Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2024, 11(1):153-161**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Design of ideal transmission ratio for wire controlled steering system

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Abstract The design of the steering-by-wire system focuses on the design of the ideal transmission ratio, this paper introduces the advantages and disadvantages of the fixed transmission ratio and the ideal transmission ratio, after which the gain value is determined by using the method of constant transverse pendulum angular velocity gain, and the design of the transmission ratio by using the three-stage to ensure that the car meets the requirements of the ideal transmission ratio in the different speed intervals. Variable angle transmission ratio analysis is carried out to illustrate the effect of the steer-by-wire system on the handling stability of the car. From the final Simulink simulation results, it can be concluded that the car with the steer-by-wire system has better control compared to the car with the conventional steering system.

Keywords steer-by-wire, Ideal transmission ratio, Simulink

1. Introduction

Traditional vehicle steering devices are mechanical, and in order for the vehicle to complete steering, the steering wheel must be manipulated by the driver, and the steering torque is transmitted to the wheels by the steering device and the steering column and other driving devices. The steering wheel module and the steering wheel module are fixedly connected in the traditional mechanical steering system by the steering gear, steering column and other components, which results in the steering ratio generally being fixed or fluctuating within a very small range of variation in the traditional mechanical steering system. Conventional fixed-angle transmission ratios produce different response situations under different operating conditions, which can lead to low steering sensitivity at low speeds and high steering sensitivity at high speeds. The driver must always control the steering wheel when the car is steering to adjust the steering changes brought about by the nonlinear components, which increases the difficulty of driving the car.

To analyze the defects of the conventional steering system, it is first necessary to specify two types of transverse angular velocity gains. The first is the ratio of the transverse angular velocity of the car wheel (ω_r) to the turning angle of the front wheel of the car (δ_f), in steady state condition, it is $G_f = \frac{\omega_r}{\delta_f}$; the second is the ratio of the transverse angular velocity of the car wheel (ω_r) to the turning angle of the steering wheel (δ_h), in steady state condition, it is $G_h = \frac{\omega_r}{\delta_h}$.

And, the transverse angular velocity of the wheels of the car (ω_r), the front wheel turning angle of the car (δ_f) and the steering wheel turning angle (δ_h) have the following relationship:

$$i = \frac{\delta_h}{\delta_f} \quad (1)$$

In this section, the vehicle speeds are set to 30km/h, 50km/h, 70km/h, 90km/h and 110km/h, and the simulation experimental conditions are set to the steering wheel angle step conditions, to summarise the changes in steering sensitivity at different vehicle speeds. The change of steering sensitivity is shown in Fig. 1.

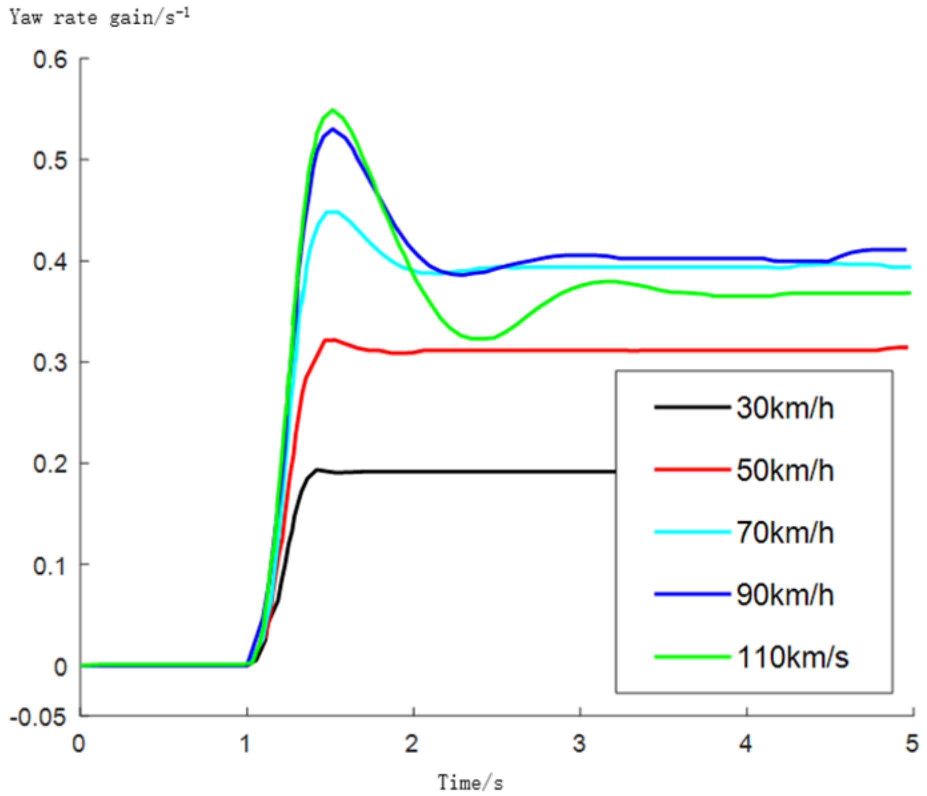

Figure 1: Steering sensitivity at different vehicle speeds

According to the data results in the above figure, it can be concluded that in the traditional steering system, the steady state value of the traverse angular velocity increases with the increase of the vehicle speed, and after reaching the maximum value, it starts to decrease. Drivers need to adjust to different response situations all the time when driving a car, which requires a high degree of concentration of the driver's attention, and over time, it is easy to cause driver fatigue, or worse, traffic accidents. The steering characteristics of the traditional steering system are mainly affected by the non-linearity of the steering system, suspension system and other components, resulting in large changes in the steering characteristics within a certain speed range, which can not ensure the stability of the car driving process.

Compared with traditional vehicles, the steering-by-wire system changes the mechanical connection between the steering wheel and the vehicle wheel into an electrical signal drive, which makes the angular transmission ratio of the SBW system vehicle can be adjusted arbitrarily. The variable angular transmission ratio of the steering-by-wire system [21] can be set arbitrarily according to the driving demand, and the angular transmission ratio of the steering can be changed cleverly according to the different working conditions of the car, which is used to increase the stability of the car driving.

The variable angle ratio of the steering-by-wire system is the ratio of the steering wheel angle (δ_{sw}) to the front wheel angle of the vehicle (δ_f) and can be expressed by the following equation:

$$i = \frac{\delta_{sw}}{\delta_f} \tag{2}$$

2. Design of Ideal Transmission Ratio

The steering sensitivity ($G_{sw} = \frac{\omega_r}{\delta_{sw}}$) under normal driving in the vehicle dynamics model can be derived as a steering sensitivity equation for the front wheel angle using the two degree of freedom vehicle model mentioned above:

$$G_f = \frac{\omega_r}{\delta_f} = \frac{u/L}{1 + \frac{m}{L^2}\left(\frac{a}{k_2} - \frac{b}{k_1}\right)u^2} \tag{3}$$

With the linear two-degree-of-freedom vehicle model, the formula for the variable angle transmission ratio can be derived from the constant angular velocity gain of the transverse pendulum as follows:

$$i = \frac{\delta_{sw}}{\delta_f} = \frac{G_f}{G_{sw}} = \frac{u/L}{\left[1 + \frac{m}{L^2}\left(\frac{a}{k_2} - \frac{b}{k_1}\right)u^2\right]G_{sw}} \tag{4}$$

In order to specifically analyse the characteristics of the angular transmission ratio based on the constant angular velocity gain of the transverse pendulum, the steering sensitivity in the above equations is set to different values and the other parameters are taken as fixed values to summarize the phenomenon of fluctuation induced by the variable angular transmission ratio of the car with the change of the vehicle speed. The relationship diagram is shown in Fig. 2.

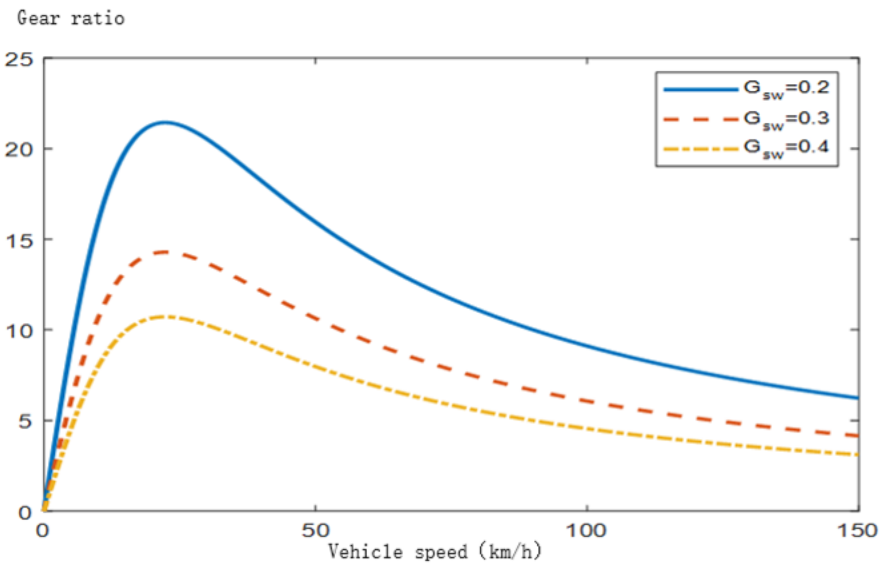

Figure. 2: Design method based on constant angular velocity of the pendulum

2.1 Design method based on constant lateral acceleration gain

In the vehicle dynamics model, the steady state lateral acceleration gain ($G_{fay} = \frac{a_y}{\delta_f}$) under normal driving, using the two-degree-of-freedom vehicle model mentioned above, a formula for the lateral acceleration gain at the steering wheel angle can be derived:

$$G_{ay} = \frac{a_y}{\delta_{sw}} \tag{5}$$

In the above equation, from the linear two-degree-of-freedom vehicle model equation : $a_y = \dot{v} + u\omega_r$, when the vehicle is in steady state, $\dot{v} = 0$, it then follows that $a_y = u\omega_r$.

With a linear two-degree-of-freedom vehicle model, the formula for the variable angle transmission ratio can be derived from the constant lateral acceleration gain as follows:

$$i = \frac{G_{fay}}{G_{ay}} = \frac{u^2 / L}{\left[1 + \frac{m}{L^2}\left(\frac{a}{k_2} - \frac{b}{k_1}\right)u^2\right] G_{ay}} \tag{6}$$

In order to specifically analyse the angular gear ratio characteristics based on the constant lateral acceleration gain, the lateral acceleration in the above equation is set to different values and the other parameters are set to fixed values to summarise the relationship between the gear ratio and steering sensitivity of the car. The relationship graph is shown in Fig. 3.

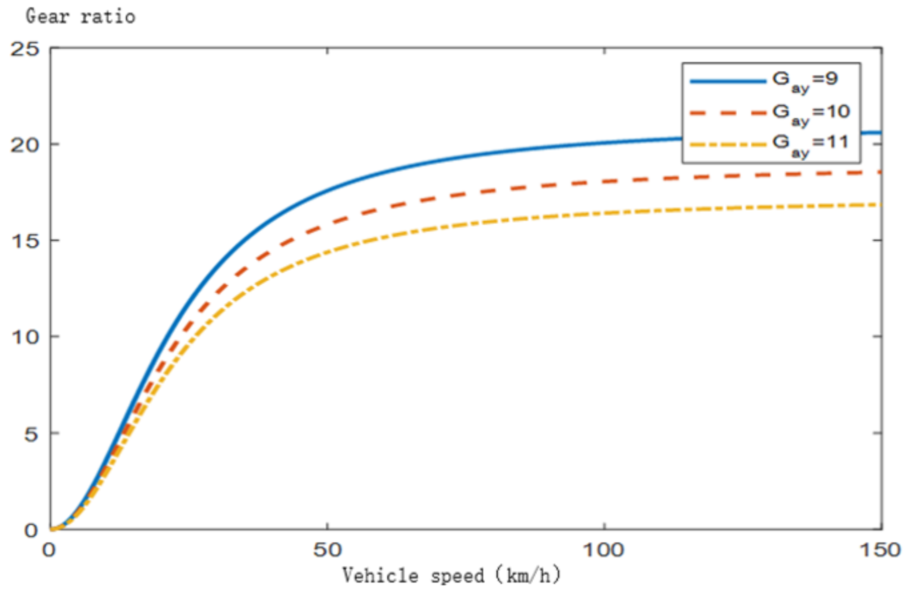

Figure 3: Design method based on constant lateral acceleration

By analyzing the change curves of the transmission ratio and vehicle speed in the design methods of the two subsections, it can be concluded that, with the increase of vehicle speed, the curve graph of the former shows a tendency of increasing and then decreasing, with the slope firstly increasing and then decreasing, while the curve graph of the latter shows an increasing tendency, with the slope firstly increasing and then decreasing. Comparing the changes of the two graphs, the ratio design method with constant steering sensitivity has a faster response to vehicle speed, so the following section will design the ratio by designing the ratio with the design method of constant steering sensitivity.

3. Calculation of the Ideal Transmission Ratio

Based on the angular transmission ratio design above, the design method of constant steering sensitivity is chosen to be used for the design of the variable angular transmission ratio. From the formula (2-2) derived above, and because the steering sensitivity is constant, so, $G_{sw} = K_s$, the ideal transmission ratio formula can be obtained:

$$i = \frac{u/L}{\left[1 + \frac{m}{L^2}\left(\frac{a}{k_2} - \frac{b}{k_1}\right)u^2\right]k_s} \tag{7}$$

When the speed of the car is 0, the transmission ratio of the car is also 0. At the same time, at very low speeds, cars with steer-by-wire systems are unable to steer themselves, which is not the case in actual car driving. Ideal transmission ratio should have a threshold, if the transmission ratio is too small, the driver driving the car at low speeds, only a small angle, the wheel angle will turn, making the steering wheel angle and the front wheel angle is too sensitive; if the transmission ratio is too large, the driver driving the car at high speeds, you need to rotate a large angle, the wheel to achieve the steering, which increases the difficulty of driving, so in the vehicle at low speeds, it is necessary to set a minimum transmission ratio of 0; at the same time, the car with wire control steering system can not steer itself at very low speeds, which does not exist in the actual car driving. Therefore, when the vehicle is travelling at low speed, it is necessary to set a minimum transmission ratio to ensure the safety of the driving process.

Through reviewing some related literature, it is found that the maximum steering wheel angle of some models shall not exceed 388°when driving at low speeds, and at the same time, the range of values of the front wheel angle of the vehicle shall be between 35°and 45°. In order to calculate the ideal transmission ratio when driving at low speeds, it is necessary to satisfy that the steering wheel angle and the front wheel angle of the vehicle are in the range of the specified values. Therefore, the minimum value of the ideal transmission ratio can be determined according to formula (1-1):

$$i_{\min} = \frac{\delta_{h\max}}{\delta_{f\max}} = \frac{388}{45} = 8.622 \tag{8}$$

The minimum transmission ratio calculated by the above formula, and then the critical vehicle speed of the ideal transmission ratio can be calculated, which is known as the transverse swing angular velocity gain, and the research shows that the steady state transverse swing angular velocity gain (steering sensitivity) of the car usually takes the value in the range of between $0.25 \sim 0.52s^{-1}$, at present, there is still no clear method used to determine the value of steering sensitivity. Through the references, the authors optimised the steering sensitivity of the car by genetic algorithm with the evaluation index of the car's handling stability and obtained $k_s = 0.32$. By substituting the optimised value of pendulum angular velocity gain into Equation (3-1), the critical vehicle speed $u_0 = 20\text{km/h}$ for the ideal gear ratio formula can be calculated.

$$i = \begin{cases} \dfrac{u/L}{k_s\left[1 + \dfrac{m}{L^2}\left(\dfrac{a}{k_2} - \dfrac{b}{k_1}\right)u^2\right]}, u > 20 \\ 8.622, u \le 20 \end{cases} \tag{9}$$

A graph of the variation of the ideal transmission ratio versus the speed at which the car is traveling can be obtained, as shown in Fig. 4 below.

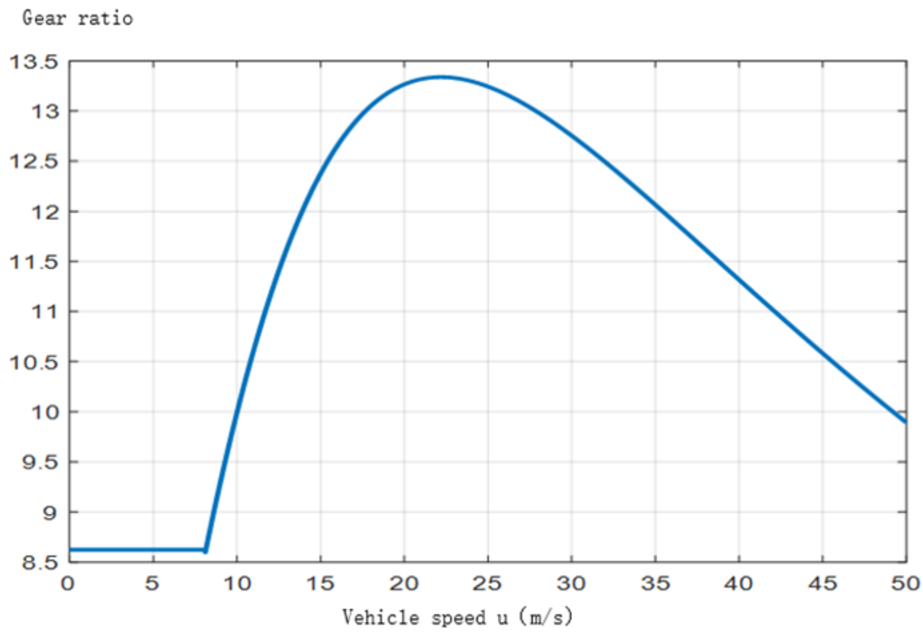

Figure 4: Graph of changes

When designing the actual ratios of the vehicle, a ratio threshold should be set at a vehicle speed of 100km/h, which is 16.5. The ideal transmission ratio formula can be obtained:

$$i = \begin{cases} 8.622, 20 \geq u \\ \dfrac{u/L}{k_s\left[1+\dfrac{m}{L^2}\left(\dfrac{a}{k_2}-\dfrac{b}{k_1}\right)u^2\right]}, 100 \geq u > 20 \\ 16.5, 100 < u \end{cases} \quad (10)$$

4. Design Simulation Verification

In order to test the ideal transmission ratio of the wire-controlled steering system designed above, the variable transmission ratio control module is added to the wire-controlled steering system built in Simulink to compare it with the traditional mechanical steering system under specific conditions and specific speeds and to analyze the steering stability of the car during driving.

The road adhesion coefficient of 0.85, steering wheel angle of 57.3°, and step time of 0.05 s are selected for this validation.This simulation is to validate the influence of variable transmission ratio on the handling stability of the car when it is moving, and the speed of the car is set to be 20 km/h, 40 km/h, 90 km/h, 110 km/h, and 110 km/h, respectively, by comparing the fixed transmission ratio of the transmission steering system with the variable transmission ratio with the steering-by-wire system, the car speeds are set to 20km/h, 40km/h, 90km/h, and 110km/h in sequence. The results of the experiment are shown in the following figure.

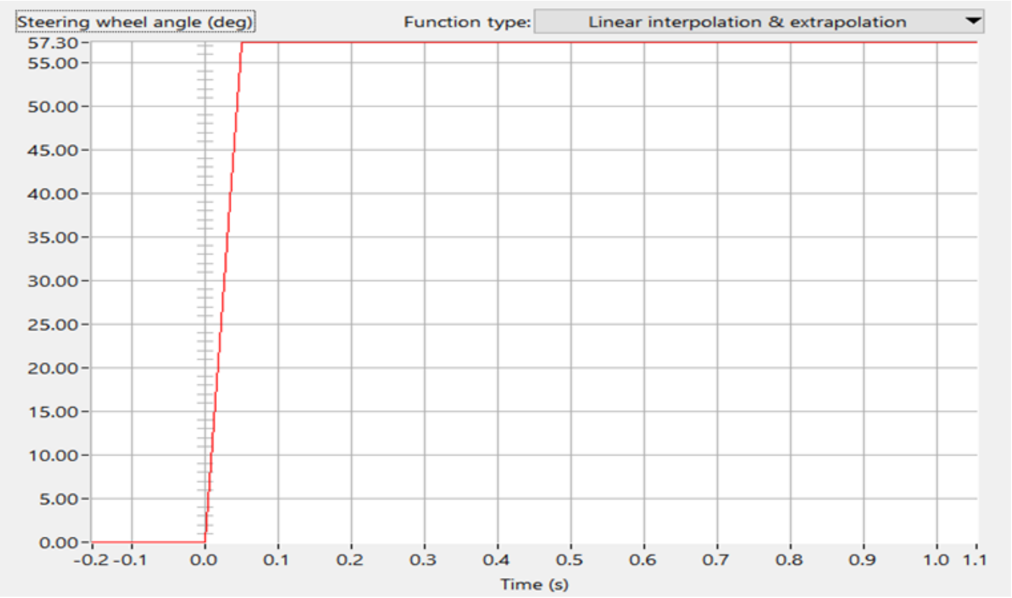

Figure 5: Steering wheel angle step condition

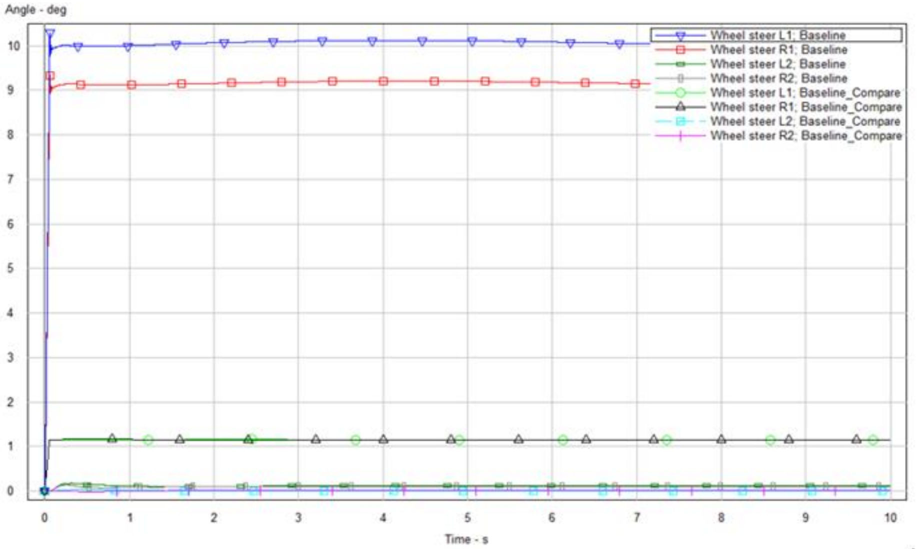

Figure 6: 20km/h Wheel Turning Angle

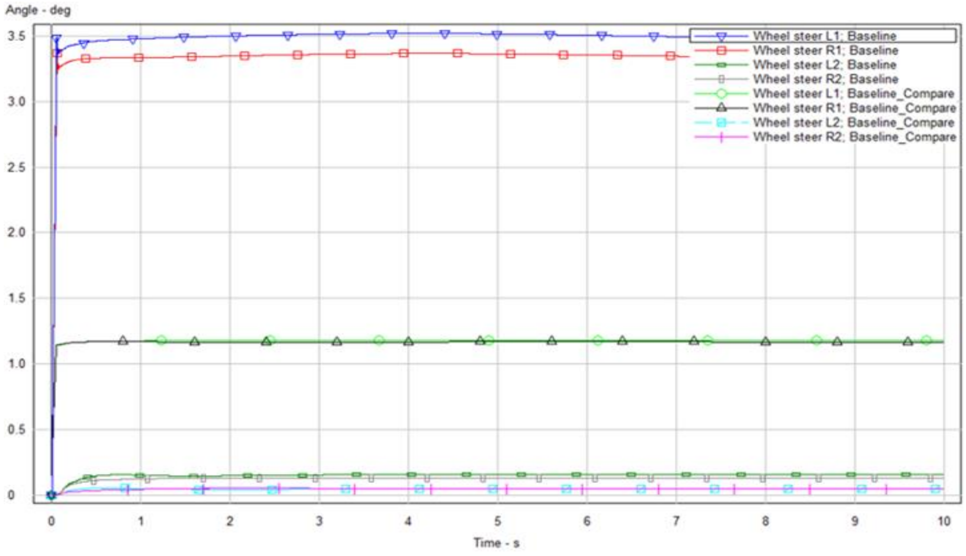

Figure. 7: 40km/h Wheel Turning Angle

Based on the curves obtained from Figure 3-8 to Figure 3-9, the following conclusions can be drawn:
When the car is driven in the low-speed zone, the car with the steer-by-wire system has a larger rotation of the wheel angle compared with the car with the conventional steering system, which meets the design requirements of the ideal transmission ratio of the car with the steer-by-wire system in the low-speed zone, and when the driver turns the steering wheel with the same angle, the car with the SBW system is able to realize a larger rotation of the wheel angle in low speed, which is in line with the requirements of the "low-speed sensitivity".

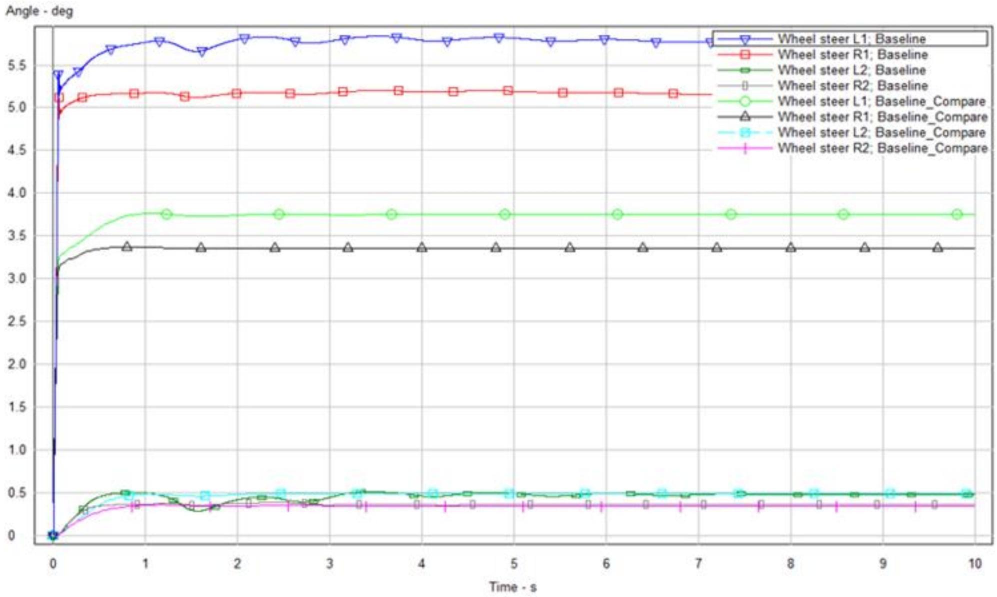

Figure 8: 90km/h Wheel Turning Angle

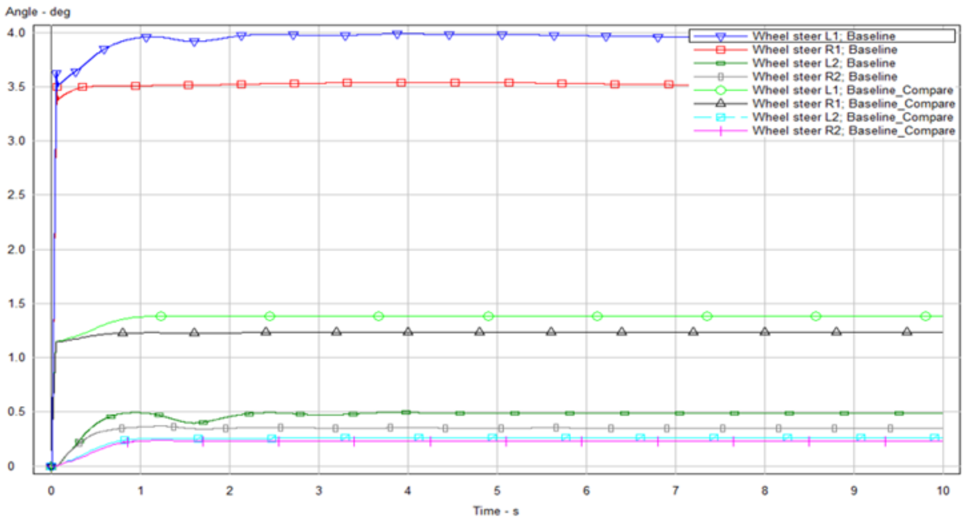

Figure 9: 110km/h Wheel Turning Angle

Based on the curves obtained from Fig. 8 to Fig. 9, the following conclusions can be drawn:
When the car is in the high-speed zone, as the speed increases, the front wheel angle starts to decrease gradually, but the decrease is not large. When the driver turns the steering wheel, the car with the SBW system is able to produce a smaller wheel angle at high speeds, which meets the requirement of "high speed stability".

5. Conclusion

This paper focuses on the design of the ideal transmission ratio of the automotive drive-by-wire steering system, which has the advantage of not having a fixed ratio compared with the traditional steering system.Before the beginning of the study, this paper firstly compares the steering characteristics of the two, analyses the advantages and disadvantages of each, and comes up with the design requirements for the variable transmission ratio of the SBW system. In this paper, two ideas are proposed to design the variable angle transmission ratio, which are the design method with constant steering sensitivity and the design method with constant lateral acceleration, and the design method with constant steering sensitivity is finally chosen after analysis. According to the genetic algorithm used in the reference to get the optimised transverse hem angular velocity gain of 0.32, the actual car driving ratio should set the threshold value, according to the steering wheel and wheel turning angle of the limit of rotation angle, to find out the minimum transmission ratio under the critical speed, and from this to determine the ideal transmission ratio of the car.

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