason is that the driver adjusts the steering wheel angle in response to sudden centrifugal force and wind effect in order to maintain the vehicle along the established road track. The time of driver's reaction and the inertia of the vehicle make the vehicle shift to the left in the adjustment process. So the vehicle has a certain reverse offset after adapting to the radius of the circular curve. The cumulative measurement of vehicle lateral offset is larger in figure 6 due to the effect of the canyon wind, which indicates that drivers need to make more adjustments to maintain the stable driving of vehicles in order to adapt to the increased wind effect. It also proves that the effect of crosswind will increase the lateral offset of vehicles and affect the safety of driving.

The trend is the same under the six conditions. The extreme values of lateral offset under the level 5 crosswind are summarized as shown in Table 5.

When the radius of the circular curve is taken as the limit value in "Standard" and the vehicle travels at the bridge-tunnel junction under level incoming wind, although there is acceleration effect of the canyon, the lateral offset does not exceed the threshold of 0.5m which causes the vehicle safety to be affected. However, the level 5 wind is only the lowest wind speed that is commonly experienced by mountainous expressways. It has been verified that the crosswind has a significant effect on the lateral acceleration and lateral offset of the vehicle. When the wind level increases gradually, the minimum radius of the circle curve given in the current standard may no longer meet the safety requirements of vehicles. Therefore, the safety value of minimum radius of circular curve under different wind levels will be studied accordingly.

4.2. Study on the minimum limit radius of circular curve under different wind speed

Explanation: The weight of the car is 1140 kg for the sprung mass, R/L stands for the right and left, 1 stands for the front wheel, 2 stands for the rear wheel, the total lateral force is the instantaneous maximum value, and the total lateral force/vehicle weight is the lateral force coefficient.

The data in Table 6 are the peak values of the transient lateral force coefficient of vehicles under different radius of circular curves corresponding to the level 5-9 wind at speeds of 80 km/h and superelevation of 8%. The lateral force coefficient is about 0.36 when the vehicle travels under the level 5 wind and the minimum radius of the circle curve is 250m, which does not reach the threshold of 0.4, so it can be judged that the vehicle can run safely. When the wind scale increases to level 6, the wind speed at the entrance of the connecting section is 40 km/h, the wind speed at the center of the connecting section is 52 km/h, and the vehicle runs on the circular curve

with a radius of 250m prescribed in the "Standard". The lateral force coefficient is about 0.44, which has exceeded the safety limit of 0.4, so the vehicle may roll over at any time. After several simulation experiments, it is found that when the radius of the circular curve is 285 m, the peak value of the instantaneous lateral force coefficient of the vehicle is 0.39, which is less than the threshold of lateral flip as 0.4, and the vehicle can drive at a stable state. So the minimum radius of the circular curve for the safe driving of the vehicle under the level 6 wind is about 285 m, which is 14% higher than the 250 m in the "Standard". Similarly, the peak value of transient transverse force coefficients under level 7~9 crosswind is analyzed. The minimum radius of circular curve under level 7 wind (52 km/h at the entrance and 67.6 km/h at the center of the connecting section) is 320 m, which is 28% higher than that in "Standard". The minimum radius of the circular curve under level 8 wind (62 km/h at the entrance and 80.6 km/h at the center of the connecting section) is 570 m, which is 128% higher than that in the "Standard". Moreover, the instantaneous vertical reaction force of the left front wheel is 0, which has the tendency of rolling. The vertical reaction force of the left tires of the vehicle under the level 9 wind (75 km/h at the entrance and 97.5 km/h at the center of the connecting section) is 0, that is, LTR (transverse load transfer rate)=1, which is regarded as being about to roll over. Therefore, when the mountain expressway encounters the strong wind at level 9, the relevant management departments should make the corresponding measures according to the real-time wind level provided by the meteorological department, such as closing some windy sections to avoid accidents. Taking the case that the vehicle speed is 80 km/h and the value of superelevation is 6%, the radius of circular curve corresponding to the level 5-9 wind is used as an example (the other conditions are similar), and the threshold of lateral force coefficient is 0.4.

Table 5. Extreme value of lateral migration of level 5 crosswind under various conditions

circular curve radius (m)		250	300	350	400	450	550	650
velocity (km/h) (km/h) / superelevation (%)	80 (8)	0.13						
	80 (6)	0.14						
	100 (8)	0.42	0.31	0.25	0.22			
	100 (6)	0.47	0.34	0.27	0.24			
	120 (8)			0.68		0.62	0.53	0.34
	120 (6)					0.66	0.57	0.49

Table 6. Peak value of Transverse Force coefficient for vehicles with different Radius of Circular Curves

Wind scale	circular curve radius /(m)	(R2) /(N)	(R1) /(N)	(L2) /(N)	(L1) /(N)	Total lateral force /(N)	Lateral force coefficient
Level 5	250	1428.8	1129	88290	625.02	4063.11	0.3564
Level 6	250	1755.4	1440.5	1046	736.63	4978.53	0.4367
	260	1709.6	1395.1	1025.5	713.18	4843.38	0.4249
	270	1668.2	1354.2	1005.9	691.75	4720.05	0.4140
	280	1630.7	1316.8	986.97968.91	672.36	4606.83	0.4041
	290	1596.3	1282.8	968.91	654.97	4502.98	0.3950
	285	1613.2	1299.4	977.81	663.52	4553.93	0.3995
Level 7	285	2220.3	1767.4	827.67	1.9039	4817.27	0.4226
	300	2155	1714.8	821.02	2.3077	4693.13	0.4117
	315	2089.3	1668.4	809.13	3.0426	4569.87	0.4009
	330	2037.6	1626.9	799.44	3.4469	4467.39	0.3919
	320	2071.6	1654.1	805.9	3.1784	4534.78	0.3978
Level 8	320	3207.5	1948.7	300.36	0	5457.56	0.4899
	370	3007.6	1820.7	355.64	0	5183.94	0.4653
	420	2878.5	1713.2	378.42	0	4970.12	0.4360
	470	2765.5	1641.8	418.25	0	4825.55	0.4233
	520	2662.3	1582.4	437.78	0	4682.48	0.4107
	570	2559.3	1539	457.67	0	4545.97	0.3988
	560	2577.6	1538.7	453.66	0	4569.96	0.4009
Level 9	570	3530.6	1724.8	0	0	5255.40	0.4610
	1070	3211.9	1527.5	0	0	4739.40	0.4157
	1570	3101.1	1458.5	0	0	4559.60	0.4000
	1600	3096.5	1455.7	0	0	4552.20	0.3993

From table 4, it can be seen that the radius of 270 m required in the “Standard” cannot meet the requirements. The radius of the circular curve under the action of the level 6 wind should be increased to 300m. Therefore, when the wind force exceeds 5-level, the vehicle has the possibility of overturning under the limit minimum radius required by the “Standard”. It is suggested that the limit values as required in the table above should be met at the bridge-tunnel junction wherever possible. In areas with limited conditions, where the alignment index cannot meet the requirements of the above table, speed limit or closed traffic should be imposed.

Four working conditions are analyzed, which are common conditions in mountain expressway alignment. At the same time, considering the acceleration effect of canyon wind and the relationship between superelevation and radius of circular curve, the superelevation with the value of 8% in the mountain area of the Standard and 6% in the ice and snow area of the north is chosen as variable to analyze. The analysis results are summarized as table 7.

Table 7. Limit minimum radius of circular curve under different wind speed

Wind scale	Velocity (superelevation)			
	80km/h (8%)	80km/h (6%)	60km/h (8%)	60km/h (6%)
Regulations in Standard	250	270	125	135
6	285	300	130	140
7	320	340	145	155
8	570	630	225	245
9	1600	2300	800	1045

Note: the “Standard” in the table is “Design Specification for Highway Route” (JTG D20-2017).

From the above calculation results, it can be seen that:

It is known from table 7 that the minimum radius of the circular curve corresponding to the wind of level 6~9 mostly exceeds the minimum radius of the circular curve specified in the “Standard”. The driving vehicle has the possibility of overturning, which affects the safety of driving. In the condition that the

vehicle speed is 80 km/h and the superelevation is 8%, the minimum radius of the circle curve corresponding to the level 6~9 wind is 285m, 320m, 570m and 1600m respectively, which is 14%, 28%, 128% and 540% higher than the 250 m required in the "Standard". When the vehicle speed is 80km/h and the superelevation is 6%, the minimum radius of the circle curve corresponding to the level 6~9 wind is 300m, 340m, 630 mand 2300m, which is 11%, 26%, 133% and 752% higher than the 270m required in the "Standard". When the vehicle speed is 60 km/h and the superelevation is 8%, the minimum radius of the circular curve corresponding to the level 6-9 wind is 130m, 145m, 22 m, 800m respectively, which is 4%, 16%, 80% and 540% higher than the 125m required in the "Standard". When the speed is 60 km/h and the superelevation is 6%, the minimum radius of the circle curve corresponding to the level 6-9 wind is 140 m, 155 m, 245 m and 1045 m respectively, which is 3%, 15%, 81% and 674% higher than the 135 m required in the "Standard". In mountainous expressways, especially in the bridge-tunnel functions, if the conditions are limited, the minimum radius studied in the table should be taken as far as possible to satisfy the requirement that vehicles can driving safely.

It can be concluded from the study that the wind effect is the same as that of no wind, and the super-elevation and the minimum radius of circular curve interact with each other. The centrifugal force can be balanced by using large value of the superelevation, and then minimal radius of circular curve can be adopted in the mountainous expressways.

4.3. Research on velocity limit for safety of vehicle driving under different wind speed

The minimum speed limit of expressways is 60 km/h, while the speed limit of mountainous expressways is mostly 60 km/h and 80 km/h. Under strong wind, on the road section with speed limit of 60 km/h, the road alignment can be optimized appropriately according to the minimum radius of circular curve suggested by the above analysis in the early stage, or part of the section can be closed in bad weather. The road section with a speed limit of 80 km/h can maintain the stability of the vehicle by reducing the speed limit value under the condition that the road alignment cannot be optimized. Next, this

paper will study the speed limit to ensure the safe driving of vehicles under different wind speeds.

The data in Table 8 are the peak values of transient transverse force coefficient of vehicles at different speeds respectively corresponding to the superelevation of 8%, radius of 250m, and superelevation of 6%, radius of 250m. It can be seen from Table 8 that changing trend of safe driving speed is the same under the two conditions with different superelevations. From Table 9, it can be concluded that 80 km/h of vehicle speed can ensure safety and stability under the wind of level 5, and 75 km/h, 70 km/h and 60 km/h of vehicle speed corresponding to crosswind of level 6~8. When the crosswind reaches level 9, it cannot meet the requirements of safe driving whether it is to optimize the alignment or limit the speed. Therefore, in order to eliminate hidden dangers, it is suggested to close the corresponding road sections. The research results can provide some suggestions and references for traffic management and safety assurance of expressways in mountainous areas. The specific analysis and summary of the speed limits to ensure the safe driving of vehicles under different wind speeds are shown in Table 7.

5. Wind tunnel test verification

5.1. Test conditions

The wind tunnel selected in the wind tunnel test is a mixed structure of steel and concrete. The size of the test section is 15m×3m×2.5m, which is a dual-purpose wind tunnel. The flow field of the tunnel is good, and the wind speed can be continuously adjusted in the range of 0~53m/s, and the turbulence intensity is less than or equal to 0.3%. The bridge model is layered with a foam board at a thickness of 1 cm, and the entire model is reduced by a ratio of 1:1000. The model of the vehicle is reduced by a ratio of 1:30. The instrument for measuring lateral force is a five-component high frequency balance with a measurement error of less than 0.3%. Dantec hotline anemometer is used to measure the wind speed in the test wind environment. Considering that blocking the wind tunnel will lead to an increase in the wind speed, real-time average wind speed measurement is selected at the cross section of the wind tunnel where the vehicle is located to correct the wind speed.

Table 8. Peak value of transient Transverse Force coefficient of vehicles under different working conditions and different speeds

Superelevation of 6%, Curve radius of 270 m, Original speed of 80 km/h									
Wind scale	Speed (km/h)	R2/(N)	R1/(N)	L2/(N)	L1/(N)	Total lateral force/(N)	Lateral force coefficient	Mass of vehicle/(kg)	
Level 5	80	1397.7	1102.4	865.14	609.48	3974.72	0.3487	1140	safe
Level 6	80	1720.3	1406.8	1030.3	716	4873.40	0.4275	1140	Speed limit of 75 km/h
	75	1420.5	1161.7	942.21	630.43	4154.84	0.3645	1140	
Level 7	75	2007.5	1677.1	1157.1	39029	4845.60	0.4251	1140	Speed limit of 70 km/h
	70	1769.1	1422.4	811.01	50118	4007.52	0.3515	1140	
Level 8	75	3038.5	1952.7	409.03	0	5400.23	0.4848	1140	Speed limit of 60 km/h
	70	2834.6	1686.9	458.07	0	4979.57	0.4470	1140	
	65	2499.7	1558.3	602.5	0	4660.50	0.4088	1140	
Level 9	60	2159.6	1376.7	718.25	0	4254.55	0.3732	1140	Close the road (LTR=1, over roll)
	60	3529.9	1833.4	0	0	5363.30	0.4705	1140	
Superelevation of 6%, Curve radius of 270 m, Original speed of 80 km/h									
Wind scale	Speed (km/h)	R2/(N)	R1/(N)	L2/(N)	L1/(N)	Total lateral force/(N)	Lateral force coefficient	Mass of vehicle/(kg)	
Level 5	80	1428.8	1129	880.29	626.02	4063.11	0.3564	1140	Safe
Level 6	80	1755.4	1440.5	1046	736.63	4978.53	0.4367	1140	Speed limit of 75 km/h
	75	1492.3	1237.6	985.42	666.01	4381.33	0.3843	1140	
Level 7	75	2089.7	1753	854.36	3.5555	4700.62	0.4123	1140	Speed limit of 70 km/h
	70	1866	1489.9	830.9	3.8268	4190.63	0.3676	1140	
Level 8	70	2914.1	1742.8	428.67	0	5085.57	0.4565	1140	Speed limit of 60 km/h
	65	2599.8	1623.4	582.19	0	4805.39	0.4314	1140	
	60	2237.8	1418.6	713.35	0	4369.75	0.3833	1140	
Level 9	60	3485.5	1802.8	0	0	5288.30	0.4639	1140	Close the road (LTR=1, over roll)

Table 9. The speed limit value to ensure the safe running of vehicle under different wind speed (km/h)

Wind scale	Velocity(superelevation)	
	250m (8%)	270m (6%)
Original speed	80	80
5	80	80
6	75	75
7	70	70
8	60	60
9	Close the road	Close the road

5.2. Results comparison

In Huang (2017), the minimum radius of horizontal curve under different wind levels is determined under the condition of avoiding vehicle lateral slip, and the safety threshold of road lateral force coefficient is 0.17. Wind tunnel test results show that the radius of the horizontal curve to ensure the safety of driving is shown in the table 10. According to the minimum radius of horizontal curve limit in Table 10, the transverse force coefficients under the minimum radius corresponding to vehicle speeds of 60 km/h and

80 km/h are obtained by using the conditions of literature wind tunnel test and the research methods in this paper, respectively, as shown in Table 11 and Table 12.

Table 10. Limit minimum radius (m) of horizontal curve under different wind scales in the literature

Wind scale	Speed (km/h)	
	60	80
6	160	310
7	180	380
8	240	510
9	370	900

From the data in the table, the values lateral force coefficient values under each level of wind are close to 0.17. The simulation results are basically consistent with the data of wind tunnel test, and the error is in an acceptable range, which proves the validity and accuracy of the numerical simulation.

Table 11. Lateral force coefficient corresponding to 60km/h

Wind scale	circular curve radius /(m)	R2/(N)	R1/(N)	L2/(N)	L1/(N)	Total lateral force/(N)	Lateral force coefficient	Mass of vehicle/(kg)
Level 6 (39km/h)	160	612.89	320.57	547.52	435.83	1916.81	0.1681	1140
Level 7 (50km/h)	180	639.1	333.27	547.35	379.83	1899.55	0.1666	1140
Level 8 (62km/h)	240	661.12	343.18	527.89	272.52	1804.71	0.1583	1140
Level 9 (75km/h)	370	744.78	386.98	539.1	164.66	1835.52	0.1610	1140

Table 12. Lateral force coefficient corresponding to 80km/h

Wind scale	circular curve radius /(m)	R2/(N)	R1/(N)	L2/(N)	L1/(N)	Total lateral force/(N)	Lateral force coefficient	Mass of vehicle/(kg)
Level 6 (39km/h)	310	617.51	359.58	546.88	341.44	1865.41	0.1636	1140
Level 7 (50km/h)	380	655.12	370.32	543.61	256.5	1825.55	0.1601	1140
Level 8 (62km/h)	510	745.71	430.54	579.39	157.33	1914.97	0.1680	1140
Level 9 (75km/h)	900	798.49	429.42	584.19	46.225	1858.33	0.1630	1140

6. Conclusion

Based on the acceleration effect of canyon on wind, the simulation software Carsim is used to simulate vehicle model, and road and wind models are established to study the driving state of vehicle at different radius of circular curve, corresponding to different superelevation and different speed under different wind levels. Lateral acceleration, lateral offset and lateral force coefficient are selected as the evaluation indexes of driving stability of vehicles, and the applicability of the minimum radius of circular curve specified in the "Standard" is evaluated. Meanwhile, the minimum radius of circular curve of mountain expressways under different wind level and different superelevation is studied. According to the sideslip and unsteady steering of wheel caused by aerodynamic lateral force under strong wind, a more suitable curve radius is proposed. And then wind tunnel test is used to verify the validity and accuracy of the data simulation in this paper. The main conclusions are as follows.

1) On mountainous expressway, the vehicle travels at a speed of 80 km/h and a circular curve radius of 250m, corresponding to a bridge-tunnel junction with a superelevation of 8%, and under level 5 incoming wind. Although there is an acceleration effect on canyon wind, the threshold value causing the vehicle to roll over is not exceeded, but it also has a certain impact on the comfort of the vehicle driving. The lateral acceleration of vehicle reaches 0.32g affected by the crosswind, which is 39% higher than the case without crosswind, and does not exceed the threshold of 0.4g. The lateral offset is 0.13m, which does not exceed the threshold value of 0.5m. The lateral force coefficient is 0.3564, which does not exceed the threshold of

0.4. The wind force on the vehicle increases with the increase of wind level. When the wind force exceeds level 5, the vehicle has the possibility of overturning under the minimum radius required by the "Standard".

- 2) In this paper, the minimum limit radius of circular curve to prevent vehicle roll is proposed when studying vehicle driving stability under crosswind in different wind levels, taking into account the acceleration effect of canyon on wind and different superelevation. The research results can provide relevant data reference for optimum design of mountainous expressways and canyon bridge-tunnel junction. For example, when the speed is 80 km/h and the superelevation is 8%, the corresponding minimum radius of circular curve is 285 m, 320m, 570m and 1600m respectively, which is 14%, 28%, 128% and 540% higher than the stipulated value in the Standard.
- 3) Under the condition that the road alignment cannot be optimized, this paper puts forward the value of speed limit to ensure the safe driving of vehicles under different wind speeds, which can provide reference for traffic management and safety guarantee of mountainous expressways. When the radius of circular curve of mountainous expressway is 250 m, the superelevation is 6% or 8%, and the acceleration effect of canyon wind is considered, the corresponding speeds of safe driving speeds are 75 km/h, 70 km/h and 60 km/h when the level of crosswind reaches 6-8. It cannot meet the requirements of safe driving whether it is optimized linearity or speed limit under wind of level 9, so it is suggested to close the traffic under level 9 wind.

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