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Simulation Analysis of the Distance Between Tunnels at the Bridge-Tunnel Junction of Mountainous Expressway on Driving Safety Under Crosswinds

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ABSTRACT To analyze the influence of the distance between tunnels at the bridge-tunnel junction in the mountainous area on the driving safety under crosswind, a vehicle dynamics model is established by Carsim software. Under the conditions of different driving speeds (60km/h, 80km/h and 100km/h), different wind scales (level 6-9) and three alignment combinations of the tunnels (tunnel-straight road-tunnel, tunnel-curving road-tunnel, tunnel-the combination of straight and curves road-tunnel), the vehicle's lateral offset and lateral force coefficient are used as evaluation indexes to study the influence of distance between tunnels on driving safety. When the distance is small, the lateral offset and lateral force coefficient of vehicle driving on the bridge-tunnel junction increase firstly and then decrease as the distance increases. But the changes of the lateral offset and lateral force coefficient are not synchronized, and the peak value of the lateral force coefficient occurs earlier than the lateral offset. Finally, the minimum safety spacing of each condition and speed limits for different distances are proposed. Under the condition of the straight-tunnel, 20m distance between tunnels cannot ensure the driving safety when the wind scale reaches level 9, and the road should be closed. Under the conditions of the curve and the combination of straights and curves, driving safety cannot be maintained at each spacing at wind scale level 8 and 9, and the road should be closed. However, when the wind speed is level 6 or 7, speed limits can be adopted to ensure driving safety. The results suggest that vehicles' lateral offset and lateral force coefficient can be effectively reduced by reducing the driving speed or increasing the distance between tunnels, so the risk of accidents caused by the crosswind can be reduced.

INDEX TERMS Crosswind, bridge-tunnel junction, Carsim, the minimum safety spacing.

I. INTRODUCTION

There are about 4.7 million traffic accidents every year, more than 200,000 traffic accidents of which cause casualties and the number of fatality accounts for 21% of the total number of casualties. Especially in mountainous expressways, steep slope and sharp curves will drastically increase the crash risk [1]. According to the crash data from Zhang's study (2014), from 2006 to 2008, 1220 crashes were reported in Su-Chang section of Hu Ning Expressway in plain area, with the cash rate of 0.45, with the crash rate (crashes per million vehicle · km) of 0.45; while the crashes number reported on the typical mountainous expressway of north Guangdong section of Jing Zhu Expressway was 1564, with the crash rate of 0.79, which is 0.34 higher than that in plain area. So, currently, traffic safety should be paid more attention while the construction develops rapidly, and a comfortable and safe traffic environment should be provided through more reasonable road alignment design. Bridges and tunnels account for a large proportion in mountainous expressways to optimize the road alignment and shorten the mileage. At bridge-tunnel junctions, the driving is greatly affected by

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the wind. Because of the advantages of improving the alignment and operating efficiency, tunnels are often adopted in the construction of expressways in the mountainous area, which greatly promotes the construction of tunnels. Nowadays, China has become the country with the fastest development of tunnel construction and the largest number of tunnels in the world (Wang, 2007). As the focus of mountainous expressway, the bridge-tunnel junction (tunnel-straight road-tunnel,tunnel-curving road-tunnel,tunnel-the combination of straight and curves road-tunnel) is the main section forming the black spot (Wu *et al.*, 2012), and the traffic accident rate is 2-3 times of that inside the tunnel. Therefore, the research on the driving status of vehicles at the bridge-tunnel junction becomes increasingly important.

Researchers have attempted to study the influence of the complex environment in mountainous areas on driving safety and reduce the risk of accidents based on simulations and tests. Zhang (2015) carried out a lot of simulation experiments on vehicle driving under the crosswind by Trucksim and Carsim software, and got the safe driving speed of vehicles under different wind scales. Considering such factors as rainfall, overspeed and alignment, Zhang *et al.* (2015) built the vehicle dynamics model by Carsim software, then took the critical adhesion coefficient and lateral acceleration as the evaluation indexes of driving risks, and finally established a driving risk evaluation model for passenger cars at curved sections and conducted the risk analysis with Matlab. Tsubokura *et al.* [7] adopted a large eddy simulation based on the fully unstructured finite volume method to study the unsteady aerodynamic response of a road vehicle subjected to transient crosswinds. Batista and Perkovič [8] proposed a static model for determining the critical wind speed for vehicle slip, overturn, and rollover, and derived a new formula for calculating the critical wind speed leading to vehicle accidents. Fuller *et al.* [9] studied the driver's responses and the vehicle's offset of five kinds of aerodynamic instability conditions under normal wind and extreme gust respectively. Wind tunnel test and numerical simulation were used to study the vehicle model, and the results showed that the aerodynamic characteristics of vehicle are affected by wind speed, wind directions and road alignment [10]. Wang *et al.* [11] used Carsim for simulation to explore the influence of different positions of the circular curve on vehicle lateral stability. And results show that the wind level affects the tunnel exit's unfavorable section on the circular curve. Yin (2017) used Carsim to simulate driving state of vehicles under crosswind, and then analyzed the results based on statistical principles. It was found that the influence of various factors on the driving stability of vehicles was in order of vehicle speed, wind direction angle, wind speed and road friction coefficient. Based on the actual wind environment of bridge-tunnel junction in Xi-Han Expressway, Wang *et al.* (2019a,2019b) analyzed the critical driving speed and critical wind speed under the crosswind with the focus on the sideslip and rollover of vehicles. By taking the radius of the circular curve, the friction coefficient of pavement and the driving speed as single variable for simulation, it was found that the slip angle and lateral acceleration of the vehicle can be effectively reduced by decreasing the vehicle speed and increasing the friction coefficient of pavement and the radius of the circular curve. By using the dynamic boundary method, Li *et al.* (2019) conducted unidirectional and bidirectional coupling analysis of vehicle stability test under crosswind, and it was found that the flow field under natural crosswind was global transient and more unstable than the flow field under standard crosswind. Therefore, the influence of different crosswind conditions should be comprehensively considered in the evaluation of crosswind stability of vehicle. Some studies have shown that traffic accidents in curve road sections with small radius account for about 10% of the total number of traffic accidents. The length and radius of the curve and the distance between curves all have an impact on driving safety [16]. Some scholars divided the influence factors of traffic accidents, and studied the influence of driver, road, traffic flow, vehicle, and environment on traffic safety ([17], Ho and Tan, 2015). Bai (2013) analyzed the instability process and the key factors that determine the instability during the turning of the vehicle by co-simulation of Carsim and MATLAB, and verified the rationality of the values taken by the specification. Li (2016) conducted a comprehensive evaluation and analysis of the alignment safety, considering driver direction control, vehicle speed control, and the risk indexes of sideslip and rollover that affect the driving safety.

At present, many researches on the safety of mountain highways, single bridge or tunnel are conducted (Shu, 2008; Wang *et al.*, 2008; Zhu *et al.*, 2010), but less research on the driving safety at bridge-tunnel junctions (Wu and Luo, 2010; Liu, 2009). Based on the basic theory of aerodynamics, Carsim was used to build the vehicle model and road model, simulating the characteristics of different alignments of the bridge-tunnel junction. Then the crosswind model of bridge-tunnel junction was used to simulate the crosswind effect of vehicles driving in the bridge-tunnel junction and the acceleration effect of wind under different bridge tunnel spacing is constructed. Lateral force coefficient and lateral offset are selected as the evaluation indexes of lateral stability, and the driving safety of vehicles under various conditions is evaluated. This article analyzes the minimum safety distance between tunnels under the crosswind by considering the phenomenon of side slip and rollover of the vehicle, providing essential data for future research and analysis.

II. ANALYSIS OF DRIVING RISK AND SELECTION OF EVALUATION INDEXES

A. VEHICLE DYNAMIC ANALYSIS UNDER CROSSWIND CONDITIONS

When the vehicle runs on the bridge-tunnel junction in the mountainous area, the vehicle is not only subjected to the gravity, support and friction, but also subjected to the mutually perpendicular aerodynamic forces (aerodynamic lift, aerodynamic drag, lateral aerodynamic force) generated by the wind and the aerodynamic moment (rolling moment,

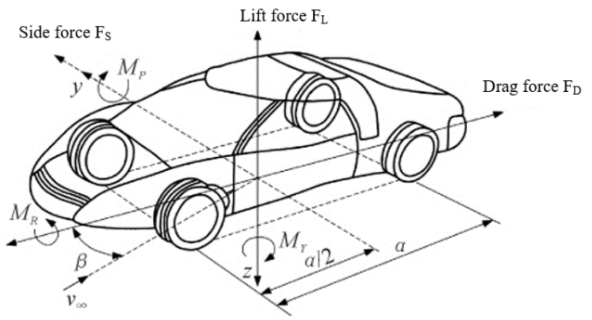

FIGURE 1. Diagram of distribution of aerodynamic forces.

pitching moment and yaw moment) around the axis (Zhang, 2011). Aerodynamic lift is the aerodynamic force perpendicular to the pavement, which will reduce the support and affect the vehicle's handling stability. Aerodynamic drag is the aerodynamic force that hinders the operation of the car, which is opposite to the running direction of the vehicle. Lateral aerodynamic is the aerodynamic force acting on the side of the vehicle. When the lateral aerodynamic force is large while the friction between the tire and the pavement is insufficient, the vehicle may sideslip and overturn. When the above three forces act on the vehicle, the rolling moment, pitching moment and yaw moment will be generated, which will reduce the vehicle's driving stability. When the vehicle is driving on the bridge-tunnel junction in the mountainous expressway, the lateral aerodynamic force generated by the crosswind may lead to sideslip or rollover of the vehicle in the straight section. In the curved section of bridge-tunnel junction, the risk of sideslip and rollover will be increased, because the lateral aerodynamic forces are superimposed on the lateral forces generated by the vehicle's turning. The distribution of aerodynamic forces is shown in Figure 1.

B. ANALYSIS OF DRIVING RISK

High-speed cars are affected by the aerodynamic forces generated by the crosswind. On the one hand, the vehicle will get a lateral offset when the value of lateral aerodynamic force that acts on the vehicle exceeds the friction between tires and pavements, and the vehicle's handling stability also will be influenced [27]. On the other hand, the driver cannot adjust the direction in time because of nervousness or lack of driving experience after the vehicle deviated, which will affect driving safety [28]. Besides, it has been found that the bridge-tunnel junction will accelerate the wind and change the wind velocity, wind direction and turbulence characteristics. The accelerating effects of different distances between tunnels are different. When the distance between tunnels is 20 m, 30 m and 50 m, the wind speed increases by 33.5%, 30.7% and 27.5% respectively. As the distance between tunnels increases, the accelerating effect of the wind decreases gradually (Wang and Chen, 2012). Therefore, the small distance between tunnels will have a great influence on the driving safety.

C. EVALUATION INDEXES

According to the Federal Highway Administration, lane departure was responsible for 44 percent of fatal crashes in the United States in 2002, and rolled-over accidents can also be considered a major cause of lane departure(National Highway Traffic Safety Administration,2002).When a vehicle is running on a short bridge, the index that shows vehicle's instantaneous risk is more considered, namely the vehicle's lateral force coefficient, because the driving time is very short and the accelerating effect of the wind is great. When a vehicle is running on a long bridge, the index that shows vehicle's cumulative risk is more considered, namely the vehicle's lateral offset, because the driving time is long and the accelerating effect of the wind is smaller. In this article, the lateral force coefficient and the lateral offset of the vehicle were selected as the evaluation indexes for the lateral stability of vehicles. In the study of travelling stability of vehicles running on bridge-tunnel junction, it is considered that the driving is relatively safe when the lateral force coefficient is less than 0.4. Based on a large number of measurement data, the relevant agencies have studied the influence of lateral force on vehicle driving stability and safety perception of drivers and passengers. When the lateral force coefficient reaches 0.4, it is difficult for the driver to control the vehicle and the vehicle is in danger of rolling over (Fan *et al.*, 2016). Standard of large span bridge lane width is 3.750 m, maximum width of 1.800 m cars, if vehicles running along the lane center, on both sides of the vehicle from the side distance of 0.975 m. Because the vehicle can't keep on the midline of the driveway, there will be a certain deviation from the lane center. The vehicle may enter the adjacent lanes when deviating from the lane center by 0.500 m, causing traffic accidents. Therefore, this research will take lateral offset of 0.500 m as the evaluation index threshold to study the influencing factors of influence on vehicle driving stability and safety (Zhou *et al.*, 2019). It is considered that the driving safety will be affected when the vehicle's lateral offset is greater than 0.5m. Based on the above evaluation indexes, the length of the bridge that makes the lateral offset and the lateral force coefficient relatively small is the optimal distance between tunnels in the bridge-tunnel group section. The meanings of each index and the calculation formula of the safety threshold are shown in Table 1.

III. CARSIM MODEL ESTABLISHMENT

Carsim software is a dynamic simulation software that is used to build simulation models based on dynamic parameters. Through simulation, the vehicle's stability, dynamic characteristics, riding comfort and economy are studied. Carsim software simulation yields data at least three to six times faster than real-time wind tunnel testing and actual testing. It can also be combined with multi-platform simulation to simulate different complex conditions and output relative data. Therefore, Carsim software is used for simulation analysis in this article. Based on the influence of the distance

TABLE 1. Evaluation indexes.

Evaluation index	Meaning	Safety threshold of index
Lateral force coefficient (f)	Different cars subjected to equal lateral forces have different stability. To accurately measure the stability, security and comfort of cars running on the circular curve, the ratio of the lateral force to the vertical force, known as the lateral force coefficient, can be approximately regarded as the lateral force per unit vehicle weight	$f \leq 0.4$ f=F/mg (F is the lateral force acting on vehicles, M is the sprung mass and G is the gravitational acceleration)
Lateral offset	Lateral displacement will be produced when the vehicle running on the bridge-tunnel junction is affected by crosswind	0.5m

between tunnels of bridge-tunnel junction in mountainous areas on driving safety, the safe distance is studied under different wind speed, driving speed and road alignments.

A. CROSSWIND MODEL

The crosswind at the bridge-tunnel junction in the canyon has a long duration and rapid change of the wind speed. And the wind is uncertain and unpredictable at present (Saher *et al.*,2020). When the vehicle runs out of a tunnel or runs toward a bridge, the strong crosswind will have a great impact on the vehicle's driving stability. When the vehicle runs out of the tunnel, it will be suddenly affected by the lateral force generated by the crosswind. If the driver doesn't control the vehicle in time, a lateral offset will occur, which may cause a traffic accident. Due to the prevailing 6-9 wind in mountainous areas, which affects the handling stability of vehicles, the safe distance between tunnels is very important under the action of level 6-9 wind scales. The wind speed was set to level 6-9 in Carsim, and different wind scales and wind speed are shown in Table 2. The lateral force coefficient and lateral offset of the vehicle under different wind speed were selected as evaluation indexes, which provided a basis for analysis of the vehicle's dynamic characteristics and driving state and the study of the safety distance between tunnels of bridge-tunnel junctions.

When the distance between tunnels of bridge-tunnel junction is 20 m, 30 m and 50 m, the wind speed increases by 33.5%, 30.7% and 27.5% respectively. As the distance increase, the accelerating effect of the wind decrease gradually (Wang and Chen, 2012). Therefore the crosswind model with an accelerating effect is adopted in the paper. Take the crosswind model of level 6 wind scale as an example, when the vehicle runs at a speed of 60km/h on the bridge-tunnel junction in spacing of 20m, the model is established by linear interpolation and extrapolation. The crosswind model is shown in Figure 2.

B. ROAD MODEL

When the vehicle runs on the road, both pavement and alignment will have an influence on the vehicle [33]. Because of

TABLE 2. Wind speed of different scales.

Wind scale	Wind speed	
	m/s	km/h
0	0-0.2	<1
1	0.3-1.5	1-5
2	1.6-3.3	6-11
3	3.4-5.4	12-19
4	5.5-7.9	20-28
5	8-10.7	29-38
6	10.8-13.8	39-49
7	13.9-17.1	50-61
8	17.2-20.7	62-74
9	20.8-24.4	75-88
10	24.5-28.4	89-102
11	28.5-32.6	103-117
12	> 32.6	117-134

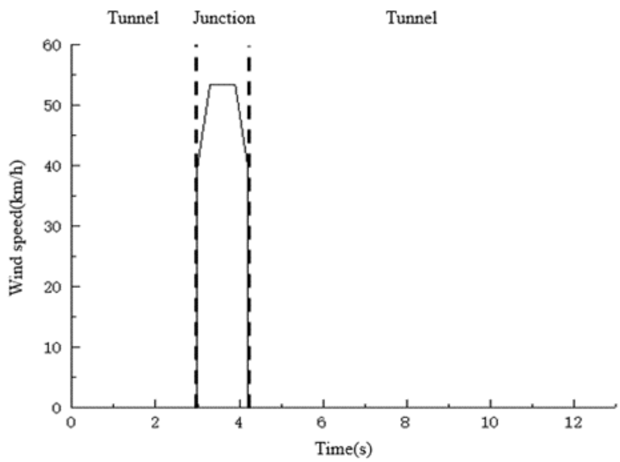

FIGURE 2. Diagram of the crosswind model.

the complex terrain of mountainous areas, the bridge-tunnel junction is generally complex and changeable. Through the analysis of road alignments and friction coefficients, three forms of straight, curve and combination of straight and curve are used to simulate the road in this study. The three kinds of road models are shown in Figure 3. In the straight road model, the road is set to a 200-meter-long line segment, and the different distances of bridge-tunnel junction are simulated by changing the action time of the crosswind. If 200m cannot ensure the driving safety, the length of the road will be increased to 300m, and so on. The friction coefficient of pavement is 0.6, which is the friction coefficient of dry pavement under normal weather. The superelevation and longitudinal gradient is 0 for the straight road. For the curved road, the superelevation is 8%, which is a common value of road in mountainous areas. The radius of the curve is the minimum radius of the circular curve corresponding to superelevation of 8% at different design speed in road alignment design code, as shown in Table 3. The friction coefficient is also 0.6 as the straight road. For the combinations of straight and curve, they are various and there is no unified standard. In order to

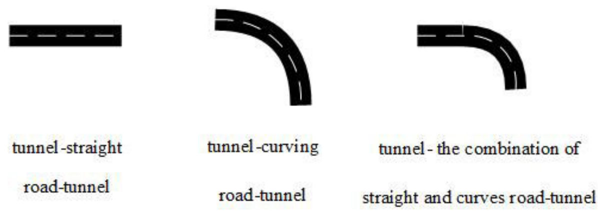

FIGURE 3. Diagram of the three kinds of road models.

make the research conclusions universal and make data easy to process, the form of virtual road section, "200m straight + 350m curve", is used for simulation, and the setting of the straight section and the curved section is the same as the conditions of the single straight and the single curve.

In road simulation, there are too many conditions and the accelerating effect of the canyon on the wind is small when the distance between tunnels is greater than 300m, so the length of straight was only simulated to 300m, and the combination of "200m straight + 350m curve" was simulated.

C. VEHICLE MODEL

In 2019, car ownership accounted for 77% of motor vehicle population(National Bureau of Statistics, 2019), and car accidents account for 60-70% of motor vehicle accidents in China(Liu, 2016), which means that car accidents account for a large proportion and cannot be ignored. Compared with trucks, cars are lighter in weight, smaller in size, and faster in speed. When running on the bridge-tunnel junction in mountainous areas, cars easily sideslip and roll because of the accelerating effect of wind. The wind will not only reduce the adhesion between the vehicle and pavement, but also change the original stress state of the vehicle, so that the lateral force increases and the vehicle loses lateral stability. When the vehicle is affected by the crosswind, the driving safety is mainly related to the vehicle's parameters and windward area. According to the statistics of China's car sales in 2017, it is found that their appearance, streamlined structural parameters and windward area are similar by comparing and analyzing vehicles that sales volume and year-on-year growth dominate. Based on the above conditions, FAW-VW Jetta 180 manual FV7150FCMBG was selected as a typical model of cars and the vehicle's parameters are defined in Carsim software. The main parameters of the vehicle are shown in Table 4.

Due to the driver's uncontrollability, the open-loop mode of Carsim is adopted to study the vehicle's handling stability, excluding the driver's performance (driving technology).

D. WIND TUNNEL TEST VERIFICATION

1) WIND TUNNEL TEST CONDITIONS

The wind tunnel test can be used to carry out mechanical experiment (Peng *et al.*,2019), and also can be verified by simulation experiment. In order to ensure the accuracy and effectiveness of the numerical simulation, the fitted wind speed profile index is compared with the wind tunnel test results on the basis of fitting the numerical calculation results,

TABLE 3. The minimum radius of the circular curve (limit value).

Design speed (km/h)	100	80	60
i_{max}=8%	400m	250m	125m

TABLE 4. Main parameters of the vehicle.

Parameter	Value
Length/mm	4501
Width/mm	1704
Height/mm	1469
Wheel base/mm	2604
Front gauge /mm	1540
Height of center of mass /mm	540
Sprung mass /kg	1140
Windward area /m^2	5

so as to obtain the aerodynamic performance of vehicles on the tunnel group section under strong crosswind, and verify the accuracy requirements of the numerical simulation.

In the wind tunnel test, a double-purpose wind tunnel is proposed to be used. The wind tunnel body is a mixed structure of steel and concrete, as shown in FIG.5. The test section size is 15m × 3m × 2.5m, the wind speed is 0-53m/s continuously adjustable, the turbulence intensity is no more than 0.3%, and the wind tunnel flow field quality is excellent. The scale ratio of the bridge model is 1:1000. The model is made of foam board layered and superposed. The shape of foam board is cut according to the contour line. The measuring instrument of deck wind environment is Dantec hot-wire anemometer. The vehicle model uses a scale ratio of 1:30, and the force balance model is a five-component high-frequency balance. The axial lateral force Fx and Fy ranges of the vertical balance are 100N and 200N, respectively; the corresponding bending moment Mx and My ranges are 50N · m and 100N · m, and the torque Mz ranges are 10.0N · m. The measurement error is less than 0.3%. At the same time, considering the increase of wind speed caused by wind tunnel obstruction caused by the model, real-time mean wind speed measurement is conducted at the cross-section position of the wind tunnel where the vehicle is located, so as to correct the incoming wind speed of vehicle crosswind.

2) WIND TUNNEL TEST RESULTS

The same conditions are selected for numerical simulation and wind tunnel test, and the bridge-tunnel junction with a distance of 20m under crosswind is taken as the research object. Then the aerodynamic coefficients (lateral force coefficient and drag coefficient) of vehicles on the bridge deck without ancillary facilities are studied by wind tunnel test. The results were shown as Figure 7 and 8.

FIGURE 4. Diagram of the car model.

FIGURE 5. Wind Tunnel Laboratory of Chang'an University.

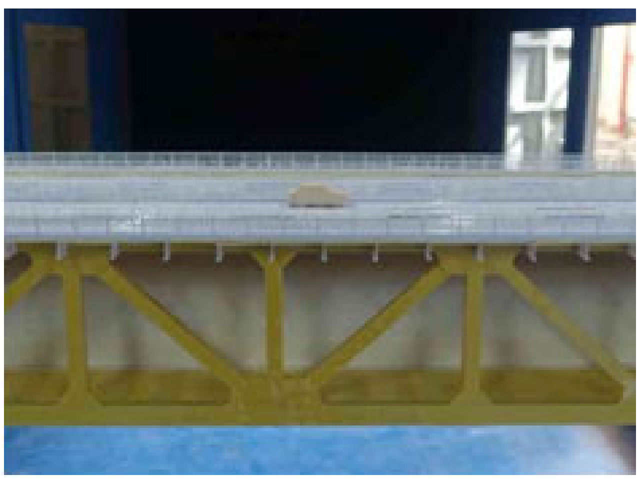

FIGURE 6. Wind tunnel test model.

Figure 7 shows that the lateral force coefficient of vehicles varies from 0.41 to 0.61, and the variation trend of the lateral force coefficient of the numerical simulation is consistent with that of the wind tunnel test. By ANOVA (analysis of variance) at 0.05 significance level, it can be obtained that $F(1,23) = 1.287$, $sig = 0.269 > 0.05$, and the null hypothesis is accepted. That is to say, there is no significant difference between the two groups in Figure 7. The conclusions of the numerical simulation are in good agreement with those of the wind tunnel test. Figure 8 shows that the vehicle resistance coefficient varies from 0.25 to 0.27. Because of the heterogeneity of variance of the two groups, ANOVA with Welch and Brown-Forsythe test is used, it can be obtained that $sig = 0.654 > 0.05$, and the null hypothesis is accepted. That is to say, there is no significant difference between the two groups in Figure 8. The range of numerical simulation data is within the range of wind tunnel test data, and the error is within the acceptable range. The variation trend of aerodynamic resistance coefficient is basically the same between the two, meeting the accuracy requirements.

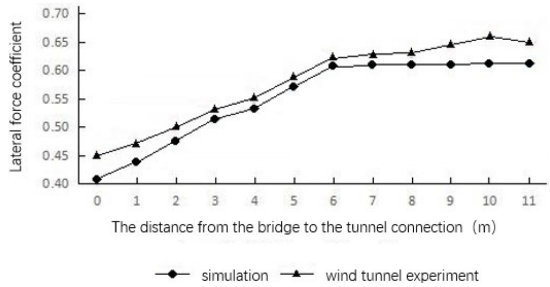

FIGURE 7. Comparative curve of vehicle lateral force coefficient change.

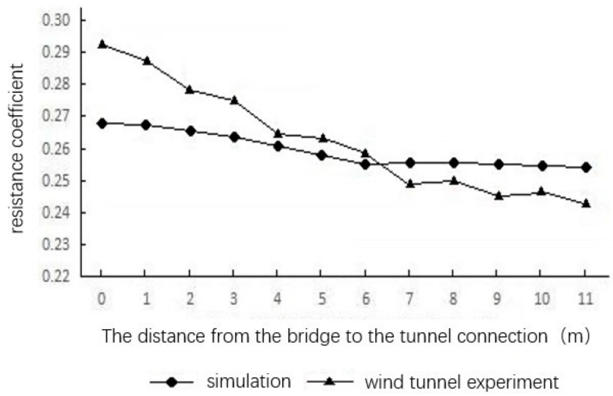

FIGURE 8. Comparative curve of vehicle resistance coefficient change.

IV. RESULTS AND ANALYSIS OF SIMULATION

When the vehicle runs on the bridge-tunnel junction, it will be affected by many factors. According to relevant studies, driving speed, wind speed, the distance between tunnels and alignment of the bridge-tunnel junction will have an impact on the driving safety. Therefore, the above factors were analyzed by controlling variables in this article and the results were classified into three categories based on the alignment, including straight, curve and combination of straight and curve.

According to the analysis on simulation results of the straight, the vehicle's moving characteristics under level 9 wind are shown in Figure 9, when the driving speed is 60km/h, 80km/h and 100km/h respectively, and the distance

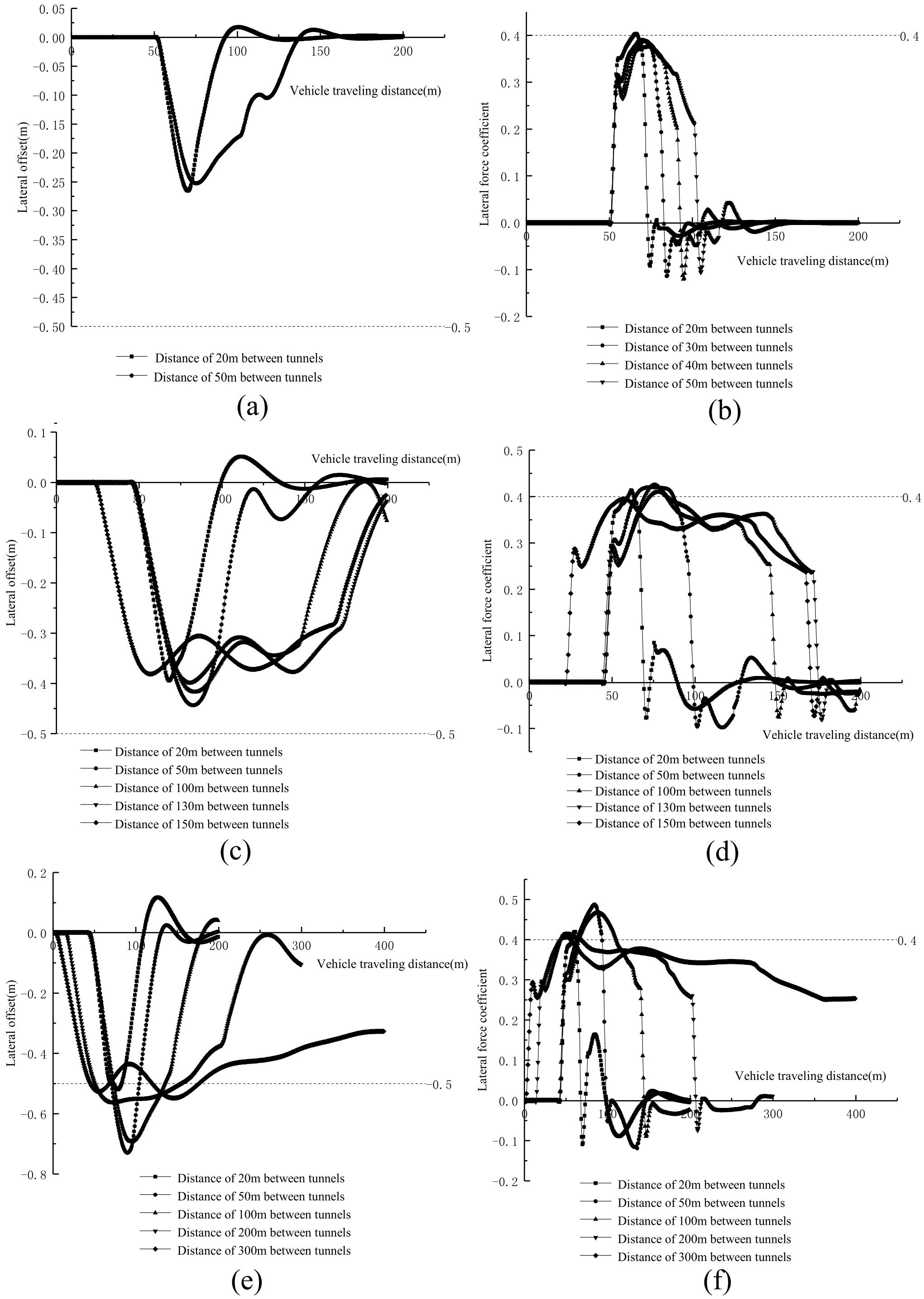

FIGURE 9. Lateral offsets and lateral force coefficients of vehicles under different conditions of level 9 wind scale: (a) The lateral offsets of the vehicle at the speed of 60km/h; (b) The lateral force coefficient of the vehicle at the speed of 60km/h; (c) The lateral offset of the vehicle at the speed of 80km/h; (d) The lateral force coefficient of the vehicle at the speed of 80km/h; (e) The lateral offset of the vehicle at the speed of 100km/h; (f) The lateral force coefficient of the vehicle at the speed of 100km/h.

between tunnels at the bridge-tunnel junction is 20m, 50m, 100m, 130m and 150m respectively.

According to Figure 9 (a), the vehicle has a lateral offset, when the vehicle runs out of the tunnel to the bridge in the distance of 20m. When running on the bridge, the vehicle will be affected by crosswind, so the lateral offset increase, and reach a maximum of 0.265m before the vehicle enters the next tunnel. After entering the tunnel, the driver will adjust the vehicle back to the center line of road. At this time, the lateral offset of the vehicle is very small and the driving won't be affected. However, as seen in Figure 9(b), the maximum lateral force coefficient of the vehicle is 0.4034, which exceeds the safety threshold of 0.4. Therefore, it is not safe for vehicles to travel at a speed of 60km/h on a straight of 20m distance between tunnels when the wind speed is level 9. The trends of lateral offset and lateral force coefficient at the distance of 30m and 50m are similar, so the reason for the change won't be explained again. When the distance between tunnels is 30m, the maximum lateral force coefficient of the vehicle is 0.390, which is smaller than the safety threshold of 0.4. In addition, the lateral offset is small when the running speed is small. When the distance between tunnels is 40m and 50m respectively, the lateral offset and the lateral force coefficient are within the safety threshold, which can ensure the driving safety. Therefore, the minimum safe distance is 30m when the speed limit is 60km/h.

Under level 9 wind scale, the trends of the lateral offset and the lateral force coefficient of the vehicle at the speed of 80km/h are approximately the same as that of the vehicle running at the speed of 60km/h. In Figure 9(c), the lateral offset is 0.395m, 0.444m, 0.417m, 0.398m and 0.381m respectively when the distance between tunnels is 20-150m, which can meet the requirements of safety threshold. However, when the distance is 20m, 50m, 100m, 130m and 150m, the maximum lateral force coefficient is 0.414, 0.420, 0.425, 0.411 and 0.395 respectively. It can be found that the lateral offset and the lateral force coefficient can meet the requirements of driving safety when the distance between tunnels is 150m. So, the minimum safety distance is 150m when the speed limit is 80km/h under level 9 wind scale.

According to Figure 9(e), the maximum lateral offset of the vehicle exceeds the safety threshold of 0.5m when the distance between tunnels is 20-300m. It also can be seen from Figure 9(f) that the maximum lateral force coefficient is greater than the safety threshold of 0.4. The simulation of the distance between tunnels that exceeds 300m is not carried out because of too many actual conditions and the small accelerating effect of the wind at a long distance. Therefore, when the speed limit is 100km/h, the minimum safe distance of 300m cannot ensure safety under level 9 wind scale.

The analysis of other straight, curve and combined alignment is the same as the above analysis, so it will not be analyzed again. According to the analysis, when the distance between tunnels is small, the lateral offset and lateral force coefficient will increase and then decrease with the increase of the distance. In addition, the maximum lateral offset and the maximum lateral force coefficient don't appear in the same distance, and the distance where the maximum lateral offset appears is smaller than the distance where lateral force coefficient appears. The reason is that the acceleration effect of the wind is not obvious when the distance between tunnels is small. As the increase of the distance, the acceleration effect of the wind will increase. However, when the distance increases to a certain level, the bridge-tunnel junction is similar to the common mountain road, and the accelerating effect of the wind will be relatively weakened, so the peak value of the lateral offset and lateral force coefficient will decrease gradually. Because the lateral force coefficient is an instantaneous risk index that can show the dynamic change of the vehicle in a short time, and the lateral offset is a cumulative risk index that show the dynamic change of the vehicle in a long time, their decrease is not synchronous. Compared with the straight, alignments of the curve and the combination are more complicated, which make driving more dangerous. Therefore, it is necessary to find the optimal distance to minimize the driving risk.

V. DISCUSSION

Taking the lateral offset of 0.5m and the lateral force coefficient of 0.4 as the thresholds, the minimum safety spacings under different conditions are shown in Table 5.

As shown in Table 5, under the condition of the straight, the distance of 300m cannot meet the requirements of driving safety when wind scale is level 9 and driving speed is 100km/h. When the speed of vehicle is 80km/h and 60km/h, the minimum safe distance is 150m and 30m respectively. Under level 6-8 wind scale and 100 km/h of driving speed, the range of the safe distance is less than or equal to 40m and greater than or equal to 300m (⩽40m, ⩾300m). Under the condition of the curve, the distance of 300m cannot ensure driving safety at all speed when the wind scale is level 8 and 9. When the driving speed is 80km/h and 60km/h, the minimum safe distance is 200m under level 7 wind scale. When the wind scale is level 6 and driving speed is 100km/h, the minimum safe distance is 20m but not more than 30m. Under the condition of the combination of straights and curves, the distance of 300m cannot ensure driving safety at all speed when the wind scale is level 8 and 9. Under level 7 wind scale, the minimum safe distance is 250m and 200m respectively at the driving speed of 80km/h and 60km/h. when the wind scale is level 6 and driving speed is 100km/h, the minimum safe distance is 20m but not more than 30m.

In addition, when the minimum safe distance cannot be adopted because of the terrain, economy and other factors, the maximum safe speed limit is given in table 6.

As shown in Table 6, under the condition of the straight, the road should be closed under the level 9 wind scale and distance of 20m, and speed limits can be adopted to ensure safety under other wind scales and distances. Under the condition of the curve and the combination of straight and curve, when the wind speed reaches level 8 or 9, the vehicle cannot maintain the speed of 60km/h and the road should be closed. When the wind scale is level 7 and the distance is smaller than 150m, the road should be closed. When the wind scale is level 6, the speed limits (80km/h or 100km/h) can be adopted at different distances.

Based on the principle of aerodynamics, existing researches have shown that different wind speed, wind direction, road conditions the vehicle's geometry size and so on will affect the aerodynamic coefficient of vehicles, and the

TABLE 5. The minimum safe distance under different conditions.

Wind scale	Driving Speed (km/h)	The minimum safety distance		
		Straight	Curve	Straight + Curve
9	100	300m is not enough	300m is not enough	300m is not enough
	80	≥150m	300m is not enough	300m is not enough
	60	≥30m	300m is not enough	300m is not enough
8	100	≤40m; ≥300m	300m is not enough	300m is not enough
	80	All distances are satisfied	300m is not enough	300m is not enough
	60	All distances are satisfied	300m is not enough	300m is not enough
7	100	≤40m; ≥300m	300m is not enough	300m is not enough
	80	All distances are satisfied	≥250m	≥250m
	60	All distances are satisfied	≥200m	≥200m
6	100	≤40m; ≥300m	20m, ≤30m	20m, ≤30m
	80	All distances are satisfied	All distances are satisfied	All distances are satisfied
	60	All distances are satisfied	All distances are satisfied	All distances are satisfied

TABLE 6. The maximum safe speed under different conditions.

Wind scale	Distance(m)	The maximum safe speed（km/h）		
		Straight	Curve	Straight + curve
9	300	80	Road closure	Road closure
	200	80	Road closure	Road closure
	150	80	Road closure	Road closure
	50	60	Road closure	Road closure
	30	60	Road closure	Road closure
	20	Road closure	Road closure	Road closure
8	300	100	Road closure	Road closure
	200	80	Road closure	Road closure
	150	80	Road closure	Road closure
	50	80	Road closure	Road closure
	40	100	Road closure	Road closure
	30	100	Road closure	Road closure
	20	100	Road closure	Road closure
7	300	100	80	80
	250	80	80	80
	200	80	80	60
	150	80	Road closure	Road closure
	50	80	Road closure	Road closure
	40	100	Road closure	Road closure
	30	100	Road closure	Road closure
	20	100	Road closure	Road closure
6	300	100	80	80
	200	80	80	80
	150	80	80	80
	50	80	80	80
	40	100	80	80
	30	100	100	100
	20	100	100	100

safety of vehicles is usually studied in the critical states of rolling, sideslip and overturn (Cheli, 2011a, 2011b, [41]). The tunnel section is also concerned in the related researches. When vehicles enter the tunnel from the crosswind area, the aerodynamic load on the vehicle will change drastically, which may increase the risk of sideslip and rollover [42], [43]. However, the existing researches are less concerned with the bridge-tunnel junction, and the influence of the distance between tunnels and alignment of bridge-tunnel junction on driving safety is not considered from the perspective of road design.

For the driving safety under the crosswind, it can be improved by changing the appearance of the vehicle to optimize aerodynamic performance, reducing wind speed by setting up wind barriers, and controlling the driving speed [44], [45]. But this study provides a new option to ensure the driving safety under crosswind by controlling the distance between tunnels. According to results of the analysis, the vehicle's lateral offset and lateral force coefficient can be reduced effectively by reducing the vehicle's speed and increasing the distance between tunnels, thus the risk of accidents caused by the crosswind can be reduced. Compared with that the tunnels are connected by straights, the results also show that the driving safety will be greatly reduced when the tunnels are connected by curves, because the vehicle running on the curve are more likely to sideslip or roll over under the combined effect of centrifugal force and wind force. Furthermore, under the conditions of different alignments and driving speed, the minimum safe distances between tunnels and speed limits under the different distances were given in the study, when the wind scale is force 6-9.

The bridge-tunnel junction of mountainous expressways is significantly affected by crosswinds and the distance between tunnels will affect characteristics of the wind field, so it is necessary to study the impact of the distance on the driving safety. However, the influence of crosswind on vehicles is not considered in China's specifications for highway alignment design, so the design method of road alignment needs to be optimized. The results of this study can provide a theoretical reference for the alignment design of the bridge-tunnel junction, and guide the selection of the distance between tunnels and speed limits to ensure the driving safety under the crosswind.

VI. CONCLUSION

Based on the vehicle dynamics, the Carsim software was used to build the crosswind model, road model and vehicle model, considering the characteristics of crosswind at the bridge-tunnel junction and the effects on the vehicle. Under the conditions of different driving speed (60km/h, 80km/h and 100km/h), different wind scales (level 6-9) and three road alignments (tunnel-straight road-tunnel, tunnel-curving road-tunnel, tunnel-the combination of straight and curves road-tunnel), the vehicle's lateral offset and lateral force coefficient were selected as evaluation indexes to study the influence of the distance between tunnels on the driving safety.

a. In the study, it was found that the changes of lateral offset and lateral force coefficient are not synchronous, and the corresponding distance is different when the two indexes reaches the peak. As the increase of the distance, the vehicle firstly tended to a more dangerous state, and then gradually tended to be safe and stable. The explicit relationship between the two indexes remains to be further studied.
b. Considering various factors comprehensively, Carsim software was used to simulate and analyze the vehicle driving on the bridge-tunnel junctions with different alignments and distance between tunnels. And it was found that the higher the speed of wind and vehicle is, the greater the safety distance required. Therefore, the vehicle's lateral offset and lateral force coefficient can be reduced effectively by reducing the vehicle's speed and increasing the distance between tunnels. In addition, the research shows that the distance required for the driving safety under the curve connection is larger than that under the straight connection. Finally, the minimum safety distance at different driving speeds and wind scales is proposed, and the speed limits are proposed when the minimum safety distance cannot be met.

Despite these conclusions, there is still some work to be done in the future. In this article, only cars were studied in the consideration of vehicle models, which has certain limitations. Therefore, buses and trucks should also be taken into consideration in subsequent studies. In addition, the simulation of the distance between tunnels that exceeds 300m is not carried out, because there are too many actual conditions and the accelerating effect of the wind is small when the distance is larger than 300m.If the safety distance between tunnels of bridge-tunnel junction cannot be adopted because of terrain constraints, it can be compensated by setting up wind barriers or driving speed limit.

REFERENCES

[1] M. Ahmed, H. Huang, M. Abdel-Aty, and B. Guevara, "Exploring a Bayesian hierarchical approach for developing safety performance functions for a mountainous freeway," *Accident Anal. Prevention*, vol. 43, no. 4, pp. 1581–1589, Jul. 2011.
[2] X. M. Zhang, X. H. Meng, and L. Zheng, "Comparison analysis of the relationship between geometric alignment and accident rate of mountainous and plain terrain freeway," *Highway Eng.*, vol. 39, no. 1, pp. 212–220, 2014.
[3] W. Yongdong, "Study on operating safety technology of highway tunnel," M.S. thesis, Chang'an Univ., Xi'an, China, 2007.
[4] W. Hongbo, Z. Dongxiao, and Z. Ronggui, "Safety evaluation techniques for tunnel-bridge linkage sections on freeways in mountainous areas," *J. Highway Transp. Res. Develop.*, vol. 29, no. 12, pp. 125–132, 2012.
[5] Z. Kun, "Simulation analysis and countermeasure of the influence of crosswind on road traffic safety," M.S. thesis, Chang'an Univ., Xi'an, China, 2015.
[6] Z. Chi, S. Dongjian, and Z. Min, "Risk analysis of passenger car moving on curved sections based on sideslip microscopic simulation," *J. Syst. Simul.*, vol. 27, no. 7, pp. 1609–1616, 2015.
[7] M. Tsubokura, T. Nakashima, M. Kitayama, Y. Ikawa, D. H. Doh, and T. Kobayashi, "Large eddy simulation on the unsteady aerodynamic response of a road vehicle in transient crosswinds," *Int. J. Heat Fluid Flow*, vol. 31, no. 6, pp. 1075–1086, Dec. 2010.
[8] M. Batista and M. Perkovič, "A simple static analysis of moving road vehicle under crosswind," *J. Wind Eng. Ind. Aerodyn.*, vol. 128, pp. 105–113, May 2014.
[9] J. Fuller, M. Best, N. Garret, and M. Passmore, "The importance of unsteady aerodynamics to road vehicle dynamics," *J. Wind Eng. Ind. Aerodyn.*, vol. 117, pp. 1–10, Jun. 2013.
[10] E. Guilmineau and F. Chometon, "Effect of crosswind on a simplified car model: Experimental and numerical analysis," *J. Fluids Eng.*, vol. 131, no. 2, pp. 104–115, 2009.
[11] L. Wang, X. Chen, and H. Chen, "Influencing factors on vehicles lateral stability on tunnel section in mountainous expressway under strong wind: A case of Xi-Han highway," *Adv. Civil Eng.*, vol. 2020, pp. 1–11, Jun. 2020.
[12] Y. Hongcheng, "The research on the influence mechanism and control method of crosswind effects on long-span bridge traffic safety," M.S. thesis, Hefei Univ. Technol., Hefei, China, 2017.
[13] W. Lu, L. Yuwen, and C. Hong, "Cross-wind environment vehicle driving feature at canyon bridge and tunnel connection segment," *J. Jilin Univ. (Eng. Technol. Ed.)*, vol. 49, no. 3, pp. 736–748, 2019.
[14] W. Lu, X. Tian, X. Heng, and L. Dawei, "A simulation analysis of driving stability in crosswind condition on expressway in mountain areas," *J. Transp. Inf. Saf.*, vol. 37, no. 3, pp. 20–27, 2019.
[15] L. Shuya, G. Zhengqi, H. Taiming, L. Jun, and Z. Ledian, "Two-way coupling analysis of vehicle stability in different crosswind conditions," *China Mech. Eng.*, vol. 30, no. 19, pp. 2276–2286, 2019.
[16] D. J. Findley, J. E. Hummer, W. Rasdorf, C. V. Zegeer, and T. J. Fowler, "Modeling the impact of spatial relationships on horizontal curve safety," *Accident Anal. Prevention*, vol. 45, pp. 296–304, Mar. 2012.

[17] M. Schmidt-Daffy, "Fear and anxiety while driving: Differential impact of task demands, speed and motivation," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 16, no. 4, pp. 14–28, 2013.
[18] C. Ho, H. Z. Tan, and C. Spence, "Using spatial vibrotactile cues to direct visual attention in driving scenes," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 8, no. 6, pp. 397–412, Nov. 2005.
[19] B. Gang, "Study on design parameters of road geometric alignment based on vehicle handling stability simulation," M.S. thesis, Jilin Univ., Changchun, China, 2013.
[20] L. Xinlei, "Research on the safety evaluation of road alignment based on vehicle driving simulation," Shandong Jianzhu Univ., Jinan, China, Tech. Rep., 2016.
[21] S. Xinggang, "Research on safety evaluation techniques of expressway in mountainous area," M.S. thesis, Chongqing Jiaotong Univ., Chongqing, China, 2008.
[22] W. Yan, K. Ling-Qi, G. Zhong-Yin, and H. Chang-Ling, "Alignment design at tunnel entrance and exit zone based on operating safety," *J. Highway Transp. Res. Develop.*, vol. 25, no. 3, pp. 134–138, 2008.
[23] Z. Zhandong, R. Jian, and Z. Wei, "Research on operating speed prediction model for passenger cars in tunnel of expressway," *J. Highway Transp. Res. Develop.*, vol. 27, no. 7, pp. 123–127, 2010.
[24] W. Hao and L. Ao, "Analysis on the cause of traffic accident in the connection section of bridge and tunnel in mountainous area," *Shanxi Archit.*, vol. 36, no. 31, pp. 267–268, 2010.
[25] L. Baixiu, "Research on safety evaluation and improvement measures of mountainous freeway bridge-tunnel sections," M.S. thesis, Chang'an Univ., Xi'an, China, 2009.
[26] Z. Yingchao, "Numerical simulation technology of automobile aerodynamics," M.S. thesis, Peking Univ. Press, Beijing, China, 2011.
[27] B. Marcu and F. Browand, "Aerodynamic forces experienced by a 3-vehicle platoon in crosswind," SAE Tech. Paper 1999-01-13[R]. [S.l.]: SAE, 1999.
[28] D. Schroeck, W. Krantz, N. Widdecke, and J. Wiedemann, "Unsteady aerodynamic properties of a vehicle model and their effect on driver and vehicle under sidewind conditions," SAE Tech. Paper 2011-01-0154 [R]. [S.l.]: SAE, 2011.
[29] S. Albatran, S. Harasis, M. Ialomoush, Y. Alsmadi, and M. Awawdeh, "Realistic optimal power flow of a wind-connected power system with enhanced wind speed model," *IEEE Access*, vol. 8, pp. 176973–176985, 2020.
[30] W. Lu and C. Hong, "Cross-wind environment numerical simulation of connection section between tunnel and bridge," *J. Chang'an Univ. (Natural Sci. Ed.)*, vol. 32, no. 5, pp. 52–57, 2012.
[31] *Traffic Safety Fact 2001.DOT HS 809 484*, Nat. Highway Traffic Saf. Admin., Washington, DC, USA, 2002.
[32] F. Li, G. Li, R. Chen, H. Liang, J. Yang, L. Cao, and L. Meng, "Speed calculation model and simulation of rollover prevention in condition of extreme turn based on lateral force coefficient," *J. Agricult. Eng.*, vol. 32, no. 3, pp. 41–47, 2016.
[33] B. Zhou, X. Wang, S. Zhang, Z. Li, S. Sun, K. Shu, and Q. Sun, "Comparing factors affecting injury severity of passenger car and truck drivers," *IEEE Access*, vol. 8, pp. 153849–153861, 2020.
[34] *China Statistical Yearbook*, Nat. Bureau Statist., China Statistical Press, Beijing, China, 2019.
[35] L. Yang, "Simulation study on the influence of underside winds with different linear shapes on driving safety," M.S. thesis, Shandong Univ. Technol., Zibo, China, 2016.
[36] P. Nian, B. Song, J. Xuan, W. Yang, and Y. Dong, "A wind tunnel experimental study on the flexible flapping wing with an attached airfoil to the root," *IEEE Access*, vol. 7, pp. 47891–47903, 2019.
[37] W. Yaqiao, "Study on comprehensive evaluation of highway alignment in mountain area," M.S. thesis, Harbin Inst. Technol., Harbin, China, 2010.
[38] J. Kang, Y. Hongcheng, and F. Zhongxiang, "Simulation analysis of the influence of crosswind on traffic safety of long-span bridges," *J. Hefei Univ. Technol. (Natural Sci.)*, vol. 42, no. 2, pp. 145–150, 2019.
[39] F. Cheli, R. Corradi, E. Sabbioni, and G. Tomasini, "Wind tunnel tests on heavy road vehicles: Cross wind induced loads—Part 1," *J. Wind Eng. Ind. Aerodyn.*, vol. 99, no. 10, pp. 1000–1010, 2011.
[40] F. Cheli, F. Ripamonti, E. Sabbioni, and G. Tomasini, "Wind tunnel tests on heavy road vehicles: Cross wind induced loads—Part 2," *J. Wind Eng. Ind. Aerodyn.*, vol. 99, no. 10, pp. 1011–1024, Oct. 2011.
[41] B. Wang and Y.-L. Xu, "Safety analysis of a road vehicle passing by a bridge tower under crosswinds," *J. Wind Eng. Ind. Aerodyn.*, vol. 137, pp. 25–36, Feb. 2015.
[42] W. Yang, E. Deng, M. Lei, P. Zhang, and R. Yin, "Flow structure and aerodynamic behavior evolution during train entering tunnel with entrance in crosswind," *J. Wind Eng. Ind. Aerodyn.*, vol. 175, pp. 229–243, Apr. 2018.
[43] F. Chen, H. Peng, X. Ma, J. Liang, W. Hao, and X. Pan, "Examining the safety of trucks under crosswind at bridge-tunnel section: A driving simulator study," *Tunnelling Underground Space Technol.*, vol. 92, Oct. 2019, Art. no. 103034.
[44] S. Mansor and M. A. Passmore, "Effect of rear slant angle on vehicle crosswind stability simulation on a simplified car model," *Int. J. Automot. Technol.*, vol. 14, no. 5, pp. 701–706, Oct. 2013.
[45] C.-R. Chu, C.-Y. Chang, C.-J. Huang, T.-R. Wu, C.-Y. Wang, and M.-Y. Liu, "Windbreak protection for road vehicles against crosswind," *J. Wind Eng. Ind. Aerodyn.*, vol. 116, pp. 61–69, May 2013.

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