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Numerical Investigation on Handling Stability of a Heavy Tractor Semi-Trailer under Crosswind

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Abstract: Due to the large lateral area of the trailer and variable road conditions, the handling stability of a heavy tractor semi-trailer under crosswind is very important for road safety. In this present work, numerical simulation is performed to study the crosswind effects on handling stability of a tractor semi-trailer. The aerodynamic characteristics of the tractor semi-trailer under different crosswind were computed by computational fluid dynamics (CFD). Then, mathematical models to reveal the relationship between the aerodynamic forces and crosswind were constructed to serve as inputs of the multi-body dynamics to analyze the handling stability under crosswind. The performance of crosswind stability is evaluated by the response of lateral acceleration, yaw rate and the lateral displacement. The lateral acceleration and yaw rate were decreased by a maximum of 14.6% and 16.5% compared to the truck without the deflector, which showed that the crosswind aerodynamics and stability were obviously improved.

Keywords: heavy tractor semi-trailer; crosswind stability; vehicle aerodynamic; dynamic characteristics; wind deflector

1. Introduction

In recent years, with the development of highways and logistics industries, more and more heavy tractor semi-trailers have been introduced into road transport. The crosswind stability, which is related to the safety of truck driving, has attracted wide concern. Due to its high center of gravity, narrow wheelbase (compared with the body height) and large area of container, the heavy tractor semi-trailer driving at high speed is more prone to lateral tilt and rollover when encountering strong crosswind [1]. Serious traffic accidents or strong psychological burden to the driver will be induced [2]. As shown in Figure 1, a sequence of scenes vividly displays some cases of wind-induced rollover of a tractor semi-trailer.

The study related to crosswind effect on vehicle performance could be basically classified into two aspects: one is crosswind aerodynamics [3], and the other is crosswind stability [4]. About crosswind aerodynamics [5], the influence of the crosswind on aerodynamic characteristics was mainly discussed, such as the fluctuation of the six aerodynamic components and the change of flow field. The most common evaluation methods for evaluating the aerodynamic performance of vehicles in

different wind environments are road tests, static wind tunnel tests and simulations with varying yaw angles [6]. As for the crosswind stability, experimental and dynamic modeling simulation methods were adopted to investigate the dynamic response of the vehicle under crosswind, the deviation from the original driving path and the driver's handling of the vehicle. Some previous works have already concentrated on dynamic aerodynamics, which clearly demonstrate the importance of time-related changes under aerodynamic forces. When driving at high speed, the influence of aerodynamic force on vehicle performance is particularly important, especially under complex crosswind circumstances. For instance, Tural Tunay et al. [7] investigated the aerodynamic coefficients with different yaw angles on Ahmed vehicle by the wind tunnel test and Particle image velocimetry (PIV) measurements, which visualized the velocity flow field under the crosswind vividly and thoroughly revealed the underlying flow phenomena related to crosswind sensitivity of the ground vehicles. Gajendra et al. [8] discussed the crosswind aerodynamics of a sedan, and their research illustrated that the drag coefficient, lift coefficient and the yaw moment would increase with the growth of yaw angle and velocity of crosswind. Makoto et al. [9] analyzed a road vehicle's aerodynamic response in transient crosswinds. Cai et al. [10] proposed a framework to analyze a vehicle running on a long bridge in windy circumstances. On this basis, the aerodynamic response of vehicles running on highways or bridges can be analyzed and the critical wind speed can be evaluated to avoid potential accidents.

Figure 1. Wind-induced rollover of a tractor trailer.

In the aspect of crosswind stability, scholars have had extensive discussions on theoretical analysis, model simulation and experiments. Kee et al. [11] carried out an investigation on the riding stability of a passenger car under crosswind by the full-scale wind tunnel test and on-road test with a crosswind generator. Their results revealed the major parameter that affects the crosswind sensitivity of passenger cars was the yawing moment. In addition, high-speed stability would be improved with the reduction of lift force, lateral force and yawing moment. Fujihashi et al. [12] evaluated vehicle behavior under crosswind by using a full-vehicle dynamic simulation model with aerodynamic forces and moments, which were obtained by numerical simulation added on the gravity center. Nakashima [13] conducted vehicle dynamics simulations to analyze the effect of unsteady aerodynamics of a simplified truck under transient crosswinds. In his study, the horizontal motion of the vehicle was considered, and the vertical motion was assumed to be balanced statically. To investigate the influence of crosswind on directional deviation and handling performance, Juhlin et al. [14] constructed a gust wind model and applied to a parameterized bus. The results showed that the crosswind velocity was the main factor on directional deviation, and the yaw moment and lateral force coefficient were also the most significant considerations among the aerodynamic coefficients. The previous research showed that the research related to crosswind aerodynamics and crosswind stability were relatively separated from each other, which did not consider the interaction between the two parts [15].

It is undeniable that the crosswind will influence the aerodynamic characteristics and may induce lateral displacement. Moreover, by considering the change of aerodynamic characteristics under crosswind, the handling stability analysis is more convincing. Therefore, in this work, a coupling approach was adopted to investigate the crosswind aerodynamic and crosswind stability of a heavy

duty tractor trailer, systematically. By this means, the aerodynamic characteristics under different crosswinds [16] were computed by computational fluid dynamics (CFD), and a mathematical model was constructed to describe the relationship between aerodynamic forces and crosswind. Then a full vehicle dynamic model of a tractor semi-trailer was constructed, and the effect of the crosswind on stability was investigated by considering the mathematical model of the aerodynamic force as an input.

Based on this coupling method, the heavy tractor trailer with and without a deflector was used to evaluate the aerodynamic characteristics and dynamic response of the truck in different crosswinds. The results have demonstrated that the deflector, which can reduce the lateral force and yawing moment, is also beneficial to improve the handling stability greatly under crosswind, and has a certain significance for engineering applications.

2. Numerical Method and Validation

2.1. Governing Equations

Computational fluid dynamics (CFD), which solves the coupling of the Reynolds averaged Navier–Stokes (RANS) equations to a turbulence model, has proven to be a very powerful and practical tool [17–21]. Two-equation models, such as κ – ε [22], κ – ω [23] and the shear stress transport (SST) model [24], are the favorable options for CFD calculations. In the current work, the Renormalization Group (RNG) κ – ε turbulence model [25] was selected to investigate the flow around the heavy truck, where the flow field induced was three-dimensional, turbulent and incompressible. It has been shown to better predict the separating flows and is widely used in engineering applications. For example, using two-equation models, previous scholars conducted research on street canyon flow [26], large tank fire [27,28], internal combustion engine [29,30] and heat exchange [31,32]. The corresponding governing equations are as follows:

Reynolds average continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0, \quad (1)$$

RANS equations:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial}{\partial x_j} \left(\mu \frac{\partial u_i}{\partial x_j} - \overline{u'_i u'_j} \right) \quad (2)$$

where u and u'_i are mean and fluctuating velocities, respectively; subscripts $i, j = 1, 2, 3$ stand for three different directions, x , y and z ; ρ is the density, p represents the mean pressure and μ denotes the dynamic viscosity.

The last terms of the right side of Equation (2) represent the Reynolds stress using the approach of the eddy viscosity principle after Boussinesq:

$$-\overline{u'_i u'_j} = \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij}, \quad (3)$$

where ν_t is the turbulence eddy viscosity, $k = \frac{1}{2} \overline{v'_i v'_i}$ is the turbulence kinetic energy and δ_{ij} is the Kronecker delta. The turbulence eddy viscosity could be computed by the function of turbulence kinetic energy (k) and turbulence dissipation rate (ε):

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (4)$$

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G - \varepsilon \quad (5)$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{v_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} G - C_{\varepsilon 2} \frac{\varepsilon^2}{k} - \frac{C_\mu \eta^3 (1 - \eta/\eta_0) \varepsilon^2}{1 + \beta \eta^3} \frac{\varepsilon^2}{k} \quad (6)$$

$$G = -\overline{u'_i u'_j} \frac{\partial u_i}{\partial x_j} = \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (7)$$

where $\eta = (k/\varepsilon)(G/v_t)^{0.5}$, $\sigma_k = \sigma_\varepsilon = 0.7149$ is the turbulent Prandtl number in the k and the ε equation [33], $C_\mu = 0.0845$, $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, $\eta_0 = 4.38$, $\beta = 0.012$.

The solutions of the governing equations were carried out in STAR-CCM+. The steady-state, implicit scheme was utilized in the incompressible flow solver. The governing equations were discretized by using a vertex centered unstructured finite volume method. The segregated solver was used in the computations. A second-order scheme was applied for the spatial discretization.

2.2. Validation Case of Heavy Tractor Semi-Trailer Model

The model studied was a full-scale heavy tractor semi-trailer (see Figure 2) with a length, width and height of 16,903, 2438 and 3988 mm, respectively. Some details such as the engine room under the cabin, together with the radiator and other small parts around the engine, were ignored in the geometry by considering the complexities involved in mesh generation. A flat surface was added to the wheel surface adjacent to the ground, and the body surface was smoothed to save the computational resource.

Figure 2. Validation model.

To validate the selection turbulence model, drag coefficient, lateral force coefficient, lift coefficient and yawing moment coefficient were compared with experimental results measured at the HD-2 Boundary Layer Wind Tunnel (HD-2 BLWT) at Hunan University and also the results from Gong [34]. The 1/6-scale truck model is used in the wind tunnel displayed in Figure 3. The numerical simulation model used in the current work is the same as that used by Gong and the experiment. The setup of the boundary conditions is also consistent with Gong's work. The boundary condition of the computational domain and grids resolution are delineated in Figures 4 and 5. Inlet 1 and inlet 2 are the velocity inlets, while outlet 1 and outlet 2 are set to the pressure outlet. In order to achieve the target of high precision, the domain was discretized by an unstructured trimmer grid in STAR-CCM+. In consideration of the large amount of separation around the tractor trailer, the resolution around the vehicle ranged from 25 to 40 mm, and two refinement regions were applied around the vehicle.

The aerodynamic coefficients at different relative inflow angles are plotted in Figure 6 and show that the computational results are in agreement with the experimental and Gong's results. Among them, the aerodynamic lift coefficient obtained from the simulation is slightly different from the comparison experimental data and Gong's results, which may be caused by the difference between the ground clearance of the truck model in the numerical simulation and the wind tunnel test. In general, the selected turbulence model and computational setup could capture the three-dimensional, turbulent and incompressible flow field around the truck.

Figure 3. 1/6-scale wind tunnel test model.

Figure 4. Boundary condition of computational domain.

Figure 5. The longitudinal section of the grids.

Figure 6. The comparison between experimental and computational results: (a) drag coefficient; (b) lateral force coefficient; (c) lift coefficient; (d) yawing moment coefficient.

3. Computation of the Aerodynamic Characteristics

3.1. Detailed Study of Target Vehicle Model

The simulation for the target model was conducted on the same analysis region as the former one. The deflector has been removed from the original model, to study the influence of the additional device on the aerodynamic characteristics and handling stability of the heavy truck under the crosswind (see Figure 7).

Figure 7. Target model.

3.2. Computational Domain and Boundary Condition

Turbulence model and calculation settings are the same as mentioned above. A large cuboid computational domain is illustrated in Figure 8; its length, width and height are 200, 37 and 20 m, respectively. The blockage ratio with respect to cross section area of the vehicle was less than 0.25%, which is satisfied with the typical requirement, less than 5% [35]. The vehicle is about 3 L far away from the inlet and the side of the truck is about 5 W away from the crosswind inlet. The boundary condition setups are as follows: a resultant velocity (V_R) whose direction is characterized by relative inflow angular (β) is added at the freestream inlet and crosswind inlet. The x-component (V_1), which is equivalent to the speed of vehicle, is set to 30 m/s. The y-component (V_2), which is equivalent to the speed of the crosswind, is changeable to simulate different crosswind intensities. Outlets were set as the pressure outlet, and the top of the computational domain was a free-slip wall so that they had no viscous effect on the results. The ground of the computational domain was set to a moving wall with the same velocity as that of the speed of the vehicle. The density of air is equivalent to 25 °C, 1.205 kg/m³. Regarding the inlet velocity and vehicle length, the Reynolds number is 2.25×10^7 . The upstream turbulence intensity was 0.5%.

Figure 8. Computational domain: (a) top view; (b) isometric diagram.

3.3. Computational Grid

The grids were hexahedron unstructured meshes generated in STAR-CCM+ (see Figure 9). To enhance the simulation accuracy, prismatic grids were generated near the vehicle surface as the boundary layer. Special attention was paid to the hook face in order to maintain the grid quality [36].

Figure 9. Mesh distribution.

Different computational grids were used to check the grid independence, which was carried out by three grid strategies, namely six million for the coarse mesh, eight million for the medium mesh and ten million for the fine mesh [37]. The drag coefficient was selected as the evaluation criterion. The results improved from the coarse mesh to medium mesh, and the drag coefficient was 0.6997 and 0.7045 for the medium and fine mesh, respectively; the deviation of the two grid strategies is approximately 0.69%, which means, a negligible change was spotted from medium mesh to fine mesh. Considering the computational cost and efficiency, the medium mesh was used in current work.

3.4. Results and Discussion

Assuming the vehicle drives at a steady velocity, relative inflow angular orientation increases with the growth of crosswind. The crosswind intensities change from zero level to the seventh level of the Beaufort scale, which means the relative inflow angle varies from 0 to 21 degrees.

Aerodynamic forces and moments on a road vehicle include drag F_D , lift F_L , lateral force F_S , rolling moment M_R , pitching moment M_P and yawing moment M_Y . The definitions and positive directions of the forces and moments are shown in Figure 10. These forces and moments refer to the gravity center of the vehicle in the present work. The expressions for aerodynamic coefficients are as follows:

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \quad (8)$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \quad (9)$$

$$C_S = \frac{F_S}{\frac{1}{2}\rho V^2 A} \quad (10)$$

$$C_{RM} = \frac{M_R}{\frac{1}{2}\rho V^2 AL} \quad (11)$$

$$C_{PM} = \frac{M_P}{\frac{1}{2}\rho V^2 AL} \quad (12)$$

$$C_{YM} = \frac{M_Y}{\frac{1}{2}\rho V^2 AL} \quad (13)$$

in which V , A and L are the relative speed, the frontal project area ($A = 9.665 \text{ m}^2$ in the current work) and the wheelbase of the vehicle ($L = 13.1 \text{ m}$ in the current work).

Figure 10. Aerodynamic forces and moments on the vehicle.

By changing the direction and value of the relative speed, the aerodynamic forces and moments can be simulated under different speeds and crosswind strength. The origin of coordinate in this numerical simulation is located at the projection of the center point between the third axis and the fourth axis of the container truck on the ground. The variation of the aerodynamic coefficients with relative inflow angles plotted in Figure 11 reveals that all aerodynamic coefficients trend to increase with these relative inflow angles, and the lateral force, and rolling and yawing moment, are the most sensitive to the relative inflow angle. In addition, the lateral force, yawing moment and rolling moment are the main causes of side-slip and rollover accidents. The lift and pitching moment may reduce the grip of tyres and thus are harmful for driving safety. It is obvious that the yawing moment and rolling moment increased notably with the increase of the crosswind speed. Previous studies [24] have shown that yawing moment made a greater impact on the handling stability, but the specific effects on the performance need to be investigated further in the dynamic simulation.

To identify the mathematical relationship of aerodynamic characteristics under crosswind, and couple with crosswind stability analysis, a polynomial was used to fit the variation of the aerodynamic coefficient with relative inflow angles. The polynomial models for the curves were given by:

$$y = \sum_{i=1}^{n+1} p_i x^{n+1-i} \quad (14)$$

in which $n + 1$ is the order of the polynomial, n is the degree of the polynomial. The order gives the number of coefficients to be fit, and the degree gives the highest power of the predictor variable. In the present work, a two-order polynomial was adopted to get the polynomial model of the aerodynamic coefficients. To evaluate the fitting precision, *R-square* was introduced. *R-square* is defined as the ratio of the sum of squares of the regression (SSR) and the total sum of squares (SST); the value of *R-square* closer to one indicates that the model accounts for a greater proportion of variance.

$$SSR = \sum_{i=1}^n \omega_i (\hat{y}_i - \bar{y})^2 \quad (15)$$

$$SSR = \sum_{i=1}^n \omega_i (y_i - \bar{y})^2 \quad (16)$$

$$R - square = \frac{SSR}{SST} \quad (17)$$

Figure 11. The variation curve of the aerodynamic coefficients to the relative inflow angles: (a) drag coefficient; (b) lateral force coefficient; (c) lift coefficient; (d) rolling moment coefficient; (e) pitching moment coefficient; (f) yawing moment coefficient.

The error analysis showed that the *R-square* for all fitting curves was larger than 0.95, which indicated good fitting accuracy. The fitting curves of aerodynamic coefficients compared with the simulation data were also shown in Figure 11, and the fitting formulas are as follows:

Aerodynamic drag coefficient:

$$C_D = -0.00051632\beta^2 + 0.03461\beta + 0.70049 \quad (18)$$

Aerodynamic lateral force coefficient:

$$C_S = 0.00315\beta^2 + 0.06589\beta - 0.21907 \quad (19)$$

Aerodynamic lift coefficient:

$$C_L = -0.00036945\beta^2 + 0.05396\beta - 0.02155 \quad (20)$$

Aerodynamic rolling moment coefficient:

$$C_{RM} = -0.000189227\beta^2 - 0.04155\beta - 0.01531 \quad (21)$$

Aerodynamic pitching moment coefficient:

$$C_{PM} = 0.000097165\beta^2 + 0.01218\beta + 0.15676 \quad (22)$$

Aerodynamic yawing moment coefficient:

$$C_{YM} = -0.00002360\beta^2 - 0.0246\beta + 0.08322 \quad (23)$$

Figure 12 shows the 3D streamlines around the semi-trailer truck at different crosswinds. It can be seen that there was a low velocity region at the front of the tractor as the air tended to stagnate, followed by acceleration to high velocity at the separation point on the corner of the tractor. As the intensity of the crosswind increases from zero level to the seventh level, the flow field around the tractor semi-trailer becomes more and more asymmetric. There are some complex vortex areas in the gap between tractor and trailer as well as at the back of the tractor, and with the increase of the crosswind, the vortex center moves from the windward side to the leeward side. The flow velocity around the tractor semi-trailer is gradually increased from the windward side to the leeward side, which will induce great increases in the lateral force and the yawing moment coefficient. The high velocity area between the tractor and the trailer becomes larger and rotated at the back of the tractor with the increase of the crosswind. The wake becomes asymmetric and the flow velocity increases from the windward side to the leeward side. The surface directly exposed to the crosswind showed generally lower velocity than the opposite side.

Figure 13 shows the distributions of pressure under different intensity crosswinds on the lateral surface of the heavy truck. On the windward side, the stagnation point shifts to the front corner of the tractor and the high-pressure zone around the stagnation point moves in the same direction. The stagnation point reaches to the front corner at zero level and transits to the lateral side of the tractor with an intensity increase of the crosswind. The high-pressure region spread to the lateral surface of the trailer at higher levels. On the opposite side, the airflow separates from the front corner of the tractor and the region of separation increases with the intensity increase of the crosswind. The separation also increases the asymmetry of the flow field. The low-pressure area enlarges with the intensity of the crosswind increasing. At the same instant, the low-pressure region on the lateral surface of the tractor and the trailer spreads to the rear section of the truck, with the intensity of the crosswind increasing. Hence, an asymmetrical pressure distribution first occurs around the front of the tractor and then spreads toward the rear section. With the increase of lateral pressure and the movement of the pressure center, the rolling moment coefficient and yawing moment coefficient increase monotonously. Regarding the drag, the balance between the high-pressure zone at the front of the tractor and the low-pressure zone at the rear of the trailer also changes with the crosswind due to the expansion of the recirculation region and the shift of the stagnation point.

Figure 12. The flow field around the tractor semi-trailer at different intensities of crosswind: (a) zero level; (b) the third level; (c) the fourth level; (d) the fifth level; (e) the sixth level; (f) the seventh level.

Figure 13. The distributions of pressure on the lateral surface at different crosswinds (left: leeward side, right: windward side): (a) zero level; (b) the third level; (c) the fourth level; (d) the fifth level; (e) the sixth level; (f) the seventh level.

4. Multi-Body Dynamic Simulation

Previous research has studied the aerodynamic forces and moments under steady conditions, and just estimated the aerodynamic changes when the vehicles generated a yaw slip [38]. However, these aerodynamic characteristics will have some effects on the vehicle dynamics. Therefore, in this work, a coupling method that combined the changing aerodynamic coefficients with the vehicle dynamics system was used to analyze the effect of crosswind on the handling stability of a tractor semi-trailer.

A six-degrees-of-freedom (6-DOF) multi-body dynamic model of a six-axle tractor semi-trailer was constructed in the software TruckSim showed in Figure 14. The model consists of an aerodynamics module, vehicle body, driving system, steering system, braking system, power transmission system and so on. Some specifications of the tractor semi-trailer such as moment of inertia and center of gravity (c.g.) are described in Table 1. The tractor and trailer are treated as a single rigid body. In order to analyze the dynamic characteristics while considering the change of the aerodynamics under crosswind, the aerodynamic module is described by the fitting curves of the aerodynamic coefficients.

Figure 14. The schematic of multi-body dynamics model.

Table 1. Main parameters for the tractor semi-trailer.

Parameters		Values
m	Vehicle total mass (powered unit)	7600 kg
m_s	Vehicle sprung mass (powered unit)	4455 kg
l_f	Distance between c.g. and the 1-axis (powered unit)	2.0 m
l_r	Distance between c.g. and the 3-axis (powered unit)	2.75 m
L	Vehicle length (powered unit)	7.25 m
H	Vehicle height (powered unit)	3.9 m
I_{xx}	Rolling moment of inertia (powered unit)	2283.9 kg•m ²
I_{yy}	Pitching moment of inertia (powered unit)	35,402.8 kg•m ²
I_{zz}	Yawing moment of inertia (powered unit)	34,802.6 kg•m ²
m_t	Vehicle total mass (trailer unit)	7570 kg
m_{ts}	Vehicle sprung mass (trailer unit)	5500 kg
l_{ft}	Distance between c.g. and the 3-axis (trailer unit)	3.3 m
l_{rt}	Distance between c.g. and the 6-axis (trailer unit)	5.01 m
L_t	Vehicle length (trailer unit)	12.2 m
H_t	Vehicle height (trailer unit)	4.2 m
I_{xxt}	Rolling moment of inertia (trailer unit)	8997.1 kg•m ²
I_{yyt}	Pitching moment of inertia (trailer unit)	150,000 kg•m ²
I_{zzt}	Yawing moment of inertia (trailer unit)	150,000 kg•m ²
K_{sf}	Upper vertical spring stiffness	0.25 N/m
K_{sr}	Lower vertical spring stiffness	0.7 N/m
C_f	Upper vertical damping	15,000 Ns/m
C_r	Lower vertical damping	30,000 Ns/m
$C_{\alpha f}$	Cornering stiffness of one tyre (front)	140,000 N/rad
$C_{\alpha r}$	Cornering stiffness of one tyre (rear)	140,000 N/rad

The proposed tractor semi-trailer is equipped with a 300 kW diesel internal engine model, a torque transfer, a transmission, a transfer case and some differentials. The brake actuator of each wheel has been simply modeled with no braking pressure, and in order to simulate an open-loop steer control, the shifting control of the vehicle was clutch disengaged. The aerodynamic model is

composed of the six aerodynamic coefficients; the force and moment vector acting on the sprung mass represent the aerodynamic effects. The aerodynamic characteristics will be changed when the aerodynamic parameters are different [39]. Finally, a multi-body dynamic model with given aerodynamic properties was established. The aerodynamic coefficients of the vehicle will be changed with the motion dynamically, and the change will have an important influence on the vehicle system dynamics. In the simulation, the driving speed was set to 30 m/s, and a crosswind with different strengths was added in the vertical direction of the vehicle driving direction.

To some degree, the lateral displacement, lateral acceleration and yaw rate could evaluate the handling stability of the tractor semi-trailer under crosswind. Figure 15 shows the variation of lateral displacement, lateral acceleration and yaw rate with time under different crosswinds. In order to obtain the dynamic response of the vehicle more clearly and accurately, the simulation time is set to 10 s. In general, when the crosswind speed increases from 0 to 16.7 m/s, the lateral displacement, lateral acceleration and yaw rate also increase gradually. Due to the rise of the lateral force coefficient and the yawing moment coefficient, the growth rate of lateral displacement increases, and the variation gradient of lateral displacement also agrees well with the trends of the lateral coefficient and the yawing moment coefficient (see Figure 15a). Because the dynamic model is an open-loop, the lateral displacement of the tractor semi-trailer will increase continually. As to the lateral acceleration, it will increase to the maximum instantly once the vehicle encounters a crosswind, and reduces gradually then. Because the effective area of crosswind decreases with the tractor semi-trailer deviated from its original path, the lateral force and yawing moment also decrease so that the lateral acceleration decreases (see Figure 15b). The yaw rate shows a similar trend with the lateral acceleration. Previous studies [40] have indicated that the yaw rate is the most important factor on the handling stability, and the greater the yaw rate is, the worse the crosswind stability is.

Figure 15. The evaluation indexes of crosswind stability at different crosswinds: (a) lateral displacement; (b) lateral acceleration; (c) yaw rate.

5. Effect of the Wind Deflector on Crosswind Stability

In current research, the crosswind stability of tractor semi-trailer with and without a wind deflector has been investigated. The aerodynamic coefficients of the tractor semi-trailer with wind deflector under different yaw angles are obtained based on the above computational process. The variation tendency of the rolling moment coefficient and yawing moment coefficient is drawn in Figures 16 and 17. It is obvious that the rolling moment coefficient decreased when the wind deflector was added, which exerted great improvement on the performance of the vehicle. The wind deflector is also beneficial to reduce the yawing moment coefficient under crosswind, especially to the large relative angles, and that will have a positive impact on the handling stability of the vehicle. Obviously, this wind deflector could improve the aerodynamic characteristics of the vehicle in the crosswind circumstance. Meanwhile, the improvement of the aerodynamic characteristics would have large effects on the handling stability of vehicle. To investigate the improvement effects of the aerodynamic characteristics on handling stability under crosswind, the fitting formulas of aerodynamic characteristics of the vehicle with a wind deflector are also applied to the multi-body dynamic model.

Figure 16. Comparison of rolling moment coefficient.

Figure 17. Comparison of yawing moment coefficient.

Figure 18 compares the lateral displacement, lateral acceleration and yaw rate of the heavy tractor semi-trailer with and without a wind deflector. It is shown in the results that the tendencies of these parameters were quite similar, but the lateral displacement, lateral acceleration and yaw rate were reduced accordingly with the wind deflector added, that is, the handling stability was improved. Therefore, it could be concluded that the wind deflector not only could improve the aerodynamic characteristics, but also could enhance the handling stability under crosswind. Comparing the

two results, the lateral acceleration and yaw rate were decreased by a maximum of 14.6% and 16.5%, respectively.

Figure 18. Comparison of lateral displacement, lateral acceleration and yaw rate with or without wind deflector: (a) lateral displacement; (b) lateral acceleration; (c) yaw rate.

6. Conclusions

In the present work, the effect of aerodynamics on the motion of a tractor semi-trailer subjected to crosswinds was analyzed. A coupling method was used to analyze the effects of crosswind on the handling stability of a tractor semi-trailer. In order to obtain the crosswind aerodynamic characteristics, the steady aerodynamics of a tractor semi-trailer were analyzed under various relative inflow angles. To get the mathematical relationship of aerodynamic characteristics under crosswind, a polynomial was used to fit the variation of the aerodynamic coefficient with relative inflow angles. The aerodynamic coefficient functions of the tractor semi-trailer were applied to the aerodynamic module in multi-body dynamic simulation to describe the aerodynamic changes of the vehicle under crosswind. Then, a series of dynamic performance responses including the lateral displacement, the lateral acceleration and the yaw rate were obtained. The dynamic responses, which considered the change of aerodynamics, showed that the crosswind had great influence on the handling stability of the tractor semi-trailer. The handling stability of the tractor semi-trailer with and without a deflector was compared. The dynamic responses indicated that the handling stability of the tractor semi-trailer has been improved a lot with a wind deflector acting on the roof, in which, the lateral acceleration and yaw rate were

decreased by a maximum of 14.6% and 16.5%, respectively. The deflector cannot only improve the aerodynamic characteristics, but also the handling stability of the vehicle, which offers a guidance to practical engineering applications. Besides that, the crosswind with a long period of non-uniform changes can promote more significant changes; this is worth improving in future studies.

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