Simulation Analysis of Steering Wheel Angle Step Input
Double-trailer Combination Handling Stability

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Abstract. The simulation software TruckSim was applied to build a simulation model of a
double-trailer combination and analyze the steering characteristics of a semi-trailer train at the
steering wheel corner step input. Through simulation analysis under different speeds and
structural parameters, the intrinsic relationship between the steering characteristics of double-
trailer trains and the speed and structural parameters is revealed, and the performance
characteristics of the steering characteristics of double-trailer trains under these conditions are
given, which provides reference for the evaluation and analysis of the steering stability of
double-trailer combination.

1. Introduction

Double-trailer combinations as an efficient type of transport vehicles, can significantly improve the
load capacity and weight, limited by the existing "Road Traffic Safety Law" and its implementing
regulations, China does not yet allow double-trailer combinations on the road, double-trailer
combinations handling stability is the first link to limit its promotion and application. In this paper, we
simulate and analyze the steering stability of a double-trailer combinations under steering wheel angle
step input conditions by modeling and setting the simulation conditions with the simulation software
TruckSim.

Domestic and foreign scholars have conducted a lot of research on the usage parameters and structural
parameters of combination vehicles. In 2004, Xu Hongguo et al. [1] applied ArcSim simulation
software to analyze the steering characteristics of the steering wheel of articulated vehicle during the
steering wheel angle step input and found the connection between the steering characteristics and the
driving speed and design parameters. Liu Hongfei [2] established a articulated vehicle motion model
and analyzed the influence of parameters such as vehicle speed, five-wheel front position and semi-
trailer wheelbase on handling stability of articulated vehicle. The orthogonal test method was used to
quantitatively analyze the influence of the structural parameters and motion parameters of the train on
the lateral movement of the semi-trailer. Finally, the structural parameters were optimized and
evaluated. In 2011, Cui Shengmin et al. [3] established a heavy articulated vehicle model through
ADAMS and conducted steering stability tests such as steering wheel angle step input, angle pulse
input, and returnability. The results of the study indicate that the tractor and semi-trailer should be
studied as a complete system, and the structural parameters and usage parameters of the trailer have a
greater impact on the handling stability of the tractor. In 2011, Wei Chaoyi et al [4] established a
dynamic model of a semi-trailer train, and used MATLAB to solve the root trajectory change trend;

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the results show that the vehicle use parameters and structural parameters need to be selected reasonably in order to improve their handling stability. In 2016, Long Jiaqing [5] built a articulated vehicle model based on TruckSim. The results show that properly increasing the mass of the tractor, lengthening the wheelbase of the tractor, lengthening the distance of the trailer from the front axle of the tractor, reducing the mass of the trailer, and shortening the distance from the articulation point of the tractor to the front axle can improve the stability of the direction of the train.

In 1981, the National Highway Authority of Australia Windup et al. [6] introduced the types of highway combination vehicles (all types of articulated vehicles) in Australia and discussed the impact of various aspects such as the structural parameters and usage parameters of vehicles. In 1985, M. El-Gindy and others of Carleton University in Canada [7] studied the steady-state steering response of articulated vehicles, full-trailer trains and B-type trailer trains, and tested the design parameters and tire side of the vehicles. The influence of partial stiffness and axle arrangement on the dynamic response of the vehicle provides a reference for the improvement of the driving stability of the articulated vehicle. In 1996, Esmailzadeh [8] used computer simulation technology to construct the dynamics and kinematics models of the articulated vehicle, and studied the effects of vehicle use parameters and structural parameters on vehicle driving stability. In 2001, Harada [9] studied the lane change behavior of heavy the articulated vehicle, proposed the use of driver-vehicle systems to evaluate lateral stability, and analyzed the impact of design parameter changes on the high-speed active safety performance of vehicles. In 2008, Hac et al [10] studied the dynamic stability of the plane yaw model of a tractor-trailer combination vehicle. The vehicle's active unified braking control and direct yaw moment control are compared, and the effect of trailer parameter changes on the dynamic stability of the vehicle combination system is studied.

In summary, in dealing with engineering problems, computer-aided design and parameter visualization are more and more widely used[11][12]. This article uses TruckSim modeling and simulation software to build a simulation model of a double-trailer combination. Then, by setting simulation conditions, the stability of the combination vehicle under low-speed and high-speed conditions is studied, and the stability of the combination vehicle is analyzed under the condition of changing the structural parameters of the semi-trailer wheelbase.

2. Vehicle Model

The double-trailer train selected for this study consisted of three vehicle units of tractor-trailer, Dolly and semi-trailer, and the parameters are shown in Table 1. In the model solver of TruckSim software, there is no model solver (S., SS + dSS + SSS) corresponding to the model of this study (3-axle tractor-trailer + 2-axle Dolly + 3-axle semi-trailer), the closest model is S., SS + dS + S, where S., SS represents 3-axle tractor-trailer, dS represents single-axle Dolly, and S represents single-axle semi-trailer, so the simplification of Dolly and semi-trailer is needed. The simulation model built by TruckSim is shown in Figure 1.

| Parameters                  | Truck               | Dolly              | Semi-trailer        |
|-----------------------------|---------------------|--------------------|---------------------|
| Dimensions (mm)             | 10333×2540×4000     | 4710×2400×1200     | 13650×2560×4000     |
| Kerb mass (kg)              | 15210               | 4010               | 13310               |
| Load (kg)                   | 9790                | -                  | 6680                |
| Wheelbase (mm)              | 4804+1363           | 2878+1328          | 6493+1295+1325      |
| Tread (mm)                  | 2060/1870/1870      | 1695/1695          | 1840/1840/1840      |
| Front overhang (mm)         | 1472                | 2878               | 2073                |
| Rear suspension (mm)        | 2694                | 500                | 2645                |
| Distance of centre of mass from front axis (mm) | 3560 | 3493 | 5596 |
| Height of the centre of mass (mm) | 1350 | 1150 | 1890 |
3. Effect of Using Parameters on Handling Stability

The steering wheel angle step test was selected for the simulation test, and the speed was selected for the low (v=30km/h) and high (100km/h) speeds, with a steering wheel angle step input of 40° (Figure 2). The vehicle first moves in a straight line at low speed and high speed respectively, then turns the steering wheel as fast as possible to the predetermined angle of the steering wheel and remains motionless for some distance, keeping the speed constant during the course of the journey.

In the simulation test, the curves of lateral speed, yaw rate, articulation angle speed and lateral acceleration of the vehicle over time were selected to evaluate the influence of the steering wheel stepping input on the stability of the train. The trajectory of motion, lateral velocity, yaw rate, articulation angle velocity, and lateral acceleration of each vehicle unit over time are shown in Figures 3 to 7.

Figure 2 shows the steering wheel corner stepped input curve with a 40° steering wheel corner applied at 5s; Figure 3 shows the motion trajectory of each unit of the vehicle under low-speed and high-speed conditions, and the radius of the motion trajectory of the double-hung train under low-speed conditions is smaller than the radius of the motion trajectory under high-speed conditions, which is consistent with the actual situation.

Figure 4. Lateral acceleration response curve.  
Figure 5. Yaw rate response curve.
As shown in Figure 4, under low-speed conditions, the peak value of the lateral acceleration of the traction truck is 0.37 m/s², and the time for the three vehicle units to reach the steady-state value is 6.75s, 7.15s, 8.65s, and there is a time lag. Under high-speed conditions, the peak values of each vehicle unit are 1.25 m/s², 1.72 m/s², and 1.62 m/s² in order. The peak lateral acceleration of the Dolly unit is the largest, and the time to reach the steady-state value is 7.11s, 10.45s, 10.05s, indicating that there is a serpentine instability under high-speed conditions.

As shown in Figure 5, under low-speed conditions, when the yaw rate of each vehicle unit transitions from the response to the steady-state, the change process is smoother, and the response time to reach the steady-state value is 6.65s, 6.98s, 9.2s, respectively, there is a time lag, and the steady-state value is equal. Under high-speed conditions, the steady-state values of each vehicle unit are equal, and the time to reach the steady-state values is 8.25s, 11.55s, 11.30s, there is a time lag, and Dolly's oscillation amplitude is the largest, and there is a serpentine motion.

![Figure 6. Roll angle response curve.](image)

![Figure 7. Lateral velocity response curve.](image)

As shown in Figure 6, under low-speed conditions, the roll angle change trend is relatively smooth, the time for each vehicle unit to reach the steady-state is 6.73s, 7.95s, 7.35s, and the steady-state values are 0.18°, 0.19°, 0.21°. Under high-speed conditions, the roll angle of Dolly and semi-trailer at steady state is large, and there are peaks, respectively 1.36° and 1.47°. The steady-state values of the three-vehicle unit are 0.59°, 1.19°, and 1.25°, respectively, and there is a tendency to zoom back in.

As shown in Figure 7, under low-speed operating conditions, the lateral speeds of the tractor unit and semi-trailer unit are both positive and tend to move in a circle. However, the lateral velocity of the Dolly unit is negative and tends to move outward. The steady-state values of each vehicle unit are 0.140m / s, -0.125m / s, 0.134m / s, the time is 6.3s, 8.1s, 8.9s, and there is a time lag. Under high-speed operating conditions, the lateral speed of each vehicle unit is negative, and there is a tendency to move outwardly. The steady-state values of each vehicle unit are -0.60m / s, -1.00m / s, -0.67m / s, the time is 11.4s, 12.0s, 12.73s. There is a serpentine movement in a semi-trailer.

4. Effect of Structural Parameters on Handling Stability

Changing the wheelbase of the semi-trailer increases the wheelbase of the semi-trailer by one meter and the speed is 30km/h. Through simulation analysis, it is found that changing the wheelbase of the semi-trailer does not have a significant effect on the vehicle units under low-speed conditions, as shown in Figure 8 to Figure 9 below. Therefore, the study analyzed the effect of increasing the wheelbase of the semi-trailer on the stability of the whole vehicle under high-speed conditions.
Figure 8. Lateral acceleration response curve (30km/h).

Figure 9. Yaw rate response curve (30km/h).

It can be seen from Figures 10 to 13 that increasing the wheelbase of the semi-trailer, the lateral acceleration, yaw rate, roll angle and lateral speed response peak of the traction truck, Dolly and semi-trailer are reduced, and the time to reach the steady-state value is shortened. It shows that increasing the wheelbase of the semi-trailer will improve the maneuverability of the double-trailer train under high-speed driving conditions.

Figure 10. Lateral acceleration response curve (80km/h).

Figure 11. Yaw rate response curve (80km/h).

Figure 12. Roll angle response curve (80km/h).

Figure 13. Lateral velocity response curve (80km/h).
5. Conclusion
In this paper, under the steering angle step input, the response laws of each vehicle unit's lateral acceleration, yaw rate, roll angle and lateral speed under low-speed and high-speed conditions are studied. Compared with low-speed operating conditions, the oscillation frequency and vibration amplitude of each unit of the vehicle increase at high-speed operating conditions, and Dolly is more active in the movement of the double-trailer train, which is the main factor for the instability of the serpentine motion of the train. At the same time, the response of the structural parameters of each vehicle unit was studied. Under low-speed conditions, changing the wheelbase of the semi-trailer has no significant effect on each unit of the vehicle. Under high-speed conditions, the stability of the double-trailer train has been improved by changing the wheelbase of the trailer.

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