Lane Keeping System Based on Electric Power Steering System

Hailin Zhang, Yugong Luo, Qingyun Jiang and Keqiang Li

Abstract For integration issues between Electric Power Steering System and Lane Keeping System, a Lane Keeping coordinated control method combining time to lane cross and judgment of driver's operating behavior has been proposed. Lane Keeping System model, Magic Formula Tire model, 7-DOF vehicle model and EPS model were built based on theoretical analysis. Then Hardware-in-the-Loop experiment was done on EPS bench. Simulation and Hardware-in-the-Loop experiment results show that Lane Keeping coordinated control method can solve coordinated problems between conventional power steering component and lane keeping executive component, and can keep the vehicle in the lane, thus ensure the safety of the vehicle while driving.

Keywords Lane keeping · Coordinated control · Hardware-in-the-loop · Vehicle model · EPS

1 Introduction

According to statistics, nearly 40 % of fatal accidents are caused by lane departure [1]. The function of Lane Keeping System is to maintain the vehicle in the lane, then ensure the drivers' safety.

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EPS system has a series of advantages such as energy saving and simple structure. Lane Keeping System based on EPS can achieve shared using of EPS structure and reduce design costs of Lane Keeping System.

In Lane Keeping System based on EPS, EPS is conventional power steering component and also lane keeping executive component. Coordinated control between these two functions is the key of the research.

Literature [2, 3] studied Lane Keeping System based on EPS, but were not related to coordinated control problems between conventional power steering component and lane keeping executive component. Literature [4] designed individual steering mechanism for Lane Keeping System. The mechanism didn't have conventional power steering function, so there weren't coordinated control problems.

For coordinated control problems mentioned above, a Lane Keeping coordinated control method combining time to lane cross [1] and judgment of driver's operating behavior has been proposed. This method combined calculation of time to lane cross and judgment of driver's operating behavior. Lane Keeping System model, Magic Formula Tire model, 7-DOF vehicle model and EPS model were built based on theoretical analysis. Then Hardware-in-the-Loop experiment was done on EPS bench. Simulation and Hardware-in-the-Loop experiment results show that coordinated control method of Lane Keeping System can decide whether EPS is to achieve conventional power steering or is to respond commands from lane keeping controller through judgment of driver's behavior and vehicle states, achieve coordinated control of these two functions and keep the vehicle in the lane in order to ensure safety while driving.

2 Overall Structure of Lane Keeping System Based on EPS

The driver has the highest priority while driving, so driver's operating behavior must be considered when designing control strategies. The controller can decide whether EPS is to achieve conventional power steering or is to respond commands from lane keeping controller through integrated judgment of time to lane cross and driver's operating behavior, thus achieve coordinated control.

Based on ideas mentioned above, this paper has established overall structure of Lane Keeping System based on EPS, which is shown in Fig. 1. Lane Keeping System is inside the dashed box. Road environmental information and driver's information are inputs of vehicle model. Vehicle's state parameters can be obtained through calculation of vehicle model. We can judge whether the vehicle has the danger of lane departure through driver's behavior and time to lane cross. If there is danger of lane departure, steering angle command is calculated by lateral driver model. Then PWM signals are generated by PID controller, input of which is error of steering angle. The motor executes PWM signals, generates corresponding front wheel steering angle, then keeps the vehicle in the lane. If there isn't danger of lane departure, EPS works under conventional power steering mode.

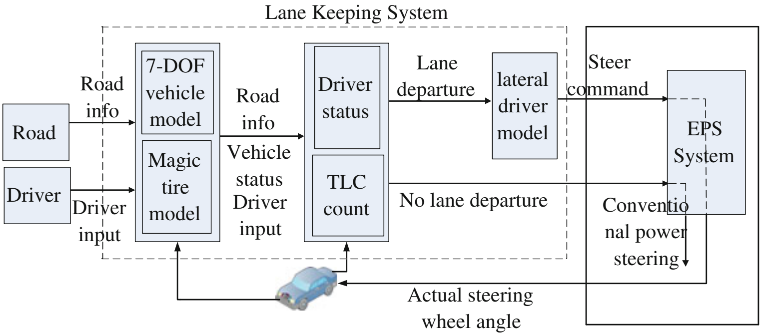


Fig. 1 Overall structure of lane keeping system based on EPS

3 Lane Keeping Coordinated Control Method

During lane keeping process, we first need to determine whether there is danger of lane departure through information on all aspects. In this paper, we determine whether there is danger of lane departure through judgment of driver's behavior and alarm algorithm based on time to lane cross (TLC).

Alarm algorithm based on TLC is to calculate time before the wheel crosses the edge of the lane through establishing vehicle motion model and predicting the trajectory of the vehicle. When the calculated time is less than certain threshold, the system will warn the driver of danger of lane departure.

Lane keeping coordinated control algorithm is shown in Fig. 2. Figure 2 shows when the driver is operating the steering wheel, the driver has the highest priority, then EPS works under conventional power steering mode. When the driver is not operating the steering wheel, if TLC is more than certain threshold, the vehicle doesn't deviate from the lane and there is no need to implement aid; if TLC is less than certain threshold, there is danger of lane departure. We calculate target angle from lateral driver model. Then PWM signals are generated by PID controller, input of which is the difference between target angle and actual angle. Then motor performs PWM signals, drives steering mechanism and keeps the vehicle in the lane.

As is shown in Fig. 2, judgment of driver's operating status is very important in lane keeping coordinated control process. In this paper, torque signal is used to judge driver's operating status. Specific judgment process is shown in Fig. 3.

In Fig. 3, the system first gets torque signal from torque sensor. When the torque is more than the set threshold, the driver is operating the vehicle. When the torque is less than the set threshold, if the time when the torque is less than the set threshold is more than certain threshold, the driver is not operating the vehicle, otherwise the driver is operating the vehicle.

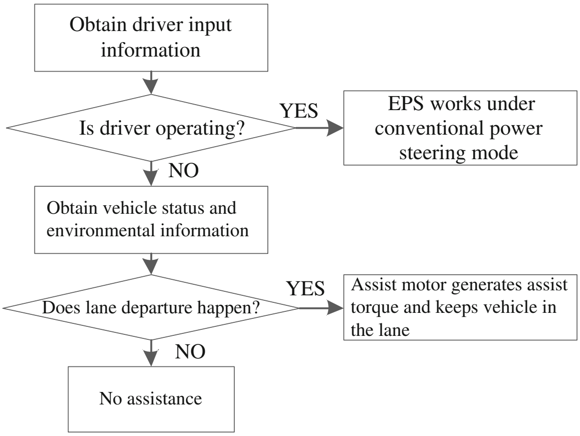


Fig. 2 Lane keeping coordinated control process

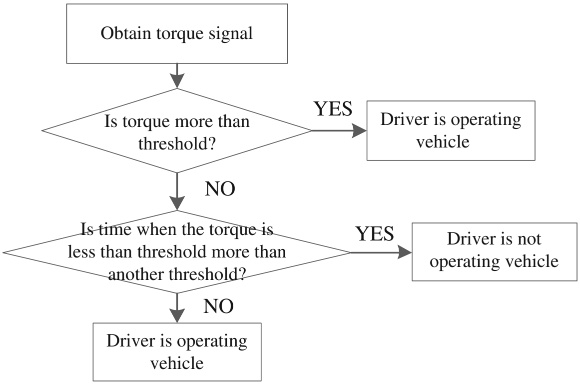


Fig. 3 Judgment of driver's operating status

4 Lane Keeping System Simulation Model

Simulation model of Lane Keeping System based on EPS are built in Matlab/Simulink. The block diagram of simulation model is shown if Fig. 4.

In Fig. 4, 7-DOF vehicle model gets front-wheel angle from EPS model and sends aligning torque and velocity to EPS model. Auxiliary mode judgment model determines whether EPS works under conventional power steering mode or lane keeping mode through integrating the driver's operating behavior and time to lane cross information. If the system works under lane keeping mode, lateral driver model calculates target steering wheel angle and sends it to EPS model, then the whole control process is completed.

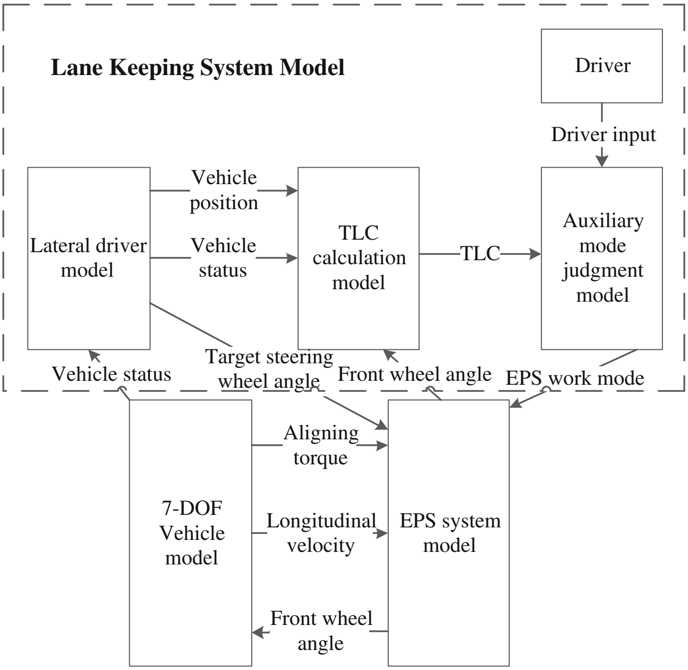
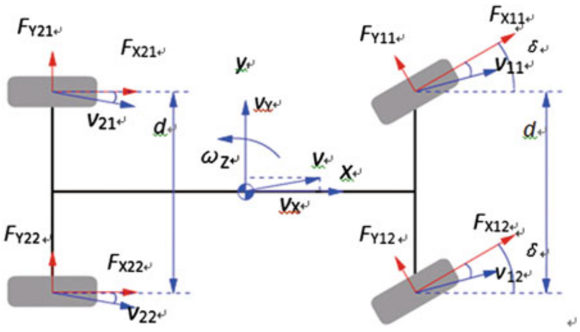


Fig. 4 Block diagram of simulation model

Fig. 5 Schematic diagram of 7-DOF vehicle model



4.1 Vehicle Model

This chapter selects seven degrees of freedom including longitudinal, lateral, yaw and four wheels' rotating, then establishes 7-DOF vehicle model.

Vehicle model is shown in Fig. 5 and the parameters are listed in Table 1.

Table 1 Meaning of parameters of 7-DOF vehicle model

Parameter	Meaning	Parameter	Meaning
m	Vehicle mass	v_{X}	x-velocity
J_{Z}	Yaw inertia	v_{Y}	y-velocity
d	Tread	ω_{Z}	Yaw velocity
a	Centroid to front axle distance	$\omega_{11},\omega_{12},\omega_{21},\omega_{22}$	Wheel angular velocity
b	Centroid to rear axle distance	δ	Front wheel angle
J_{F}	Front wheel rotation inertia	$F_{\mathrm{X11}},F_{\mathrm{X12}},F_{\mathrm{X21}},F_{\mathrm{X22}}$	Longitudinal force of tire
J_{R}	Rear wheel rotation inertia	$F_{\mathrm{Y11}},F_{\mathrm{Y12}},F_{\mathrm{Y21}},F_{\mathrm{Y22}}$	Lateral force of tire
r	Wheel radius	$T_{\mathrm{D11}},T_{\mathrm{D12}}$	Wheel drive torque
		$T_{\mathrm{B11}},T_{\mathrm{B12}},T_{\mathrm{B21}},T_{\mathrm{B22}}$	Wheel brake torque

7-DOF vehicle model equations are as follows.

$$\begin{cases} m(\dot{v}_{\mathrm{X}}-\dot{v}_{\mathrm{Y}}\omega_{\mathrm{Z}})=\sum F_{\mathrm{X}}=(F_{\mathrm{X11}}+F_{\mathrm{X12}})\cos\delta-(F_{\mathrm{Y11}}+F_{\mathrm{Y12}})\sin\delta+F_{\mathrm{X21}}+F_{\mathrm{X22}} \\ m(\dot{v}_{\mathrm{Y}}+\dot{v}_{\mathrm{X}}\omega_{\mathrm{Z}})=\sum F_{\mathrm{Y}}=(F_{\mathrm{X11}}+F_{\mathrm{X12}})\sin\delta+(F_{\mathrm{Y11}}+F_{\mathrm{Y12}})\cos\delta+F_{\mathrm{Y21}}+F_{\mathrm{Y22}} \\ J_{\mathrm{Z}}\dot{\omega}_{\mathrm{Z}}=\sum M_{\mathrm{Z}}=[(F_{\mathrm{X12}}-F_{\mathrm{X11}})\cos\delta+(F_{\mathrm{Y11}}-F_{\mathrm{Y12}})\sin\delta]\cdot\frac{d}{2}+(F_{\mathrm{X22}}-F_{\mathrm{X21}})\cdot\frac{d}{2} \\ \qquad +[(F_{\mathrm{Y11}}+F_{\mathrm{Y12}})\cos\delta+(F_{\mathrm{X11}}+F_{\mathrm{X12}})\sin\delta]\cdot a-(F_{\mathrm{Y21}}+F_{\mathrm{Y22}})\cdot b \\ J_{\mathrm{F}}\dot{\omega}_{11}=\sum M_{\mathrm{Y11}}=T_{\mathrm{D11}}-T_{\mathrm{B11}}-F_{\mathrm{X11}}\cdot r \\ J_{\mathrm{F}}\dot{\omega}_{12}=\sum M_{\mathrm{Y12}}=T_{\mathrm{D12}}-T_{\mathrm{B12}}-F_{\mathrm{X12}}\cdot r \\ J_{\mathrm{R}}\dot{\omega}_{21}=\sum M_{\mathrm{Y21}}=-T_{\mathrm{B21}}-F_{\mathrm{X21}}\cdot r \\ J_{\mathrm{R}}\dot{\omega}_{22}=\sum M_{\mathrm{Y22}}=-T_{\mathrm{B22}}-F_{\mathrm{X22}}\cdot r \end{cases} \tag{1}$$

4.2 Tire Model

The tire plays a role of media between vehicle and road. Tire model is the basis of vehicle dynamics simulation. Magic tire model proposed by Pacejka is used in this paper [5].

The general form of magic tire model is as follows.

$$y(x) = D\sin\{C\ \operatorname{atan}[B(x+S_h)(1-E) + E\ \operatorname{atan}(B(x+S_h))]\} + S_v \tag{2}$$

of which: D is peak factor, C is shape factor, B is sharpness factor, E is curvature factor, S_h is lateral offset, S_v is longitudinal offset, $y(x)$ stands for longitudinal force, lateral force or aligning torque.

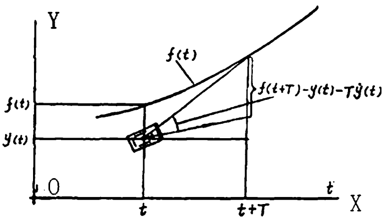


Fig. 6 Schematic diagram of lateral driver model

4.3 Lateral Driver Model

Single point preview driver model proposed by Guo Konghui is used in this paper. Schematic diagram is shown in Fig. 6 [6, 7].

In Fig. 6, XOY is a fixed coordinate system, $f(t)$ is the center line equation of expected trajectory, T is preview time, $y(t)$ is the current vehicle coordinates.

To track $f(t)$, the optimal steering wheel angle is:

$$\delta = \frac{2iL}{d^2}[f(t+T) - y(t) - T\dot{y}(t)] \tag{3}$$

Of which: δ is the optimal steering wheel angle, i is the gear ratio of steering system, L is wheelbase, d is preview distance.

During lane keeping control process, if lane departure happens, we can calculate target steering wheel angle from lateral driver model mentioned above if lane center line and related parameters are given. The difference between target steering wheel angle and actual steering wheel angle is sent to PID controller, from which PWM signals are generated. Motor performs PWM signals and then the whole lane keeping control process is completed.

4.4 EPS System Model

Schematic diagram of column-type power steering system is shown in Fig. 7. Parameters of EPS model are all shown in Fig. 7. The meanings of related parameters are listed in Table 2 [8, 9].

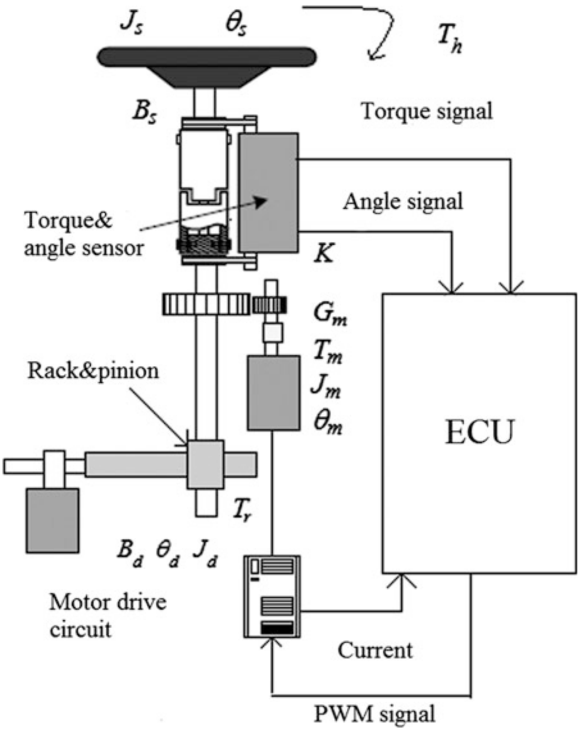
Dynamic equations of steering system are as follows:

$$\begin{cases} T_h - K(\theta_s - \theta_d) = B_s\dot{\theta}_s + J_s\ddot{\theta}_s \\ K(\theta_s - \theta_d) + T_a - T_r = B_d\dot{\theta}_d + J_d\ddot{\theta}_d \\ \theta_m = G_m\theta_d \end{cases} \tag{4}$$

Voltage equation of DC motor is:

$$U = L\dot{I} + IR + K_E\dot{\theta}_m \tag{5}$$

Fig. 7 EPS structure



Dynamic equation of motor is:

$$\begin{cases} T_m = K_a I \\ T_m - T_a/G_m = B_m\dot{\theta}_m + J_m\ddot{\theta}_m \end{cases} \tag{6}$$

Steering system dynamics can be solved through Eqs. (4), (5), (6). Relevant parameters are calculated for further solution.

5 Lane Keeping Hardware-in-the-Loop Experimental Platform

Hardware-in-the-loop (HIL) experimental platform is built based on simulation. HIL experimental platform is shown in Fig. 8.

HIL experimental platform consists of dSPACE system, EPS bench and motor drive module. Simulation model of Lane Keeping System based on EPS is running in dSPACE system. dSPACE collects torque and angle signals from EPS bench, current signal from motor drive module. These signals are sent to simulation model running in dSPACE system. After a series of calculation, PWM signals are

Table 2 Meanings of parameters of EPS model

Parameter	Meaning
J_s	Inertia of steering wheel and upper steering shaft
J_d	Inertia of front wheel and steering mechanism equivalent to steering shaft
B_m	Motor damping coefficient
B_d	Damping coefficient of front wheel and steering mechanism equivalent to steering shaft
θ_d	Angle of front wheel equivalent to steering shaft
T_r	Aligning torque
L	Motor inductance
K_E	Motor back EMF coefficient
I	Motor current
T_a	Assistant torque
G_m	Worm gear ratio
J_m	Motor rotation inertia
B_s	Steering shaft damping coefficient
T_h	Steering wheel input torque
θ_s	Steering wheel angle
θ_m	Motor angle
U	Motor voltage
R	Armature resistance
K	Torsion bar stiffness
K_a	Motor torque coefficient
T_m	Motor torque

Fig. 8 HIL experimental platform

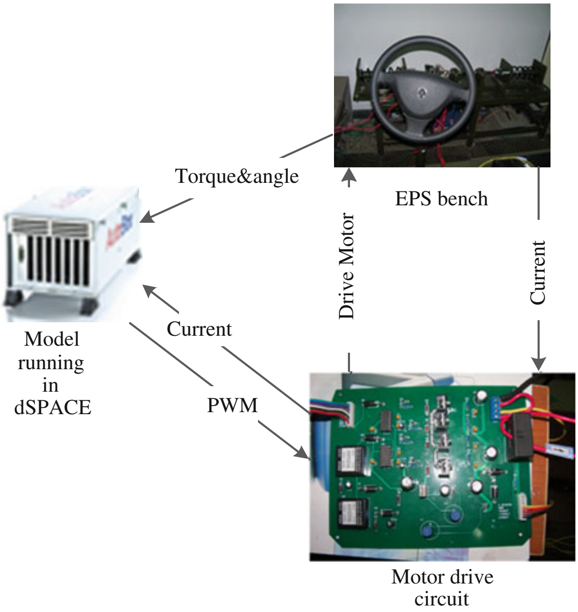
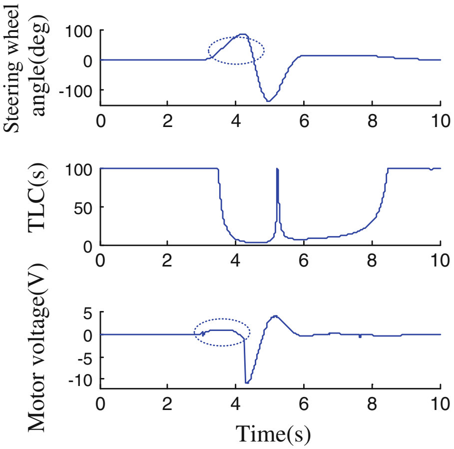


Fig. 9 Parameters change in simulation case 1



sent to drive motor in order to change front wheel angle and control vehicle trajectory.

6 Analysis of Simulation and HIL Experimental Results

In EPS system, the effect of EPS will be weakened with the increase of velocity. In order to take obvious power steering effect and lane keeping effect into account, the choice of velocity is 20 km/h.

6.1 Analysis of Simulation Results

Simulation case 1: straight line driving, velocity 20 km/h, ground friction coefficient 0.9, lane width 3.5 m, TLC threshold 3.5 s. Steering wheel angle, TLC and motor voltage are shown in Fig. 9.

From 3 to 4.3 s (Inside the dashed oval frame), there is driver input and motor works under conventional power steering mode. Motor voltage from 3 to 4.3 s in Fig. 9 presents conventional power steering state. After 4.3 s, there is no driver input. If TLC is less than 3.5 s, motor begins to work to adjust vehicle position. If TLC is more than 3.5 s, motor doesn't work and doesn't provide auxiliary. In summary, the control method can achieve coordinated control effect.

Control results of trajectory of vehicle centroid in case 1 are shown in Fig. 10. When there is danger of lane departure, Lane Keeping System takes over control of the vehicle and controls vehicle centroid near the centerline of the lane in order to ensure the safety of the vehicle.

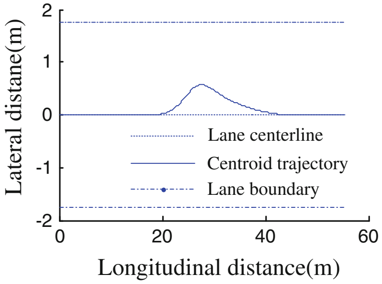


Fig. 10 Control results of trajectory of vehicle centroid in simulation case 1

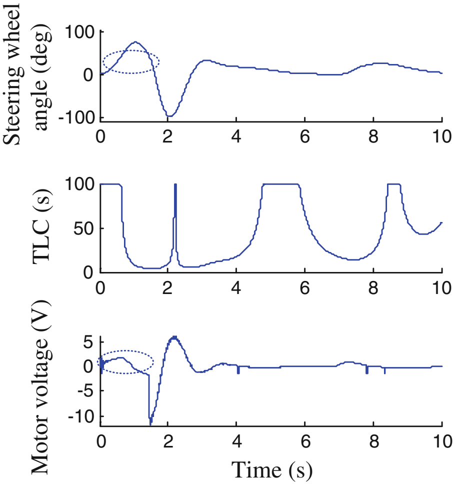


Fig. 11 Parameters change in simulation case 2

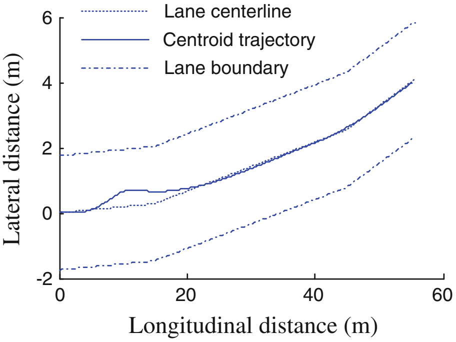
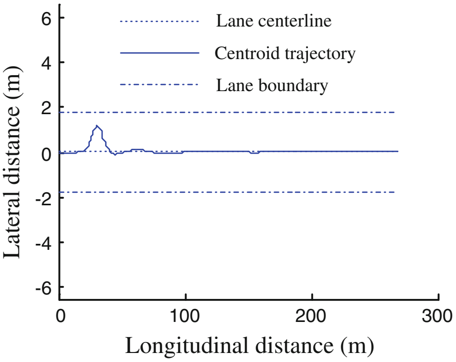


Fig. 12 Control results of trajectory of vehicle centroid in simulation case 2

Simulation case 2: curve line driving, velocity 20 km/h, ground friction coefficient 0.9, lane width 3.5 m, TLC threshold 3.5 s. Steering wheel angle, TLC and motor voltage are shown in Fig. 11.

From 0 to 1.5 s (Inside the dashed oval frame), there is driver input and motor works under conventional power steering mode. Motor voltage from 0 to 1.5 s

Fig. 13 Trajectory of vehicle centroid in HIL case 1



presents conventional power steering state. After 1.5 s, there is no driver input. If TLC is less than 3.5 s, motor begins to work to adjust vehicle trajectory. If TLC is more than 3.5 s, motor doesn't work and doesn't provide auxiliary. In summary, the control method can achieve coordinated control effect.

Control results of trajectory of vehicle centroid in case 2 are shown in Fig. 12. When lane departure happens, the system can adjust the vehicle's position in a very short time, thus ensure traffic safety. Simulation results verify that Lane keeping control method designed in this paper is effective.

6.2 *Analysis of HIL Experimental Results*

During HIL experiment, when the driver is not operating, hands are completely off the steering wheel. When the driver is operating, hands are on the steering wheel.

HIL case 1: straight line driving, velocity 20 km/h, ground friction coefficient 0.9, lane width 3.5 m, TLC threshold 3.5 s.

Control results of trajectory of vehicle centroid in HIL case 1 are shown in Fig. 13. The results show that when lane departure happens, the system can adjust the vehicle to the center line of the lane, which is in line with expected result.

Parameters' changing in HIL case 1 is shown in Fig. 14. From 3.5 to 4.5 s (Inside the dashed oval frame), the torque exceeds the set threshold. According to Fig. 3, the driver is operating. After 4.5 s, the torque is less than the set threshold and persists for some time. According to Fig. 3, the driver is not operating. From 3.5 to 4.5 s, the driver is operating when EPS works under conventional power steering mode and there is assist current in motor. After 4.5 s, the driver is not operating. The system changes to lane keeping process. When TLC is less than the set threshold, motor begins to work to adjust vehicle position through changing front wheel angle. When TLC is more than the set threshold, there is almost no current in the motor and the system works without assistance of the motor. The results show that control method designed in this chapter can achieve coordinated control effects.

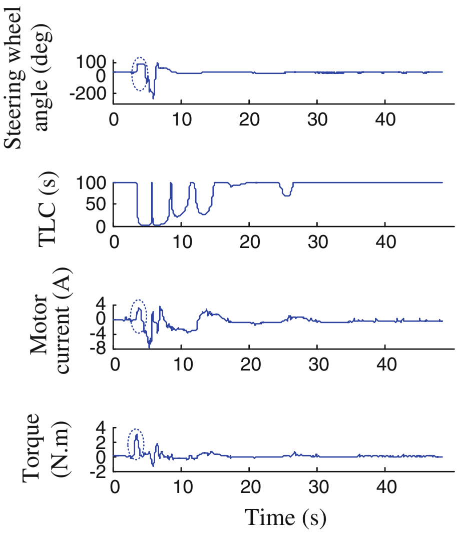


Fig. 14 Parameters change in HIL case 1

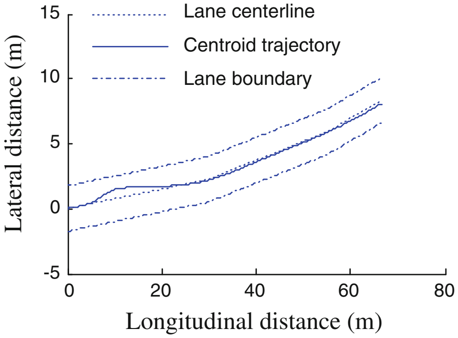


Fig. 15 Trajectory of vehicle centroid in HIL case 2

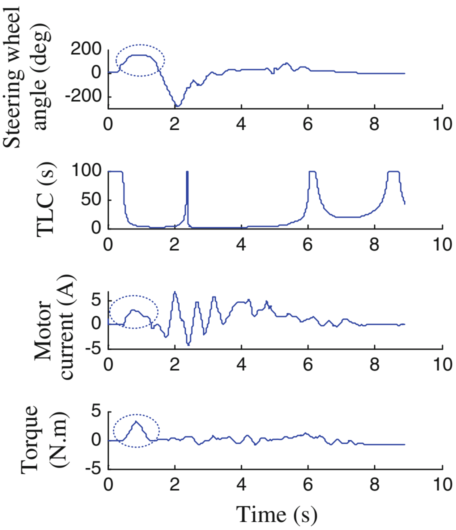
HIL case 2: curve line driving, velocity 20 km/h, ground friction coefficient 0.9, lane width 3.5 m, TLC threshold 3.5 s.

Control results of trajectory of vehicle centroid are shown in Fig. 15. Parameters' changing in HIL case 2 is shown in Fig. 16.

In Fig. 15, when lane departure happens during cure line driving, the system can adjust vehicle position in a short time and keep the vehicle near the centerline of the lane, which verifies the effectiveness of the control method.

In Fig. 16, from 0.5 to 1.5 s (Inside the dashed oval frame), the torque exceeds the set threshold. According to Fig. 3, the driver is operating. After 1.5 s, the torque is less than the set threshold and persists for some time. According to Fig. 3, the driver is not operating. From 0.5 to 1.5 s, there is driver operating when EPS works under conventional power steering mode and there is assist current in motor. After 1.5 s, there isn't driver operating. The system works under lane

Fig. 16 Parameters change in HIL case 2



keeping mode. If TLC is less than the set threshold, motor works to change front wheel angle and to adjust vehicle trajectory. If TLC is more than the set threshold, there is no assistance of the motor in the system. Results show that control method designed in this paper has coordinated control effects.

7 Conclusions

For coordinated control problems in Lane Keeping System based on EPS, a lane keeping coordinated control method considering TLC and judgment of driver's operating behavior has been proposed. Lane keeping simulation model was built based on this. Simulation study of control method and HIL experiments under relevant cases were done. Conclusions are as follows:

1. Lane keeping coordinated control method designed in this paper considers both driver's operating status and lane departure information and can solve coordinated control problems between conventional power steering component and lane keeping executive component when the driver has the highest priority, which is in line with reality.
2. Complete lane keeping simulation model based on EPS has been established by integrating lateral driver model, 7-DOF vehicle model, magic tire model and EPS model. The integrated model can simulate vehicle dynamics well while lane keeping process.
3. Simulation and HIL experimental results show that lane keeping coordinated control method designed in this paper can keep the vehicle in the lane and ensure traffic safety with good control effect.

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