Research on Braking in a Turn and Parameter Optimization of Centre-axle trailer combination Based on TruckSim

Bingtao Li², Sheng Chang¹,²*, Xianchao Zhu², Meiling Yang³

¹School of Automotive Engineering, Changshu Institute of Technology, Suzhou, Jiangsu, 215500, China
²School of Mechanical Engineering, Jiamusi University, Jiamusi, Heilongjiang, 154007, China
³Corresponding author: csheng@cslg.edu.cn

Abstract: This paper uses TruckSim dynamics simulation software to build a non-linear model of a center-axle trailer combination, conducts a braking in a turn simulation to study its braking in a turn stability, and a straight-line braking test was carried out on the train through the built-up centre-axle trailer combination braking performance test system, and the reliability of the simulation model was ensured by comparing the test and simulation results. In order to improve the braking performance of the train, a comprehensive evaluation index for evaluating the braking performance of the train is proposed by taking the structural parameters of the train as the optimization variable. The uniform test method is used to optimize the design of the variables, and the braking in a turn is performed on the high adhesion road. Simulation and analysis results show that the optimization reduces the probability of brake folding and improves braking stability.

1. Introduction
In recent years, road transportation has become the main force in my country's cargo transportation. With the advancement and implementation of the advanced concept of multimodal transportation, the current automobile and train transportation methods can no longer meet the requirements of the existing freight system. In 2016, GB 1589 "Limits of dimensions, axle load and masses for road vehicles, trailers and combination vehicles" formally was revised officially to add centre-axle trailer[1]. The development of centre-axle trailer combination can improve the vehicle capacity based on my country's road system, fundamentally improve the vehicle system, solve the problem of limited and overloaded load, and realize the healthy and orderly development of the logistics industry. For the production system of transportation vehicles in my country, tractors and trailers are produced, matched, and combined by different companies. For ultra-long trains such as centre-axle trailer combination, dangerous working conditions such as jackknifing, rollover, and swerve are easily generated during braking[2,3], the reasonableness of its matching seriously affects the safety of the train, and the braking performance is an important factor to ensure the safety of the train. This article aims to improve the braking performance of the centre-axle trailer combination and improve the rationality of train matching.

2. Establishment of Nonlinear Simulation Centre-axle trailer combination
The vehicle dynamics simulation software TruckSim is used to establish a multi-degree-of-freedom simulation model of the centre-axle trailer combination.
non-linear simulation model of a centre-axle trailer combination. In order to ensure the effectiveness of the simulation model, the same structural parameters as the actual vehicle are established. The simulation parameters are obtained based on the actual vehicle measurement, as shown in the Tab. 1, the whole vehicle model is shown in Fig. 1.

Table 1 Basic parameters of central axle freight trains

| Parameter                                           | Tow truck value | Trailer value |
|-----------------------------------------------------|-----------------|---------------|
| Curb weight (kg)                                    | 7860            | 5300          |
| Rated contained mass (kg)                           | 9140            | 12700         |
| Wheelbase (mm)                                      | 5600            | 1310          |
| Front/rear axle track (mm)                          | 2040/1860       | 1885          |
| Front/rear suspension (mm)                          | 1500/2900       | 60/3210       |
| Height of frame from ground (mm)                    | 1050            | 950           |
| Center of mass height (mm)                          | 1460            | 1180          |
| Longitudinal distance between center of mass and    | 2000/2500       | 555           |
| front axle (mm)                                     |                 |               |
| Longitudinal distance between traction ring center   | 7250            | 5455          |
| and front axle (mm)                                 |                 |               |
| Vertical height from the center of the traction ring | 400             |               |
| to the ground (mm)                                  |                 |               |

Figure 1. TruckSim centre-axle trailer combination simulation model

3. Real vehicle test

The centre-axle trailer combination used in the actual vehicle test is composed of a tow truck produced by a vehicle company and a two-axle centre-axle trailer. As shown in Fig. 2, the test site is carried out at the Highway Transportation Comprehensive Test Site of the Ministry of Transport, and is restricted to the test site and anti-rollover protection device, this actual vehicle test adopts the linear brake to verify.

According to GB/T 13594-2003 “Antilock braking performance and test procedure for motor vehicles and their trailers”, the test sample vehicle was subjected to a high-attachment road brake test. The test is carried out under no-load condition of the train, and the initial braking speed was 40km/h. The test equipment mainly includes the INDAS-5000 data acquisition system, high-precision inertial navigation test system, steering angle measuring equipment, wheel speed sensor, CAN module, PC, etc. The test system composition is shown in Fig. 3, and the test and simulation results are shown in Fig. 4.
It can be seen from Fig. 4 a) that the error between TruckSim simulation results and actual vehicle test braking distance results is 1.23%. At the same time, it can be seen from Fig. 4 b) that the simulation speed change of TruckSim is consistent with the actual vehicle test speed change trend, which is in good agreement. Therefore, the non-linear model of the center-axle trailer combination established by TruckSim can simulate the braking performance of the train.

4. Braking in a turn simulation analysis

Simulation conditions: a high-adhesion pavement with a radius of 100m and a road adhesion coefficient of 0.8 is build in TruckSim. Speed control is adopted for the no-load centre-axle trailer combination in software, and the speed is set to 40km/h, and the steering wheel is set to the driver preview setting, and make it carry out a left turn braking test along the center of the road, the pressure of the brake chamber is 0.7MPa, until the train stops. Analyze the yaw rate and lateral acceleration of the train to study the stability of the train when brake in a turn.
It can be seen from Fig. 5 and Fig. 6 that when an unloaded centre-axle trailer combination is fully activated at 40km/h during a turn on a high adhesion coefficient road, the braking time is about 2s, and the yaw rate and lateral acceleration of the towing truck will first surge to the peak, the peak of yaw rate appears at 0.45s, which is 0.096rad/s, the yaw rate surges to the peak appearing time accounts for 22.5% of the entire braking time; the yaw rate of the centre-axle trailer first decreased slightly, and then the peak value appeared at 1.25s, which was 0.035rad/s, and the yaw rate gradually increased to the peak value accounting for 62.5% of the entire braking time. The peak lateral acceleration of the tow truck appears at 0.125s, which is 0.193g, and the peak lateral acceleration of the centre-axle trailer appears at 2.025s, which is 0.08g, which is the end of train braking. At the same time, the peak yaw rate and lateral acceleration of the tow truck will appear ahead of the time when the central axle trailer appears, and then as the train speed decreases, the yaw rate and lateral acceleration will gradually decrease, and the peak yaw rate of the tow truck is about 2.74 times that of the centre-axle trailer, and the peak lateral acceleration is 7.72 times that of the centre-axle trailer. It fully shows that the centre-axle trailer combination is the most dangerous moment in the early stage of braking in a turn, and the tow truck is more likely to lose stability during braking in a turn than the centre-axle trailer.

5. Parameter optimization

5.1. Optimization variables and evaluation indicators

According to the previous analysis, consider the position of the traction seat, the allowable rotation angle of the traction rod, the loading position of the center of mass, and the wheelbase of the centre-axle trailer as the optimization variables, which are represented by the symbols A, B, C, and D, as shown in Tab. 2.

| Parameter symbol | Parameter meaning | unit |
|------------------|-------------------|------|
| A                | Longitudinal distance from the center point of the traction ring to the first axle of the traction truck | mm   |
| B                | Allowable turning angle of tow bar | °     |
| C                | The distance between the trailer's centroid loading position and the towing point | mm   |
| D                | Central axle trailer wheelbase | mm   |

According to the traffic accident statistics annual report from 1997 to 2017, the common accidents of articulated trains during braking are jackknifing (about 30%) and rollover (about 50%), collision (about 20%) caused in part by not leaving a safe distance to take emergency braking[4]. Therefore, the braking performance evaluation indicators are selected as: braking distance, rear magnification factor of yaw rate (the ratio of the peak yaw rate of the centre-axle trailer to the peak yaw rate of the tow truck), and the rear magnification factor of lateral acceleration (the ratio of the peak lateral acceleration of the central axle trailer to the peak lateral acceleration of the tow truck), and weighting the three established indicators to obtain a comprehensive evaluation index score.

\[ S = \frac{1}{0.2S_1 + 0.3S_2 + 0.5S_3} \times 100 \]  

\[ \text{Where, } S \text{——Comprehensive evaluation index score of braking performance; } 
S_1 \text{——Braking distance; } 
S_2 \text{——The rear magnification factor of the yaw rate; } 
S_3 \text{——The rear magnification factor of lateral acceleration.} \]
5.2. Optimization variables and evaluation indicators

Orthogonal experimental design needs to consider the interaction between various factors, when the number of levels is large, the number of trials is too much, so the uniform test is used to optimize the parameters\(^5\). Therefore, the uniform test is used to optimize the parameters. The optimization parameters are 4, and each factor is selected at 6 levels. \(U_6(6^4)\) is selected for the uniform test design.

Consider not changing the parameters such as the front and rear suspension of the train, the distance from the center of the traction ring to the first axle of the trailer, and rated load mass. According to the selected four influencing parameters, the equal step length is taken as the level value, and the uniform test is designed from the \(U_6(6^4)\) uniform test design table. Use TruckSim simulation model to simulate the left-turn braking test of a centre-axle trailer combination with full load. The simulated vehicle speed is 60km/h, the turning radius is 100m, the road adhesion coefficient is 0.8, and the braking air pressure is 0.7MPa. The test scheme of uniform design and model scoring results are shown in Tab. 3.

| Level | A       | B       | C       | D       | \(S_1\)  | \(S_2\)  | \(S_3\)  | Model scoring |
|-------|---------|---------|---------|---------|---------|---------|---------|---------------|
| 1     | 1(6900) | 2(35)   | 3(5500) | 6(1600) | 43.079  | 0.906   | 0.798   | 10.768        |
| 2     | 2(7000) | 4(45)   | 6(7000) | 5(1500) | 44.810  | 0.940   | 0.910   | 10.309        |
| 3     | 3(7100) | 6(55)   | 2(5000) | 4(1400) | 43.116  | 0.899   | 0.832   | 10.742        |
| 4     | 4(7200) | 1(30)   | 5(6500) | 3(1300) | 43.951  | 0.965   | 0.883   | 10.503        |
| 5     | 5(7300) | 3(40)   | 1(4500) | 2(1200) | 44.031  | 0.932   | 0.846   | 10.516        |
| 6     | 6(7400) | 5(50)   | 4(6000) | 1(1100) | 43.400  | 0.982   | 0.821   | 10.639        |

It can be seen from Tab. 3 that the model with the level 1 scheme has the highest score, and the model with the level 2 scheme has the lowest score. Therefore, level 1 is considered for scheme design. That is, when the weight sum of the braking distance and the rear amplification factor is the smallest, it indicates that the braking performance of the train is optimal.

5.3. Comparison of optimization results

The level 1 scheme is compared with the real vehicle model in TruckSim simulation. The simulated vehicle speed is 60km/h, the turning radius is 100m, the road adhesion coefficient is 0.8, the brake pressure is 0.7MPa, and the driver previews the control for full-load left braking in a turn. Simulation results of evaluation indicators before and after optimization are analyzed, as shown in Fig. 7 to Fig. 9.
It can be seen from Fig. 7 to Fig. 9 that the braking distance of the centre-axle trailer combination is reduced from 43.31m to 43.07m, a decrease of 0.55%. Before optimization, the peak yaw rate of the towing truck and the centre-axle trailer are 11.346deg/s and 10.853deg/s respectively, the peak lateral acceleration is 0.279g and 0.229g respectively, and the rear magnification factor of yaw rate is 0.957, and the rear magnification factor of lateral acceleration is 0.821. The optimized peak yaw rate is 10.985deg/s and 9.953deg/s, the lateral acceleration peaks are 0.279g, 0.223g, the rear magnification factor of yaw rate is improved by 5.28%, and the rear magnification factor of lateral acceleration is improved by 2.62%. It can be seen that the optimized parameters greatly improve the braking in a turn performance of the train, especially reducing the probability of braking jackknifing and improving the braking stability.

6. Conclusion
This paper uses TruckSim to establish a multi-degree-of-freedom non-linear simulation model of a centre-axle trailer combination and builds a braking performance test system for centre-axle trailer combination. The TruckSim simulation model and actual vehicle test are used in linear braking. A comparative verification was carried out to ensure the validity of the simulation model. Then, the braking in a turn of the train was simulated and analyzed. The analysis found that the train is the most dangerous moment in the early stage of braking in a turn, and the towing truck is more prone to instability during braking in a turn than the centre-axle trailer. In order to improve the braking performance of the train, the structural parameters of the train are used as optimization variables to establish a comprehensive evaluation index score. The uniform test method is used to optimize the design of the variables, and the braking in a turn simulation and analysis are carried out on the high adhesion road. The probability of braking jackknifing has improved braking stability.

References
[1] GB 1589-2016. Limits of dimensions, axle load and masses for road vehicles, trailers and combination vehicles[S], Beijing: China Standard Press, 2016.
[2] Another Song XN, Su J, Wang DJ, Liu HF, Liang JC, Li SW. Braking Stability of Tractor-semitrailer Running on Curved Road[J]. Journal of Traffic and Transportation Engineering, 2010, 10(01): 50-55.
[3] Wang GL, Wei CY, Lu YH, Zhou KK, Zhang H. Establishment and Test of Tractor-semitrailer Model[J]. Journal of Agricultural Machinery, 2005(11): 23-26+43.
[4] Yang SD, Zhou SP. Research on the status of traffic accidents Based on SPSS Statistical Analysis[J]. Modern trade industry, 2019, 40(13): 122-123.
[5] Zhang JM, Ren ZK, Zhang H, Zhang HW. Handling Stability and Parameter Optimization of Centre-axle Trailer Combination[J]. Journal of Traffic and Transportation Engineering, 2018, 18(02): 72-81.