ISSN 2706-655X Vol.3, Issue 4: 58-62, DOI: 10.25236/IJFET.2021.030409

Study on the maximum speed of Hong Kong Zhuhai Macao Bridge under typhoon condition

Ruisi Zhang[1,*], Han Xu[1], Xiaoshan Cui[2]

[1]*School of Economics, Qufu Normal University, Rizhao Shandong, 276827, China*
[2]*School of Computing, Qufu Normal University, Rizhao, Shandong, 276827, China*
**Corresponding author*

Abstract: *This paper analyzes the correlation between the maximum safe driving speed of vehicles on the main body of the whole bridge and the typhoon series based on different wind directions. Firstly, the joint probability density model of typhoon wind level and wind direction is constructed. Secondly, the mathematical model for safe driving of vehicles is constructed based on the aerodynamic six component force. The circular curve, up and down ramp and combined alignment are selected as the representative road routes of bridge, tunnel and castle. The 1:1 light vehicle is set up with different wind speed levels for fluid simulation. Finally, it is concluded that there is a negative correlation between the maximum safe driving speed range of vehicles on the main body of the whole bridge and the typhoon series of 1-16.*

Keywords: *Joint probability density model, Fluid simulation, Safe driving speed range*

1. Introduction

The Hong Kong-Zhuhai-Macao Bridge is a microcosm of the development and progress of China's reform and opening up in the past 40 years. It is also a bridge project with the largest scale, the highest technical difficulty and the most complex construction in the history of China's highway construction. In this paper, the relationship between the maximum safe driving speed and the number of typhoons on the main body of the bridge will be calculated under the condition of different typhoon directions.

2. Model Establishment and Solution

2.1 Traffic Safety Analysis under the Influence of Typhoon

The natural wind speed in nature generally does not exceed 10m/s (wind power level 5), but its confluence speed with the oncoming flow generated by vehicles may reach the action intensity of typhoon (wind power level 16) [1]. Therefore, the driving safety problems of vehicles under the action of typhoon can be summarized as follows:

(1) Sideslip problem: when the vehicle is loaded into the original balance system by typhoon load, the resultant force is greater than the adhesion between the vehicle and the ground, and the balance of the system is broken.

(2) Roll problem: under the action of a high-speed typhoon, the vehicle is subject to a large aerodynamic lateral force, and its aerodynamic center does not coincide with the vehicle's mass center, resulting in the generation of roll moment, which is greater than the balance moment generated by the vehicle's gravity component, resulting in the roll phenomenon of the vehicle in the process of driving.

(3) Sideslip problem: if the driver can't correct the steering wheel in time when the vehicle passes the road with wind speed change, the vehicle will sideslip due to the increase of lateral offset, enter other lanes, and even induce road traffic accidents.

2.2 Joint Probability Density Function of Maximum Entropy of Wind Speed and Direction

Based on the maximum entropy principle, the maximum entropy wind speed probability density function (where λ is the Lagrange multiplier) and the maximum entropy Weibull wind speed probability density function (where $f(V_{typhoon}, \eta, k)$ is the Weibull probability distribution) is established. According to the principle of multi-order mixed von Mises distribution and correlation, we derive the modified maximum entropy joint probability density function $f(v, \theta)$ of wind speed and direction.

$$p(V_{typhoon}) = \exp(-\sum_{i=0}^{N} \lambda_i v_t^i) = e^{-\sum_{i=0}^{N} \lambda_i v_t^i}$$

$$p(V_{typhoon}) = f(V_{typhoon}, \eta, k) \exp(-\sum_{i=0}^{N} \lambda_i v_t^i)$$

$$f(v, \theta) = 2\pi g(\zeta) p(V_{typhoon}) f(\theta)$$

$$\zeta = \begin{cases} 2\pi[F(V_{typhoon}) - F(\theta)] & F(V_{typhoon}) \geq F(\theta) \\ 2\pi + 2\pi[F(V_{typhoon}) - F(\theta)] & F(V_{typhoon}) \geq F(\theta) \end{cases}$$

Where ζ is the angle and $g(\zeta)$ is the probability density function of ζ; $F(V_{\text{typhoon}})$ is the probability distribution function of wind speed; $F(\theta)$ is the probability distribution function of wind direction.

Through the simulation example analysis, 16 wind direction and azimuth verification is used to test the empirical data, and Chebyshev Neural Network is used to predict, which verifies the high accuracy of the model.

2.3 Modeling of the Relationship between Wind Speed and Vehicle Speed

The vehicle is subject to its own gravity M_Y, centrifugal force M_R, ground friction F_D and inertia when driving. In addition, the flow field around the vehicle will produce irregular disturbance, and the airflow interacts with the vehicle body to produce aerodynamic force acting on the vehicle body. It is difficult for the aerodynamic action points to coincide with the vehicle centroid, resulting in aerodynamic moment action. The stress analysis of vehicle under typhoon condition is carried out.

2.3.1 Force analysis of vehicle in typhoon environment

SAE standard reference coordinates are established, in which the coordinate origin is located at the intersection of wheelbase center line and wheelbase center line on the ground projection, and all air forces are simplified to the coordinate origin. The angle between the synthetic flow of typhoon and oncoming flow and the x-axis is called sideslip angle, which is expressed by $\beta (\beta = \tan^{-1}(V_{typhoon} / V_{vehicle}))$. a is the wheelbase of the vehicle, then the synthetic air velocity $V_\infty = \sqrt{{V_{typhoon}}^2 + {V_{vehicle}}^2}$ [2]. The combined action of the two air currents makes the aerodynamic resistance of the asymmetric flow field around the vehicle hinder the vehicle movement, as shown in the figure.

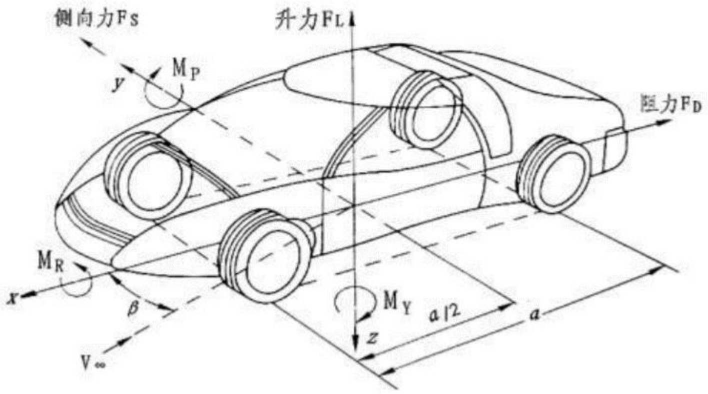

Figure 1: Force diagram of vehicle in equilibrium state under crosswind action

In this paper, the circular curve, up and down ramp and combination alignment of Expressway Alignment are selected as the representative of alignment, and the possible dangerous situation of vehicle driving is analyzed and studied based on typhoon effect, gravity and other factors.

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2.3.2 Critical force analysis of sideslip in curve

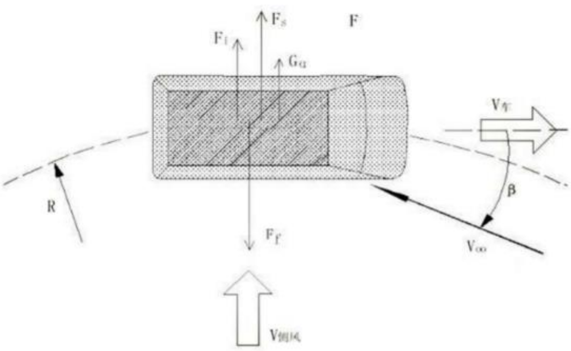

Figure 2: Horizontal force diagram of vehicle driving in curve

In order to ensure that the driving direction of the vehicle can be controlled at this time and the dangerous situation of lateral slip does not occur, the curve driving of the vehicle in the crosswind environment must meet the formula (1) that is:

$$F_l \cos\alpha + F_s + G_a \leq F_f \tag{1}$$

The critical stress analysis formula that the vehicle can keep safe driving state and no lateral slip when driving in the curve under typhoon environment can be expressed as follows:

$$\frac{mV_{vehicle}^2}{R}\cos\alpha + \frac{1}{2}\rho AC_s\left({V_{typhoon}}^2 + {V_{vehicle}}^2\right) + mg\sin\alpha$$
$$\leq \mu_s\left[mg\cos\alpha - \frac{1}{2}\rho AC_L\left({V_{typhoon}}^2 + {V_{vehicle}}^2\right) - \frac{mV_{vehicle}^2}{R}\sin\alpha\right] \tag{2}$$

2.3.3 Critical force analysis of roll in curve

When the vehicle is driving in the curve, the moment is as shown in the figure.

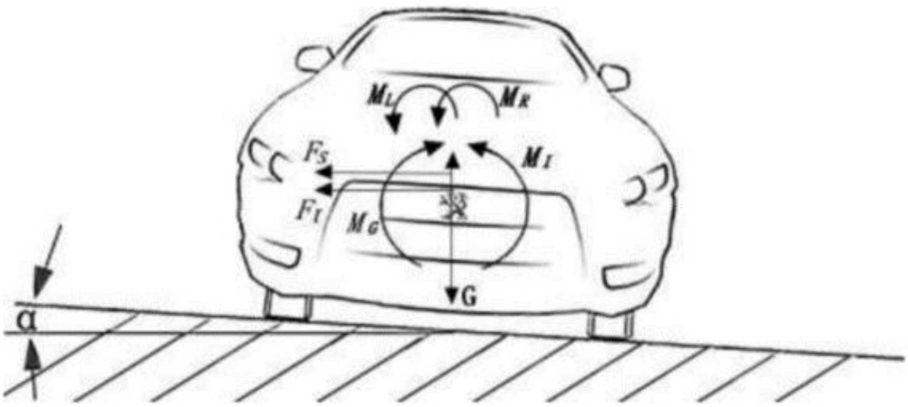

Figure 3: Critical force diagram of vehicle roll in curve

W stands for the width of the vehicle body. The moment generated by the gravity of the vehicle itself is the only moment that can balance the vehicle's roll tendency and stabilize the vehicle's driving state. Then the bending vehicle can ensure the vehicle's smooth driving in the typhoon environment, and the stress state of no roll accident can be expressed as follows:

$$M_l + M_R + M_L \leq M_G \tag{3}$$

$$\left(\frac{mV_{车}^2}{R}\right)\frac{H}{2}\cos\alpha + \frac{1}{2}\rho AC_{RM}V_\infty^2 \mathrm{a} + \frac{1}{2}\rho AC_L V_\infty^2\left(\frac{W}{2}/\cos\alpha\right) \leq \mathrm{mg}\cos\alpha\,\frac{W}{2} \tag{4}$$

Under the action of higher wind speed, the larger the area of wind force, the more prone to rollover. In the case of a certain model, the aerodynamic coefficient will have a significant impact on the roll stability of the vehicle. The aerodynamic roll moment can be obtained by FLUENT software simulation [3].

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2.3.4 Force analysis on safe driving of uphill vehicles

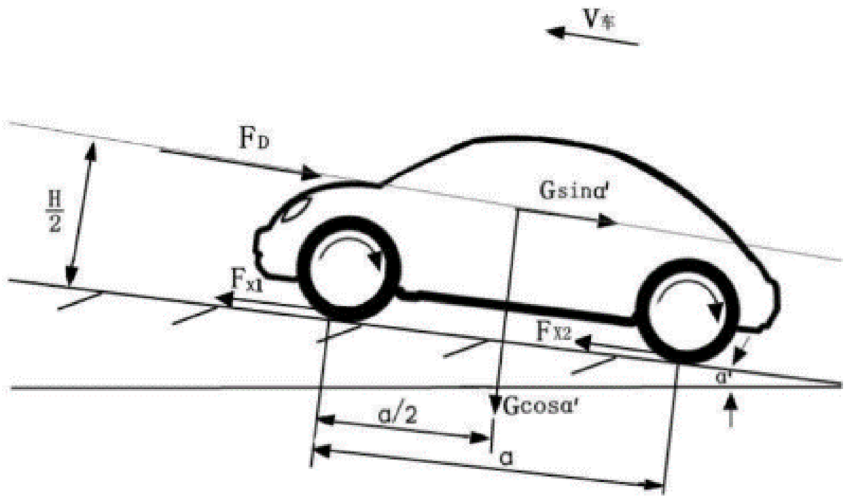

Figure 4: Force analysis on safe driving of uphill vehicles

The requirement for vehicles to drive uphill under the action of typhoon is that the resultant force of resistance in the windward direction should be less than the longitudinal adhesion limit of the ground. It can be expressed as:

$$\frac{1}{2}\rho AC_D V_\infty^2 + (G - F_L)\sin\alpha + f\cos\alpha \le [G(\frac{a}{2a})\cos\alpha - G(\frac{H}{2a})\sin\alpha - \frac{1}{2}\rho AC_D V_\infty^2(\frac{H}{2a})]\mu_x \quad (5)$$

2.3.5 Parking problems of downhill vehicles

When the force exerted on the back of the car by the typhoon and the resultant force of the car's self weight component, on the premise that the car's braking torque is enough not to fail, the resultant force overcomes the longitudinal adhesion limit of the car's wheels, causing the car to be unable to park and slide down.

2.3.6 Safety problems of vehicle cornering in straight line

When the vehicle is running in a straight line, the yaw moment is the most disadvantageous situation because the center of mass and aerodynamic center cannot coincide. Under the effect of yaw moment, the vehicle will yaw with the wind. At this time, the driver must adjust the steering angle to ensure the driving direction. When the typhoon suddenly acts or disappears, the aerodynamic force of the vehicle will change suddenly. The vehicle side offset is often regarded as the lateral driving stability criterion of the vehicle. The driver's perception of the side offset is often not very sensitive, which will lead to the delay of the driver's operation and control of the vehicle.

3. Conclusion

(1) Under the action of crosswind, the vehicle's lateral force changes most violently, which poses a great threat to the vehicle's driving safety. Excessive lateral force will directly cause the dangerous situation of vehicle sideslip in the process of driving. When the wind speed is higher than 7.5m/s, it is suggested that the driving speed on the curve should be lower than 100km/h.

(2) In the case of general setting of curve conditions, the aerodynamic coefficients of vehicles under various working conditions are calculated by simulation software, and then the three mathematical models of driving in curve are substituted to determine the speed threshold of safe driving under the action of crosswind with different intensities. However, the physical information such as curve radius is relatively simple, It is necessary to continue in-depth, combined with the actual road curve of different radius, slope, and different road conditions, to expand the refinement, in order to get more accurate safe driving speed threshold. With the help of corner speed limit and navigation tips and other means, it can provide certain reference for drivers and ensure the driving quality.

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Table 1: Relationship between wind level and maximum safe driving speed

Wind scale	wind speed(m/s)	Maximum safe driving speed(km/h)
0	0.0-0.2	66.00
1	0.3-1.5	66.07-66.11
2	1.6-3.3	65.92-66.06
3	3.4-5.4	65.51-65.87
4	5.5-7.9	64.79-65.44
5	8.0-10.7	63.66-64.70
6	10.8-13.8	61.97-63.52
7	13.9-17.1	59.56-61.80
8	17.2-20.7	56.20-59.33
9	20.8-24.4	51.54-55.90
10	24.5-28.4	45.46-51.16
11	28.5-32.6	36.59-44.96
12	32.7-36.9	19.83-36.60
13	37.0-41.4	
14	41.5-46.1	
15	46.2-50.9	
16	51.0-56.0	

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