Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Investigations on control algorithm of steady-state cornering and control strategy for dynamical correction in a steer-by-wire system*

Ying XU[†1], Chang-fu ZONG[2], Hsiao-hsiang NA[2], Lei LIU[†‡1]
([1]Department of Computer Science and Technology, Jilin University, Changchun 130025, China)
([2]State Key Laboratory of Automobile Dynamic Simulation, Jilin University, Changchun 130025, China)
[†]E-mail: yxu_yang@126.com; liulei@jlu.edu.cn

Received Mar. 11, 2008; Revision accepted Aug. 26, 2008; Crosschecked Mar. 27, 2009

Abstract: To improve the handling performance of a steer-by-wire (SBW) vehicle, a series of control logics are proposed. Firstly, an algorithm for enhancing the maneuvering in steady-state cornering is presented. On this basis, two categories of control strategies are used to dynamically correct and compensate the transient state steering responses and vehicle behaviors. Simulator tests including subjective evaluations and virtual field tests are both conducted to make comprehensive investigations on the series of control logics. The subjective evaluations demonstrate that the SBW vehicle with a specifically selected value of steering sensitivity tends to be more desirable for driving than a conventional one in which a fixed steering ratio exists. The virtual field tests indicate that the control strategies for dynamical correction and compensation could effectively improve the handling performances of an SBW vehicle by reducing the work load of drivers, enhancing the track-holding performance, and improving steering response properties.

Key words: Steer-by-wire (SBW), Steady-state cornering, Steering sensitivity, Dynamical correction
doi:10.1631/jzus.A0820173 **Document code:** A **CLC number:** U46; TP311

INTRODUCTION

As the vehicle electronic technologies applied to steering systems appear more and more conspicuous nowadays, the handling performance, regarded as one of the most significant vehicle attributes, has been improved greatly. However, due to the existence of mechanical linkages between the steering wheel and the pinion found in current vehicles, which directly lead to an invariable steering ratio, the steering sensitivity (typically depicted as 'steady-state yaw rate gain in response to steering wheel input' and hereinafter referred to as 'steering sensitivity' for short) always shows non-linear characteristics with respect to vehicle speed and lateral acceleration. Such characteristics, as a result, always compel the drivers to adjust their maneuvers while driving to actualize a safe control (e.g., altering the steering wheel angle input to compensate for the vehicle motion behavior when negotiating the same turn at different speeds), and it is becoming even more difficult when undergoing limit operation conditions on account of the lack of time for adjustments as well as at the possible presence of remarkable changes on steering properties (e.g., from understeer to oversteer).

Currently, the appearance of a fire-new technology known as steer-by-wire (SBW) has pointed out a way to fully overcome the disadvantages generated by the fixed steering ratio (Führer and Schedl, 1999; Harter *et al*., 2000; Yih, 2005). In an SBW system, the conventional mechanical linkage between a steering wheel and a pinion is replaced with electronic sensors, controllers, and actuators. This notable improvement obviously gives an opportunity to design the steering ratio into a variable one, by which the real-time modifications to steering sensitivity can be realized and the optimizations to vehicle handling

‡ Corresponding author
* Project (Nos. 50475009 and 50775096) supported by the National Natural Science Foundation of China

performances can thus be achieved.

Researches on SBW have been widely and rapidly developed in Japan and western countries nowadays. Tajima *et al*.(1998; 1999) first established the control logics on steering properties based on a study of driver behaviors when negotiating a steady-state cornering (Takimoto, 1997); however, they did not consider the motion control in transient state. Segawa *et al*.(2000; 2002) researched the stability control of SBW vehicles. In recent years, studies on control strategies of the SBW vehicle have shifted to the designing of the hand wheel torque (Chai *et al*., 2004; Hiraoka *et al*., 2006). In contrast to Japanese researchers, researchers from western countries inclined to address the process of manufacturing real SBW prototypes, with little attention on the investigations of steering control strategies. Correspondingly, the steering ratio of the SBW prototypes was either set according to the theory generated by Tajima (Yao, 2006) or designed empirically as a function of the vehicle speed (Kaufmann *et al*., 2001; Cesiel *et al*., 2006; Verschuren and Duringhof, 2006).

Deriving from the theories generated by (Tajima *et al*., 1998; 1999; Segawa *et al*., 2000; 2002), this paper proposes a series of control logics to improve the handling dynamics of an SBW vehicle integrally, including both the steady-state cornering maneuvering and the transient state steering response characteristics. In Section 2, an algorithm with the concept of 'ideal steering ratio' is proposed to enhance the steady-state cornering maneuvering of an SBW vehicle, and corresponding subjective evaluations on the driving simulator are conducted to investigate the availability of this algorithm. On this basis, two categories of control strategies are proposed in Section 3 for a better handling performance in transient state by reducing the work load of drivers, enhancing the track-holding ability, and improving steering response properties. Experimental approaches by means of virtual field simulator tests are then employed to examine the effects of the implementation of each strategy.

ALGORITHM TO MAINTAIN THE STEERING SENSITIVITY CONSTANT

It is assumed that if the steering sensitivity of a vehicle remains unchanged regardless of the vehicle speed and lateral acceleration when passing through a curve, a more precise feed-forward steering control could be easily achieved by drivers; at the same time, the necessity of feedback adjustments might be minimized (Takimoto, 1997). Besides reduction in the work load of drivers and enhancement in the handling performances of a vehicle in terms of the 'steering positioning control performances' and the 'evasive maneuverability' (Tajima *et al*., 1998), such steady-state response properties can also lead to improvement in the limit driving performances (e.g., to avoid the mutation of steering properties).

In a real SBW vehicle, it is the steering actuator that fulfils the task of steering. Hence, the speed ratio between the steering wheel and the steering actuator can be designed variably by adopting corresponding control logics on the actuator. In this section, a control algorithm with the concept of the 'ideal steering ratio' is proposed to maintain the steering sensitivity.

Ideal steering ratio

The 'ideal steering ratio' is referred to as a numerical variable speed ratio of the steering wheel angle to the front wheel angle that could keep the steering sensitivity unchanged. This is the most important parameter adopted by the algorithm proposed in this section, and is important for the designing of SBW systems.

To explain the 'ideal steering ratio' in detail, the steering gain $G^{r}_{\delta_{\mathrm{fw}}}$, referred to as the stead-state yaw rate gain of a vehicle in response to the front wheel angle, is pre-defined as follows:

$$G^{r}_{\delta_{\mathrm{fw}}} = r / \delta_{\mathrm{fw}}, \quad (1)$$

where r represents the yaw rate of a vehicle in steady state and δ_{fw} is the corresponding front wheel angle.

As previously mentioned, the steering sensitivity of a vehicle is typically depicted as the steady-state yaw rate gain in response to the steering wheel input. Hence, we have

$$G^{r}_{\delta_{\mathrm{sw}}} = r / \delta_{\mathrm{sw}}, \quad (2)$$

where δ_{sw} is the steering wheel angle.

Combining Eqs.(1) and (2) leads to

$$G^{r}_{\delta_{\mathrm{sw}}} = G^{r}_{\delta_{\mathrm{fw}}} \cdot \delta_{\mathrm{fw}} / \delta_{\mathrm{sw}}. \quad (3)$$

δ_{fw}/δ_{sw} might be formally regarded as the reciprocal of the steering ratio of a vehicle. So Eq.(3) can be rewritten as

$$G^r_{\delta_{sw}} = G^r_{\delta_{fw}} / i_s, \tag{4}$$

where $i_s=\delta_{fw}/\delta_{sw}$ is the nominal steering ratio of an SBW vehicle.

As expected, if $G^r_{\delta_{sw}}$ is kept as a constant, it will be easier to achieve more precise maneuver during driving. Therefore, the key, by Eq.(4), is to keep the ratio of $G^r_{\delta_{fw}}$ to i_s unchanged. Here, a reasonable i_s to realize this conception is regarded as the 'ideal steering ratio'.

Computation of the 'ideal steering ratio'

With the assumption of the yaw rate gain in response to the front wheel angle, $G^r_{\delta_{fw}}$ can be obtained; meanwhile, a suitable value can be set to the steering sensitivity, $G^r_{\delta_{sw}}$. Thus, the 'ideal steering ratio' can be easily calculated by Eq.(4). In this subsection, computer simulations based upon the 29-DOF (degree of freedom) real-time vehicle dynamics model (Guan *et al*., 2001) are conducted to demonstrate the computation of the 'ideal steering ratio', and then simulator tests are carried out to determine a suitable value for $G^r_{\delta_{sw}}$.

The 29-DOF real-time vehicle dynamics model (Fig.1) was developed by the State Key Laboratory of Automobile Dynamic Simulation, Jilin University, China. This vehicle model was primarily constituted by six sub-models: engine model, steering model, power train model, braking model, vehicle body model, and tire model. Here, a unified semi-empirical tire model (Guo and Ren, 1999) was adopted to maintain a high accuracy of the simulations.

Computer simulations on the steady-state circular driving behaviour test (ISO 4138) have been conducted separately at five different speeds (40, 60, 80, 100, and 120 km/h) to examine the steady-state values of the yaw rate at different front wheel angles. Fig.2a shows the relationship between the yaw rate and the front wheel angle under these conditions in terms of a series of fitted curves. After successfully recording the yaw rate values at each front wheel angle, the yaw rate gain in response to the front wheel angle, $G^r_{\delta_{fw}}$, can be calculated by Eq.(1). Fig.2b plots the calculated steering gain $G^r_{\delta_{fw}}$ at each front wheel angle. If a suitable value can be evaluated for $G^r_{\delta_{sw}}$, the 'ideal steering ratio' can be easily calculated by Eq.(4). Fig.2c shows the fitted 'ideal steering ratio' at each front wheel angle with the value of $G^r_{\delta_{sw}}$ set to be 0.5 s^{-1}.

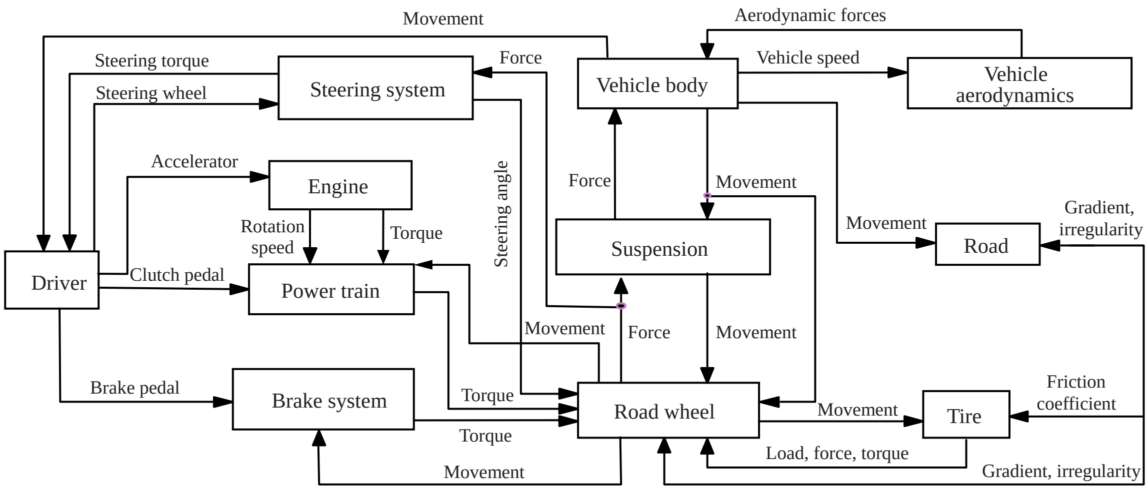

Fig.1 Architecture of the 29-DOF vehicle model

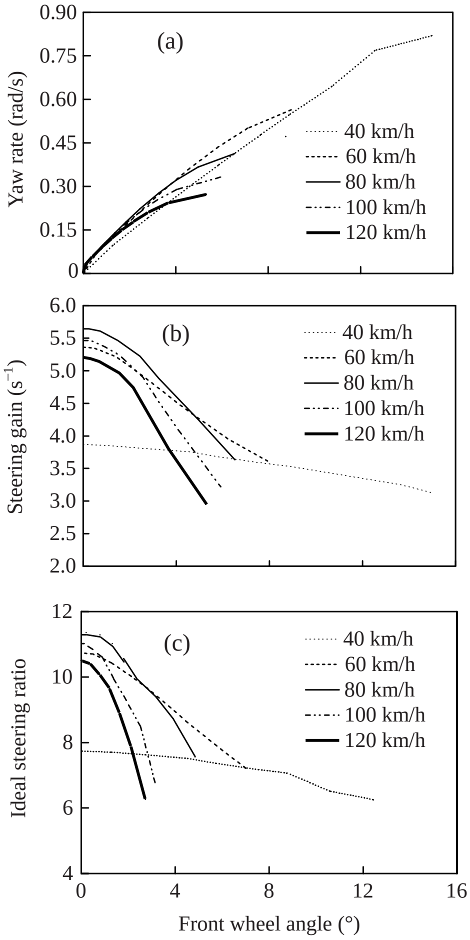

Fig.2 Relationship between the yaw rate (a), the steering sensitivity (b), the 'ideal steering ratio' (c) and the front wheel angle

It is demonstrated that in a real SBW vehicle, the steering actuator has taken on the task of cornering entirely, and it is also indicated that the 'ideal steering ratio' represents a variable speed ratio between the steering wheel and the front wheel. Therefore, a means to relate the swerving motion of front wheels to the steering input of drivers is needed to be devised for the implementation of the 'ideal steering ratio'. It is designed to be a multiplex function in response to the steering wheel angle δ_{sw} and the vehicle speed u based on Fig.2, so as to actualize the practicality of this algorithm in a real SBW system.

As the relationship between the recorded yaw rates and front wheel angles under each speed condition is revealed in Fig.2a, the relationship between the steering angle δ_{sw} and the front wheel angle δ_{fw} can be revealed by Eq.(2) (as previously mentioned, $G^{r}_{\delta_{sw}}$ is set to be 0.5 s^{-1}). Thus, it is possible to establish an i_s function of the steering wheel angle δ_{sw} and the vehicle speed u according to Fig.2b. Fig.3 shows the 3D plot of the i_s surface.

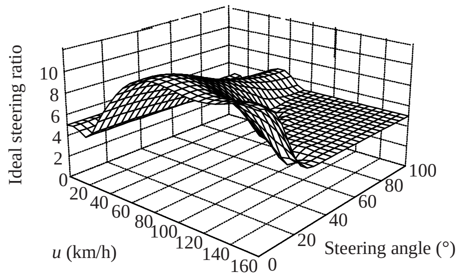

Fig.3 Three-dimensional plot of the i_s surface

Determination of a suitable $G^{r}_{\delta_{sw}}$

In an SBW system, the yaw rate gain in response to the steering wheel input, $G^{r}_{\delta_{sw}}$, is set to be a constant to enhance handling performances of a vehicle. However, the value of $G^{r}_{\delta_{sw}}$ itself would also have a distinct influence on the motion responses of an SBW vehicle in steady state. For this reason, investigations on the determination of a suitable $G^{r}_{\delta_{sw}}$ are required. In this subsection, subjective evaluations on driving simulator are carried out to fulfill this task.

Ten drivers, aging from 32 to 45, with an average driving experience of approximately 8 years, were invited to participate in this test with the use of the ADSL (Automobile Dynamic Simulation Laboratory) driving simulator (Guo *et al*., 1999). The configuration and operation of the ADSL simulator are shown in Fig.4. With a real car installed in it, a true-to-nature driving environment was provided for the test drivers. The vehicle model employed in this simulator is the 29-DOF real-time vehicle dynamics model mentioned above. After inserting the algorithm with the concept of the 'ideal steering ratio' into the steering module, simulator tests in terms of subjective evaluations were performed to determine a more acceptable $G^{r}_{\delta_{sw}}$. Three levels of the steering ratio marked as CONSR, G1 and G2 were projected for the test. For each level, three test conditions, involving the double lane change test (ISO 3888-1, at 80 km/h), the steady-state circular driving behavior test (ISO 4138, with a constant radius of 40 m and a lateral acceleration of 5 m/s^2), and the pylon course slalom test (GB/T

6323.1-94, at 80 km/h) were selected to give a comprehensive judgment to each steering ratio level. Here, CONSR is referred to as the conventional steering system with a fixed steering ratio of 16.3375, while G1 and G2 suggest the properties of the 'ideal steering ratio' registered from $G_{\delta_{sw}}^{r}=1.0\ \mathrm{s}^{-1}$ and $G_{\delta_{sw}}^{r}=0.5\ \mathrm{s}^{-1}$, respectively. The value of the fixed steering ratio provided above was measured from the real car installed in the ADSL simulator for this test. With all the parameters in the vehicle model set to be the same as those of a real one, the comparison between the different modes of steering ratios is expected to be fair.

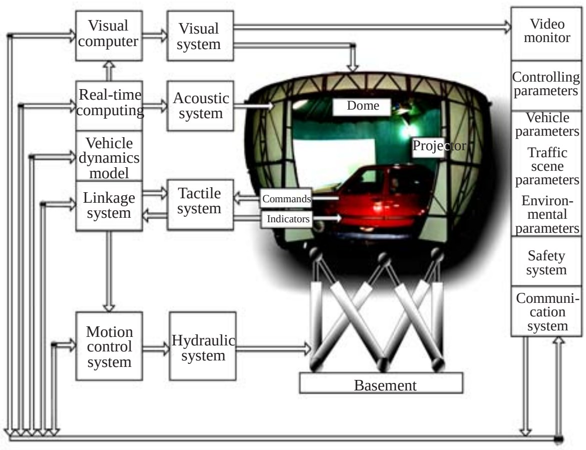

Fig.4 Configuration and operation of the ADSL driving simulator

During the tests, drivers were required to apperceive carefully the handling attributes and the vehicle responses at each steering ratio level on the simulator and then present the feelings in conformity to their driving experience. After completing the role in a single test, 10 ratings from the poorest to the best marked as numbers 1 to 10 were offered as a criterion to judge the handling performance. The step-to-step procedure of the test was arranged as follows:

(1) To become familiar with the ADSL driving simulator, test drivers were firstly given a training period in which each of them should drive in the virtual environment of pylon course slalom test pad at 80 km/h totally for 45 min or longer (depending on the driver's requirement). During this period, only the conventional fixed steering ratio was provided for each driver to minimize the potential difference between driving a real car and a simulator. The time span of 45 min proved to be adequate for their familiarity with the driving simulator.

(2) After being trained, drivers were required to have each of the three listed test courses experienced for five times or more, till they were confident of making a decision on the feeling rate for a single test. Here, the test courses were selected in random order.

(3) Average calculating operations were conducted for the scores of each of the three steering ratio levels experienced by 10 drivers, and a standardized method was used to give a clear sight of the test results.

Fig.5 illustrates the standardized test results, showing that the handling performances of an SBW vehicle at the two selected steering sensitivities can be effectively improved compared with a conventional vehicle. The test results also show that within the introduced SBW steady-state algorithms, the value of $G_{\delta_{sw}}^{r}$ itself could have a distinct influence on drivers' maneuvering behaviors and habits, where the level of G2 ($G_{\delta_{sw}}^{r}=0.5\ \mathrm{s}^{-1}$) will be considered a more desirable pattern for driving. It is expected that the participation of more drivers with different ages, sexes, driving experience, etc. in further investigations will present a more comprehensive and reliable conclusion on this issue.

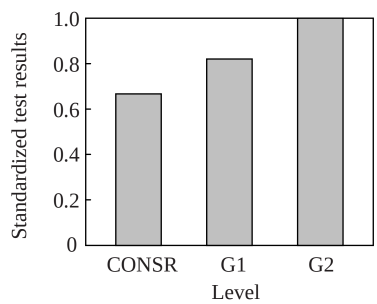

Fig.5 Standardized simulator test results for determination of $G_{\delta_{sw}}^{r}$

CONTROL STRATEGIES TO DYNAMICALLY CORRECT TRANSIENT STATE STEERING RESPONSES

An algorithm with the concept of the 'ideal steering ratio' was proposed and established to improve the handling performances of a vehicle in relation to the steady-state cornering. However, the motion response of an SBW vehicle in transient state when negotiating a turn should also be paid great attention to for its significant impact on the handling dynamics and the quality of stability. In this section, we study the control strategies of dynamically correcting and compensating the transient state steering responses of an SBW vehicle for realizing better stability performances.

Characterizations of the transient state control strategies

The control strategies can be divided into two categories, namely the yaw rate feedback control (hereinafter expressed as 'yaw rate control') and the yaw rate – lateral acceleration integrated feedback control (hereinafter expressed as 'integrated control' for short) by the features of the feedback component.

1. Yaw rate control

Fig.6 shows the block diagram of the strategy of yaw rate control, where the target front wheel angle δ_{fw}^* of an SBW system is determined by incorporating the front wheel angle δ_{FI}^* and the accessional front wheel angle δ_{FB}^*. Here, δ_{FI}^* is calculated by dividing the steering wheel angle δ_{sw} by the 'ideal steering ratio' i_s while δ_{FB}^* is generally decided by a model following control method (Nakajima *et al*., 1999) with a 2-DOF vehicle model. The 2-DOF model was used here as a reference, indicating an ideal motion response of the yaw rate and the lateral acceleration (Ellis, 1993).

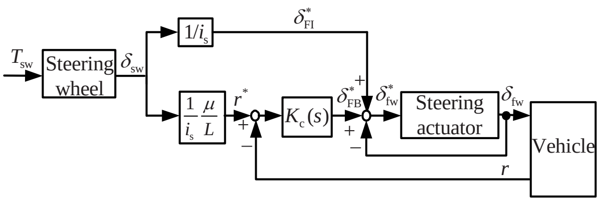

Fig.6 Block diagram of the yaw rate control

Together with the target yaw rate r^*, the pre-defined steering gain K_c, and the actual yaw rate r of the vehicle [the feedback component in this strategy can be obtained either by sensing (usually with a gyroscope) or by estimation (Gao *et al*., 2004; Wenzel *et al*., 2006)], the value of δ_{FB}^* can be registered. The target yaw rate r^* introduced here is expected to be an ideal motion response that primarily pertains to three parameters: vehicle speed u, wheel base L, and steering ratio i_s.

2. Integrated control

The integrated control implements both the above-mentioned yaw rate feedback control and a lateral acceleration feedback logic to improve the yaw motion response and to develop the lateral stability performances of an SBW vehicle simultaneously. Fig.7 shows the control block diagram of this strategy. We can find that a feedback component value S is employed to generate the target front wheel angle δ_{fw}^*. Here, S is referred to as a linear combination of $r{\cdot}u$ and the lateral acceleration a_y:

$$S = K_1 a_y + K_2 ru, \tag{5}$$

where K_1 and K_2 are the combination coefficients that may reflect the impact on the motion responses dominated by lateral acceleration and yaw rate, respectively. Specifically, when undergoing severe lateral wind, the lateral movement of a vehicle, rather than the yaw, is considered to be the dominant factor as for the motion response, and the value of K_1 should be correspondingly set higher than K_2. But when encountering a side slip, the situation turns to be different. Here, the equation $K_1+K_2=1$ should also be guaranteed to convey the factual motion responses of a vehicle momently. Usually, K_1 and K_2 are both set to be 0.5 to keep a balance between the impacts of lateral movement and yaw. More details on the effects of K_1 and K_2 will be explored in future investigations.

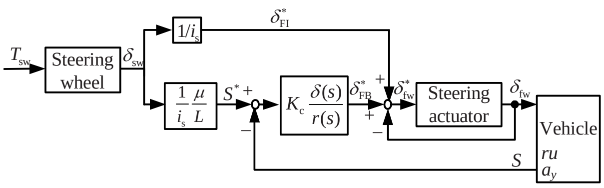

Fig.7 Block diagram of the integrated feedback control

Simulator tests on transient control strategies

Experimental approaches by means of simulator tests were conducted for a comprehensive understanding of the control strategies. We used the same ADSL driving simulator embedded with the same car as mentioned in Section 2.

The ISO double lane change test (ISO 3888-1) was employed as the test method. Four categories of steering systems, including the conventional steering system, the SBW systems with front wheel control (by adopting only the algorithm to maintain the steering sensitivity constant, without any feedback component), with yaw rate feedback control, and with the integrated control (K_1 and K_2 are both set to be 0.5), were introduced into the tests for comparison. Tests on low-adhesion roads were also performed and the test method was primarily referred to ISO 3888-1 but differed in the selection of the road adhesion coefficient and test speed. In such a case, the conventional steering system was excluded for its relatively low probability in passing through the test track. General information on the simulator tests is described in Table 1.

Table 1 General information on simulator tests for high adhesion coefficient (0.9) and low adhesion coefficient (0.2)

Parameter	Description	
	0.9	0.2
Test speed (km/h)	80	40
Test method	ISO 3888-1	ISO 3888-1*
Steering system mode	Conventional; Front wheel control; Yaw rate control; Integrated control	Front wheel control; Yaw rate control; Integrated control

*Differ in the selection of the road adhesion coefficient and test speed

The results of simulator tests on the high-adhesion road are shown in Fig.8. Compared with the conventional steering system, the SBW system with various control strategies generally requires fewer steering wheel inputs during the entire test path (Fig.8a), which implies a reduction in the work load of drivers (Zong and Guo, 2000). Moreover, the integrated control needs the lowest steering angle input, then the raw rate control, and then the front wheel control. The motion responses in terms of lateral acceleration and yaw rate generated by the integrated control tend to be more rapid than those of other modes while the amplitude is relatively small (Figs.8b and 8c). Such features suggest that the integrated control mode denotes a better handling performance and a higher quality of stability (Abe and Chen, 1998). It is shown in Fig.8d that the ISO double lane change test could be better fulfilled by the integrated control than by any other steering system modes, which indicates a superior track-holding ability. Thus, a safety maneuvering can be successfully achieved.

Fig.9 shows the results of simulator tests on the low-adhesion road. Compared with the front wheel control strategy, although the steering angle inputs generated by the yaw rate control and the integrated control are somewhat higher, the maneuvers, in terms of frequent correction (just like oscillation) on the steering wheel found in the front wheel control

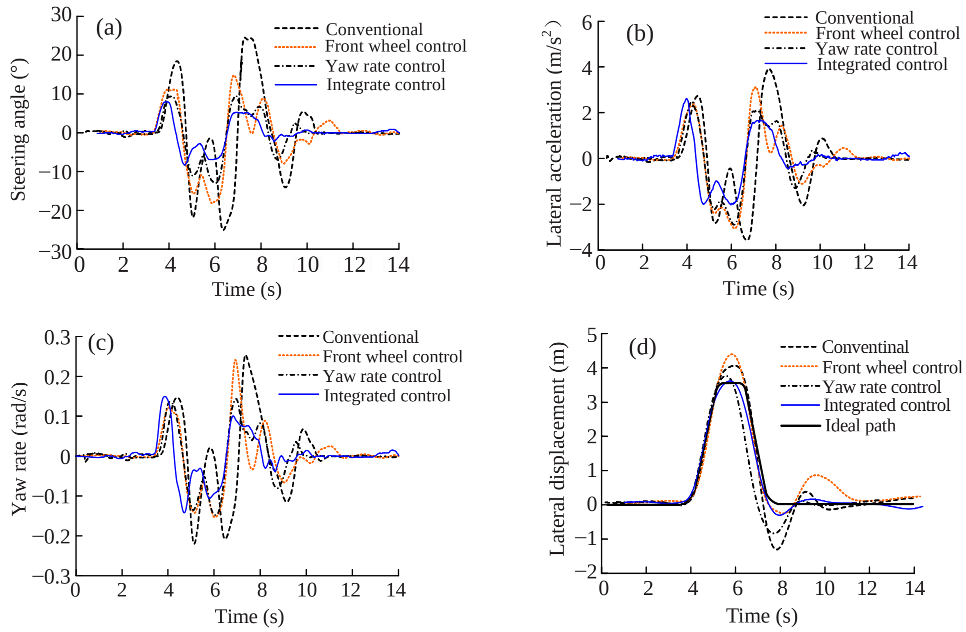

Fig.8 Results of simulator tests on a high-adhesion road
(a) Steering wheel angle; (b) Lateral acceleration; (c) Yaw rate; (d) Lateral displacement

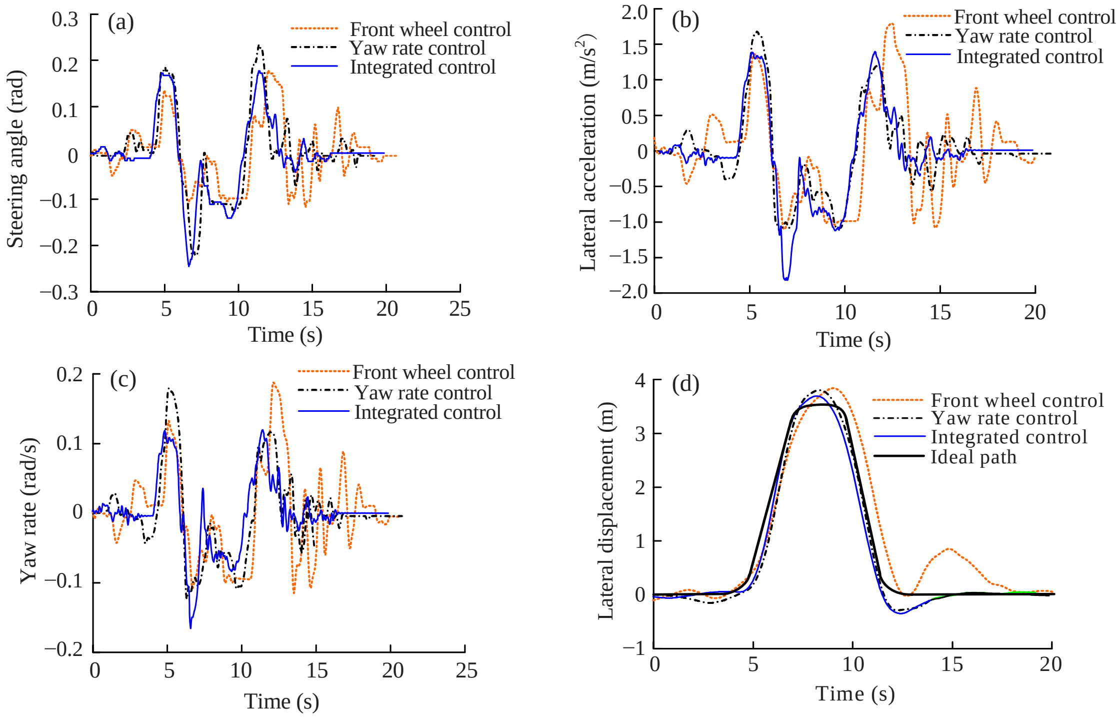

Fig.9 Results of simulator tests on a low-adhesion road
(a) Steering wheel angle; (b) Lateral acceleration; (c) Yaw rate; (d) Lateral displacement

to maintain a suitable attitude at the final section of the test track, can be avoided (Fig.9a). This feature suggests that, with the introduction of feedback, the driver could pass the lane change test on low-adhesion roads more easily, without experiencing bustling maneuvers. There are no significant differences between the yaw control and the integrated control, as seen in Figs.9a~9c. The running paths in relation to the two feedback control strategies are nearly the same but differ a bit at the second lane-changing position (Fig.9d). With the integrated control there is little lag between the steering wheel input and vehicle behavior responses, so the driver can make a better track-holding maneuvering.

CONCLUSION

To improve the steady-state cornering response characteristics of a vehicle, an algorithm to maintain the steering sensitivity was introduced in this study. Experimental approaches by means of simulator tests were conducted to examine the availability of this algorithm. Test results showed that the distribution of steering sensitivity $G_{\delta_{sw}}^{r}$ has a distinct influence on the motion responses of an SBW vehicle and can be considered a more desirable driving pattern for drivers when $G_{\delta_{sw}}^{r}$ is set to be 0.5 s^{-1}.

On this basis, two categories of control strategies, the yaw rate control and the integrated control, were presented with the aim of dynamically correcting and compensating for the transient state steering responses. Simulator tests in terms of double lane change test were employed to have a comprehensive validation on each strategy. As a result, it is indicated that on high-adhesion roads, the integrated control could effectively reduce the workloads of drivers, as well as realize better handling and stability performances with more rapid motion responses and superior track holding ability; while on low-adhesion roads, the integrated control and the yaw rate control could avoid the bustling maneuvers possibly experienced by drivers. As for the track-holding ability, the integrated control strategy was in the ascendant.

References

Abe, M., Chen, X.B., 1998. Motion Responses and Handling Dynamics of Automobile. China Machine Press, Beijing, p.212-214 (in Chinese).

Cesiel, D., Gaunt, M.C., Daugherty, B., 2006. Development of a Steer-by-wire System for the GM Sequel. SAE Paper, 2006-01-1173.

Chai, Y.W., Saitou, Y., Kano, Y., Abe, M., 2004. A Study on Effects of Derivative Parameters in a SBW System for Active Interface Vehicle on Driver-vehicle System Performance. Proc. AVEC, p.233-238.

Ellis, J.R., 1993. Vehicle Handling Dynamics. Mechanical Engineering Publications Limited, London, p.55-62.

Führer, T., Schedl, A., 1999. The Steer-by-wire Prototype Implementation: Realizing Time Triggered System Design, Fail Silence Behavior and Active Replication with Fault-tolerance Support. SAE Paper, 1999-01-0400.

Gao, Z.H., Zheng, N.N., Cheng, H., 2004. Soft sensor of vehicle state based on vehicle dynamic and Kalman filter. *J. Syst. Simul.*, **16**(1):22-24 (in Chinese).

Guan, H., Guo, K.H., Lin, B.Z., 2001. 29-DOF Vehicle Dynamic Model for Real-time Simulation. Technical Report, State Key Lab of Automobile Dynamic Simulation (in Chinese).

Guo, K.H., Ren, L., 1999. A Unified Semi-empirical Tire Model with Higher Accuracy and Less Parameters. SAE Paper, 1999-01-0785.

Guo, K.H., Guan, H., Zong, C.F., 1999. Development and Applications of JUT-ADSL Driving Simulator. Proc. IEEE Int. Vehicle Electronics Conf., **1**:1-5. [doi:10.1109/IVEC.1999.830603]

Harter, W., Pfeiffer, W., Dominke, P., Ruck, G., 2000. Future Electrical Steering System: Realizations with Safety Requirements. SAE Paper, 2000-01-0822.

Hiraoka, T., Nishihara, O., Kumamoto, H., 2006. Steering Reactive Torque Control for Steeri-by-wire Vehicle. Proc. AVEC, p.1-6.

Kaufmann, T., Millsap, S., Murray, B., Petrowski, J., 2001. Development Expierence with Steer-by-wire. SAE Paper, 2001-01-2479.

Nakajima, T., Adachi, K., Ooike, M., Kanda, K., 1999. A Rear Wheel Steer Control System Using Model Following Control Method. Proc. JSAE, p.44-99.

Segawa, M., Nishizaki, K., Nakano, S., 2000. A Study of Vehicle Stability Control by Steer-by-wire System. Proc. AVEC, p.1-7.

Segawa, M., Kimura, S., Kada, T., Nakano, S., 2002. A Study of Reactive Torque Control for Steer-by-wire System. Proc. AVEC, p.1-5.

Tajima, J., Yuhara, N., Takimoto, S., Kawai, T., Shimizu, Y., 1998. Research on Effect of Steering Characteristics on Control Performance of Driver-vehicle System from a Viewpoint of Steer-by-wire System Design. Proc. AVEC, p.1-7.

Tajima, J., Yuhara, N., Sano, S., Takimoto, S., 1999. Effects of Steering System Characteristics on Control Performance from the Viewpoint of Steer-by-wire System Design. SAE Paper, 1999-01-0821.

Takimoto, S., 1997. A Study of Driver's Behavior in Turning a Curve. Proc. JSAE Spring Convention, No. 9732748.

Verschuren, R.M.A.F., Duringhof, H.M., 2006. Design of a Steer-by-wire Prototype. SAE Paper, 2006-01-1497.

Wenzel, T.A., Burnham, K.J., Blundell, M.V., Williams, R.A., 2006. Dual extended Kalman filter for vehicle state and parameter estimation. *Veh. Syst. Dynam.*, **44**(2):153-171. [doi:10.1080/00423110500385949]

Yao, Y.X., 2006. Vehicle Steer-by-wire System Control. SAE Paper, 2006-01-1175.

Yih, P., 2005. Steer-by-wire: Implications for Vehicle Handling and Safety. PhD Thesis, Department of Mechanical Engineering, Stanford University, California, USA.

Zong, C.F., Guo, K.H., 2000. Objective evaluation index for handling and stability of vehicle. *Nat. Sci. J. Jilin Univ. Technol.*, **30**(1):1-6 (in Chinese).