Simulation Analysis of Vehicle Handling Stability Based on Trucksim

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Abstract: Based on the Trucksim simulation platform and referring to the parameters of the real vehicle, the vehicle body model, tire model, powertrain model, steering system model and braking system model was constructed. After the parametric modeling of the whole vehicle, the steering wheel angle step test was selected for simulation verification referring to the standards of automobile handling stability test in China. Besides, the vehicle handling stability was analyzed with changing part of the vehicle structure parameters. The research result shows that, although the response forms of vehicle motion parameters are different, they all indicate that the faster the vehicle speed is, the more obvious the vibration of vehicle parameter curve will be, and the vehicle handling stability performance will decrease accordingly. In the steering wheel angle step test, by changing the height of the vehicle's center of mass and the front and rear wheelbases, it can be explained that reducing the height of the vehicle's center of mass and increasing the wheelbase can improve the handling stability of the vehicle.

1. Introduction

According to the analysis report of bus traffic accidents from 2012 to 2017 [1], there have been 40 major bus traffic accidents in the past five years, resulting in a total of 649 deaths and more than 700 injuries of varying degrees. Among these accidents, more than half of them are caused by bus rollover. The performance which directly related to the bus rollover is the handling stability, especially the handling stability of the high-speed vehicle. Therefore, it is of great significance to study the operation stability of passenger vehicles. The traditional study on the handling stability of the vehicle is to produce a sample vehicle and carry out relevant tests, and then analyze the test data to find out the problems existing in the design part. After modifying the design parameters, the test is repeated until it meets the test expectation. With the rapid development of computer technology, the virtual simulation experiment of handling stability can realize the whole vehicle simulation under various environments and calculate the control stability according to various parameters. Therefore, it can reduce the actual prototype test times, shorten the development cycle, reduce the development cost, and save various resources.

For the research of vehicle handling stability, "no feedback" is basically adopted in the early stage. Broulhet [2] first introduced the concept of slip angle, which was a measure of the stability of an automobile in emergency steering. In the early stage, researchers mainly studied the effect of tire [3], suspension and steering system [4] on vehicle handling stability in the process of vehicle driving. Whitecomb [5] and Segel [6] applied mathematical theories such as linear control theory to vehicle...
models, established mathematical models of vehicles with various degrees of freedom, and systematically analyzed steady-state characteristics and transient responses of vehicles. With the development of automobile industry and computer technology, automobile researchers have gradually shifted from mechanical analysis to virtual simulation. They have successively put forward theories such as optimal control technology [7] and neural network technology [8], etc., and established a closed-loop model fitting with reality by using virtual test technology. In 1996, VehicleSim, TruckSim and other vehicle simulation software were developed by the MSC, which can build a real vehicle model and test a variety of conditions. Guo Konghui [9] applied computer dynamic simulation research on "driver-vehicle-road" feedback control system model. Guan Xin et al. [10] proposed a suspension model applied to real-time vehicle dynamics simulation, and established a vehicle dynamic model suitable for real-time simulation. The degree of freedom of the real-time vehicle model was increased to 29. Wei Lang, et al. [11] developed the vehicle four-wheel active steering control system, which can effectively improve the steering maneuverability of four-wheel vehicles.

Based on the parameters of a certain type of passenger vehicle, the Trucksim vehicle modeling method and approach were used to conduct vehicle parametric modeling and build vehicle dynamics model. The test requirements of standard specifications were combined with the actual typical working condition test environment, and corresponding road models were established with different working conditions and test requirements. According to the test requirements, the steering wheel angle step test was selected to carry out simulation operation, and the corresponding road model and driving condition model were set. By comparing the changes of bus handling stability under different design parameters, the results were analyzed.

2. Vehicle dynamics modeling based on Trucksim

2.1 Body model

Vehicle body model can be built with Trucksim based on parameters of the vehicle's overall size, mass and moment of inertia for each shaft. The whole vehicle modeling includes sprung mass and unsprung mass. Among them, sprung mass modeling should firstly determine the coordinate system of centroid of the vehicle body. In the coordinate system of the vehicle body's centroid, the centroid is set as the origin, the forward direction of the vehicle is the positive direction of X-axis, and the vertical direction is the positive direction of Z-axis. The Y-axis is judged by the righthand spiral rule. The simulation model studied in this paper is one of Yutong buses. Besides the vehicle parameters are shown in Table 1.

| Parameters                                           | Symbol | Value     | Unit  |
|------------------------------------------------------|--------|-----------|-------|
| Height                                               | H      | 3460      | mm    |
| Width                                                | W      | 2500      | mm    |
| Length                                               | L      | 9000      | mm    |
| Distance between front wheelbase and the center of mass of the body | L1     | 2100      | mm    |
| Distance between ground and the center of mass of the body | h      | 1200      | mm    |
| Distance between longitudinal symmetry plane and center of mass of the body | Y      | 0         | mm    |
| Sprung mass                                           | M      | 9650      | Kg    |
| Roll moment of inertia of the body                   | Ixx    | 11676.5   | Kg • m2 |
| Pitch moment of inertia of the body                  | Iyy    | 46706     | Kg • m2 |
| Yaw moment of inertia of body                        | Izz    | 46706     | Kg • m2 |
| Product of inertia of vehicle body on X and Y axis   | IXY    | 0         | Kg • m2 |
| Product of inertia of vehicle body on X and Z axis   | IXZ    | 0         | Kg • m2 |
| Product of inertia of vehicle body on Y and Z axis   | IYZ    | 0         | Kg • m2 |
2.2 Tire model
Tire is an important part of vehicle dynamics analysis, the characteristics of tires directly affect the vehicle dynamics, braking, handling stability, smoothness and safety. The tire modeling in TruckSim mainly includes tire dimensions, steady-state mechanical properties, etc. One of the most important modeling is the tire mechanical properties. This part can adopt the empirical or semi-empirical tire model through parameter setting modeling. The simplified model in this paper can reflect the mechanical properties of tires under various working conditions. The total number of Yutong large bus tires is 6, the front axle is single tire and the rear axle is double tires. The tires are 275/70R22.5, that is, the width of the tires is 275mm, and the flat ratio of the tires is 70%. The calculated tire radius $R$ is: $R=275 \times 0.7+22.5 \times 25.4/2=478.25$mm. The shape and mechanical parameters of the tire are shown in Table 2.

| Parameters                  | Value | Unit |
|-----------------------------|-------|------|
| Radius                      | 478.25| mm   |
| Width                       | 275   | mm   |
| Effective rolling radius    | 510   | mm   |
| The vertical stiffness      | 980   | N/m  |
| Maximum vertical load       | 100000| N    |
| The moment of inertia       | 14    | Kg.m²|
| Rolling resistance coefficient | 0.0041| /    |
| Twins tires space           | 310   | mm   |

2.3 Powertrain model
The modeling of powertrain includes engine model and transmission system model. The mainly work is to set the engine power, transmission ratio of the transmission system and other automobile power device parameters. When configuring these parameters, the power and drivability requirements must be considered. The type and output torque of the engine determine the dynamic performance of the vehicle. The values of maximum speed and specific power are clearly stipulated in the national indexes of bus power performance, which can be used as the basis for the preliminary determination of engine performance in this simulation. In the Ministry of Transport JT/T325-2010 [12], it is stipulated that the maximum speed of large-sized and high-class vehicles shall not be less than 110km/h and the specific power shall not be less than 11kW /t. The relevant parameters of the vehicle engine studied in this paper are shown in Table 3.

| Parameters                  | Value | Unit |
|-----------------------------|-------|------|
| Maximum powerful            | 150   | Kw   |
| Maximum speed               | 2500  | rpm  |
| Idle speed                  | 725   | rpm  |
| The moment of inertia of crankshaft | 1.15 | Kg.m²|

The gear shift strategy of the transmission directly affects the dynamic performance of the vehicle, and is also directly related to the acceleration performance of the vehicle. This simulation adopts a five-speed manual transmission based on QJ805. The transmission of each gear is shown in Table 4. Other parameters of the transmission such as shift time, up-down efficiency, moment of inertia, etc. adopt the default values of the simulation software.
Table 4 Transmission ratios in each gear of the five-speed manual transmission model

| Gear | 1   | 2   | 3   | 4   | 5   | R   |
|------|-----|-----|-----|-----|-----|-----|
| Ratio| 5.82| 3.23| 1.96| 1.26| 1   | -4.97|

2.4 Steering system model
Steering system is a mechanism used to maintain or change the direction of the vehicle. When the vehicle is running, it ensures that there is a coordinated angle relationship between the wheels. The setting of the steering system in Trucksim is generally to select the steering shaft form, set the transmission ratio, and model the nonlinear characteristics of the system. The front suspension of the bus studied in this paper adopts a non-independent suspension, so the steering trapezoid is selected as an integral steering trapezoid. The model is shown in Fig.1.

2.5 Braking system model
When a vehicle is braking, it is usually the driver who presses down the brake pedal to generate pedal force. The brake pressure enters the brake cylinder through the ABS system, and the braking torque is generated by fluid power to decelerate the vehicle. Fig.2 shows the working process of the braking system. According to the relevant test parameters and standards for passenger vehicles, the maximum braking torque of the front axle is selected in Trucksim as 7.5 kN·m; The maximum braking torque of the rear axle is 10 kN·m, and the ABS braking system is selected in the braking module. ABS starts to work when the slip rate is greater than 0.2 and stops working when it is less than 0.1, so the slip rate has been maintained between 0.1 and 0.2 all the time.

3. Simulation analysis and optimization of handling stability based on steering wheel angle step test
Vehicle body model, tire model, powertrain model, steering system model and brake system model are
established through Trucksim to complete the construction of parameterized model of vehicle dynamics. On this basis, according to the test requirements, the steering wheel angle step test is selected for vehicle simulation test.

3.1 Simulation modeling of steering wheel angle step test

For the transient response when the steering wheel is input, it is usually determined by the steering wheel angle step test. According to GB/T 6323-2014 “Test Method for Vehicle Handling Stability”, the test condition of steering wheel angle step is set in the Trucksim interface, the reference speed is set according with 70% of the highest speed of passenger vehicles, that is 70 km/h. At the same time, 65 km/h and 75 km/h driving speed are added for analysis and comparison. After driving at the reference speed for 5 seconds, the steering wheel is turned to make the lateral acceleration of the passenger vehicle become 2.5 m/s², then the steering wheel angle is maintained, and the whole process takes 30s. The formula relationship between the lateral acceleration and the steering radius of the front wheel is calculated as follows,

\[ a = \frac{v^2}{R} \]  
\[ R = \frac{L}{\sin \beta} \]

Where, \( a \) is the lateral acceleration of the vehicle, \( V \) is the instantaneous speed of the vehicle, \( R \) is the steering radius of the vehicle, \( L \) is the length of the vehicle, \( \beta \) is the steering angle of the front wheel.

The front wheel steering angle 3.4° can be calculated with the lateral acceleration of 2.5 m/s², under the condition of ignoring the free travel of the steering wheel. And the steering wheel angle should be set to 85° according to the steering ratio 25:1. Meanwhile, the maximum lateral acceleration required by the test safety (generally 0.4g) can be calculated with the formula under the vehicle speed of 65km/h, 75km/h, respectively.

3.2 Simulation and verification of steering wheel angle step test

According to the steering wheel angle step simulation conditions established above, the roll angle-time curves, lateral acceleration-time curves and slip angle-time curves are generated as shown in Fig.3, Fig.4 and Fig.5. Where, the Baseline is the time curve corresponding to the reference speed of 70km/h, the No.1 line is the time curve corresponding to the speed of 65km/h and the No.2 line is the time curve corresponding to the speed of 75km/h.

![Fig.3 Roll angle-time curve](image1) ![Fig.4 Lateral acceleration-time curve](image2) ![Fig.5 Slip angle-time curve](image3)

It can be seen from the three curves that at a driving speed of 70km/h, the transient response changes at the 5s, and the curve is basically stable around the 15s, then the vehicle enters a steady state, and the response time is about 10s. At a traveling speed of 65km/h, the vehicle enters the steady state earlier and the overshoot is less than the time curve of 70km/h. However, in the 75km/h time curve, it
is found that after the transient response entered at the 5s, all the values oscillate significantly and could not enter a stable state. Thus, it shows that the vehicle speed has a great influence on the handling stability of the vehicle, and the handling stability of the bus decreases with the increase of the vehicle speed.

3.3 The influence of different structural parameters on the steering wheel angle step input test of passenger vehicle

According to the research of the steering wheel angle step input test for passenger vehicles, the influence of this condition on the vehicle handling stability is preliminarily analyzed by comparing the motion parameters of the steering wheel step transient response input at different speeds. On this basis, through the adjustment of the center of mass position of the vehicle and the wheelbase of the two vehicle structural parameters, the changes in the handling stability of the passenger vehicle are studied, and an optimization plan is proposed at the same time.

3.3.1 Influence of center of mass height on handling stability

When the vehicle is subjected to lateral acceleration while turning, the height of the vehicle's center of mass will also change, which will change the rolling moment of the vehicle. The roll moment mainly affects the roll angle, so changing the height of the vehicle's center of mass will change the stability of vehicle handling. Therefore, in order to explore the influence of the height of the center of mass on the handling stability of the vehicle, the height of the center of mass of the vehicle will be changed. The centroid height in the original vehicle parameters is 1200 mm, and the height of the center of mass is increased and decreased by 200 mm, respectively. Then the other parameters remain the same, and the steering wheel angle step test is carried out. The steering stability of the passenger vehicle is analyzed according to the slip angle, yaw rate, and roll angle parameters. The simulation results of steering wheel angle step test under three centroid heights of the vehicle are as shown in Fig.6, Fig.7 and Fig.8. Where, the Baseline is the curve of centroid height of the original vehicle, No.1 line is the curve of centroid height of 1000mm, and No.2 is the curve of centroid height of 1400mm, respectively.

Fig. 6 Slip angle-time curve at different height of center of mass

Fig. 7 Yaw rate-time curve at different height of center of mass
Fig. 8 Roll angle-time curve at different height of center of mass

It can be seen from the three figures that with the change of the height of the center of mass, slip angle and yaw rate of the vehicle are not changed significantly within a certain range, while the roll angle of the vehicle changes obviously. Reducing or increasing the center of mass by 200 mm, the side slip angle has been reduced or increased by 20%, it indicates that on the basis of the original height of the center of mass, reducing the center of mass height without affecting the safety of vehicle performance can improve the handling stability of vehicle.

3.3.2 Influence of front and rear wheelbases on handling stability

For two-axle vehicle, the wheelbase is the distance between the center point of the front axle and the center point of the rear axle. Wheelbase is an extremely important item in the design parameters of the vehicle. Its length is closely related to performance of the vehicle, especially influence on the handling stability of the vehicle. Therefore, in order to investigate the influence of the change of wheelbase on the handling stability of the vehicle, the wheelbases of the vehicle will be changed by setting the fixed front axle position in Trucksim unchanged, and changing the distance from the rear axle to the front axle. Based on the parameters of the original vehicle, the wheelbase is set at 4600mm, and the wheelbase was shortened and increased to 4400mm and 4800mm respectively, while other parameters remained unchanged. Then the steering wheel angle step test is carried out, and the steering stability of the passenger vehicle is analyzed according to the slip angle, yaw rate, and roll angle parameters. The simulation results of steering wheel angle step test under different front and rear wheelbase of the vehicle are as shown in Fig.9, Fig.10 and Fig.11. Where, the Baseline is the curve of the wheelbase of 4600 mm, No.1 line is the curve of the wheelbase of 4400 mm, and No.2 is the curve of the wheelbase of 4800 mm, respectively.

Fig. 9 Slip angle-time curve with different wheelbase
According to the analysis of three figures, with the increase of front and rear wheelbase, the slip angle, yaw rate, and roll angle of the center of mass of the vehicle are all reduced with certain degree. It can be seen that increasing the wheelbase appropriately can lower the slip angle, yaw rate, and roll angle of the vehicle without changing the front axle position, it can also enhance the handling stability of the vehicle.

4. Conclusion

The vehicle dynamic simulation platform Trucksim is used to study the vehicle dynamics and the mechanism characteristics of each subsystem of the vehicle, and the parameterized vehicle model is built. According to the related standards on handling stability test of the vehicle, factors affected the performance of the handling stability is analyzed, and the handling stability performance can be optimized by improving the motion and structure parameters of the vehicle. Some conclusions can be got as follows.

1) The speed is an important factor affecting the vehicle handling and stability, and too high speed will lead to the decline of the vehicle handling and stability performance;

2) The height of the vehicle's center of mass has a great impact on the vehicle's handling and stability performance, and reducing the height of the center of mass is conducive to improving the handling stability;

3) The change of front and rear wheelbase of the vehicle has an impact on the vehicle's handling stability, and an appropriate increase of the front and rear wheelbase of the vehicle can improve the vehicle's handling stability performance.

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