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Design of Variable Steering Ratio for Steer-by-Wire System Based on Driver's Steering Characteristics

Kun Yang, Haobin Jiang *, Long Chen, Yixiao Chen and Bin Tang

Automotive Engineering Research Institute, Jiangsu University, Zhenjiang 212013, China; yc8325@163.com (K.Y.); chenlong@ujs.edu.cn (L.C.); cyx2502@163.com (Y.C.); tangbin@ujs.edu.cn (B.T.)
* Correspondence: jianghb@ujs.edu.cn

Abstract: Aiming at the characteristic of a variable and optimized steering ratio of the Steer-by-Wire System (SBW), this paper studies the design method of the steering ratio starting from the influence of the steering ratio on the vehicle steering maneuverability and the driver's steering burden. Through the analysis of the influencing factors of the steering ratio and the analysis of the driver's steering characteristics, a yaw rate gain control model is established. Combined with the evaluation index of handling stability, the yaw rate gain is optimized, and the optimal yaw rate gain corresponding to different scenarios and different drivers' steering characteristics is determined, so as to design the characteristics of the variable steering ratio that meet the preferences of different drivers. In order to verify the control effect of the variable gain steering ratio, a comprehensive feedback control strategy for the front wheel angle is established, and vehicles with a fixed steering ratio and a constant gain steering ratio are selected as references. Comparative tests under typical working conditions are carried out in the "driver-vehicle-road" closed-loop simulation system. The results show that the variable gain steering ratio considering the driver's steering characteristics can not only improve the handling stability of the vehicle at medium and high speeds, but also enhance the driver's steering comfort, enabling the SBW to achieve the goal of "the vehicle adapting to the person".

Keywords: Steer-by-Wire System; variable steering ratio; driver's steering characteristics; closed-loop simulation test

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1. Introduction

Due to the constraints of its own mechanical connection, the traditional mechanical steering system cannot change its steering ratio reasonably according to the driving conditions [1]. This leads to the fact that the steering sensitivity of the vehicle is always changing, and it is difficult for the driver to control the response state of the vehicle [2]. The SBW controls the vehicle's steering by using electrical signals and a motor-driven steering system. This physical decoupling transmission characteristic enables it to design a reasonable variable steering ratio strategy to meet the driver's requirements for the vehicle's steering characteristics under different working conditions, which helps to improve the stability and comfort of the vehicle's steering [3–5].

At present, there are mainly two control strategies for attaining the variable steering ratio of the SBW. The first is to design an ideal steering ratio based on the vehicle's yaw rate gain [6,7] and lateral acceleration gain [8,9]. Reference [10] takes into account the influence of the tire's nonlinear characteristics on the vehicle's stability. By establishing a nonlinear two-degrees-of-freedom vehicle model and designing the steering ratio based on

the invariance of the steering gain, this method effectively improves the driving stability of the vehicle on the road with a low traction coefficient. In order to improve the steering characteristics of the vehicle, the paper [11] analyzes the influence of the vehicle speed and the steering wheel angle on the vehicle's yaw rate, and designs a variable steering ratio considering the change in the vehicle speed and a variable steering ratio considering the changes in both the vehicle speed and the steering wheel angle, respectively. The simulation and real vehicle test results show that the design scheme of the variable steering ratio considering the changes in the vehicle speed and the steering wheel angle has excellent performance. The paper [12] proposes an ideal lateral acceleration gain value that changes with the vehicle speed, improves the vehicle's handling performance at different vehicle speeds, and reduces the driver's steering burden by designing a variable steering ratio. In order to study the design method of the variable steering ratio of the SBW based on the joystick, the paper [13] proposes different variable steering ratio design schemes based on the vehicle speed, the steering wheel angle and the yaw rate gain and arranges eight drivers to conduct a simulated driving test. The test results show that the drivers have a high evaluation of the variable steering ratio designed based on the variable yaw rate gain.

The other is to design the variable steering ratio by using intelligent control methods such as fuzzy control [14,15], expert system [16] and neural network [17,18] in view of the complexity and nonlinear characteristics of the SBW. The paper [19] uses a hierarchical multi-level fuzzy control algorithm to design a variable steering ratio to improve the vehicle's steering stability and driving comfort. The paper [20] uses a fuzzy neural network to design the change in the variable steering ratio of the forklift's SBW with the vehicle speed. The test shows that the designed variable steering ratio can make the forklift have better steering characteristics. The paper [21] proposes an adaptive learning algorithm for the variable steering ratio to ensure that it can still provide a consistent driving feel and ensure driving stability in unstable situations such as fluctuations in vehicle parameters. The paper [22] combines the fuzzy variable steering ratio and the linear quadratic regulator optimal control to achieve the ideal steering characteristics of the four-wheel steering vehicle with sensitive steering at low speeds and stable steering at high speeds.

Although these methods can achieve the control of the vehicle's steering stability, due to the differences in the driver's operating habits, the required steering characteristics of different drivers are different. The SBW should be adjusted to the ideal state of steering characteristics according to the driver's personal habits and steering intentions. Therefore, this paper takes the driver's ideal vehicle steering characteristics into account in the design of the variable steering ratio, establishes a vehicle dynamics model including the SBW, and designs the characteristics of the variable steering ratio that meet the needs of different drivers in combination with the driver's preferences, road parameters and the vehicle's motion state. Taking the objective evaluation index of the vehicle's handling stability as the optimization objective function, the steering gains of different drivers are optimized. Finally, a comprehensive feedback control strategy for the front wheel angle is established, and combined with the test of the "driver-vehicle-road" closed-loop system, the effectiveness of the proposed control strategy is verified [23–25].

The contributions of this paper are as follows:

1. This paper classifies drivers' steering behavior characteristics through data clustering and identification models and integrates them into the variable steering ratio design of the SBW, achieving personalized steering characteristic matching of "the vehicle adapting to the person", which significantly improves drivers' steering comfort and the person–vehicle collaboration performance of vehicles.
2. A yaw rate gain optimization framework based on multi-objective evaluation indicators is proposed. Combined with genetic algorithms, dynamic adjustment of

yaw rate gains for different drivers is carried out, which not only ensures vehicle handling stability but also effectively reduces drivers' steering operation intensity and safety risks.

3. By constructing a "driver-vehicle-road" closed-loop simulation system, the superiority of the variable gain steering ratio strategy is verified under multiple working conditions. Tests show that this strategy can simultaneously reduce drivers' operational risks and burdens, enhance vehicle dynamic stability, and provide theoretical and experimental support for the practical application of SBW.

The rest of this paper is organised as follows: Section 2 introduces the analysis of influencing factors of the steering ratio, Section 3 introduces the design method of the variable gain steering ratio considering driver characteristics, Section 4 introduces the tests, and Section 5 summarizes the paper and future prospects.

2. Analysis of Factors Affecting Steering Ratio Characteristics

The steering ratio ensures the coupling of the positional relationship between the steering wheel of the SBW and the front steering wheels, and mainly affects the steering response characteristics of the vehicle. The steering characteristics of an automobile are divided into steady-state steering characteristics, transient steering characteristics (including time domain and frequency domain), and central area steering characteristics. Among them, the steady-state steering characteristics are mainly related to the vehicle's structural parameters and have nothing to do with the steering ratio of the steering system; the transient steering characteristics mainly reflect the change in the vehicle's driving trajectory and the transition process to the steady state, which are related to the steering ratio of the steering system; the central area steering characteristics are mainly related to the force transmission ratio. Therefore, starting from the evaluation index of the transient steering characteristics, the steady-state yaw rate gain, the influences of the vehicle speed, the front wheel angle, and the road traction coefficient on the characteristics of the steering ratio are analyzed.

In order to study the design of the variable steering ratio of the SBW, it is first necessary to establish a vehicle dynamics model of the SBW. The two-degrees-of-freedom vehicle dynamics model can describe the vehicle's motion state when the tires are operating in the linear region. Therefore, this model is commonly used as a reference model for the whole vehicle. According to the differential equations of the two-degree-of-freedom vehicle dynamics, the expressions of the front wheel angle and the yaw rate response can be obtained, as shown in Equation (1). It characterizes the response of the yaw rate to the front wheel angle input under different driving conditions. Taking the Buick GL8 as an example, some parameters of the vehicle are shown in Table 1. Based on the vehicle body coordinate system, the origin is defined as the vehicle's center of mass, with the vehicle's forward direction as the positive x-axis, the horizontal left direction as the positive y-axis, and the direction perpendicular to the vehicle's floor upward as the positive z-axis (following the right-hand rule).

$$\begin{aligned} \frac{\omega_r}{\delta_f} &= \frac{u/(a+b)}{1+\frac{m}{(a+b)^2}\left(\frac{a}{k_2}-\frac{b}{k_1}\right)u^2} = \frac{u/(a+b)}{1+Ku^2}, \\ K &= \frac{m}{(a+b)^2}\left(\frac{a}{k_2}-\frac{b}{k_1}\right), \end{aligned} \tag{1}$$

where ω_r is the yaw rate; δ_f is the front wheel angle; u is the component of the centroid velocity on the ox-axis of the vehicle coordinate system; a is the distance from the center of mass to the front axle; b is the distance from the center of mass to the rear axle; k_1 is the front wheel lateral deflection stiffness; k_2 is the rear wheel lateral deflection stiffness; K is the stability coefficient.

Table 1. Vehicle section parameters.

Parameter	Notation	Unit	Value
Vehicle mass	m	kg	2372
Distance from the centre of mass to the front axle	a	m	1.46369
Distance from the centre of mass to the rear axle	b	m	1.50131
Front wheel lateral deflection stiffness	k_1	N/rad	−92,600
Rear wheel lateral deflection stiffness	k_2	N/rad	−110,100
Moment of inertia about z-axis	I_z	kg·m^2	5337

Since the steering wheel angle is the direct input value for the driver to control the steering motion of the automobile, the expression of the variable steering ratio under the input of the steering wheel angle is derived from Equation (1) as follows:

$$i = \frac{\delta_{sw}}{\delta_f} = \frac{1}{G_r} \cdot \frac{u/(a+b)}{1+Ku^2}, \tag{2}$$

where i is the variable steering ratio; δ_{sw} is the steering wheel angle; G_r is the steady-state yaw rate gain.

$$G_r = \frac{\omega_r}{\delta_{sw}}. \tag{3}$$

2.1. Influence of Vehicle Speed on the Characteristics of the Steering Ratio

When the vehicle is steering at a low speed, the system is required to have a relatively small steering ratio to meet the requirement of steering sensitivity [26]. However, if the steering ratio is set too small, it is likely that the wheels will reach the extreme position and lock up with a small steering angle, which will impose an additional load on the steering execution motor and affect the performance and service life of the motor. When the vehicle is driving at a high speed, the system is required to have a relatively large steering ratio to improve the steering stability of the vehicle at high speeds [27]. Similarly, an excessively large steering ratio will make the system response too sluggish and reduce the steering safety.

Based on this principle, the speed-varying characteristics of the designed steering ratio are required to satisfy the following relationship:

$$i = \begin{cases} i_{\min} & u < u_0, \\ f(u) & u_0 \le u \le u_1, \\ i_{\max} & u > u_1, \end{cases} \tag{4}$$

where $i_{\min}$ is the lower limit value of the steering ratio; $i_{\max}$ is the upper limit value of the steering ratio; u_0 is the vehicle speed corresponding to the lower limit value of the steering ratio; u_1 is the vehicle speed corresponding to the upper limit value of the steering ratio; $f(u)$ is a nonlinear function of the steering ratio changing with the vehicle speed.

According to the two-degrees-of-freedom vehicle dynamics model, the changing characteristics under different vehicle speeds (20 km/h, 40 km/h, 60 km/h, 80 km/h, 100 km/h, 120 km/h) are determined, and the curve of the changing characteristics of the steering ratio with the vehicle speed is obtained, as shown in Figure 1. It can be found from Figure 1 that the steering ratio increases as the vehicle speed increases.

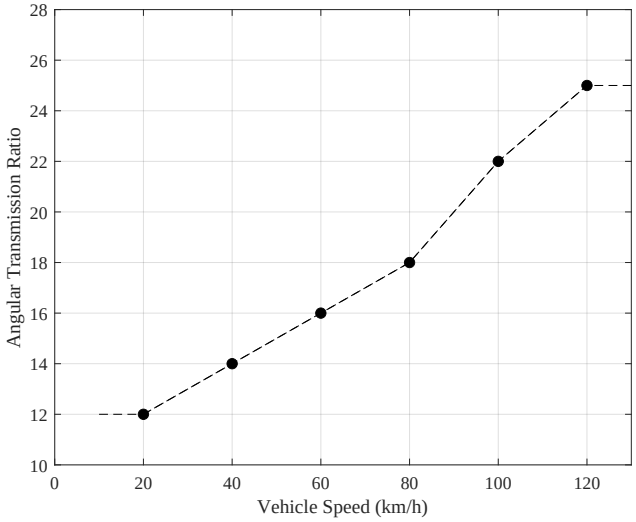
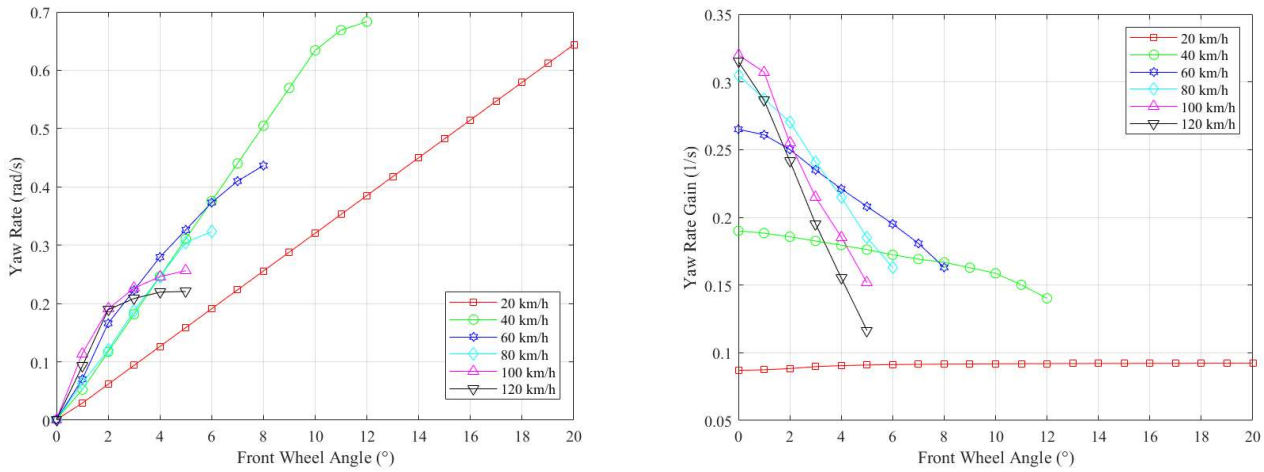


Figure 1. Characteristics diagram of the steering ratio changing with the vehicle speed.

2.2. Influence of the Front Wheel Angle on the Characteristics of the Steering Ratio

It can be seen from Equations (2) and (3) that there is a direct relation between the steering ratio and the yaw rate gain. The yaw rate gain is not only affected by the vehicle speed but also closely related to the front wheel angle. During the vehicle's driving process, the change in the front wheel angle will cause the change in the force state of the tires, which in turn leads to a specific change trend of the yaw rate gain. And this change characteristic of the yaw rate gain has a direct impact on the response of the steering ratio.

Incorporate the characteristic of the steering ratio changing with the vehicle speed into the two-degrees-of-freedom vehicle dynamics model. With the help of the angle step input test carried out for the vehicle's transient steering characteristics, obtain the response characteristic diagram of the steady-state yaw rate changing with the front wheel angle under different vehicle speed conditions, and calculate the steady-state yaw rate gain according to the steady-state yaw rate. The specific results are shown in Figure 2.



（a） （b）

Figure 2. The steady-state response characteristic diagram of the front wheel angle: (**a**) the response characteristic diagram of the yaw rate to the front wheel angle under different vehicle speeds; (**b**) the response characteristic diagram of the yaw rate gain to the front wheel angle under different vehicle speeds.

As can be seen from Figure 2, when the vehicle is performing a steering operation at a constant vehicle speed, the tires are in the linear working area when the front wheel angle is small. At this time, the response of the yaw rate to the front wheel angle shows an almost linear characteristic (Figure 2a), and the yaw rate gain also basically remains at a fixed value (Figure 2b). However, as the front wheel angle gradually increases, the vehicle's driving state changes. Nonlinear factors such as tire saturation, load transfer, and coupled dynamics cause the yaw rate and yaw rate gain to no longer exhibit a linear relationship [27]. In this situation, even a small change in the front wheel angle can lead to a significant deviation in the vehicle's trajectory, exposing the vehicle to a high risk of instability. This nonlinear response characteristic requires the driver to continuously adjust the yaw rate gain when performing large-angle steering operations, which undoubtedly increases the driver's workload and driving difficulty.

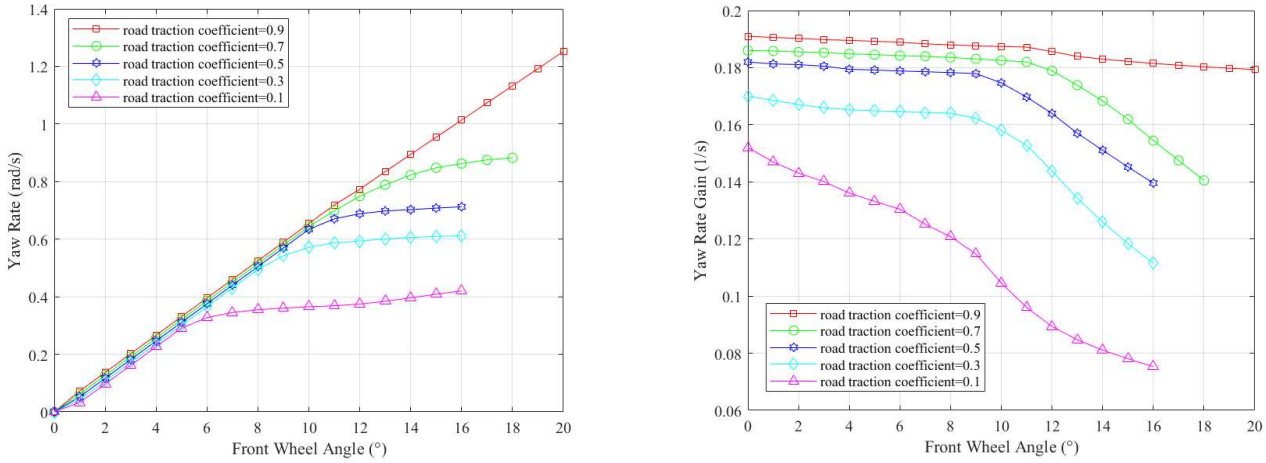
In addition, when the vehicle is performing steering operations at different vehicle speeds, when the vehicle speed is low, the front wheel angle and the yaw rate change linearly. At the same time, the effect of the front wheel angle on the yaw rate gain is weak, that is, the variable steering ratio is not significantly affected by the front wheel angle under this working condition. Therefore, when the vehicle speed is lower than 20 km/h, the variable steering ratio can be approximately regarded as a constant value, without considering the influence of the front wheel angle on it. However, when the vehicle speed is higher than 100 km/h, the dynamic characteristics of the vehicle change significantly, and there is a purely nonlinear change relationship between the front wheel angle and the yaw rate. During this process, the yaw rate gain drops sharply as the front wheel angle increases, which in turn causes the variable steering ratio to change violently. This drastic change seriously threatens the vehicle's handling stability and increases the safety risk during the vehicle's driving process. In view of this, when the vehicle speed is higher than 100 km/h, it is necessary to reasonably set the change amplitude of the variable steering ratio in the design and control strategy formulation of the vehicle steering system to ensure the safety and stability of the vehicle during driving.

2.3. Influence of Road Traction Coefficients on the Characteristics of the Variable Steering Ratio

When the vehicle has a steady-state response, there is a linear relationship between the lateral forces and the sideslip angles of the front and rear wheels of the vehicle. However, during the actual driving process of the vehicle, the tires are very likely to enter the nonlinear region. Especially on the road surface with a low traction coefficient, the lateral force exerted by the ground on the tires often tends to be saturated, and the vehicle is at risk of skidding.

In order to analyze the influence of the road traction coefficient on the steering characteristics, Figure 3 shows the curves of the yaw rate and the yaw rate gain changing with the front wheel angle when the vehicle speed is 40 km/h and the vehicle is on roads with different traction coefficients.

As can be seen from Figure 3, when the front wheel angle is small, the change in the road traction coefficient has little effect on the yaw rate, and the yaw rate gain remains basically unchanged. This indicates that at this time, the ground can provide sufficient lateral force to make the vehicle generate a sufficient yaw angle, enabling the vehicle to track the target path. As the front wheel angle increases, the yaw rate no longer changes linearly with the front wheel angle, and the yaw rate gain also drops sharply. At this moment, the lateral force exerted by the ground on the tires gradually reaches saturation. Therefore, when driving on a road surface with a low traction coefficient, it is necessary to reduce the front wheel angle while reducing the vehicle speed to prevent the risk of skidding.



（a） （b）

Figure 3. The steady-state response characteristic diagram of the road traction coefficient: (**a**) the response characteristic diagram of the yaw rate to the front wheel angle under different road traction coefficients; (**b**) the response characteristic diagram of the yaw rate gain to the front wheel angle under different road traction coefficients.

3. Design of Variable Gain Steering Ratio

As can be known from the analysis in the previous section, the vehicle speed, the front wheel angle, and the road traction coefficient have a significant impact on the response characteristics of the variable steering ratio. During the actual driving process of the vehicle, the dynamic combined changes in the vehicle speed, the front wheel angle, and the road traction coefficient will all trigger complex responses of the variable steering ratio.

Therefore, in order to reduce the driver's driving burden under dynamic and complex working conditions, this paper comprehensively considers the steering behavior characteristics of different drivers. The driver's steering behavior characteristics are combined with the vehicle dynamics model to realize the design of the variable gain steering ratio.

3.1. Yaw Rate Gain Based on Steering Characteristics

First, a double lane change condition in accordance with GB/T 40521 [28] is set, and the steering behavior parameters such as the vehicle speed, the front wheel angle, and the yaw rate of the driver under different road traction coefficients are accurately and continuously collected. The differences in the road traction coefficients cover a variety of typical situations ranging from dry and good road surfaces to wet, slippery, icy and other adverse road surfaces, so as to ensure that the collected data can reflect the steering behavior of drivers under different road conditions [29].

In this paper, 20 drivers were selected for data collection, including drivers of different genders, different driving years, and different ages. The specific distribution is shown in Table 2.

Table 2. Sample structure of test drivers.

Gender	18–25 Years Old		26–35 Years Old		Over 36 Years Old	
	Num. of People	Avg. Drv. Age (Year)	Num. of People	Avg. Drv. Age (Year)	Num. of People	Avg. Drv. Age (Year)
Male	4	2	4	4	3	8
Female	3	1	4	2	2	5

Figure 4 shows the data collection platform established in this paper based on Prescan 8.4 and Simulink 2022a. First, a double lane change test condition and a Buick GL8 vehicle model are built in Prescan. Second, the Prescan model is imported into Simulink to output vehicle driving data, such as vehicle speed, front wheel angle, yaw rate, etc. Then, the driver simulates driving operations by controlling the Logitech G29 driving simulator, and transmits the operation signals to the Simulink vehicle model. Finally, the operation results are fed back to the Prescan driving scenario, presenting the corresponding vehicle driving states, such as position, speed, and attitude on the road, realizing the interactive cycle between the driver and the virtual driving scenario.

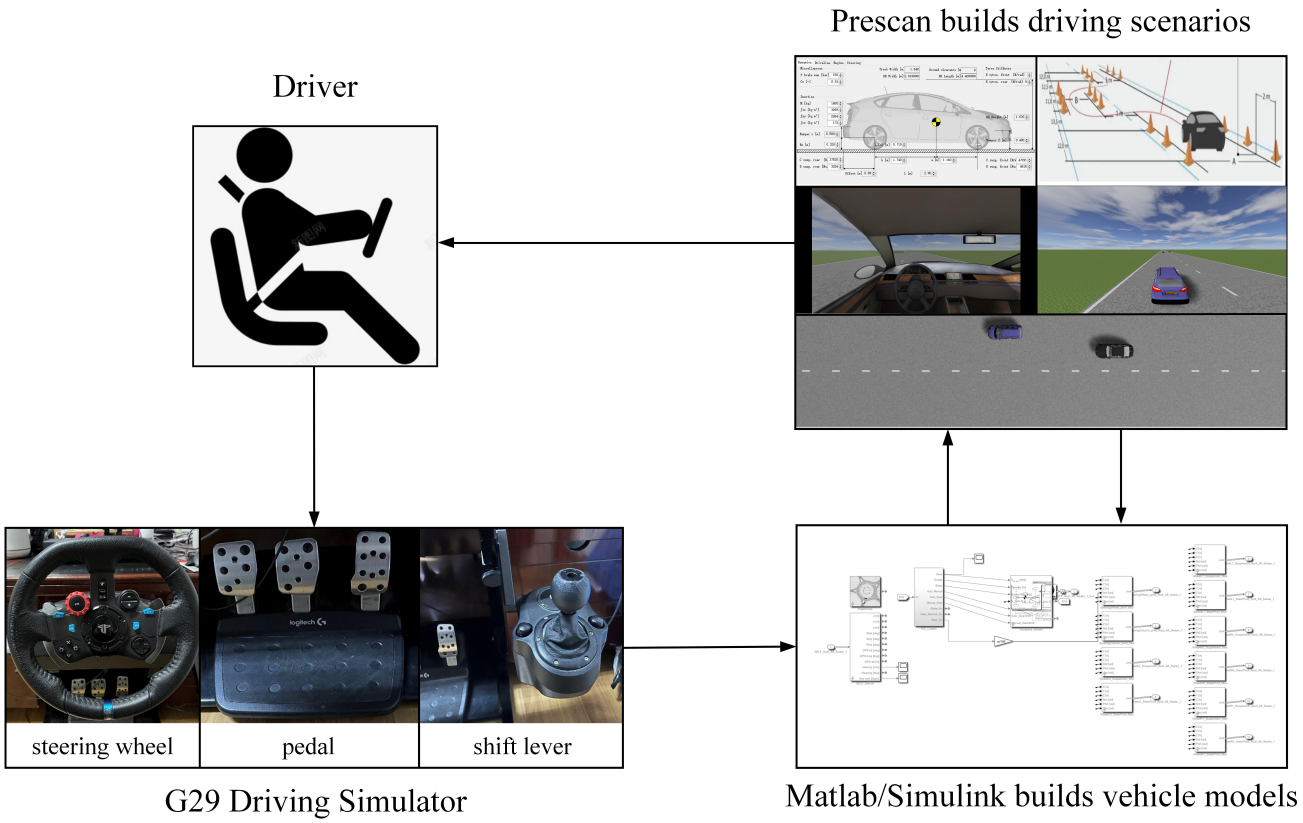
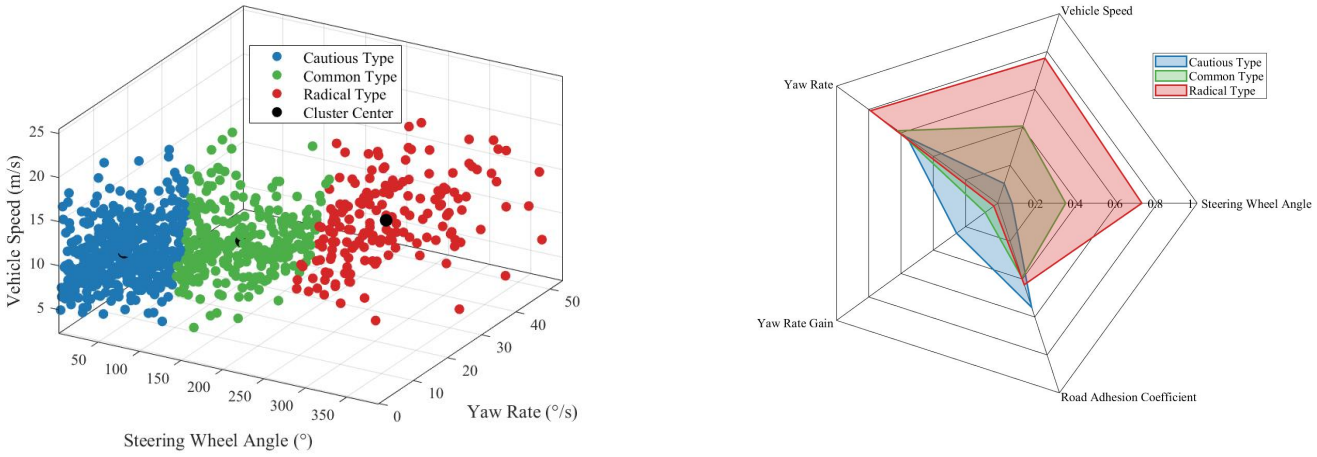


Figure 4. Driving data collection platform.

In order to comprehensively reflect the mapping relationship between the driver's steering characteristics and the yaw rate gain, each driver was familiar with the test scenarios in advance and conducted multiple tests. The steering wheel angle, longitudinal vehicle speed, yaw rate and road traction coefficient of each group of steering data were extracted, and the yaw rate gain of each group was calculated according to Equation (3). A total of 1000 groups of driving data were obtained, representing the steering behavior characteristics of the drivers. Through the K-means algorithm [30], clustering calculations were carried out on the average values of each group of characteristic indicators. The steering behavior characteristics of the drivers were classified into three types: cautious type, common type and radical type, and the yaw rate gains corresponding to the steering characteristics of the three types of drivers were obtained. Figure 5 shows the clustering results of multiple groups of tests and the variation rules of the steering behavior characteristics of different drivers.



（a） （b）

Figure 5. Clustering results of the driver's steering characteristics: (**a**) taking the three dimensions of the steering wheel angle, the longitudinal vehicle speed and the yaw rate as examples, the clustering results of the steering characteristics of different drivers; (**b**) a diagram showing the differences in each dimension of the steering characteristics of the three types of drivers.

As can be seen from Figure 5a, drivers with different steering characteristics show obvious distribution differences in these three dimensions. The data points of cautious drivers mainly concentrate in the area where the steering wheel angle and the yaw rate are relatively low and the vehicle speed is moderate, indicating that the steering characteristics of this type of driver are relatively conservative and the operation is relatively stable. The data points of common drivers are distributed in the middle area, showing that their driving behavior is in a relatively moderate state. The data points of radical drivers are distributed in the area where the steering wheel angle and the yaw rate are relatively high and the vehicle speed also changes greatly, indicating that this type of driver has a larger range of driving operations and more radical steering characteristics. Since the five characteristic indicators cannot be directly reflected in the clustering diagram, the yaw rate gains corresponding to the three steering characteristics are obtained through Table 3. Figure 5b intuitively shows the values of each dimension after normalization, clearly presenting the characteristic differences of drivers with different steering characteristics in multiple indicators.

Table 3. The distribution of the clustering centers of the three types of steering characteristics.

Steering Characteristics	Steering Wheel Angle (°)	Vehicle Speed (m/s)	Yaw Rate (°/s)	Road Traction Coefficient	Yaw Rate Gain (1/s)
Cautious Type	51.47	6.85	9.71	0.61	0.42
Common Type	144.36	13.73	10.84	0.48	0.29
Radical Type	257.68	33.59	11.68	0.52	0.21

According to the distribution relationship of the three steering behavior characteristics, a driver steering behavior identification model can be established to classify the driver's characteristics. For two groups of data with close steering characteristics, the category of the clustering points is determined by the mutual relationship between the variables, realizing the organic unity of the data information and the variable information. The characteristic type of the driver is judged by the maximum probability method, that is, the number of occurrences within a certain period of time is set, and according to the proportion limit of each characteristic type (such as 80%, the specific limit is calibrated according to the identification accuracy rate), the characteristic category to which the driver belongs is

judged. Finally, new drivers who have not participated in any previous tests and typical working conditions are selected for testing and eigenvalue recording. Their steering data are input into the driver steering behavior model to obtain the identification results of the steering characteristic types of these drivers.

3.2. Optimize the Yaw Rate Gain

Although the yaw rate gain obtained from clustering can achieve the preliminary classification of the driver's steering characteristics, due to the randomness and robustness limitations of clustering, the obtained clustering results may not necessarily meet the requirements of vehicle handling stability. Therefore, this paper adopts an objective multi-objective evaluation index function [31,32] for vehicle handling stability and constructs an optimization model from the dimensions such as the driver's operation burden level, rollover risk, and skidding risk. The clustering results are adjusted through a multi-objective collaborative optimization algorithm to achieve the optimal matching between the yaw rate gain and the evaluation indexes of vehicle handling stability. Reference [32] experimentally verified the effectiveness of the handling stability evaluation indices. Considering that the vehicle type and working conditions selected in this paper highly match those in [32], the equations and parameter values of the handling stability evaluation indices in [32] are referred to in this paper to optimize the yaw rate gain:

$$\begin{aligned} J_b &= \int_0^t \left[\frac{\dot{\delta}_{sw}}{\hat{\dot{\delta}}_{sw}}\right]^2 dt, \\ J_r &= \int_0^t \left[\frac{a_y(t)}{\hat{a}_y}\right]^2 dt, \\ J_e &= \int_0^t \left[\frac{u\dot{\beta}(t)}{\hat{\beta}}\right]^2 dt, \\ J_s &= \int_0^t \left[\frac{F_{yi}(t)/F_{zi}(t)}{\hat{\mu}}\right]^2 dt (i = 1, 2), \end{aligned} \tag{5}$$

where t is the test time; J_b is an evaluation indicator that takes into account the driver's manoeuvre burden; $\dot{\delta}_{sw}$ is the angular speed of steering wheel rotation; $\hat{\dot{\delta}}_{sw}$ is the standard threshold value of steering wheel rotation speed, taken as 1.0 rad/s; J_r is the evaluation index considering the rollover hazard; $a_y(t)$ is the lateral acceleration; $\hat{a}_y$ is the standard threshold value of lateral acceleration, taken as 0.3 g; J_e is the evaluation index considering the directional error; u is the longitudinal speed; $\dot{\beta}(t)$ is the angular velocity of the centre-of-mass side deviation; $\hat{\beta}$ is the standard threshold value of centre-of-mass side deviation angular velocity, taken as 0.08 g; J_s is the evaluation index considering the sideslip hazard; F_{y1} and F_{y2} are the lateral force of the front and rear wheels, respectively; F_{z1} and F_{z2} are the vertical load of the front and rear wheels, respectively; and $\hat{\mu}$ is the standard threshold value of the lateral traction coefficient, which is taken as 0.3.

The above four indicators are weighted and combined, and their average value is the comprehensive evaluation index of vehicle handling stability.

$$J_{TE} = \sqrt{\frac{\varepsilon_1 J_b^2 + \varepsilon_2 J_r^2 + \varepsilon_3 J_e^2 + \varepsilon_4 J_s^2}{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4}}, \tag{6}$$

where $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = 0.25$.

Taking the comprehensive evaluation index of handling stability as the objective function, the genetic algorithm is adopted to optimize the yaw rate gain values under the steering characteristics of different drivers, and the optimization results shown in Table 4 are obtained.

Table 4. Optimization results of yaw rate gain under different driver's steering characteristics.

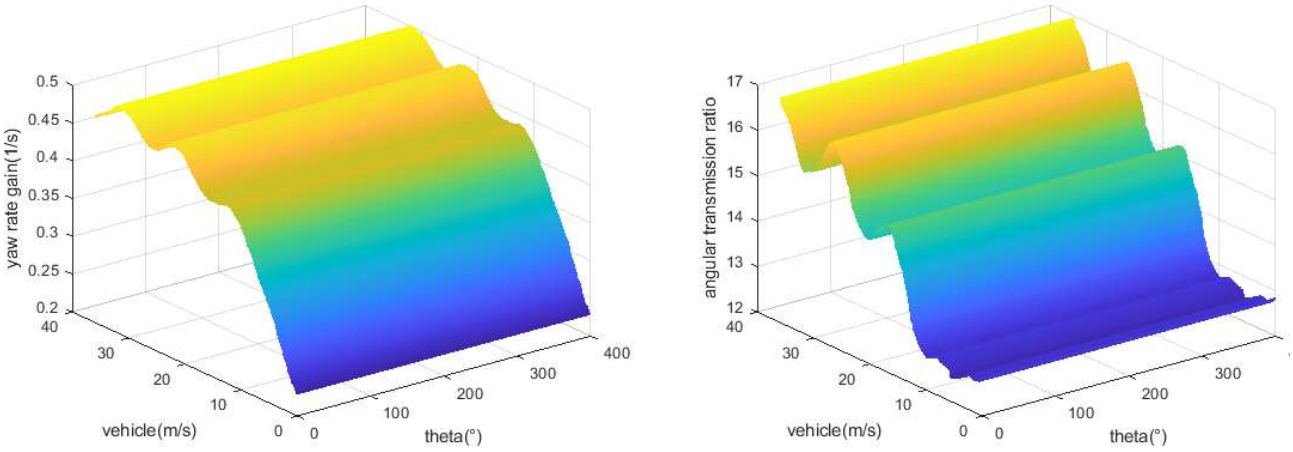
Driver's Steering Characteristics	Cautious	Common	Radical
Initial yaw rate gain	0.48	0.29	0.21
Initial evaluation value	1.79	3.16	5.07
Optimized yaw rate gain	0.46	0.26	0.16
Optimized evaluation value	1.54	2.08	2.54
Adjustment ratio	4.17%	10.34%	23.81%

It can be seen from the optimization results in Table 4 that the optimized yaw rate gains are all smaller than the initial yaw rate gains, and the evaluation values are also smaller than the initial evaluation values, indicating that the optimized handling stability is stronger. The yaw rate gains of the optimized cautious-type, common-type, and radical-type drivers are 0.46, 0.26, and 0.28, respectively, which are adjusted by 4.17%, 10.34%, and 23.81% compared with the clustering results. This shows that radical-type drivers are more likely to be at risk of rollover and sideslip during driving. In order to ensure the vehicle's handling stability, the adjustment amount of their yaw rate gain is the largest.

Figure 6a shows the curve of the optimized yaw rate gain changing with the driver's steering characteristics. The corresponding expression of the variable steering ratio is:

$$i = \begin{cases} \frac{1}{G_r} \cdot \frac{u_0/(a+b)}{1+Ku^2} & u < u_0, \\ \frac{1}{G_r} \cdot \frac{u/(a+b)}{1+Ku^2} & u_0 \le u \le u_1, \\ \frac{1}{G_r} \cdot \frac{u_1/(a+b)}{1+Ku^2} & u > u_1, \end{cases} \tag{7}$$

where i is the variable steering ratio; u_0 is the vehicle speed corresponding to the lower limit value of the steering ratio; u_1 is the vehicle speed corresponding to the upper limit value of the steering ratio.



（a） （b）

Figure 6. Curves of yaw rate gain changes based on steering characteristics: (**a**) the curve of the optimized yaw rate gain changing with the driver's steering characteristics; (**b**) the curve of the variable steering ratio changing with the driver's steering characteristics.

Figure 6b shows the curve of the variable steering ratio changing with the driver's steering characteristics.

4. Experimental Verification

To validate the effectiveness of the designed SBW variable steering ratio characteristics in improving vehicle steering performance and reducing driver workload, this paper employs a multi-platform collaborative modeling approach to deeply integrate these characteristics into the vehicle dynamics model system. Specifically, the PreScan simulation platform was used to construct test scenarios, a high-precision vehicle active steering control model was built in Simulink, and real-time interaction between the driver and the vehicle active steering system was achieved using a G29 driving simulator. Traditional fixed steering ratio vehicles and constant-gain variable steering ratio vehicles were selected as control benchmarks. Based on a closed-loop "driver-vehicle-road" simulation system, systematic comparative tests were conducted under various typical driving conditions. The aim was to comprehensively evaluate the practical application value of the SBW variable steering ratio characteristics by quantitatively analyzing vehicle dynamic responses and driver operation behavior characteristics under different conditions.

This paper carries out three types of experiments. The first is a trajectory tracking test. Under steering conditions with different curvatures and adhesions, three steering ratio strategies are compared to verify the differences in the steering angles and steering frequencies required for the vehicle to follow the ideal trajectory at low speeds, so as to evaluate the steering lightness of the strategy. The second is a handling stability test, which verifies the improvement of the steering ratio strategy on high-speed steering stability through the steering wheel angle input condition. The third is a driver steering characteristics test, which selects drivers with different driving styles to test under complex working conditions covering various curvatures, and verifies the adaptability of the steering ratio strategy to different drivers. Through the comparison of multiple working conditions, these tests comprehensively evaluate the application value of the variable steering ratio design from the dimensions of steering flexibility, vehicle dynamic stability, and driver adaptability.

4.1. Trajectory Tracking Test

First, trajectory tracking tests were performed under steering conditions with different curvatures. This test mainly examines the driver's steering workload during low-speed vehicle operation. The test condition was a steady-state turning scenario with a vehicle speed of 15 m/s, a road traction coefficient of 0.8, a fixed steering ratio of 20, and a constant yaw rate gain of 0.3. The test results are shown in Figure 7.

As can be seen from Figure 7, compared with the traditional fixed steering ratio and fixed-gain steering ratio control strategies, the vehicle with variable-gain steering ratio control only needs to turn the steering wheel at a relatively small angle (Figure 7a) during the steering process to achieve the same steering effect as the large-angle steering in the traditional structure (Figure 7b–d). This greatly reduces the driver's operation burden and fatigue during the steering process.

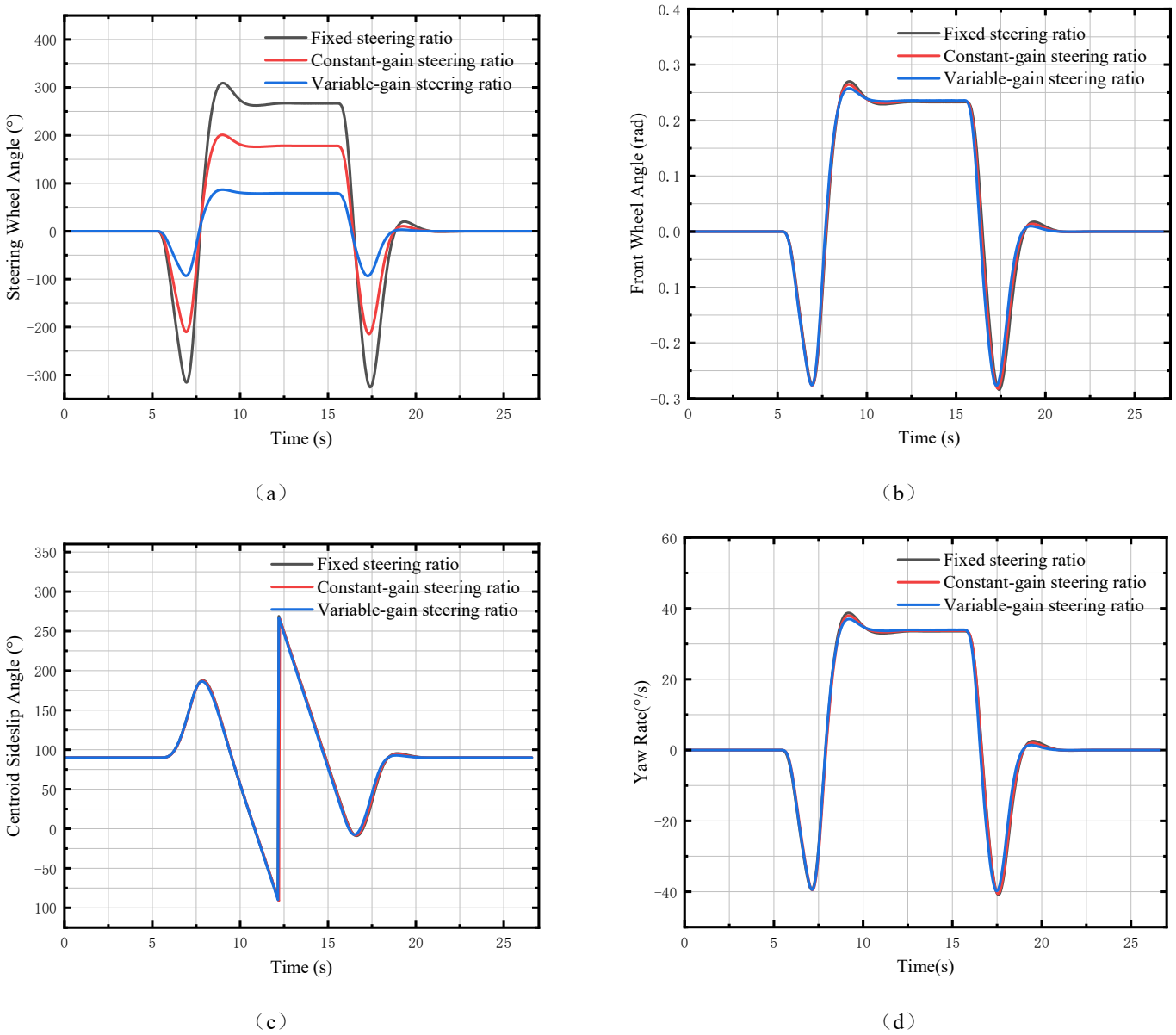


Figure 7. Response characteristics of each control strategy under the steady-state turning condition: (**a**) curve of the steering wheel angle changing with time; (**b**) curve of the front wheel angle changing with time; (**c**) curve of the sideslip angle of the center of mass changing with time; (**d**) curve of the sideslip angle of the center of mass changing with time.

The test condition is the double lane change condition, with a vehicle speed of 15 m/s, a road traction coefficient of 0.6, a fixed steering ratio of 20, and a fixed yaw rate gain of 0.3. The test results are shown in Figure 8. It can be seen from Figure 8 that under different test conditions, when driving a vehicle with a variable-gain steering ratio, the steering wheel angle is more concentrated in the range of medium and small angle values, and the situation of frequent large-angle steering is less (Figure 8a). The control difficulty is lower, and it can achieve the same control effect as other types of vehicles (Figure 8b–d). This is consistent with the conclusion under the steady-state turning condition.

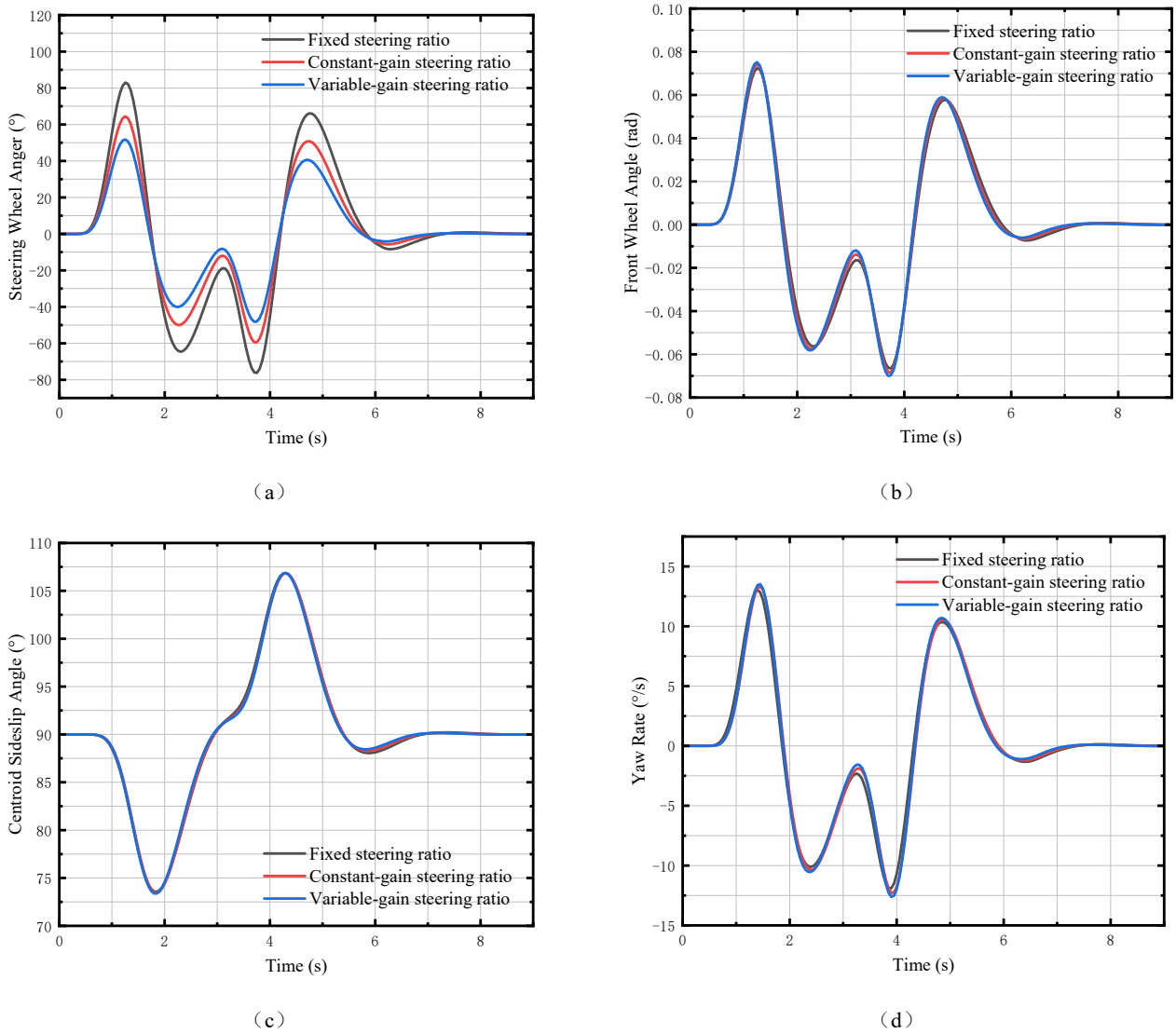


Figure 8. Response characteristics of each control strategy under the double lane change condition: (**a**) curve of the steering wheel angle changing with time; (**b**) curve of the front wheel angle changing with time; (**c**) curve of the front wheel angle changing with time; (**d**) curve of the yaw rate changing with time.

4.2. Handling Stability Test

Secondly, to verify the impact of the designed ideal variable steering ratio on vehicle handling stability, this paper selects the steering wheel sine condition and the steering wheel angle step condition for verification. According to the national test standard GB/T 6323-2014 [33], the vehicle speed is set to 25 m/s and the road traction coefficient is 0.85. Three vehicles equipped with different steering ratio control strategies are given the same steering wheel angle input, and the test results are shown in Figure 9.

It can be seen from Figure 9 that under the high-speed and high-angle steering wheel input (Figure 9a), the sideslip angle of the center of mass (Figure 9b) and the yaw rate (Figure 9c) of the variable-gain vehicle are both smaller than those of the fixed steering ratio vehicle and the fixed-gain vehicle. This indicates that the steering system with the variable-gain steering ratio design can ensure the safety of sudden steering, effectively reduce the probability of dangerous events under high-speed and high-angle conditions, and improve the handling stability of the vehicle.

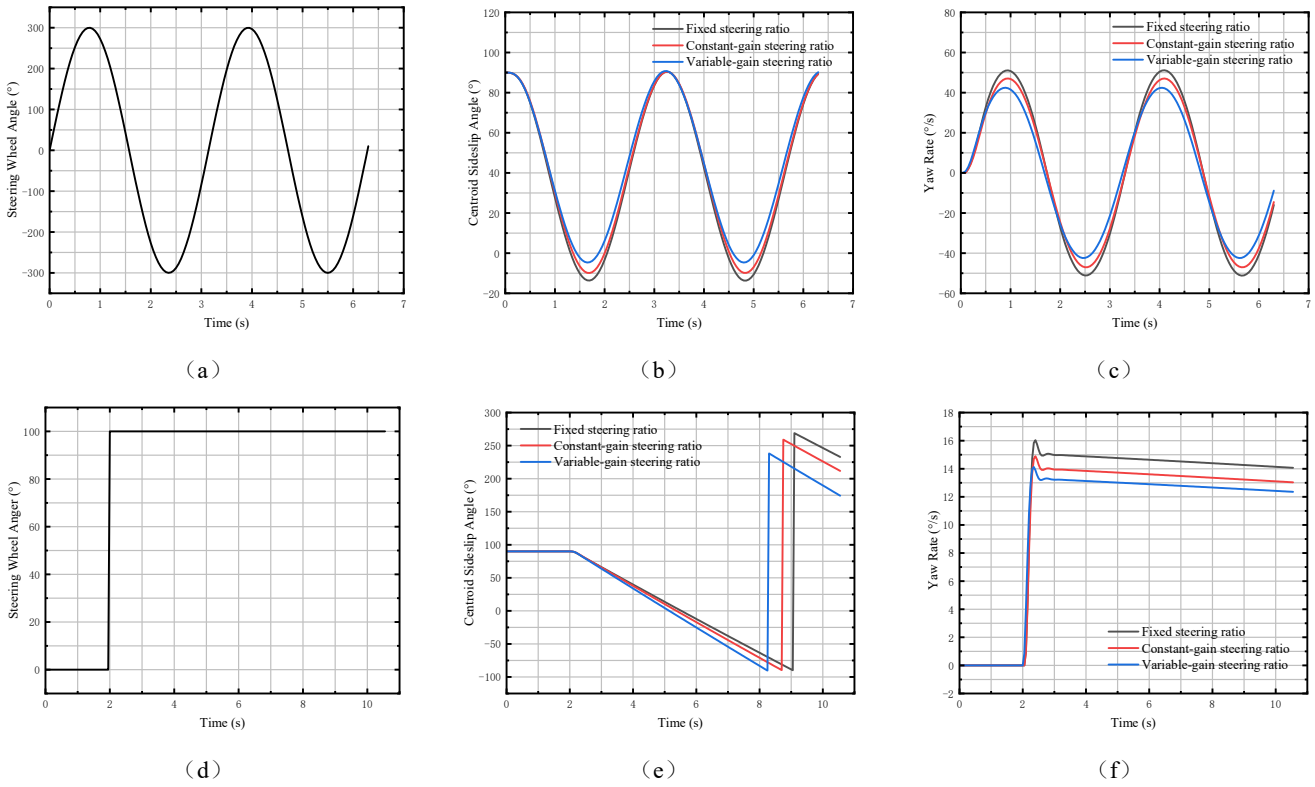


Figure 9. Response characteristics of the same steering wheel angle input: (**a**) angular sine input; (**b**) curve of the sideslip angle of the center of mass changing with time under the sine condition; (**c**) curve of the yaw rate changing with time under the sine condition; (**d**) angular step input; (**e**) curve of the sideslip angle of the center of mass changing with time under the step condition; (**f**) curve of the yaw rate changing with time under the step condition.

4.3. Test of Driver's Steering Characteristics

In addition, in order to verify the adaptability of different drivers to the variable gain steering ratio control strategy, this paper selects drivers with different steering characteristics as the test subjects. These drivers have differences in aspects such as steering operation habits, reaction speed, and control preferences for the vehicle steering system. Drivers were familiar with the test vehicles and test scenarios in advance. Subsequently, several rounds of targeted tests are carried out under the complex working conditions shown in Figure 10. The complex working conditions cover steering conditions with various curvatures, aiming to simulate various driving situations that drivers may encounter in reality to the greatest extent. Through multiple rounds of tests, accidental factors that may interfere with the test results are minimized as much as possible to ensure the reliability and accuracy of the data. After the tests are completed, a large amount of data is carefully sorted out and deeply analyzed. Finally, the test results of drivers with three kinds of steering characteristics are intuitively presented in the form of Figure 11.

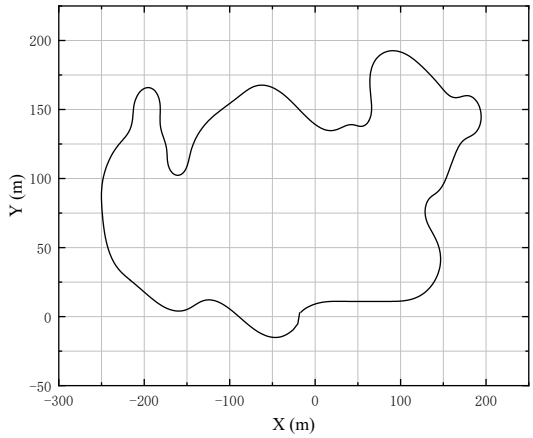


Figure 10. Test conditions for driver characteristics.

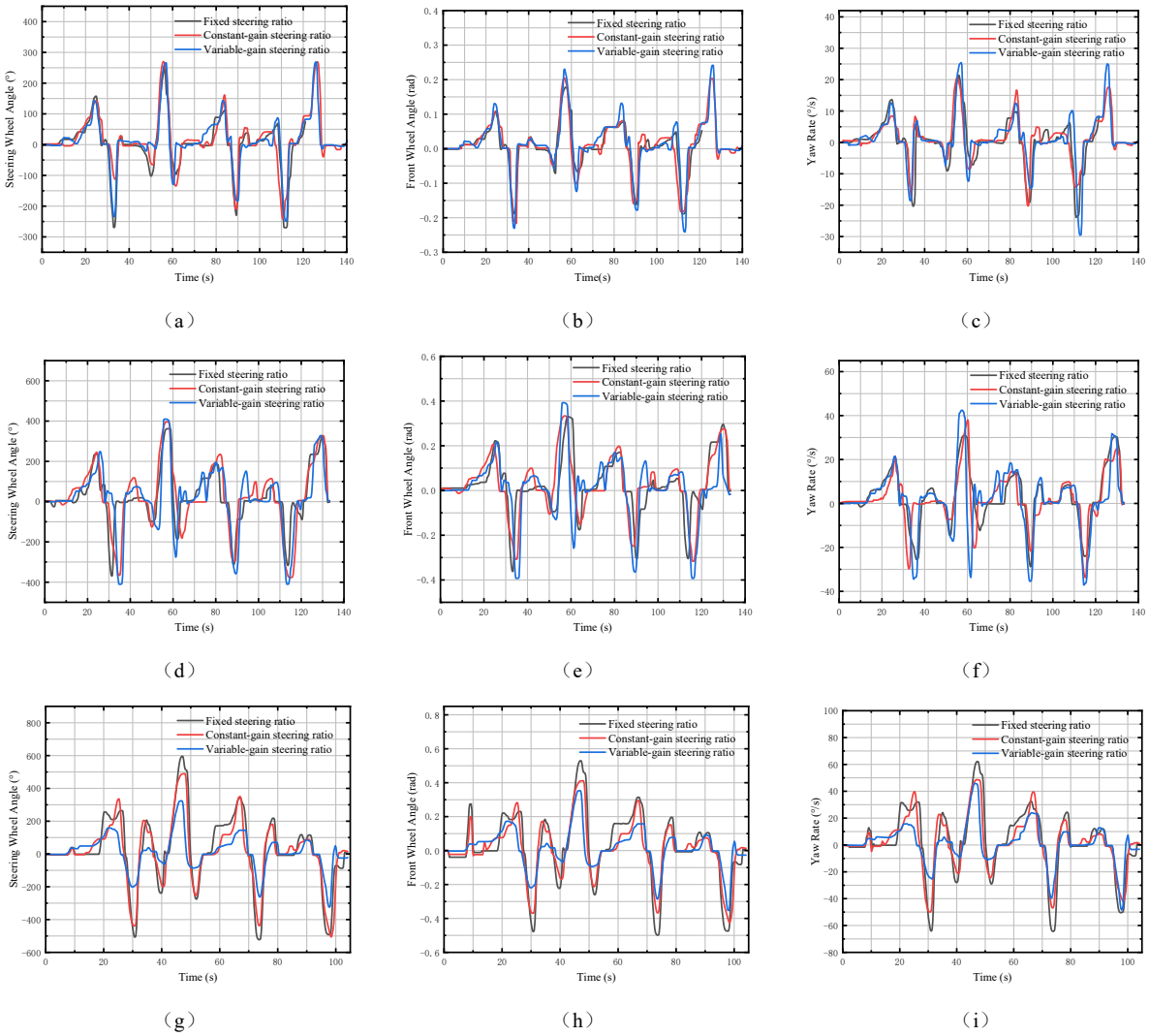


Figure 11. Response characteristics of drivers with three types of steering characteristics: (**a**) curve of the steering wheel angle of cautious type drivers changing with time; (**b**) curve of the front wheel angle of cautious type drivers changing with time; (**c**) curve of the yaw rate of cautious type drivers changing with time; (**d**) curve of the steering wheel angle of common type drivers changing with time; (**e**) curve of the front wheel angle of common type drivers changing with time; (**f**) curve of the yaw rate of common type drivers changing with time; (**g**) curve of the steering wheel angle of radical type drivers changing with time; (**h**) curve of the front wheel angle of radical type drivers changing with time; (**i**) curve of the yaw rate of radical type drivers changing with time.

As can be seen from Figure 11, under the variable-gain steering ratio control strategy that takes into account different driver characteristics, the operation behaviors of the three types of driver steering characteristics tend to be consistent. For cautious drivers (Figure 11a–c) and common drivers (Figure 11d–f), their steering operations are bolder to some extent. After using the variable-gain steering ratio control strategy, the angular velocity of the steering wheel of cautious and common drivers during the steering process increases to a certain extent, and at the same time, the adjustment range of the steering wheel angle increases slightly. This indicates that the variable-gain steering ratio control strategy has better operability and steering flexibility, and drivers can more easily operate the vehicles equipped with this strategy, resulting in a more comfortable driving experience. For radical drivers (Figure 11g–i), after using the variable-gain steering ratio design, their steering behavior becomes smoother. During the steering process, the angular velocity of the steering wheel decreases, and the standard deviation of the steering wheel angle also decreases, indicating that they reduce the adjustment range of the steering wheel angle during the steering process.

5. Conclusions

This paper focuses on the design of variable steering ratios for SBW systems based on drivers' steering characteristics. By analyzing the influencing factors of steering ratio, a yaw rate gain control model is established, and the gain is optimized in combination with handling stability indexes to design variable steering ratio characteristics suitable for different drivers' preferences. The study selects 20 drivers with different characteristics for data collection, uses the K-means algorithm to classify steering behaviors into cautious type, common type and radical type, optimizes the yaw rate gain through a genetic algorithm, and finally verifies the effectiveness of the strategy in the "driver-vehicle-road" closed-loop simulation system. Compared with the traditional fixed steering ratio and constant-gain steering ratio, this design method can not only reduce the vehicle's yaw rate and centroid sideslip angle by 20–35% under medium and high speed conditions to improve the vehicle's handling stability, but also reduce the driver's steering operation burden by about 40%, realizing the personalized matching of "the vehicle adapting to the person". Based on the current research results, in the future, from the perspective of hardware development, the application of new sensors and actuators can be studied to improve the response speed and control accuracy of the system. At the same time, the collaborative control strategy between the SBW system and other vehicle active safety systems (such as electronic stability program and anti-lock braking system) can be explored to build a more efficient integrated vehicle dynamics control system.

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