Coordination of the Authority between the Vehicle Driver and a Steering Assist Controller

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Abstract: - Driver steering control performance varies with time during the vehicle driving course. A serial vehicle steering assist controller is designed to provide steering correction that can compensate the difference between the current driver and an "idealized" driver model. Using variable structure model reference adaptive control, a robust adaptive controller for lane keeping assist is developed. To reduce the complexity in control computations, a simplified version of the robust adaptive steering assist controller is also developed. Due to the significant variations in human driver behaviour, the stability of the compensated system is not guaranteed and conflict between the driver and the steering assist controller exist. A model predictive control based driver model and a dual-loop structure driver model are employed to represent the variations in driver intention, and the conflict between the controller and the driver is observed from computer simulations. A simple decision making algorithm is implemented and the conflict situations are successfully avoided for different driver behaviour modes and driving scenarios. Future work of this research will focus on implementing the designed controller on a driving simulator and experiments with human drivers on the driving simulator.

Key-Words: - vehicle steering assist, driver interaction

1 Introduction

Most vehicle crashes are caused by the mistakes of the human drivers. Several vehicle active safety systems have been developed and implemented to help the driver to avoid vehicle crashes. These active safety systems will eventually provide their functions while the human driver is still in control of his vehicle, and how the driver interacts with the designed active safety systems becomes an inevitable challenge. Considering the active safety systems developed for vehicle lateral control, the human driver steering behavior has a rich and well-developed literature. The human factor research indicates that three components are commonly observed in the guidance and control levels of human driving, namely, the precognitive, the pursuit, and the compensatory behavior [1]. In the control engineering community, several driver steering control models have been developed to represent the pursuit and compensatory behavior of the human driver. Specifically the well-known cross-over principle driver steering control model is developed (e.g., [2-4]), where the human driver is suggested to counter-balance the vehicle dynamics and maintain a consistent frequency responses near the cross-over frequency. A survey of the early driver steering control models has been presented by Reid in [5]. Furthermore, Hess and Modjtahedzadeh [6,7] augmented the cross-over principle model with the high frequency modes to represent the neuromuscular dynamics of the human driver. To describe the pursuit component in the driver behavior, the neural network and optimal control have been modified to include preview and used as the driver steering control model in [8-11]. These models developed in the literature have been found to be useful in representing different aspects of human steering control behavior. However, they are more complicated and application to controller design for active safety systems is difficult.

The driver models reported in the literature are mostly developed to describe the average driver behavior. They are useful in the analyses and simulations, however, for the control design purposes a simplified model with the potential to be updated on-line is more desirable. For this purpose, several time series based driver steering control model have been reported [12-14]. In this research, these driver steering control models are employed to benefit the design of vehicle active safety systems. Specifically, the variations in driver behavior are modeled as uncertainty in the driver model parameters, and a serial steering assist controller is to be designed using the adaptive control technique.

Lateral control of the vehicle can be performed completely by an active steering controller and such vehicles are generally termed autonomous vehicles, an example is presented in [15]. On the other hand, systems that only issue warning to the driver and has no direct control of vehicle steering has also been reported in the literature, as in [16]. With control authority in-between the above two extremes, the steering assist systems provide partial steering control action for the vehicle and the interactions between the driver and the controller worth particular attention. Due to the large uncertainty in the driving environment, the adaptive control technique has been applied to vehicle steering assist control, as reported in [17-19]. However, these papers describe the adaptive control with respect to vehicle parametric variations or the changes in the vehicle-road interaction, the driver variations are not considered. In [20,21], Chen *et al*. reported the development of a serial steering assist controller with respect to the driver model parametric uncertainty using the model reference adaptive control (MRAC). The driver is modeled as an unknown time-invariant, or slowly time-varying, linear system with input delay. The robust adaptive controller is developed based on this simplified driver model. While the presumed driver nature may be appropriate for the compensatory behavior during normal highway driving scenarios, the pursuit behavior and other human considerations may be more suitably modeled by other complex driver models, e.g. the optimal preview model and the neural network model (see [8-11] for example). The consequence of this difference is that the MRAC designed based on the simplified driver models may not function properly when the driver pursuits his goal (including trajectory tracking and driving comfort), and this may lead to a conflict situation between the driver and the controller. This conflict issue is seldom discussed in the steering assist controller design, and is usually avoided by limiting the control authority of the designed controller. The level of the control authority is largely determined by trial-and-error. The research reported in this article aims to design the relative control authority between the driver and the controller by implementing a decision making algorithm.

2 Vehicle/Driver Models and the Control Structure

The objective of this research is the problem arises from the inadequacy of the driver model used in the MRAC design. The problem is first illustrated using computer simulations since human behavior is not repeatable. The simulations include a vehicle model, a pursuit-oriented driver model, and a MRAC design. The models and the MRAC design will be presented in this section and the difference between the driver objective and the control objective will be evident in simulations. A simple decision making algorithm (Weight shift) will be presented in section 3 to resolve this conflict situation. Driving simulator experiments with human drivers will be conducted afterwards to verify the benefit of the decision making algorithm.

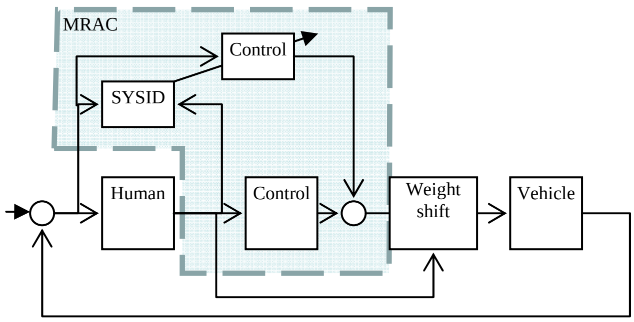

Fig. 1 Block diagram of the proposed control structure

2.1 Vehicle model

To investigate vehicle lateral motions, a dynamics model for the vehicle is needed. In this study, a 3DOF model for the lateral, yaw, and roll motions is adopted [22]. The basic structure of this model is briefly summarized below:

$$\begin{bmatrix} Y_\delta \\ N_\delta \\ 0 \\ 0 \end{bmatrix} \delta_f = \begin{bmatrix} mu & 0 & m_R h & 0 \\ 0 & I_z & I_{xz} & 0 \\ m_R hu & I_{xz} & I_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\beta} \\ \dot{r} \\ \dot{p} \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} -Y_\beta & mu - Y_r & 0 & -Y_\phi \\ -N_\beta & -N_r & 0 & -N_\phi \\ 0 & m_R hu & -L_p & -L_\phi \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ r \\ p \\ \phi \end{bmatrix} \tag{1}$$

and

$$m = m_R + m_{NR}$$
$$Y_\beta = -(C_{\alpha f} + C_{\alpha r})$$

$$\mathrm{Y_r} = \frac{bC_{\alpha r} - aC_{\alpha f}}{u}$$
$$Y_\phi = \mathrm{C}_{\alpha r}\frac{\partial \delta_r}{\partial \phi} + C_{rf}\frac{\partial r_f}{\partial \phi}$$
$$\mathrm{Y}_\delta = C_{\alpha f}$$
$$N_\beta = bC_{\alpha r} - aC_{\alpha f}$$
$$N_r = -\frac{a^2 C_{af} + b^2 C_{\alpha r}}{u}$$
$$N_\phi = aC_{rf}\frac{\partial r_f}{\partial \phi} - bC_{\alpha r}\frac{\partial \delta_r}{\partial \phi}$$
$$N_\delta = aC_{\alpha f}$$
$$L_p = -c_R$$
$$L_\phi = m_R g h - k_R$$

where δ_f is the vehicle front steering angle, β is the side slip angle, r is the vehicle yaw rate, ϕ and p are the vehicle roll angle and roll rate respectively. m is the total vehicle mass, including the sprung mass (m_R) and the un-sprung mass (m_{NR}). h is the distance form the roll axis to CG, a is distance from front to CG, b is distance from rear to CG, I_z is moment of inertia about z-axis, I_x is moment of inertia about x-axis, I_{xz} is product of inertia about x-z axes, k_R is effective suspension roll stiffness, c_R is effective suspension roll damping coefficient. The coordinate system is defined according to the SAE convention.

Equation (1) can be denoted as $E\dot{x} + Fx = G\delta_f$, assuming constant vehicle speed, the state space model of the form $\dot{x} = Ax + B\delta_f$ is yielded, where $A = -E^{-1}F$ and $B = -E^{-1}G$.

2.2 VSMRAC steering assist controller

A vehicle steering assist controller [21] designed using the Variable Structure Model Reference Adaptive Control (VSMRAC) is employed in this study. The VSMRAC is designed to address the delay and parametric uncertainty in the driver model, and the Lyapunov Stability Theorem is applied to ensure the stability of the compensated system. The control structure of the VSMRAC is shown in Fig. 2.

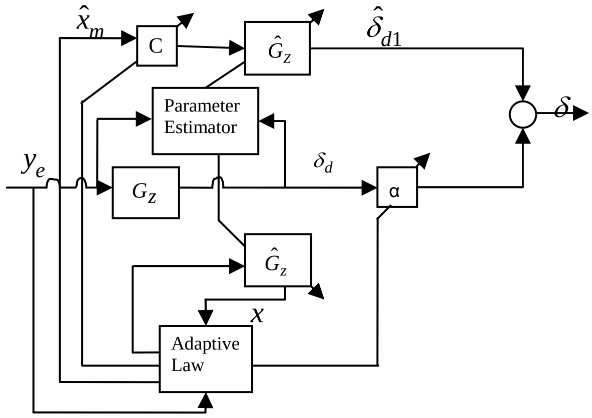

Fig. 2 Structure of the VSMRAC [21]

The driver model structure is assumed to be of the form:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t-h) \\ x(t_0) &= x_0 \end{aligned} \tag{2}$$

where $x(t) \in R^n$ is the state variable, $u(t) \in R$ is the input variable of the driver, in this study the input to the driver is assumed to be the vehicle lateral position error. h>0 is a known input delay.

The control objective is the select $u(t)$ such that $e(t)$ converges to zero

$$\lim_{t\to\infty} e(t) = \lim_{t\to\infty}(x(t) - x_m(t)) = 0 \tag{3}$$

let the control $u(t)$ be of the form

$$u(t) = c(t)\hat{x}_m(t+h\,|\,t) + \alpha(t)u_m(t) \tag{4}$$

where $c(t) \in R^{1\times n}$ and $\alpha(t) \in R$ are the adaptation terms to achieve reference model tracking, $\hat{x}_m(t+h\,|\,t)$ is the predicted state variables based on the reference model, defined in the following equations:

$$\dot{z}(t) = A_m z(t) + B_m u_m(t) \tag{5}$$
$$z(t_0) = x_m(t_0) \tag{6}$$
$$x_m(t+h\,|\,t) = z(t) + e^{A_m h}[x_m(t) - z(t-h)] \tag{7}$$

and $z(t) \in R^n$ is the predictor state variable. With the introductions of an auxiliary model and an appropriate sliding function, the update laws of the adaptation gains can be determined by examining the derivative of the Lyapunov function. Thus the stability of the designed VSMRAC can be assured. The details of the control derivations can be found in [21].

2.3 Robust MRAC steering assist controller

Since the VSMRAC is complicated in computations, and the advantage of the predictor and the sliding mode control is not fully justified, a simpler robust adaptive vehicle steering assist controller design is attempted in this research. The procedures described in [23,24] are followed closely and a robust MRAC controller that can handle model parametric uncertainty and input disturbance is developed. The structure of the robust MRAC is shown in Fig. 3. This controller uses only output feedback and has the advantage of eliminating the need for an abstract observer in the future. The stability of the system is assured by Lyapunov stability theorem, and the robustness to input disturbance is achieved by a compensating term determined based on the output error. The controller design is briefly outlined as follow:

Consider the plant to control as a linear system with unknown parameters.

$$\begin{aligned} \dot{x}_p &= A_p x_p + B_p u \\ y_p &= h_p^T x_p \end{aligned} \tag{8}$$

It can be expressed in transfer function form as:

$$G_p(s) = k_p \frac{Z_p(s)}{R_p(s)} = h_p^{\ T}(sI - A_p)^{-1} B_p \tag{9}$$

where $Z_p(s)$ is an unknown Hurwitz polynomial of order *n-1*, $R_p(s)$ is an unknown polynomial of order n, and k_p is an unknown gain with fixed sign. Let the reference model to track be:

$$G_m(s) = k_m \frac{Z_m(s)}{R_m(s)} \tag{10}$$

The controller is designed as:

$$u = kr + \theta_1^T \omega_1 + \theta_0 y_p + \theta_2^T \omega_2 \tag{11}$$

with

$$\dot{\omega}_1 = \Lambda \omega_1 + \ell u$$

$$\dot{\omega}_2 = \Lambda \omega_2 + \ell y_p$$

let

$$\omega(t) = [r(t),\ \omega_1^T(\mathrm{t}),\ \mathrm{y_p(t)}\ \ \omega_2^T(t)]^T$$

$$\theta(\mathrm{t}) = [\mathrm{k(t)},\ \theta_1^{\mathrm{T}}(\mathrm{t}),\ \theta_0(\mathrm{t}),\ \theta_2^{\mathrm{T}}(\mathrm{t})]^{\mathrm{T}}$$

and we have

$$\mathrm{u} = \theta^{\mathrm{T}}(t)\omega(t) \tag{12}$$

where $k: R^+ \to R$, $\theta_1, \omega_1 : R^+ \to R^{n-1}$, $\theta_0 : R^+ \to R$, $\theta_2, \omega_2 : R^+ \to R^{n-1}$, and Λ is an asymptotically stable matrix. Substituting the *u(t)* in the equation (8) and defining $\tilde{K} = k - k^*$, $\tilde{\theta}_1 = \theta_1 - \theta_1^*$, $\tilde{\theta}_0 = \theta_0 - \theta_0^*$, $\tilde{\theta}_2 = \theta_2 - \theta_2^*$ for change of variables, and $\phi = [\tilde{K}\quad \tilde{\theta}_1^T \quad \tilde{\theta}_0 \quad \tilde{\theta}_2^T]^T$, we yield

$$\begin{aligned} \dot{x}_p &= A_p x_p + B_p(kr + \theta_1^T \omega_1 + \theta_0 y_p + \theta_2^T \omega_2) \\ &= A_p x_p + B_p k^* r + B_p \theta_1^{*T} \omega_1 + B_p \theta_0^* \ y_p + B_p \theta_2^{*T} \omega_2 \\ &\quad + B_p \begin{bmatrix} \tilde{K} & \tilde{\theta}_1^T & \tilde{\theta}_0 & \tilde{\theta}_2^T \end{bmatrix} \begin{bmatrix} r \\ \omega_1 \\ y_p \\ \omega_2 \end{bmatrix} \\ &= A_p x_p + B_p k^* r + B_p \theta_1^{*T} \omega_1 + B_p \theta_0^* \ y_p \\ &\quad + B_p \theta_2^{*T} \omega_2 + B_p \phi^T \omega \end{aligned} \tag{13}$$

and

$$\begin{aligned} \dot{\omega}_1 &= \Lambda \omega_1 + \ell(kr + \theta_1^T \omega_1 + \theta_0 y_p + \theta_2^T \omega_2) \\ &= (\Lambda + \ell \theta_1^{T^*})\omega_1 + \ell k^* r + \ell \theta_0^* \ h_p^{\ T} x_p \\ &\quad + \ell \theta_2^{*T} \omega_2 - \ell \phi^T \omega \end{aligned} \tag{14}$$

$$\begin{aligned} \dot{\omega}_2 &= \Lambda \omega_2 + \ell y \\ &= \Lambda \omega_2 + \ell h_p^{\ T} x_p \end{aligned} \tag{15}$$

Collecting terms and define $x = \begin{bmatrix} x_p^T & \omega_1^T & \omega_2^T \end{bmatrix}^T$, the equations can be simplified as

$$\begin{aligned} \dot{x} &= A_{mn} x + b_{mn}[\phi^T \omega + k^* r] \\ y_p &= h_{mn}^T x \end{aligned} \tag{16}$$

where

$$A_{mn} = \begin{bmatrix} A_p + B_p \theta_0^{*T} h_p^{\ T} & B_p \theta_1^{*T} & B_p \theta_2^{*T} \\ \ell \theta_0^* h_p^{\ T} & \Lambda + \ell \theta_1^{*T} & \ell \theta_2^{*T} \\ \ell h_p^{\ T} & 0 & \Lambda \end{bmatrix}$$

$$b_{mn} = \begin{bmatrix} B_p k^* \\ \ell \\ 0 \end{bmatrix}$$

$$h_{mn} = \begin{bmatrix} h_p^T & 0 & 0 \end{bmatrix}^{\mathrm{T}}$$

Similarly the reference model is converted as

$$\begin{aligned} \dot{x}_{mn} &= A_{mn} x_{mn} + b_{mn} k^* r \\ y_m &= h_{mn}^T x_{mn} \end{aligned} \tag{17}$$

with $x_{mn} = \begin{bmatrix} x^{*T}_{\ p} & \omega^{*T}_{\ 1} & \omega^{*T}_{\ 2} \end{bmatrix}^T$

Define the errors as $e = x - x_m$ and $e_y = y_p - y_m$, the following function is a suitable Lyapunov function

$$V = \frac{1}{2}(e^T pe + \frac{1}{|k_p|}\phi^T \phi) \tag{18}$$

Differentiating V with time,

$$\dot{V} = \frac{1}{2}(\dot{e}^T pe + e^T p\dot{e} + \frac{2}{|k_p|}\phi^T \dot{\phi})$$

$$= -e^T Qe + \frac{1}{|k_p|}(\text{sgn}(k_p)e_y\omega + \dot{\phi})\phi^T \quad (19)$$

The natural choice of the adaptation term is $\dot{\phi} = -\text{sgn}(k_p)e_y\omega$ and this will yield the Lyapunov function *V(t)* to be negative definitive.
Considering the existence of the input disturbance, according to [24] the error equation is written as

$$\dot{e} = A_{mn}e + b_{mn}\phi^T\omega + b_{mn}d(t) \quad (20)$$

Assuming an upper bound of the input disturbance can be determined, i.e., $|d(t)| \le \bar{d}$, a robust term to address the input disturbance can be designed as $u_s = -\bar{d}\,\text{sgn}(e_y)$ and added to the control equation (12). Using the same Lyapunov equation the modified control law will ensure negative definiteness of the $\dot{V}$ term.

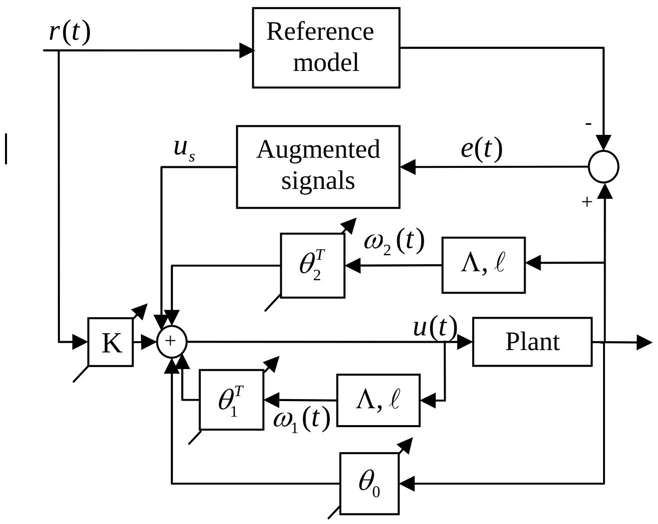

Fig. 3 Structure of the Robust MRAC [23]

2.4 Driver steering control model

Although in the design of the VSMRAC the driver is modeled as a simple linear system with delay, in the simulations the driver model is replaced by a pursuit oriented driver model. In [25] Ungoren and Peng reported a Model Predictive Control (MPC) based driver model and intended to use the model update to represent the driver adaptation. In this study this MPC based driver model is employed and with the adaptation part removed. As indicated in [25], the resulting model is in effect very similar to the optimal preview driver model presented by MacAdam in [9]. The structure of the MPC driver model is shown in Fig. 4. Effectively, the MPC driver model is minimizing a cost function based on a sliding function to account for the future trajectory tracking error and error rate. The future trajectory is predicted based on a linear vehicle model. Different weighting functions and coefficients can be tuned to represent different driver behavior. For the detailed control implementation and computations the interested readers are referred to [25] and [26] for references.

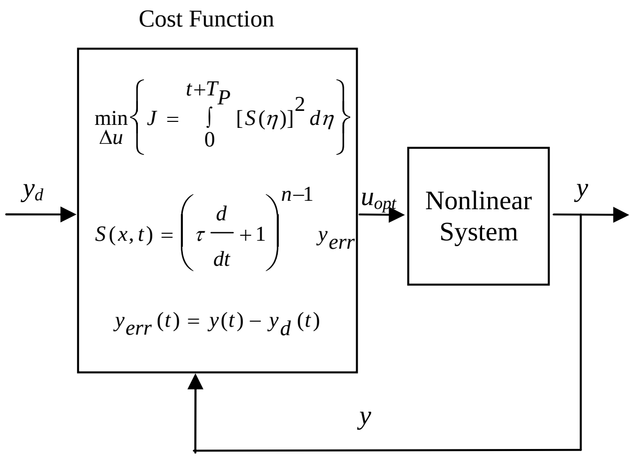

Fig. 4 MPC Driver model structure [25]

2.5 Simulations

With the vehicle model, driver model, and the VSMRAC, computer simulations are conducted to validate the stability of the compensated systems. The stability of the VSMRAC with constant linear driver model with delay has already been verified in [21], as guaranteed by Lyapunov Stability Theorem. However, when using the pursuit oriented driver steering control model, such as the model predictive control (MPC) driver model, the situation is similar to using a variable gain driver model in the simulations and the gain variations can be significant. Consequently the assumptions used to develop the VSMRAC are not valid and the closed-loop system may not be stable. For carefully tuned MPC driver model, the simulations results show that the VSMRAC still performs reasonably well during a continuous lane change type scenarios. This implies that with this set of MPC driver model parameters, the difference between the MPC driver model and the assumed structure in VSMRAC is not significant. The robustness of the VSMRAC is capable to handle the discrepancy. However, Fig. 5 to Fig. 7 show the same simulations with another set of MPC driver model parameters. In this case, the MPC driver model corresponds to a driver trying to track his future goal which is significantly different than what is assumed in the VSMRAC. Therefore, it is evident that in the second cycle of the lane changes (near 70sec) the driver steering angle (δ_d) starts to increase and the VSMRAC output (δ_c) exhibits radical modifications. Consequently the closed-loop system becomes unstable. Furthermore, a second set of simulations is presented where the driver model is close to the assumed driver model in the MRAC design, however, in this case the desired tracking of the controller is different from the desired tracking of the driver model. This corresponds to the situation where the driver wants to track a reference trajectory where the controller is not capable to perceive. In Fig. 8 and Fig. 9 it is again obvious that the conflict between the driver and the controller exists.

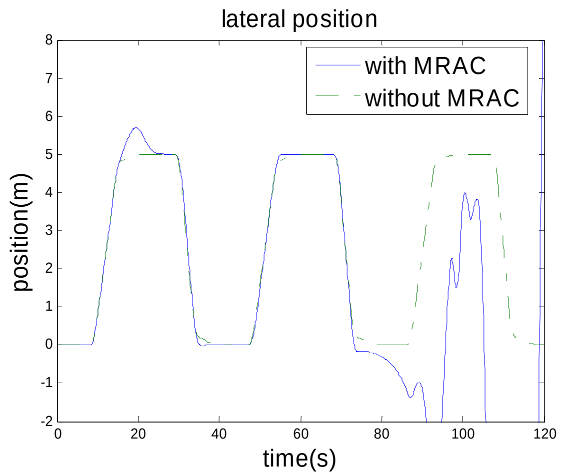

Fig. 5 Simulations with MPC driver model and VSMRAC: Lateral position

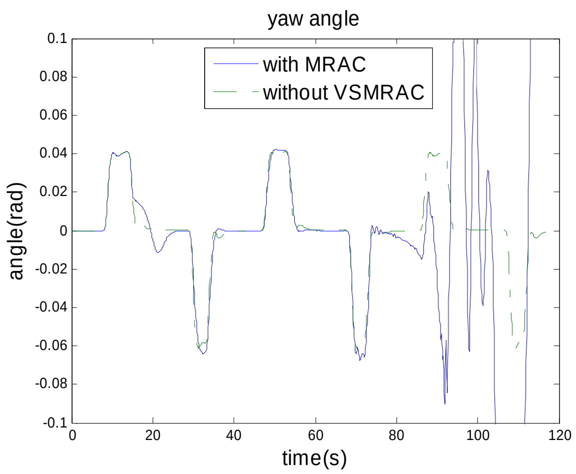

Fig. 6 Simulations with MPC driver model and VSMRAC: Yaw angle

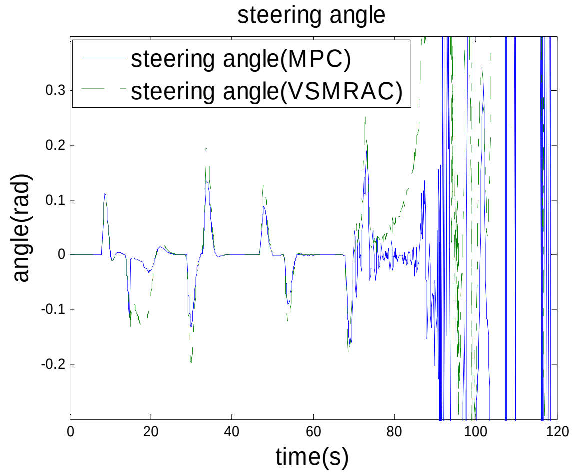

Fig. 7 Simulations with MPC driver model and VSMRAC: Steering angle

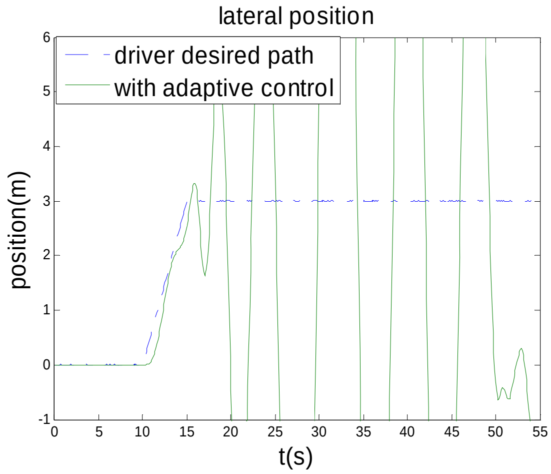

Fig. 8 Simulations of different desired trajectory: lateral position

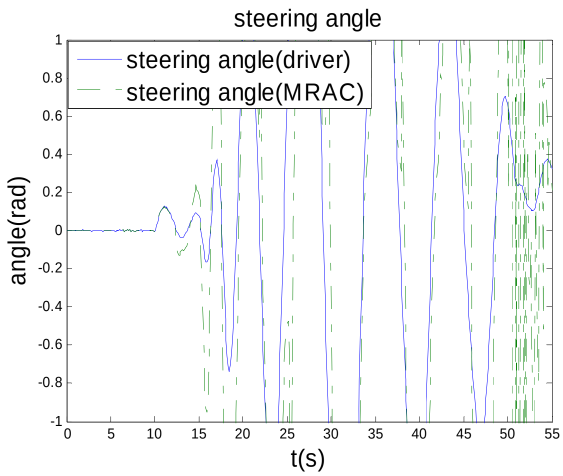

Fig. 9 Simulations of different desired trajectory: steering angle

3 The Decision Making Algorithm and Simulations

3.1 Control authority shifting

Using the structure presented in Fig. 1, the control authority shifting strategy is designed as a leverage rule adjusted by a factor β. That is, the actual steering input to the vehicle is

$$\delta_S = \beta\delta_c + (1-\beta)\delta_d \quad (21)$$

and $0 \le \beta \le 1$ is the shifting parameter to be design. Clearly the controller has no effect when β=0 and full control when β=1. In other words, β indicates the steering assist level, with 1 indicating full assist and 0 indicating driver override. For consistent vehicle steering characteristics, eventually β must reach a steady state value. This steady state value, β_r, relies on the current driver state to determine its value. A driver state assessment system, e.g., the on presented in [27], need to be incorporated to provide this function. For example, when the difference between the control action and the driver action is observed, β_r will be set to 1 only when the driver is assessed as absolutely fatigue and will be 0 otherwise. This means that the driver is allowed to override the control action unless the controller can be certain that the driver is 100% fatigue. While this idea is still highly arguable, it is beyond the scope of this paper. In this paper the adjustment of β during the short duration before it converges to the steady state value is of concern. It is proposed to use a simple adjusting rule commonly seen in adaptive control literature to tune the value of β, i.e.,

$$\dot{\beta} = -k(\beta - \beta_r) \quad (22)$$

and k determines the converging rate of β and can be adjusted to achieve the desired converging rate.

3.2 Simulations with the control authority shifting

The designed robust adaptive steering assist controller together with the control authority shifting strategy are evaluated using computer simulations with different driver models and driving scenarios. In this section several different driving scenarios are presented to illustrate the performance of the proposed strategy. In cases 1-1 and 1-2, the driver is modeled as a MPC regulator with different controller parameters. The driver model parameters for case 1-2 correspond to a lower performance driver behavior as an attempt to model a fatigue driver. For case 1-1, at 15 sec simulation time the driver decides to change lane while the controller is not aware of this change. The simulation results of case 1-1 are presented in Fig. 10-12. It is observed that once the difference between the driver and controller actions become significant, the control authority shifting algorithm starts and eventually β=0, indicating successful override from the driver. For case 1-2, it is assumed that the lane departure is not intended by the driver and is due to the inadequacy in driver steering control. Fig. 13-15 show the simulation results for case 1-2. The shifting algorithm once again attempts to let the driver override but eventually when the tracking error decreases the steering assist becomes effective again.

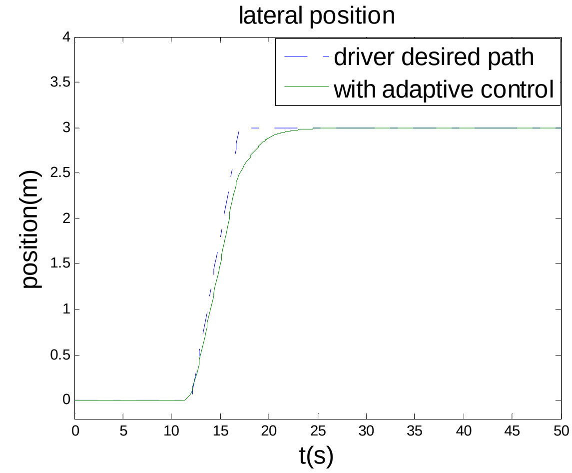

Fig. 10 Simulations of steering assist with authority shifting: case 1-1, lateral position

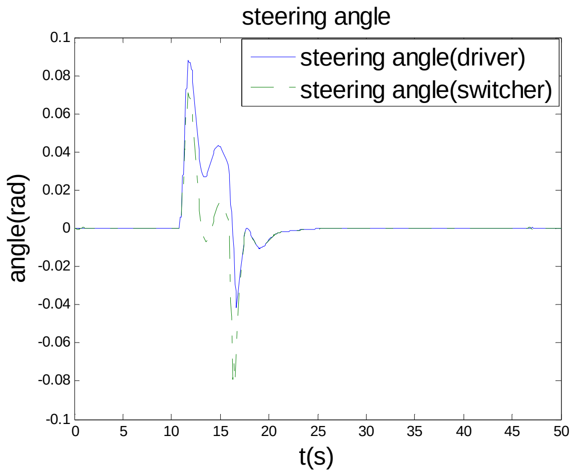

Fig. 11 Simulations of steering assist with authority shifting: case 1-1, steering angle

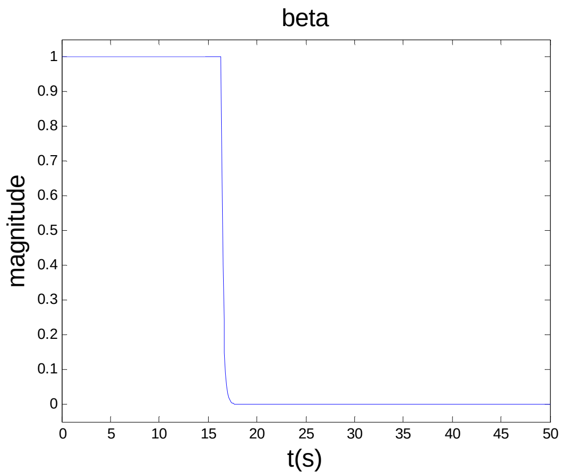

Fig. 12 Simulations of steering assist with authority shifting: case 1-1, β

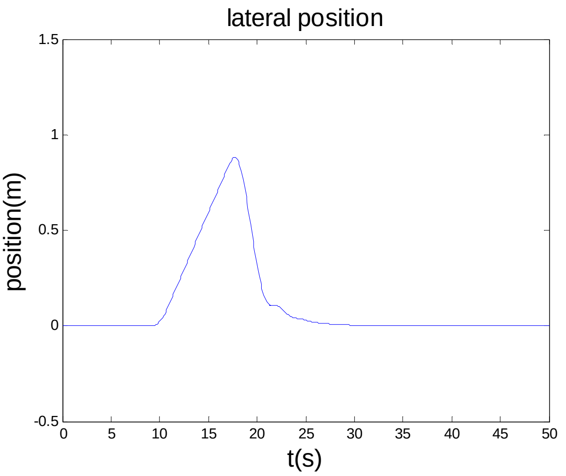

Fig. 13 Simulations of steering assist with authority shifting: case 1-2, lateral position

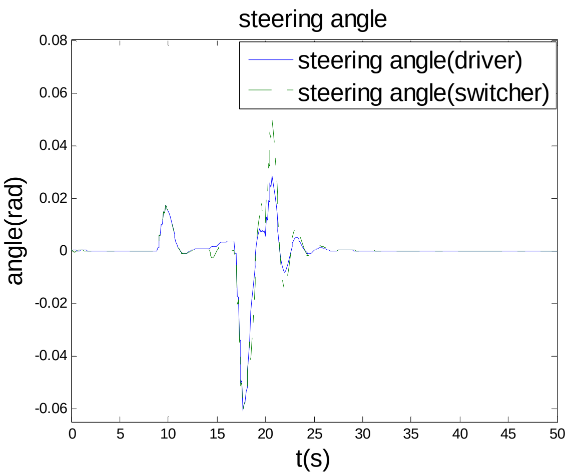

Fig. 14 Simulations of steering assist with authority shifting: case 1-2, steering angle

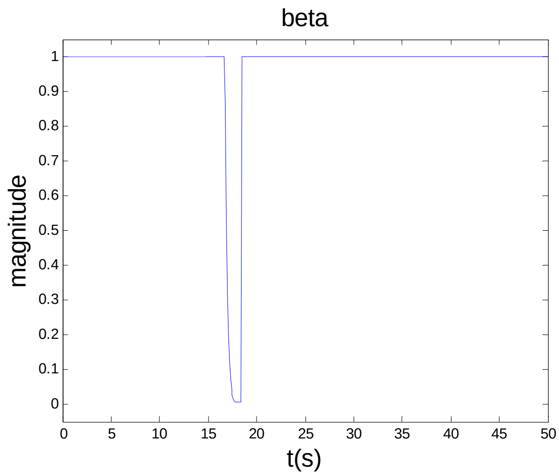

Fig. 15 Simulations of steering assist with authority shifting: case 1-2, β

In cases 2-1, 2-2, and 2-3, the driver steering control is modeled by a dual-loop structure (STI model) as presented in [3]. The parameters of the STI driver model are selected artificially to represent a driver with higher fatigue level. The difference between this set of simulations and cases 1-1, 1-2 is primarily on the complexity of the driver steering control model used. While the STI driver model in effect is very close to the driver model structure used in the controller design, the MPC driver model used in cases 1-1, 1-2 is significantly different by nature. Consequently, the robustness requirements for the simulations in cases 2-1, 2-2, and 2-3 mainly come from the driver model parametric uncertainty and the error in the desired trajectory.

In case 2-1 the driver is assumed to execute a lane change maneuver which is not specified to the controller. The simulation results of case 2-1 are shown in Fig. 16-18. It is observed that once the lateral deviation becomes large, the controller subsides and eventually the driver is in full-control. In case 2-2 the driver is assumed to perform the lane keeping task, and all the lateral deviations are due to the tracking error of the specified driver steering control model. Fig. 19-21 show the simulation results. It is observed that in this case the lateral position error is never too large to indicate the conflict between the driver and the controller, and hence the control authority shifting algorithm is not initiated. The MRAC steering assist controller continues to assist the vehicle steering and β=1 during the complete simulations. To exaggerate the performance degradation of the driver, the STI driver model parameters are tuned again to represent a even lower performance driver. This choice of driver model can be considered as modeling a high fatigue level driver. The simulation results presented in Fig. 22-24 indicate the increase of lateral position error and the corresponding decrease of β. However, because in this case the driver is still a stabilizing controller, eventually the lateral position error decreases and the lane keeping assist function is effective.

The above simulation results indicate that the proposed robust adaptive lane keeping assist controller can improve the lane tracking performance, and the control authority shifting algorithm allows the driver to override the steering assist controller when needed. These simulation results help maturing the design concept. With the promising results from the simulations, the designed structure will be evaluated with human drivers on a driving simulator. Currently the vehicle dynamics simulation software tool CarSimRT® from the Mechanical Simulations Co. is acquired and used to construct a driving simulator in the lab, as shown in Fig. 25. The designed lane keeping assist controller and the control authority shifting algorithm will be implemented on the simulator and human-in-the-loop driving simulator experiments will be conducted.

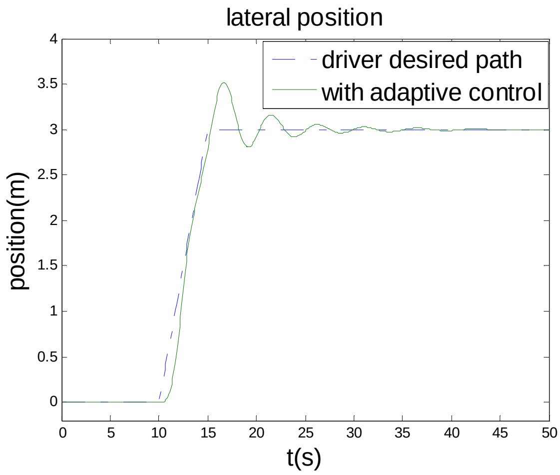

Fig. 16 Simulations of steering assist with authority shifting: case 2-1, lateral position

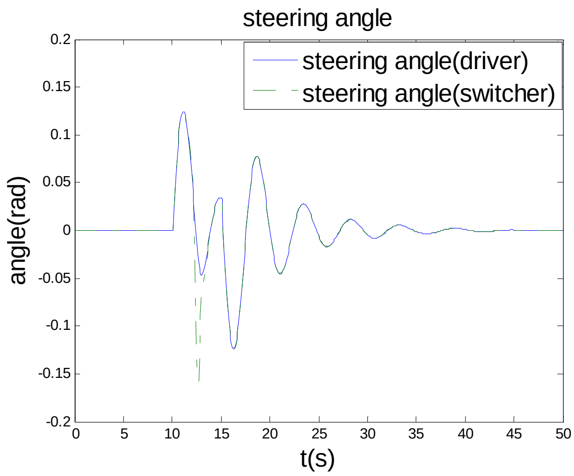

Fig. 17 Simulations of steering assist with authority shifting: case 2-1, steering angle

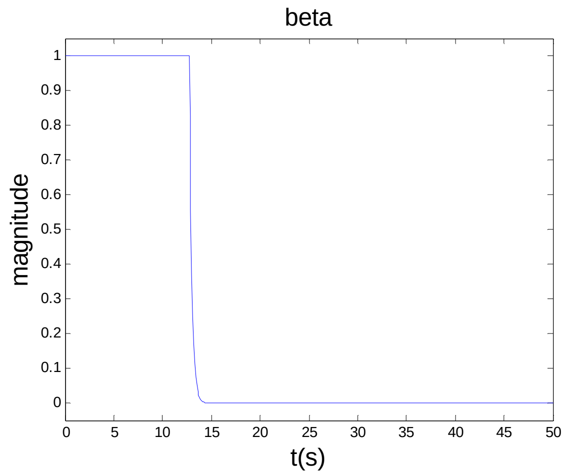

Fig. 18 Simulations of steering assist with authority shifting: case 2-1, β

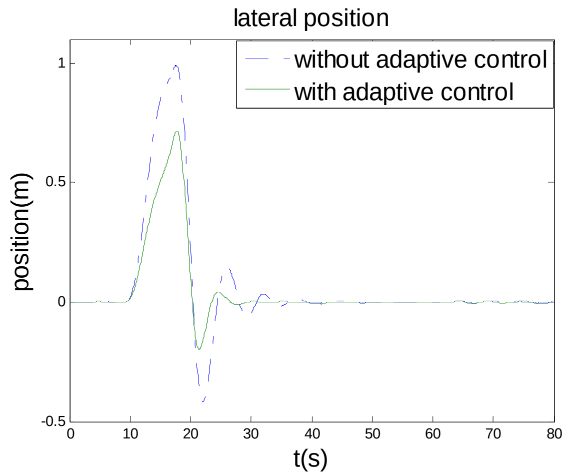

Fig. 19 Simulations of steering assist with authority shifting: case 2-2, lateral position

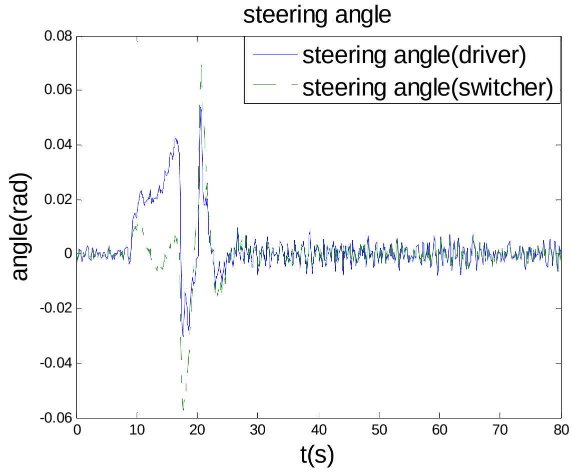

Fig. 20 Simulations of steering assist with authority shifting: case 2-2, steering angle

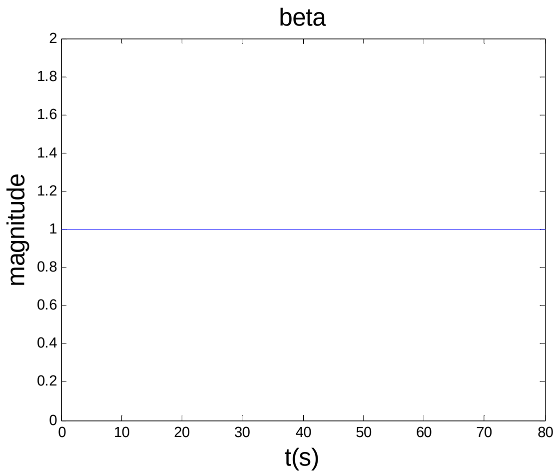

Fig. 21 Simulations of steering assist with authority shifting: case 2-2, β

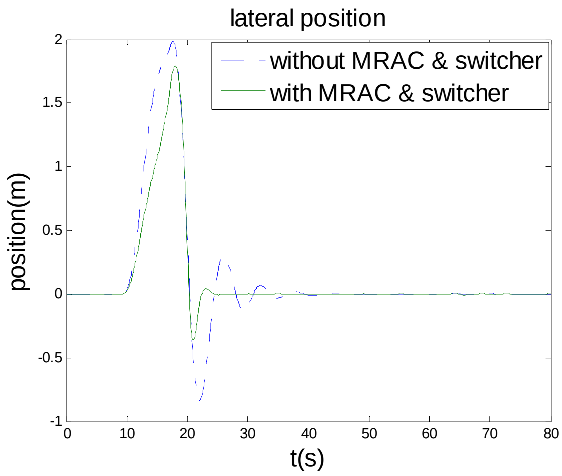

Fig. 22 Simulations of steering assist with authority shifting: case 2-3, lateral position

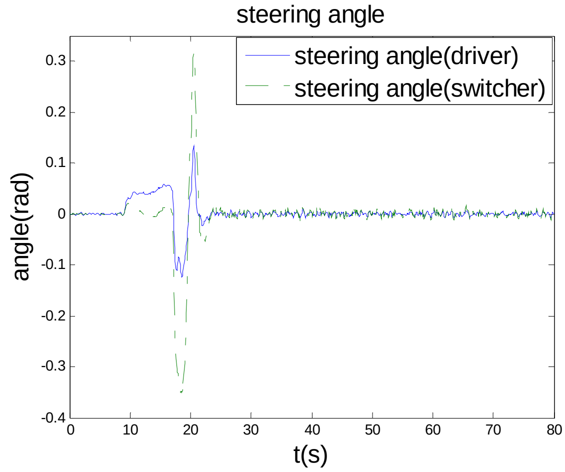

Fig. 23 Simulations of steering assist with authority shifting: case 2-3, steering angle

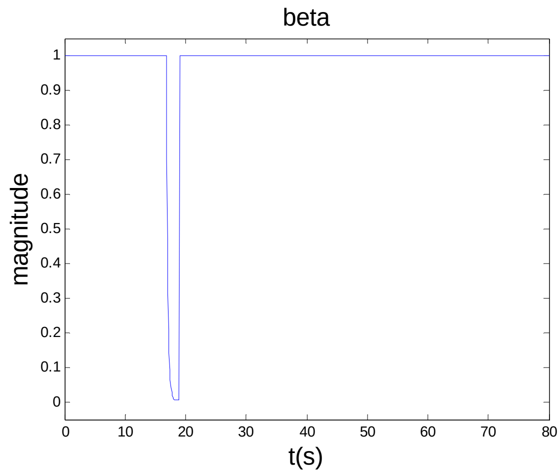

Fig. 24 Simulations of steering assist with authority shifting: case 2-1, β

Fig. 25 CarSim driving simulator scene

4 Conclusion

In this research the conflict between a steering assist controller and the human driver is investigated using computer simulations. The steering assist controller is designed based on a simplified driver steering control model, and a variable-structure model reference adaptive control is proposed to address the delay and parametric uncertainty in the driver model. As an attempt to reduce the control complexity, a simplified robust adaptive control for steering assist is also developed. In the simulations the driver steering behaviour is modelled by different driver control models, e.g., model predictive control, to represent different control strategies commonly reported in the literature to represent realistic human driving behaviour. Due to the violation of the assumptions made in the control derivations, the stability of the compensated system is not guaranteed and the simulations illustrate the conflict between the driver command and the controller actions. A simple decision making algorithm is programmed to shift the control authority of the steering assist controller whenever the difference between the driver command and the controller output is too large. The computer simulation results indicate that this shifting successfully avoid the conflicting situations when the driver model is a reasonably well steering controller. An on-line driver state assessment algorithm need to be incorporated to the decision of the final control authority. Future work of this research will include the driving simulator experiments with the human driver to validate the designed steering assist system and the control authority shifting algorithm.

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References:

[1] D.H. Weir and D.T. McRuer, Measurement and Interpretation of Driver Steering Behavior and Performance, *SAE Preprint* n. 730098 for Meet Jan. 1973, p8-12.

[2] G.N., Ornstein, The Automatic Analog Determination of Human Transfer Function Coefficients, *Medical and Biological Engineering*, 1, 1963, 377 – 387.

[3] D.T. McRuer, R.W. Allen, D.H. Weir, and R.H. Klein, New Results in Driver Steering Control Models, *Human Factors*, v19, n4, 1977, p 381-397.

[4] R.W. Allen, T.J Rosenthal, and H.T. Szostak, Analytical Modeling of Driver Response in Crash Avoidance Maneuvering – Volume 1: Technical Background. *NHTSA*, *DOT HS* 807 270, April, 1988.

[5] L. D. Reid, A Survey of Recent Driver Steering Behavior Model Suited to Accident Studies, *Accident Analysis and Prevention*, 15, 1983, pp. 23-40.

[6] R. A. Hess and A. Modjtahedzadeh, A Control Theoretic Model of Driver Steering Behavior, *IEEE Control Systems Magazine*, v10, 1990, pp. 3-8.

[7] Modjtahedzadeh, A., and Hess, R.A., Model of Driver Steering Control Behaviour for Use in Assessing Vehicle Handling Qualities, *ASME Journal of Dynamic Systems, Measurement and Control*, v115, n3, Sep, 1993, p456-464

[8] C. MacAdam and G. Johnson, Application of Elementary Neural Networks and Preview Sensors for Representing Driver Steering Control Behaviour, *Vehicle System Dynamics*, v 25 n 1, 1996, p 3-30.

[9] C. MacAdam, An Optimal Preview Control for Linear Systems, *ASME J. of Dynamic Systems, Measurement and Control*, vol. 192, 1980, p188 –190.

[10] G. Prokop, Modeling human vehicle driving by model predictive online optimization, *Vehicle System Dynamics*, 35, 2001, 19 – 53.

[11] R.S. Sharp, D. Casanova, and P. Symonds, Mathematical Model for Driver Steering Control, with Design, Tuning and Performance Results, *Vehicle System Dynamics*, v33, n5, May, 2000, p289-326

[12] H. Soma and K. Hiramatsu, Dynamic Identification of Driver-Vehicle System Using AR-method, *Vehicle System Dynamics*, 24, 1995, p 263-282.

[13] T. Pilutti and A.G. Ulsoy, Identification of Driver State for Lane-Keeping Tasks, *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans*, v 29, n 5, 1999, p 786-502.

[14] L.K. Chen and A.G. Ulsoy, Identification of A Driver Steering Model, And Model Uncertainty, From Driving Simulator Data, *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 123, 2001, p623-629.

[15] A. N. Malik, T. S. Qureshi, and M.O. Ali, Implementation of an Autonomous Tracking System for UGVs using FPGAs, *7th WSEAS Int. Conf. on Artificial Intelligence, Knowledge Engineering and Data Bases (AIKED'08)*, Univ. of Cambridge, UK, Feb 20-22, 2008, p333-337.

[16] B.F. Wu, C.J. Chen, Y.P. Hsu and M.W. Chung, A DSP-Based Lane Departure Warning System, *Proc. of the 8th WSEAS Int. Conf. on Mathematical Methods and Computational Techniques in Electrical Engineering*, Bucharest, October 16-17, 2006, p 240-245.
[17] F. Momiyama, Y. Lwamoto, and M. Nagai, Stability and Controllability Augmentation by Adaptive Control of Steering and Differential in Trucks and Buses, *Proceedings-Society of Automotive Engineers*, 1990, p595-602.
[18] Q. Wang, J. Ma., and T. Kobayashi, Adaptive Lane Keeping Control of Vehicles, *Proceedings of the SICE Annual Conference*, Okayama, 2005, p2200-2204.
[19] M. Netto, S. Chaib, and S. Mammar, Lateral Adaptive Control for Vehicle Lane Keeping, *Proceedings of the American Control Conference*, 2004, v3, p2693-2698.
[20] L.K. Chen, and D.Y. Hu, Adaptive Control With Respect to Driver Model Uncertainty, *Proc. 2006 AVEC*, Taipei, Taiwan, paper no. AVEC060174.
[21] L.K. Chen, and L.C. Lin, Robust Adaptive Control Design For Vehicle Lane Keeping Assist, *ASME International Mechanical Engineering Congress and Exposition*, IMECE2007-41802.
[22] L. Segel, The Tire as a Vehicle Component, in Paul, B., Ullman, K., and Richardson, H. (eds), Mechanics of Transportation Suspension Systems, ASME, New York, AMD-Vol 15.
[23] K.S. Narendra and A.M. Annaswamy, *Stable Adaptive Systems*, Prentice- Hall, New Jersey, 1989.
[24] G. Feng, New Robust Model Reference Adaptive Control Algorithm, *IEE Proceedings: Control Theory and Applications*, v 141, n 3, May, 1994, p 177-180.
[25] A.Y. Ungoren and H. Peng, An Adaptive Lateral Preview Driver Model, *Vehicle System Dynamics*, v43, n4, April, 2005, p245-259.
[26] E.F. Camacho and C. Bordons, *Model Predictive Control in Process Industry*, Springer-Verlag, 1995.
[27] P. Bouchner, R. Pieknik, S. Novotny, J. Pekny, M. Hajny and C. Borzova, Fatigue of Car Drivers - Detection and Classification Based on the Experiments on Car Simulators, *WSEAS Transactions on Systems*, v 5, n 12, December, 2006, p 2789-2794.