FSEC Racing Car Handling Stability Analysis and Optimization

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Abstract. In this paper, the whole vehicle virtual prototype of the E22 pure electric formula racing car of Wuhan University of Technology for the 2020 season is built with the help of vehicle dynamics simulation software VI-CarRealTime tool, using multi-body dynamics as the theoretical basis. The suspension system of the vehicle is optimized. The steady-state steering characteristics of the car were analyzed through the simulation results of the virtual working conditions, and the four-wheel positioning parameters were optimized and matched to the specific working conditions. The optimized and matched car makes the steering characteristics of the car more consistent with the handling habits of the team's drivers, improves the handling stability of the car, saves the optimization cycle for the whole car design process of the university's formula car, and provides a reference for the design and optimization of the FSEC car.

1. Introduction
Formula Student Electric China (FSEC) is an automotive design and manufacturing competition for teams of students from automotive engineering-related disciplines. The dynamic events of the FSEC are divided into straight line acceleration test, figure-of-eight loop test, high-speed obstacle avoidance test, efficiency test and endurance test. According to the different score settings of each race condition, the weight distribution of car performance should also change with the score percentage in the process of car optimization and tuning. And the rules of Formula Student China allow the use of specific performance tuning parameters in different race conditions. In order to shorten the car performance optimization cycle, design specific tuning for the corresponding race conditions, and optimize the matching degree between each subsystem of the car, so as to maximize the integration of the vehicle's overall performance and bring out the best performance of each subsystem.

2. FSEC Racing Virtual Prototype Build

2.1. Body subsystem establishment
According to the main parameters of E22 racing car body of Wuhan University of Technology, as shown in Table 1. By making corresponding modifications to the body template parameters in VI-CarRealTime software, the body model of Wuhan University of Technology E22 racing car is completed.
Table 1  Basic vehicle parameters

| Variable Name                  | Variable Value | Units |
|-------------------------------|----------------|-------|
| Full load mass m              | 304            | kg    |
| Gravitational acceleration g  | 9.81           | m/s²  |
| gravitational force G         | 2979.2         | N     |
| Distance from the front axis to the center of mass a | 0.8353         | m     |
| Distance from rear axis to center of mass b  | 0.7416         | m     |
| Axis distance L               | 1.578          | m     |
| height of center of mass h    | 0.27           | m     |

2.2.  Brake Subsystem Establishment

When the vehicle is driving on a horizontal road, the forces are as shown in Figure 1.

![Figure 1 Vehicle braking force analysis diagram](image)

The rolling resistance dipole moment of the car, the air resistance and the inertia dipole moment generated when the rotating mass is decelerated are neglected in the figure. Balancing the equations for the contact point moments between the front and rear wheels and the ground, respectively, we get:

\[ F_{Z1}L = Gb + m \frac{du}{dt} \]  \hspace{1cm} (1)

\[ F_{Z2}L = Ga - m \frac{du}{dt} h_g \]  \hspace{1cm} (2)

In the formula: \( F_{Z1} \) — Normal reaction force of the ground on the front wheel; \( F_{Z2} \) — Normal reaction force of the ground on the rear wheel; \( G \) — Vehicle Gravity; \( L \) — Vehicle Wheelbase; \( a \) — Distance from the centerline of the front axle of the vehicle to the center of mass; \( b \) — Distance from the centerline of the rear axle of the vehicle to the center of mass; \( m \) — Vehicle full load mass; \( h_g \) — Vehicle center of mass height; \( \frac{du}{dt} \) — Vehicle deceleration.

Since the dynamic test track is a concrete road and the braking test is an asphalt road, the adhesion coefficient of the road is 0.75, taking into account the amplification factor 2 introduced by the hot-melt tires, the adhesion coefficient is 1.5 and the maximum deceleration is 1.5 g. The braking force distribution coefficient is 0.6924 by analyzing the braking force distribution curves of the front and rear brakes, so the braking force distribution coefficient is 0.7. The braking subsystem was created by modifying the relevant parameters in the VI-CarRealTime template, and the braking subsystem dynamics parameters are shown in Table 2.
Table 2  Brake subsystem parameter table

| Variable Name                               | Variable Value | Units |
|---------------------------------------------|----------------|-------|
| Braking force distribution factor           | 0.7            |       |
| Caliper single chamber bore                 | 1.25           | in    |
| Number of pistons                          | 2              |       |
| Total wheel cylinder cross-sectional area   | 1587.1         | mm²   |
| Total friction area                         | 1.83           | in²   |

2.3. Suspension subsystem establishment
Wuhan University of Technology E22 racing car front suspension arrangement in the form of convergent unequal-length double wishbone, longitudinal coil spring independent suspension. The rear suspension arrangement is in the form of convergent unequal-length double wishbone, transverse coil spring independent suspension. This type of suspension can produce larger camber compensation as well as effectively reduce the range of motion of the center of the suspension sway. The main components are springs, shock absorbers, rocker arms, push and pull rods and upper and lower swing arms. One side of the push and pull rod is connected to the outer hard point of the upper swing arm, and the other side is connected to the rocker arm, which together form the guiding mechanism of the suspension.

2.4. Steering subsystem template creation
The steering mechanism used in the FSEC race car of Wuhan University of Technology is a rack and pinion steering machine. According to the actual situation of the track and the possible understeering phenomenon, the minimum turning radius is designed to be 3.8 m, and the maximum outside tire turning angle is 27°; in order to meet the space and fast steering requirements, the steering wheel turning angle range ±135° is determined, the steering system angle transmission ratio is 5:1, and the control steering wheel hand force is ≤78 N. By modifying the parameters in the steering subsystem template, the E11 racing car steering subsystem is obtained Model.

3. Simulation and optimization of four-wheel alignment parameters
The suspension system has a large proportion of influence on the handling stability of the whole vehicle, so it is necessary to simulate and debug the motion characteristics of the suspension before the dynamics simulation of the whole vehicle. The four wheel alignment parameters are caster angle, kingpin inclination, camber angle and toe angle. These four values determine the spatial position of the kingpin, including the kingpin camber angle and the kingpin drag distance, the kingpin camber angle and the wear radius. The front wheel camber and front wheel beam values determine the position of the tire. The front wheel camber and front beam angle of a race car are both negative, i.e., "camber front". The reason for setting the camber angle to a negative value is to make the outer front wheel, which bears most of the vertical load, as perpendicular to the ground as possible during cornering, and the factors affecting camber are mainly suspension geometry, main pin rear camber and main pin camber.

Referring to the rules of Formula Student China, the tire jump travel is at least 50 mm when the car is riding with a driver, so a parallel wheel jump simulation condition of 30 mm is set in VI-SuspensionGen module, and the change curves of two sets of suspension hard point parameters before and after optimization are recorded, and the wheel jump simulation results are shown in Fig. 2-Fig. 5. The change range of wheel front beam angle is optimized from -0.15°~0.55° to -0.08°~0.56 degrees during the whole tire hopping process; the change range of wheel camber angle is optimized from 1.38°~1.62° to 0.31°~0.41°. The variation range of the rear camber of the main pin is optimized from 2.4°~4.14° to 2.68°~3.56°; the variation range of the inside camber of the main pin is optimized from 5.36°~8.36° to 3.88°~4.58°. The optimized wheel hop analysis shows that the variation range of the four wheel alignment parameters is significantly reduced, which improves the stability of the suspension and allows the simulation analysis of the whole vehicle dynamics.
Figure 2 Variation curve of front suspension front beam angle with wheel hop

Figure 3 Variation curve of front overhang camber with wheel hop
4. Simulation analysis and optimization of steady-state steering characteristics

In order to verify the steady-state steering characteristics of the E22 race car, a simulation condition with a constant turning radius is established, and the vehicle is allowed to accelerate to a specified value at a certain initial speed within a constant radius track, so as to evaluate the steady-state steering characteristics of the vehicle.

4.1. Simulation condition establishment

The setup conditions for this simulation condition are shown in Table 3.
Table 3  Fixed turning radius simulation parameters setting

| Parameter                  | Setting          |
|----------------------------|------------------|
| Vehicle initial speed (mm/s) | 5000             |
| Duration (s)                | 30               |
| Steering radius (mm)        | 20000            |
| Vehicle end speed (mm/s)    | 30000            |

4.2. Analysis of simulation results
The understeering-degree-time image obtained by the post-processing function of VI-CarRealTime software is shown in Figure 6.

![Figure 6 Time-insufficient steering degree image](image)

Analysis of the data in the figure shows that the understeer is always greater than 0 under steady-state driving conditions, and the expression for the understeer gradient (K) is

\[
K = \frac{d\delta}{da_y} \bigg|_{a_y=0} - \frac{L}{V^2}
\]

\[
\delta = \frac{L}{R} + Ka_y
\]

where \( \delta \) is the steering angle (rad), L is the wheelbase of the vehicle (m), R is the steering radius (m), \( a_y \) is the lateral acceleration, K is the understeer (rad/m/s²), and V is the travel speed of the vehicle.

This shows that the steering characteristic of the vehicle in steady state is understeer. This steering characteristic can let the college student driver get familiar with the vehicle faster, while ensuring driving safety to a certain extent, and is conducive to later tuning, which is in line with the design expectation.

5. Simulation of figure-of-eight winding test
The purpose of the figure-of-eight loop test is to measure the steering ability of the car when making a fixed-radius turn on flat ground.
5.1. Course layout
The two concentric circles are arranged in a figure of eight. The distance between the two centers is 18.25 m. The diameter of the inner circle is 15.25 m and the diameter of the outer circle is 21.25 m. Between the inner and outer circles of the track is a 3-meter track. The cars enter and exit on a 3.0m wide track tangent to the two circles.
The line between the centers of the two circles is defined as the start-finish line. A lap from the start-finish line around one of the circles and back to the start-finish line is defined as one lap.

5.2. Simulation condition establishment
The simulation condition uses the above-mentioned model of Wuhan University of Technology E22 electric formula vehicle, and sets five different sets of wheel positioning parameters, defines the initial speed of the vehicle into the track as 10m/s, and carries out the simulation [5]. According to the simulation lap time, the vehicle handling stability performance is evaluated, and the scoring expression is

\[
\text{grades} = 47.5 \times \left( \frac{T_y}{T_{max}/T_{min}} \right)^2 - 1 + 2.5
\]

Where, \(T_y\) is the simulation result lap speed (s), \(T_{max}\) is the fastest lap speed (s) among all simulation results, \(T_{min}\) is the fastest lap speed (s) among all simulation results, \(T_{max}\) is the fastest lap speed (s) among all simulation results, 11.1375\(T_{max}=1.25\times T_{min}\).
The simulation results are shown in Table 4:

| Serial number | Camber (°) | Front beam angle (°) | Lap time (s) | grades |
|---------------|-----------|----------------------|--------------|--------|
| 1             | -2/-0.5   |                      | 8.91         | 50     |
| 2             | -4/-0.5   |                      | 8.92         | 49.7   |
| 3             | -2/-2.5   |                      | 8.94         | 49.1   |
| 4             | -4/-2.5   |                      | 8.97         | 48.2   |

According to the simulation results, the optimized suspension model with -2/0.5 positioning parameters has the fastest lap time around the ring of eight, which is 0.17 seconds faster than the model without optimized suspension parameters.

6. Conclusion
This paper introduces the simulation and optimization process of the whole car dynamics of the university electric formula car, establishes the model of Wuhan University of Technology E22 type racing car, and analyzes the main parameters of the suspension in VI-CarRealTime software, and gets a set of suspensions that meet the design requirements, which can effectively control the front beam angle, wheel camber, main pin internal camber, main pin rear camber of the racing car with the wheel hopping. The amount of variation with wheel runout. The simulation of steady-state steering characteristics verifies the understeering characteristics of the car and provides a reference for the later tuning of the car. The four-wheel alignment parameters of the car were optimized to obtain the best combination of wheel camber and front beam angle in the eight-round simulation condition.

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