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Application of Stackelberg Game Theory for Shared Steering Torque Control in Lane Change Maneuver *

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Abstract—**Human-machine interactions play a crucial role in determining driver-automation conflicts, as well as stabilities of the co-piloting system. Therefore, this paper proposed a Stackelberg-based shared control scheme to describe the driver-automation interactions, in which driver and electric power steering (EPS) system are modeled as game players. Both agents have their own target paths and give their torque control strategies to track the paths through a steering interface. The interactive pattern is deliberately designed dependent on the Stackelberg game principles, with driver the leader and EPS the follower to save more steering efforts for the driver. In the beginning, a dynamic model of the driver-automation system and path-tracking optimal control problem are given to describe the maneuver behavior of driver and EPS controller. In particular, a Stackelberg-based shared control scheme is adopted to deal with interaction patterns of the steering torque between the driver and EPS system. Furthermore, a Stackelberg equilibrium solution is derived by application of a model predictive control method. Numerical analyses are processed to validate the shared control algorithm in a lane change maneuver, and the related results show that the Stackelberg-based shared control scheme is capable of saving more maneuver force for driver than that of the Nash scheme. It indicates that the proposed scheme enables the driver-automation system to overtake or avoid collision easily, which may be conductive to understanding of the steering mechanism of intelligent co-pilot vehicles.**

I. INTRODUCTION

More than 70% of the road crashes are caused by human error [1]. The emergence of driver-automation co-piloting opens up a new frontier to enhance vehicle active safety. However, due to the mechanical connection between driver and EPS motor, steering strategies of both agents have strong mutual influences. The mutual influences, namely the driver-automation interaction, has not been modeled properly in the designing of steering assistance system, which leads to serious driver-automation conflicts or even instability of the co-piloting system [2]. Focusing on this issue, we proposes a Stackelberg-based shared control scheme for driver-automation shared path-tracking, where driver the leader derives his/her strategy by taking into account EPS'optimal responses to track his/her taget path, and EPS the follower reacts to the driver's steering maneuver by using its optimal response to make the vehicle follow its own target [3]. This leader-follower structure helps to model the driver-automation interaction and mitigate the conflicts between both agents.

The haptic guidance control is basically divided into model-free control and model-based control. For model-free control, the haptic force of the torque-overlay pattern in this research was obtained by the product of correcting angle and a stiffness term [4], which but the behavior of human driver and the driver-automation interaction were not considered adequately. In addition, while designing control strategies, the model-free schemes took little consideration about the steering dynamics, which plays an important role in the steering control. Therefore, model based haptic feedback control should be further investigated.

To better describe the driver steering behavior, many model-based control methods were taken to model the driver steering command [5], among which the model predictive control (MPC) method is a reasonable way and has been widely used [6]. Gerdes [7] provided a MPC based envelope control algorithm to realize steering shared control during obstacle avoidance, with assumption that the driver holds the same target path as the control system. In some dangerous circumstances, such as emergency collision avoidance, the target path of driver and machine may differ. To some extent, the leader-follower game based control structure can minimize human-machine conflicting, and might be more suitable to model the steering interaction between human and machine to reduce the control input of both sides and improve the stability of the co-pilot system [8]. Cole et al. established game based steering angle-overlay control framework [3], and it was found that the Nash and Stackelberg paradigms can reasonably represent the human-machine interaction during collision avoidance. But due to the mechanical decoupling between driver and front road wheel, these angle-overlay based approaches will weaken the driver-automation interaction and may deprive the driver's ultimate control authority during driving. Flad et al. tentatively established the Nash equilibrium based torque-overlay co-pilot mechanism with a simplified steering dynamics [9]. In summary, the previous work reviewed above primarily established the shared control methodology based on differential game. From author's point of view, the driver-automation interaction need to be reinforced with torque interaction mechanism by incorporating steering dynamics, and the Stackelberg based steering torque interaction problem should also be further studied to mitigate driver-automation conflicts and also save more steering effort for the driver. In addition, the application potential should also be evaluated preliminarily.

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This paper mainly concentrates on modeling of a novel torque-overlay based haptic feedback control to enhance human-machine steering interaction by refining the steering system dynamics, investigating Stackelberg game based shared control strategy with different human-machine target consistencies, and discussing the proposed controller's torque interaction with an feedback based external driver model.

The remaining parts of this paper are arranged as follows: modeling of steering and vehicle system dynamics is elaborated in section II, together with disturbance observer designing for steering resistance moment. Section III depicts the designing philosophy of Stackelberg game based shared control algorithm for a co-pilot path-tracking maneuver. Next, section VI presents the test road model for lane-keeping tasks and the corresponding simulation results are given. Finally, a brief conclusion is provided in section V.

II. Modeling of Steering and Vehicle System

A. Driver-Vehicle Dynamic Model

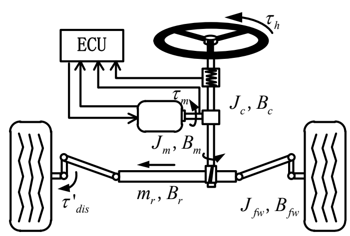


Figure 1. Path tracking and steering resistance torque observing performance with an identical human-machine target.

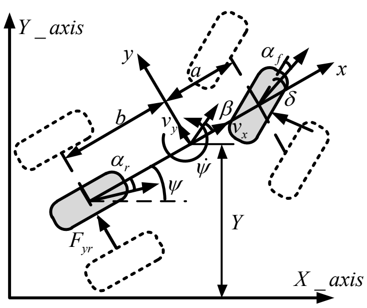


Figure 2. 2-DOF vehicle dynamic model used for path tracking.

Figures 1 and 2 show the brief structure of the steering interface and the vehicle lateral dynamics in this research. Considering the cascade relation between the driver-vehicle system and the 2-DoF vehicle lateral dynamics [9, 10], the six-order vehicle model can be defined as,

$$\begin{aligned} \dot{x} &= Ax + B_h\tau_h + B_m\tau_m + Nw \\ y &= Cx \end{aligned}, \qquad (1)$$

where $x=[\theta_{sw}\ \dot{\theta}_{sw}\ v_y\ \dot{\psi}\ \ Y\ \ \psi]^T$ represent steering wheel angle, angular velocity, vehicle lateral speed, yaw rate, lateral displacement, and yaw angle, respectively. And $y=[Y\ \psi]^T$. τ_h and τ_c are steering torques of driver and EPS motor, respectively. For the disturbance variable $w=\tau_f\,\mathrm{sgn}(\dot{\theta}_{sw})+\tau_{dis}$, τ_f refers to friction torque of the steering system, and τ_{dis} refers to steering resistance torque. The parameters of the steering and vehicle system are listed in Table I. The parameter matrices can be expressed as,

$$A=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -\dfrac{B_{eq}}{J_{eq}} & 0 & 0 & 0 & 0 \\ -\dfrac{C_f}{mN_s} & 0 & \dfrac{C_f+C_r}{mv_x} & \dfrac{aC_f-bC_r}{mv_x}-v_x & 0 & 0 \\ -\dfrac{aC_f}{I_zN_s} & 0 & \dfrac{aC_f-bC_r}{I_zv_x} & \dfrac{a^2C_f+b^2C_r}{I_zv_x} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & v_x \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix},\ C=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}^T,$$

$$B_h=\begin{bmatrix} 0 & \dfrac{1}{J_{eq}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,\ B_m=\begin{bmatrix} 0 & \dfrac{N_m}{J_{eq}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,\ N=\begin{bmatrix} 0 & -\dfrac{1}{J_{eq}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

where N_m and N_s are motion ratios of the steering motor reducer and the steering system, respectively. m is the vehicle mass; a and b are the distance from center of gravity to the front axle and rear axle, respectively. I_z is the moment of inertia of the vehicle, v_y is vehicle lateral speed, and C_f and C_r are the front and rear tire cornering stiffness, respectively.

TABLE I. Parameters of Steering System And Vehicle System

Steering system		Vehicle system	
J_{eq}[kg•m^2]	0.1	m [kg]	1406
B_{eq}[Nm•s/rad]	0.8	I_z[kg•m2]	1802
N_s[-]	15.8	C_f, C_r[N/rad]	-140000,-100000
N_m[-]	12	a, b [m]	1.016,1.562

The above combined system enables the driver and motor to manipulate the vehicle simultaneously to track the desired path, while the steering angle θ_{sw} is liberated to be a state variable. By discretizing the proposed continuous-time system (1) at a sample of T_s, the discrete-time system used for shared controller designing is obtained as,

$$\begin{aligned} x(k+1) &= A_d x(k) + B_{hd}\tau_h(k) + B_{md}\tau_m(k) + N_d w(k) \\ y(k) &= Cx(k) \end{aligned}, \qquad (2)$$

where

$$A_d=e^{AT_s},\ B_{hd}=B_h\int_0^{T_s} e^{A\tau}d\tau,\ B_{md}=B_m\int_0^{T_s} e^{A\tau}d\tau,\ N_d=N\int_0^{T_s} e^{A\tau}d\tau.$$

B. Luenberger Disturbance Observer

Due to the uncertain vehicle dynamics and highly nonlinear self-aligning torque variations, steering resistance torque cannot be directly acquired. Therefore, the steering resistance moment need to be observed to improve the path-tracking accuracy during human-machine interaction. A Luenberger observer is built to acquire this torque, which regards steering resistance torque as a state variable and observes this torque through steering angle and steering torque input. The basic structure of the observer can be derived from the dynamics of the steering system:

$$\begin{aligned} \dot{\hat{x}}_o &= (A_o - LC_o)\hat{x}_o + B_o u_o + Ly_o \\ \hat{y}_o &= C_o\hat{x}_o \end{aligned}, \qquad (3)$$

where $\hat{x}_o=\begin{bmatrix} \hat{\theta}_{sw} & \dot{\hat{\theta}}_{sw} & \hat{w} \end{bmatrix}^T$, $u_o=[\tau_h\ \ \tau_m]^T$, $\hat{y}_o=\hat{\theta}_{sw}$, $y_o=\theta_{sw}$, $C_o=[1\ \ 0\ \ 0]$,

$$A_o = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{B_{eq}}{J_{eq}} & -\frac{1}{J_{eq}} \\ 0 & 0 & 0 \end{bmatrix}, B_o = \begin{bmatrix} 0 & 0 \\ \frac{1}{J_{eq}} & \frac{N_m}{J_{eq}} \\ 0 & 0 \end{bmatrix}.$$

The feedback gain matrix $L=[l_1\, l_2\, l_3]^T$ determines poles of the observer. Since the system (3) is observable completely, the poles can be assigned arbitrarily by adjusting l_1, $l_2$and l_3. For the sake of observer stability, the poles of the disturbance observer must possess a negative real part. And the imaginary part of the poles need setting reasonably to ensure observer dynamic performance. Observing results of the steering resistance moment is used for game-based shared controller designing in next section.

III. SHARED STEERING TORQUE CONTROL

A. Shared Control Framework

The driver steering behavior during path-tracking can be reasonably simplified as a MPC controller [8], which provides steering torque command according to the road information. Given the shared control framework in this paper, the EPS control strategy is also designed as an identical MPC controller to derive a concise shared control law. Different from the conventional MPC method, the shared MPC control framework in this paper is modeled as a Stackelberg differential game, with the human driver being the leader and the EPS being the follower in this game. Let the predictive horizon and the control horizon of the shared MPC controller be n_p and n_c, and assuming that the disturbance torque w remaining unchanged within predictive horizon. The predicted outputs of the system in the next n_p steps can be formulated as,

$$Y_p(k) = \Psi x(k) + \Theta_h U_h(k) + \Theta_m U_m(k) + \mathrm{S}_d w(k), \quad (4)$$

where $Y_p(k) = \left[y(k+1\,|\,k) \quad y(k+2\,|\,k) \quad \cdots \quad y(k+n_p\,|\,k) \right]^T$,

$U_h(k) = \left[\tau_h(k) \quad \tau_h(k+1) \quad \cdots \quad \tau_h(k+n_c-1) \right]^T$,

$U_m(k) = \left[\tau_m(k) \quad \tau_m(k+1) \quad \cdots \quad \tau_m(k+n_c-1) \right]^T$,

$\Psi = \left[CA \quad CA^2 \quad \cdots \quad CA^{n_p-1} \right]^T$,

$\mathrm{S}_d = \left[CN \quad CN + CAN \quad \cdots \quad \sum_{i=1}^{n_p} CA_d^{i-1} N \right]^T$, and

$$\Theta_x = \begin{bmatrix} CB_{xd} & 0 & \cdots & 0 & 0 \\ CA_d B_{xd} & CB_{xd} & \cdots & 0 & 0 \\ \vdots & \vdots & \cdots & CB_{xd} & 0 \\ CA_d^{n_c-1} B_{xd} & CA_d^{n_c-2} B_{xd} & \cdots & CA_d B_{xd} & CB_{xd} \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ CA_d^{n_p-1} B_{xd} & CA_d^{n_p-2} B_{xd} & \cdots & CA_d^{n_p-n_c+1} B_{xd} & \sum_{i=0}^{n_p-n_c} CA^i B_{xd} \end{bmatrix}.$$

In the Stackelberg game, the leader driver and the follower EPS hold different target paths. Suppose that the lateral displacement and the yaw angle of the desired path is $y_r = [Y_r \quad \psi_r]^T$, then the reference outputs of the driver and the EPS within the control horizon can be expressed as follows:

$$R_h(k) = \left[y_{rh}(k+1) \quad y_{rh}(k+2) \quad \cdots \quad y_{rh}(k+n_p) \right]^T,$$

$$R_m(k) = \left[y_{rm}(k+1) \quad y_{rm}(k+2) \quad \cdots \quad y_{rm}(k+n_p) \right]^T.$$

B. Stackelberg Equilibrium Solution

The Stackelberg equilibrium solution based on MPC method is in general achieved by successively solving the following two problems:

$$V_2^{MPC} = \left\| \Gamma_{ym} \left[Y_p(k) - R_m(k) \right] \right\|^2 + \left\| \Gamma_{um} U_m(k) \right\|^2, \quad (5)$$

$$V_1^{MPC} = \left\| \Gamma_{yh} \left[Y_p(k) - R_h(k) \right] \right\|^2 + \left\| \Gamma_{uh} U_h(k) \right\|^2, \quad (6)$$

where Γ_{yx} and Γ_{ux}, ($x = h, m$) respectively represent the output and control input weighting matrices:

$\Gamma_{yx} = \mathrm{diag}\big(\underbrace{q_{yx}, q_{\psi x}, \cdots, q_{yx}, q_{\psi x}}_{2n_p}\big)$, $\Gamma_{ux} = \mathrm{diag}\big(\underbrace{q_{ux}, q_{ux}, \cdots, q_{ux}}_{n_c}\big)$,

$\Gamma_{\Delta ux} = \mathrm{diag}\big(\underbrace{q_{\Delta ux}, q_{\Delta ux}, \cdots, q_{\Delta ux}}_{n_c}\big)$.

By substituting equation (4) into (5) and (6), the cost functions of EPS and driver can be formulated as:

$$V_2^{MPC} = \left\| \Gamma_{ym} \left[\Theta_m U_m(k) - E_m(k) \right] \right\|^2 + \left\| \Gamma_{um} U_m(k) \right\|^2, \quad (7)$$

$$V_1^{MPC} = \left\| \Gamma_{yh} \left[\Theta_h U_h(k) - \mathrm{E}_h(k) \right] \right\|^2 + \left\| \Gamma_{uh} U_h(k) \right\|^2, \quad (8)$$

where

$$E_m(k) = R_m(k) - \Psi x(k) - \mathrm{S}_d w(k) - \Theta_h U_h(k) \quad (9)$$

$$E_h(k) = R_h(k) - \Psi x(k) - \mathrm{S}_d w(k) - \Theta_m U_m(k) \quad (10)$$

Distinguished from the Nash game, in the Stackelberg game, the leader driver moves first, and the follower EPS observes this move and moves next. Hence, the Stackelberg equilibrium can be found by backward induction [11]. For EPS system, the optimal control input is obtained by minimizing the equation (7), which can be equivalent to calculate the least-squares solution of the following equation:

$$\begin{bmatrix} \Gamma_{ym} \left(\Theta_m U_m(k) - E_m \right) \\ \Gamma_{um} U_m(k) \end{bmatrix} = 0. \quad (11)$$

The least-squares solution of (11) can be obtained by using the QR algorithm (represented by the backlash operator '\') :

$$U_m^*(k) = \left(\begin{bmatrix} \Gamma_{ym}\Theta_m \\ \Gamma_{um} \end{bmatrix} \backslash \begin{bmatrix} \Gamma_{ym} \\ 0 \end{bmatrix} \right) E_m = L_m E_m. \quad (12)$$

When choosing the optimal strategy, the leader driver takes the EPS's optimal strategy (12) into equation (10), and then the cost function (8) becomes:

$$V_1^{MPC} = \left\| \Gamma_{yh} \left[\Theta_h U_h(k) - R_h(k) + \Psi x(k) + \mathrm{S}_h w(k) + \Theta_m L_m E_m \right] \right\|^2 + \left\| \Gamma_{uh} U_h(k) \right\|^2. \quad (13)$$

By substituting equation (9) into (13), the optimal control input is also equivalent to calculate the least-squares solution of the following equation:

$$\begin{bmatrix} \Gamma_{yh}\left(\Theta_{h1}'U_h(k) - R_h(k) + \Theta_{m1}'R_m(k) + \Psi_1'x(k) + S_{d1}'w(k)\right) \\ \Gamma_{uh}U_h(k) \end{bmatrix} = 0 \quad (14)$$

And the optimal driver input $U_h^*(k)$ in Stackelberg game is expressed as,

$$U_h^*(k) = L_h'\left[R_h(k) - \Theta_{m1}'R_m(k) - \Psi_1'x(k) - S_{d1}'w(k)\right], \quad (15)$$

where, $\Psi_1' = \Psi_h - \Theta_m L_m \Psi_m$, $S_{d1}' = S_d - \Theta_m L_m S_d$, $\Theta_{m1}' = \Theta_m L_m$, $\Theta_{h1}' = \Theta_h - \Theta_m L_m \Theta_h$, and $L_h' = \left(\begin{bmatrix} \Gamma_{yh}\Theta_{h1}' \\ \Gamma_{uh} \end{bmatrix} \backslash \begin{bmatrix} \Gamma_{yh} \\ 0 \end{bmatrix}\right)$.

Equation (13) is the Stackelberg equilibrium solution for the leader driver. Substituting equation (15) into (12), we have the Stackelberg equilibrium solution for the follower EPS formulated as:

$$U_m^*(k) = L_m\left[T_2'R_h(k) + \Theta_{m2}'R_m(k) + \Psi_2'x(k) + S_{d2}'w(k)\right], \quad (16)$$

where $T_2' = -\Theta_h L_h'$, $\Theta_{m2}' = \mathrm{I} + \Theta_h L_h \Theta_{m1}'$, $\Psi_2' = -\Psi + \Theta_h L_h'\Psi_1'$, and $S_{d2}' = -S_d + \Theta_h L_h' S_{d1}'$.

In summary, the human-machine interaction based on Stackelberg equilibrium for path-tracking maneuver can be expressed as:

$$\begin{bmatrix} U_h^*(k) \\ U_m^*(k) \end{bmatrix} = \begin{bmatrix} L_h' & L_h'\Theta_{m1}' & L_h'\Psi_1' & L_h'S_{d1}' \\ -L_m T_2' & L_m\Theta_{m2}' & L_m\Psi_2' & L_m S_{d2}' \end{bmatrix} \begin{bmatrix} R_h(k) \\ R_m(k) \\ x(k) \\ w(k) \end{bmatrix}.$$

Then the first samples of $U_h^*(k)$ and $U_m^*(k)$ can be used to represent the Stackelberg game based human-machine shared control law:

$$\tau_h^*(k) = K_{rh1}R_h(k) + K_{rm1}R_m(k) + K_{x1}x(k) + K_{w1}w(k), \quad (17)$$

$$\tau_m^*(k) = K_{rh2}R_h(k) + K_{rm2}R_m(k) + K_{x2}x(k) + K_{w2}w(k), \quad (18)$$

where $[K_{rh1} \quad K_{rm1} \quad K_{x1} \quad K_{w1}]$ and $[K_{rh2} \quad K_{rm2} \quad K_{x2} \quad K_{w2}]$ are the first row of $[L_h' \quad L_h'\Theta_{m1}' \quad L_h'\Psi_1' \quad L_h'S_{d1}']$ and $[-L_m T_2' \quad L_m\Theta_{m2}' \quad L_m\Psi_2' \quad L_m S_{d2}']$, respectively.

Equations (17) and (18) respectively present the shared steering torque control strategy for the driver and EPS system, which is the Stackelberg equilibrium solution for the optimization problems (5) and (6). This strategy benefits the leader driver to take less steering effort during a path-tracking maneuver.

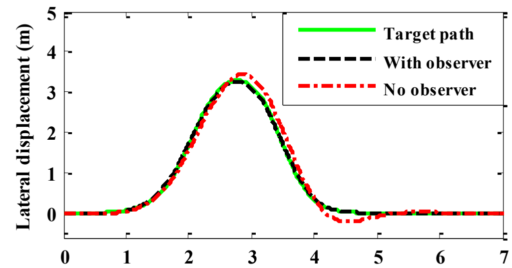
IV. Numerical Analysis

For validating the proposed Stackelberg game based shared control logic, numerical simulation is conducted by Simulink to evaluate the control effect. The shared control algorithm is encoded in Matlab S-Function while utilizing a 7-DoF nonlinear vehicle model as the controlled plant. To verify the proposed shared control framework comprehensively, the driving conditions of identical and conflicting human-machine target paths are investigated, whose simulating parameters are listed in Table 2.

TABLE II. Simulation Parameters for Identical and Conflicting Human-Machine Target Path.

Identical target path		Conflicting target path	
T_s	0.01s	T_s	0.01s
v_x	20 m/s	v_x	20 m/s
n_p	100	n_p	250
n_c	100	n_c	250
q_{yh}, q_{ym}	82,82	q_{yh}, q_{ym}	11,11
$q_{\psi h}$, $q_{\psi m}$	106,106	$q_{\psi h}$, $q_{\psi m}$	270,270
q_{uh}, q_{um}	2,1	q_{uh}, q_{um}	28,28

A. Disturbance Observer Performance



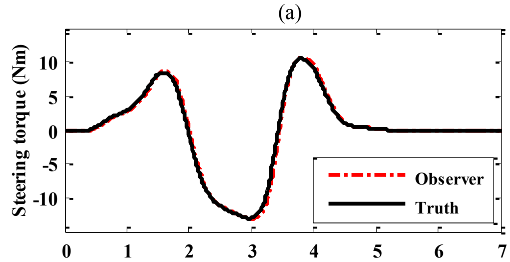


Figure 3. Path tracking and steering resistance torque observing performance with identical human-machine target.

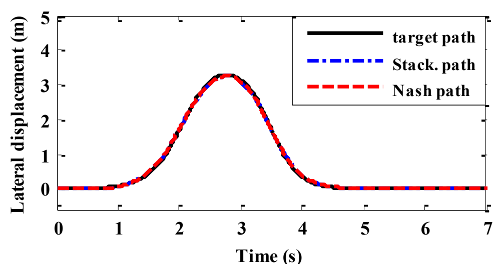
To better validate the role of the Luenberger disturbance observer in the path-tracking control, the EPS motor is set as the sole control input of the steering system (setting the driver weighting coefficients to be zero), then the shared controller degenerates into a typical MPC based path-following controller. The path-tracking performances of this controller with or without disturbance observer (Using observer value or zero as the disturbance information for the controller) are shown in Fig. 3(a) and Fig. 3(b), respectively, in which the truth disturbance torque τ_{dis} are derived from the 7-DoF nonlinear vehicle model with the following expression:

$$\tau_{dis} = \left[F_z n_\sigma \sin\sigma \sin\delta + F_y\left(r_\tau + n_p\right)\right]\cos\tau\cos\sigma, \quad (19)$$

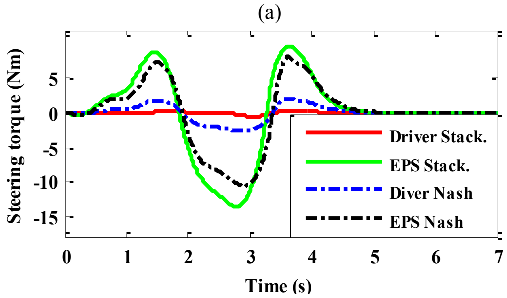
where σ and τ are the kingpin inclination angle and caster angle, respectively. n_σ and n_τ are lateral and trailing offsets at wheel center, respectively. r_τ is trailing offsets at the ground. The simulating results indicate that when the steering system is interfered by the steering resistance moment, the controller with disturbance observing information leads to better path tracking performance than that without the disturbance observer. Accordingly, the steering resistance moment obtained by disturbance observer is used by all of the subsequent simulations.

B. Game-Theoretic Solution

On condition that the driver and the EPS hold the same target path, the vehicle practical trajectory and the driver-automation interaction torque are shown in Fig. 4(a) and Fig. 4(b), respectively. Here it should be noted that the EPS steering torque shown in the figure is the equivalent torque about steering wheel to make intuitive comparison. To better illustrate the significance of the proposed Stackelberg framework, shared control scheme based on Nash game is presented to make comparison with the proposed strategy, and the Nash equilibrium solution is acquired by simultaneously solving cost function (7) and (8) [8]. The tracking performance implies that both game strategies are able to follow the target path well. The driver steering torque calculated by Stackelberg equilibrium strategy in Fig. 4(b) is much less than that solved by Nash equilibrium strategy, which means the game-based strategies can describe a large range of driver-automation interaction, thus different interactive patterns enable the individuals to choose their preferred steering assistance level. And the Stackelberg strategy saves more steering effort for the driver, which implies the proposed scheme assists the driver to overtake or avoid collision easier.



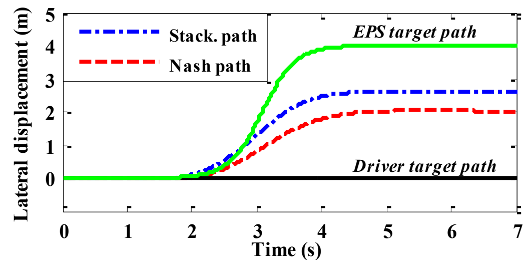
(a)



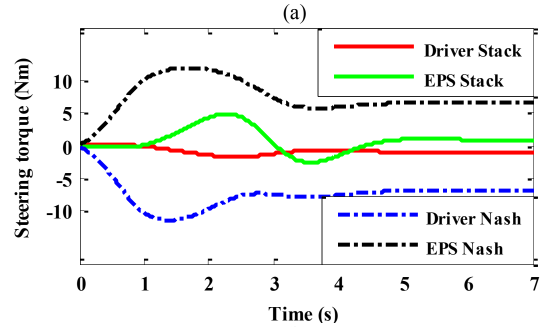
(b)

Figure 4. Path tracking performance and driver/EPS steering torque input with identical human-machine target during double lane change maneuver.

In some scenarios, the control system detects obstacles ahead of the vehicle and plans a single lane change path while the driver is not conscious of the dangerous and keeps driving straight, so the target paths of driver and EPS are conflicting. By setting identical driver and EPS weighting matrices as Tab.2, the vehicle trajectory and the interaction torque are shown in Fig. 5(a) and Fig. 5(b), respectively. In Fig.5(a), the final lateral displacement of Nash game strategy is located in the middle position between the driver and EPS target path, which means that the driver and the EPS have equal status in the game. The result vehicular path of Stackelberg game strategy finally comes closer to the EPS target path, but this do not means the EPS benefits more in the Stackelberg game. In fact, as is shown in Fig. 5(b), the driver with Stackelberg game strategy takes much less effort to maneuver the vehicle. By comparison, in Nash game, conflict between driver and EPS occurs at the beginning of the simulation and the steering torque of both players are so enormous that the steering torque is even beyond human limit. But owning to the leader-follower structure, the driver benefits more in the game and exert smaller torque in the conflicting lane change, thus the proposed strategy manage to mitigate the conflict torque between both agents.



(a)



(b)

Figure 5. Path tracking performance and driver/EPS steering torque input with conflicting human-machine target during single lane change maneuver.

C. Exclusive Interaction with an External Driver

When it comes to practical implementation, the control strategy of the human driver may not remain within the proposed game framework. Therefore, this subsection will tentatively investigate the interaction performance of the above EPS controller with an external driver model. While keeping the weighting parameters of the EPS controller invariant, a concise feedback based controller is adopted [12], to represent external driver model, which is depicted as follow:

$$\tau_h^* = K_{Yp} e_Y^{pre} + K_{Yd} \dot{e}_Y^{pre} + K_\psi e_\psi^{pre} , \tag{20}$$

where e_Y and e_ψ are the lateral and yaw error at the preview point, respectively, and proposed driver model is defined as a proportional-derivative (PD) controller. It is previously defined for $K_{Yp} = 0.6$, $K_{Yd} = 0.8$, and $K_\psi = 5$, dependent on the preview distance of 10 meters.

The path tracking and driver-automation interaction are shown in Fig. 6(a), (b) and Fig. 7(a), (b), respectively. On condition that the human and machine targets are identical in Fig. 6(a), and Fig. 6(b) indicates the EPS controller with Stackelberg strategy saves more steering effort for the driver than that with Nash strategy. But due to the external driver model, the torque interaction results are not located at the equilibrium point exactly, and the driver assisted by Stackelberg based EPS exerts larger effort than that in Fig.4. When the driver and the EPS hold the conflicting target path as is described in figure 7(a), it is found that the Nash EPS controller leads to an poor tracking performance. In comparison, the driver assisted by Stackelberg EPS controller achieves better path-following performance and meanwhile spends less steering effort, which means the potential application prospect of proposed Stackelberg based steering control strategy.

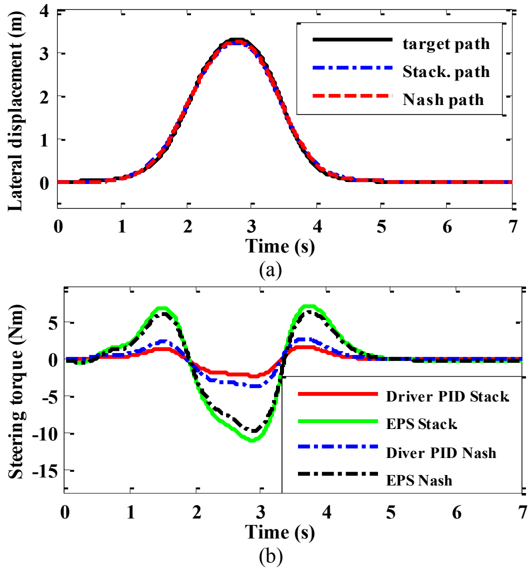


Figure 6. Path tracking performance and external driver model/EPS steering torque input with identical human-machine target during double lane change maneuver.

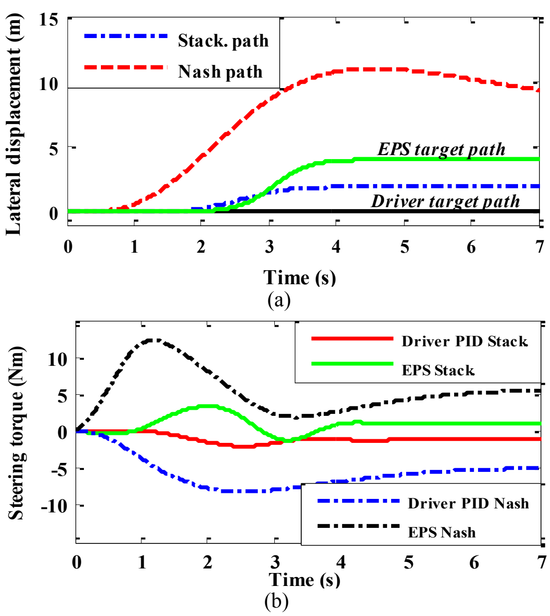


Figure 7. Path tracking performance and external driver model/EPS steering torque input with conflicting human-machine target during single lane change maneuver.

V. CONCLUSION

This paper proposed a Stackelberg-game-based shared control scheme for a path-tracking manipulation, to achieve a steering torque method considering human-machine interactions of intelligent co-pilot vehicle. After modeling of the steering and vehicle dynamics, the mechanism of driver-automation systems is analyzed, and an overall system is integrated to enable a reasonably overlaying of the steering torques from the driver and EPS system. Addtionally, a Luenberger observer is designed to acquire steering resistance torque to improve the path tracking accuracy. With respected to the shared controller, a model predictive control problem is demonstrated to obtain the Stackelberg equilibrium solution, for establishment of the steering interaction strategy.

The numerical analysis indicates that the proposed control strategy enables driver to take less effort to track target path accurately. On condition that the driver and EPS system hold conflicting targets, the presented shared controller enables the actual vehicle trajectory to approach to the collision avoidance path planed by EPS system, and save more labor than that of the Nash game strategy. Due to the Stackelberg-based shared control framework, the leader driver can benefit more by controlling the steering torque at Stackelberg equilibrium point during co-piloting path tracking.

On the other hand, it is validated that the proposed EPS controller can be considered for the engineering application by further studying of the interaction strategy with the external driver model. This novel control scheme is conductive to the designing of the co-pilot lane change controller and the relief of the human-machine conflicting.

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