The Implementation of the Active Steering System Application with Interactive Torque Delivery based on Lane Keeping System

Tong-Kai Jhang, Kun-Lung Ku, Jin-Yan Hsu and Chien-Hung Yu

***Abstract*—Lane Keeping System (LKS), one of the systems in Advanced Driving Assist System(ADAS), is now commonly applied as an active lateral motion control for vehicles. The Electric Power Steering (EPS) system and Lane Detection (LD) module are integrated for LKS operation. LKS functions when the vehicle travels to an unintentional lane departure depending on the Time-to-Lane-Crossing (TTLC). On the other hand, LKS may be capable of keeping the vehicle travel in the lane, but it may cause driving discomfort as well. The feedback torque to the steering system is thus necessary to be redefined to decrease the steering torque impulse. In this paper, an active steering control system determines the assistive steering torque by overlapping the torque delivered from the driver command and the LKS. The system will correct the trajectory back to the lane with the overlapping torque, providing interactive steering torque feedback.**

Two experiments are adopted in this paper to verify the effectiveness of interactive torque feedback under active steering torque control type and original angle control type LKS. The result shows that the active steering control type LKS helps the driver easily adjust the trajectory with less driver torque than the original angle control. Also, it provides smoother lateral vehicle motion which meets the ISO11270 standard and brings better driving experience.

Keywords — Lane Keeping System; Active Steering Control; Interactive Torque Feedback

I. Introduction

According to the report of Global Status Report on Road Safety 2015, road traffic injuries are a leading cause of preventable death. Over millions of people die or sustain serious injuries due to road traffic crashes from drink-driving, distracted driving, etc[1]. Also, the report shows that vehicles sold in 80% of all countries fail to meet priority safety standard [1].

A pretty effective way to make the traffic safer is to apply ADAS in vehicle control systems. There have been increasing research efforts towards the development of autonomous vehicle since ADAS reduces the rate of occurrence of driver mistakes to provide traffic safety[2,3]. Due to the advance of sensing and computing technology, it brings the possibility to integrate ADAS systems to provide safer driving environment.

LKS is one of the systems in ADAS. It controls the lateral motion of the vehicle. Many literature proposed lateral control algorithm for the path tracking. M.S. Netto and S.Mammer[4] proposed a self-tuning regulator for lane keeping system. The solution is robust with respect to outer disturbance such as road curvature and lateral wind. H. Du, et al[5] applies sliding mode(SM) control on LKS to provide smooth toque feedback. H.M. Fahmy et al[6] made an approach of LKS by minimizing a cost function, and thus an optimized trajectory can be obtained. Also, the functionality was available under a wide range of the vehicle speed. Ungoren and Peng[7] developed an adaptive predictive control(APC) framework, with the use of preview information and weight adjustment to determine optimal steering action.

Most of above approaches are only based on the capability of correction of vehicle trajectory. However, the interaction between the LKS and the driver is not concerned. In this paper, an active steering control system, integrating the LKS and EPS, is established. It determines the assistive steering torque based on the LKS steering angle demand and the driver steering torque to determine the final steering torque command. When the system detects the error from the reference and the current trajectory, it will compensate the steering torque for lateral control. As the steering torque demand is adaptive to the torques mentioned, the system smoothly control the vehicular lateral motion.

The reminder of this paper is organized as follows: the system architecture which includes the explanation of LD, LKS and Constant Acceleration model is described in section 2. The experiments are done to evaluate the effectiveness of the active steering control system. The results shows that an interactive torque command is delivered to the steering system and it satisfies the ISO11270 standard. Finally, the conclusion is made in section 4.

II. System Architecture and Algorithm Design

A. Lane Detection System

The information of the lane marking is necessary for the LKS, so a vision-detecting system, Lane Detection(LD) System[8], is adopted to detect the lane geometry. It includes a vision sensor and an image processing unit. While the lane marking is detected by the vision sensor, the lane characteristics are sent to the image processing unit to calculate the two sides of lane geometry and vehicular lateral deviation. The lane geometry is described in the form of a

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second-order polynomial equations as eq.(1),(2). The coordinate of the information is based on the position of vision sensor which is mounted behind the windshield.

$$y_L = a_L + b_L x + c_L x^2 \tag{1}$$

$$y_R = a_R + b_R x + c_R x^2 \tag{2}$$

where y_x is the lateral distance from the lane at look-ahead distance x; a_x, b_x and c_x are the coefficients of the lane curvature; L and R denote the left and right side of the vehicle or lane.

As the information mentioned is obtained, the center line of the lane, which is the target trajectory of the vehicle, can be further calculated. The equation of the center line is as eq.(3). One thing worth mentioning, the curvature of the lane(κ) and the course angle(ψ) can also be calculated as eq. (4),(5).

$$y = \frac{(a_L + a_R)}{2} + \frac{(b_L + b_R)}{2} x + \frac{(c_L + c_R)}{2} x^2 . \tag{3}$$

$$\kappa = \partial^2 y / \partial x^2 \tag{4}$$

$$\psi = \tan^{-1}(\partial y / \partial x) \tag{5}$$

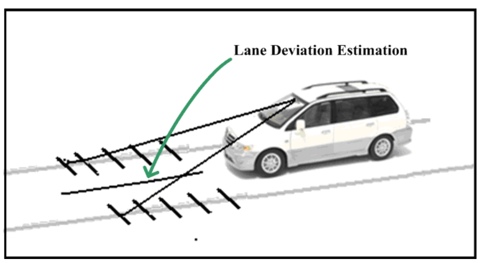

Figure 1. Schematic diagram of the lane recognition estimation.

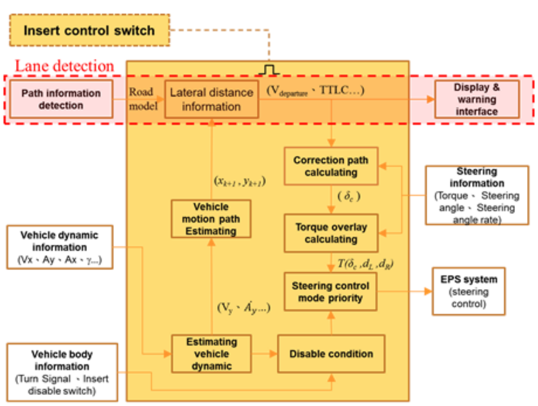

Figure 2. Schematic diagram of the lane recognition estimation.

B. Lane Keeping System

As the information of the lane curvature and lateral deviation is obtained, the LKS can further be developed. The control algorithm of LKS is shown as Fig. 2. As a possible lane departure is detected, and the condition of Time-to-Lane Crossing(TTLC) is met, the LKS activates. It will firstly warn the driver to correct the trajectory by sound or steering wheel trembling and then send a torque command to keep the vehicle traveling inside of the lane.

TTLC mentioned above is a value which is relevant to the lateral departure rate and the lateral distance from the outer edges of tires to lane boundaries. It is used to evaluate whether the vehicle deviates from the track or not.

A TTLC threshold is set for LKS. When the TTLC reaches the threshold, and meanwhile LKS is stand-by, LKS operates to assist the driver correcting the trajectory. TTLC is calculated as eq.(6) and (7), where d_L and d_R are the lateral distances between the lane boundaries and the outer edges of tires at the current position; V_{dL} and V_{dR} are the lateral departure rates; S_L and S_R are the distance from the left and right side of the lane boundaries; K is the sampling time.

$$TTLC_L = d_L / V_{dL} . \tag{6}$$

$$TTLC_R = d_R / V_{dR} \tag{7}$$

$$V_{dL} = (S_{L,K} - S_{L,K-1}) / T \tag{8}$$

$$V_{dR} = (S_{R,K} - S_{R,K-1}) / T \tag{9}$$

Though LKS is capable of keeping the vehicle in the lane, it may bring driving discomfort if the vehicle is controlled to correct its direction frequently and heavily. The look-ahead distance as the vision of the system is thus critical for LKS. The CA model[9] is applied in this paper to estimate the future trajectory. The discrete CA model is as follows.

$$\begin{bmatrix} X_{k+1} \\ V_{k+1} \\ a_{k+1} \\ Y_{k+1} \\ V_{k+1} \\ a_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & T & 0.5T^2 & 0 & 0 & 0 \\ 0 & 1 & T & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & T & 0.5T^2 \\ 0 & 0 & 0 & 0 & 1 & T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_k \\ V_k \\ a_k \\ Y_k \\ V_k \\ a_k \end{bmatrix} \tag{10}$$

where X_k, Y_k are the coordinate of the vehicle location; V_k, a_k are the longitudinal speed and the acceleration of the vehicle; k is the sample time.

When LKS is activated, it sends the steering angle command(δ_c)which is determined by the information of the lane deviation. δ_c is calculated as follows, where y_e are lateral deviation between target trajectory and vehicle future trajectory at the preview time, t_p; ψ is heading angle; γ is yaw rate, and L is the wheelbase ; the three k are the control gains.

$$\delta_c = k_1 y_e + k_2(\psi - \gamma\, t_p) + k_3 \rho L \quad (11)$$

In the interactive control system, δ_c should be bounded by the limitation of lateral acceleration and jerk in ISO11270, as TABLE I shows. With the definition of lateral acceleration gain limitation, the physical limitation, as equation (11), can be re-determined by equation (12)-(13).

$$\delta_c^{\max} = a_y^{\max}(L + K_{us}\mathrm{V}_x^2)/\mathrm{V}_x^2 \quad (12)$$

$$\delta_c^{\max} = J_y^{\max}\; T(L + K_{us}\mathrm{V}_x^2)/\mathrm{V}_x^2 \quad (13)$$

TABLE I. STEERING CONTORL LIMITATION OF LANE KEEPING SYSTEM

Parameters	Values	unit
Maximun lateral acceleration	≤ 3	m/s^2
Maximun lateral jerk	≤ 5	m/s^3

The ISO11270 Standard is for the vehicle behavior when operating vehicle lateral control – Lane Keeping Algorithm (LKA). The Control is mainly based on the lane information from the camera. As lane information is available and LKA is on and ready for work, the driver should hold the steering wheel, so to make sure the driver can take charge whenever LKA fails. For smoother and safer lateral control by LKA, some operating condition is set. The vehicle speed should cover 72 – 108kph range operation; the limit of lateral acceleration is 3 m/s^2; the limit of lateral jerk is $5m/s^2$; the maximum longitudinal acceleration is $3m/s^2$.

C. Electric Power Steering System with Active Steering Assistive Control

Electric Power Steering System(EPS) is realized with the control of motor. Due to its quick response, it is suitable to operate as a power source of steering control system with low delay time. EPS consists of a motor and steering mechanism. As it is electrified, further applications such as LKS and Lane Following System(LFS) are able to provide accurate lateral control.

In this paper, a 3-phase permanent magnet synchronous motor(PMSM) is adopted, since it has characteristics such as high power factor, high efficiency and high power/volume rate. It fits well with the high torque delivery and low volume demand of EPS. The internal model control is also applied to design a current control method for the motor. The motor is modeled in d-q frame and is then transformed to rotational reference frame, so it is intuitive to control the motor.

Since the dynamic response influences the effect of the control, a column-type EPS mathematical model is applied in this paper. The model is as eq.(14)-(17).

$$T_h - K_{tb}(\theta_{sw} - \theta_{sc}) - B_{sw}\dot{\theta}_{sw} = J_{sw}\ddot{\theta}_{sw} \quad (14)$$

$$K_{tb}(\theta_{sw} - \theta_{sc}) + K_m n(\theta_m - n\theta_{sc}) - T_f - T_{rp} - B_{sc}\dot{\theta}_{sc} = J_{sc}\ddot{\theta}_{sc} \quad (15)$$

$$T_{rp}/r_s - b_r\dot{x}_r - F_r - f_r = m_r\ddot{x}_r \quad (16)$$ (3)

$$T_m - K_m(\theta_m - n\theta_{sc}) - B_m\dot{\theta}_m = J_m\ddot{\theta}_m \quad (17)$$

where J and B are the Inertia and damping coefficient of the item, T_h is the torque from the driver on the steering wheel, K_{tb} is the Stiffness of the torsion bar, θ_{sw} is the steering wheel angle, θ_{sc} is the steering column angle, θ_m is the mechanical motor position of the rotor, n is the reduction gear ratio, K_m is the stiffness between the motor and reduction gear, T_f is the friction torque on the steering column, T_{rp} is the steering torque on the shaft between the rack and pinion, x_r is the displacement of the rack, r_s is the stroke ratio, F_r is the alignment force on the rack from the wheel, f_r is the friction of the rack, m_r and b_r are mass and the damping coefficient of the rack, T_m is the electromagnetic drive torque, θ_m is the mechanical motor position of the rotor, K_m is the stiffness of the shaft between the motor and reduction gear.

Based on EPS, two steering control algorithms such as angle control and interactive steering control are designed for vehicle lateral control, whose block diagrams are shown in Fig. 3 and Fig. 4 respectively. In angle control algorithm, the system defines the control effort and sends the command to the current control loop for motor operation; In interactive steering control, a function of TTLC is designed for LKS to determine its torque delivery. It will be further combined with the driver torque on the steering wheel. Since the driver torque is included, the EPS will adjust the output current according to the gap of the driver torque and the actual torque needed.

Besides the torque command determination, the frequency response of the systems is critical to the effectiveness of control algorithm. In this paper, a phase compensator, which is shown in Fig. 5, is built to meet the phase margin which the control algorithm requires. In experiment, the implementation of phase compensator should be discretized, so that it is available in hardware.

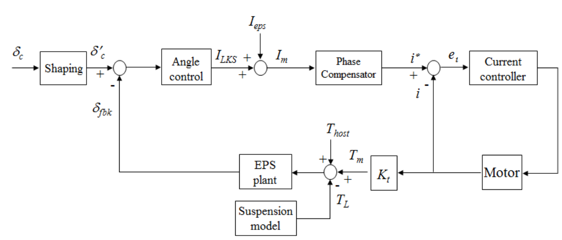

Figure 3. Block diagram of LKS in angle control

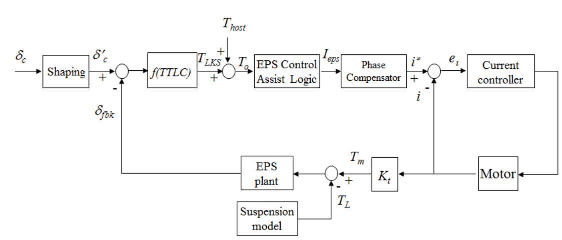

Figure 4. Block diagram of LKS in interactive steering torque control

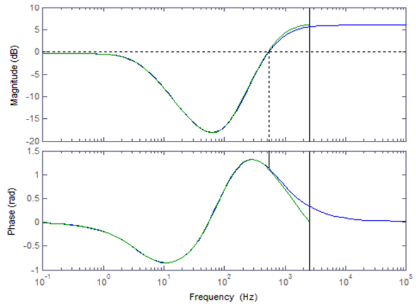

Figure 5. Frequency response of the stability compensator

III. Experiment And Result

Two experiments are done to verify the effectiveness of the active steering control system. One is the angle control case, which will be called case 1, and the other is the interactive torque control case, as case 2. The specification of the testing vehicle is listed as Table II shows. The scenario is set that the vehicle travels on a flat road with a constant longitudinal speed and a constant departure speed. An initial course angle, which is the angle between the direction of the vehicle and the target trajectory, is set as well.

For the interactive steering system, once the outcome of TTLC calculation reaches the threshold, the system activates to fix the vehicle trend. The LKS torque command will be defined by its algorithm. The driver command will also be considered to adjust the actual torque output through EPS. As the LKS steering angle command decreases, the EPS adjusts its own torque command to smoothly control the vehicle trajectory.

TABLE II. The Specification of the Testing Vehicle

Items (Unit)	**value**
Length (mm)	4625
Width (mm)	1825
Height (mm)	1645
Weight (kg)	1505
Wheelbase (mm)	2720
Tread (front/rear in mm)	1555/1565
Tire size	215/55R17
The gear ratio of from steering wheel to the front wheel (-)	19
Understeer gradient (-)	0.003
Motor torque constant (-)	0.0573
Torsion bar stiffness, K_{tb} (N-m/deg)	1.3
Steering wheel damping constant, B_{sw} (N-m-sec/deg)	0.032
Steering wheel inertia, J_{sw} (kg-m^2)	0.019
The reduction gear ratio of column EPS, n	20.5
Friction torque on the steering column and shaft, T_f (N-m)	1.437
Stroke ratio, r (m)	0.0063
Rack mass, m_r (kg)	1.8
Rack damping constant, b_r (N-sec/m)	508
Items (Unit)	**value**
Steering column damping constant, B_{sc} (Nm-sec/deg)	0.032
Steering column inertia, J_{sc} (kg-m^2)	0.000443
Rack friction, f_r (N)	23.1
Stiffness between the motor and reduction gear, K_m (Nm/deg)	5.26
Motor rotor damping constant, B_m(Nm-sec/deg)	0.065
Motor rotor inertia, J_m(kg-m^2)	0.00151

In consideration of driving comfort during the LKS intervene, limitations on a_y, J_y from ISO11270 are set for the interactive steering system. The test condition is listed as TABLE IV.

TABLE III. Initial Condition for Lane Keeping System

Parameters	**Values**	**tolerance**	**unit**
Logitudinal velocity	21	±1	m/s
Lateral departure rate	0.5	±0.1	m/s
Steering angle before correcting motion	0	±2	deg
TTLC working threshold	≦1	-	sec
Lane width	3.75	-	m
Preview time of type1	0.64	-	sec

Some vehicle behavior under steering control are obtained from the results. Fig. 6 and Fig. 7 show the trajectories of the vehicular sides of case 1 and case 2 respectively. The lane information and the system activation are also obtained to completely show how systems in two cases act.

When the TTLC value is less than the threshold, the LKS activates, as the activation flag is 1. The system starts to control the vehicle trajectory back to the lane until the TTLC value is larger than the threshold. Once the LKS inactivates, the activation flag goes to 0.

From Fig. 6 and Fig. 7, it can be concluded that, despite that the vehicular side in case 2 gets more chance to cross the lane boundary, it provides smoother lateral control than the one in case 1. Also, it meets the requirement of ISO11270 standard.

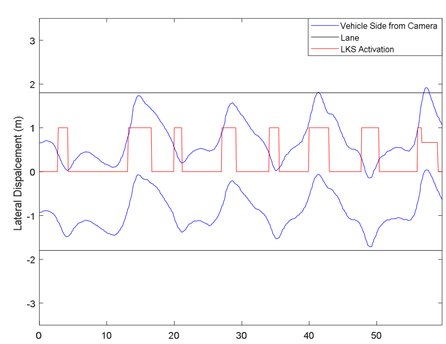

Figure 6. Trajectory of the vehicle side and Lane Information under angle-control LKS

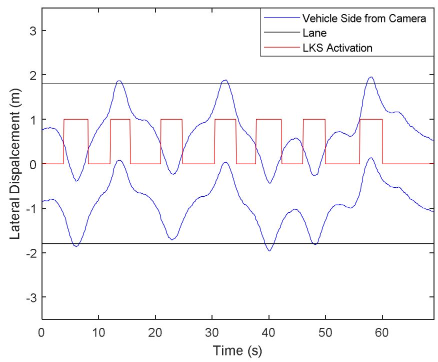

Figure 7. Trajectory of the vehicle and Lane Information under interactive torque control LKS

Fig. 8 and Fig. 9 are the steering wheel angle of case 1 and case 2 respectively. When the control system activates, the steering wheel angle for correcting the trajectory gets larger. It can be observed that the steering wheel angle impulse of case 2 is smaller than the one in case 1. It is mainly because the case 2 type takes the torque from the driver into account, and it makes the system possible to adaptively provide smooth lateral control, while the original type delivers the LKA-calculated torque directly, which has larger impulse. The larger steering wheel angle impulse means more violent movement of the vehicle lateral dynamic, and it causes poorer driving comfort. It can be further determined through the behavior of lateral acceleration and lateral jerk, which will be mentioned later.

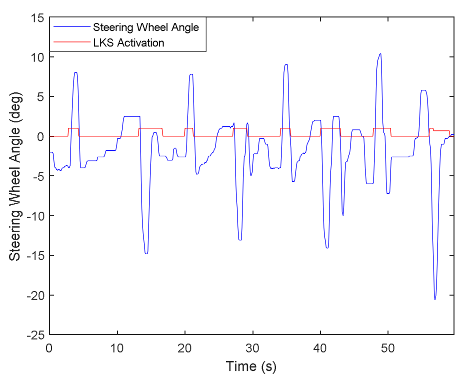

Figure 8. Steering wheel angle under angle-control LKS

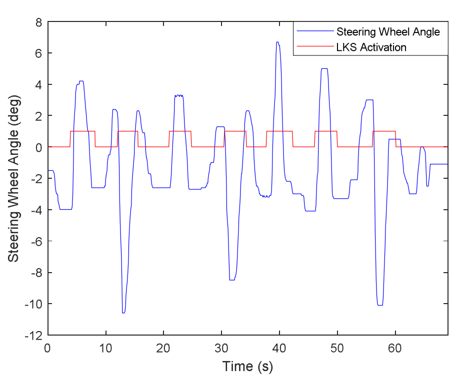

Figure 9. Steering wheel angle under interactive torque control LKS

The torque delivered from the driver in case 1 and case 2 are shown as Fig. 10 and Fig. 11 respectively. Torque delivered from the driver easily occurs in case 1 which can be observed in Fig.10. It means that the driver needs to provide more torque to keep the vehicle in the lane. In contrary, the torque from the driver in case 2 reaches only 2 N-m in maximum for the lateral control. It is proved that the driver adjusts the lateral motion and corrects the vehicle trajectory more easily and with less control effort in case 2.

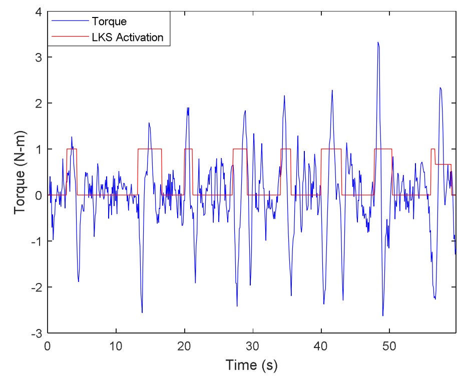

Figure 10. Torque delivery from actuator under angle-control LKS

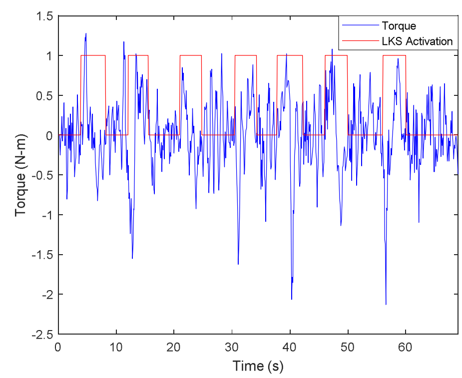

Figure 11. Torque delivery under interactive torque control LKS

The lateral acceleration of case 1 and case 2 are shown in Fig. 12 and Fig. 13 respectively. Since the attitude of lateral acceleration deeply affects driving comfort, it is also taken into consideration. The lateral jerk is calculated through the lateral acceleration, and they are basically in the same trend. The lateral jerk of case 1 and case 2 are shown in Fig. 14 and Fig. 15 respectively.

It can be observed that the impulse of lateral acceleration and the lateral jerk of case 2 are gentler than it under the ones of case 1 respectively. Comparing the data of lateral acceleration from Fig. 12 and Fig. 13, it can be seen that the attitude of the impulse in case 2 is 40% less than it in case 1 in average. Also, comparing the data of lateral jerk from Fig. 14 and Fig.15, the maximum value gap reaches 2 m/s^3, which may tremendously affects the driving comfort. It can be proved from the outcome of Steering wheel curve. Case 2 type provides smaller steering angle command, so to provide lateral acceleration and lateral jerk with smaller impulse. However, 2 cases both meet the ISO11270 Standard.

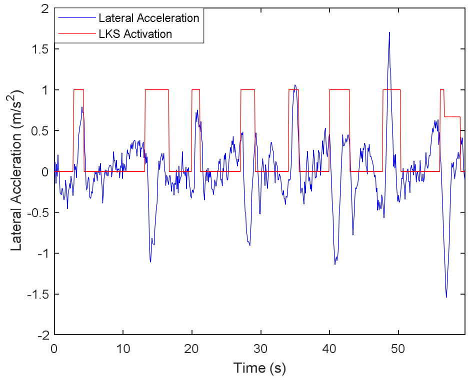

Figure 12. Lateral acceleration of the vehicle under angle-control LKS

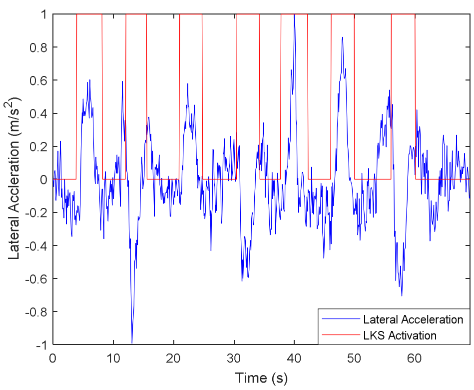

Figure 13. Lateral acceleration of the vehicle under interactive torque control LKS

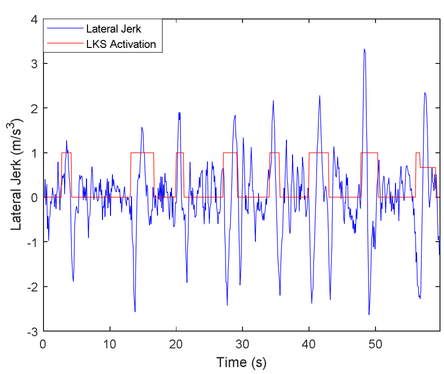

Figure 14. Lateral jerk of the vehicle under angle-control LKS

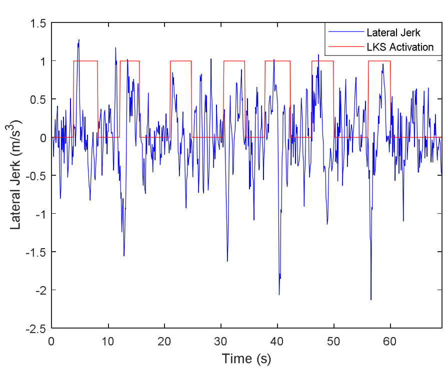

Figure 15. Lateral jerk of the vehicle under interactive torque control LKS

IV. Conclusion

In this paper, an interactive torque control system is designed for the lateral control of the vehicle. It is based on EPS to determine the torque output by integrating its original torque and steering angle command from Lane Keeping System(LKS). The main purpose of the system is to emphasize on the driving comfort and the way the system controls the vehicular lateral motion.

By the Experiments under interactive steering control and original angle control, LKS are established to verify their effectiveness. According to the obtained results, the steering wheel angle under interactive steering control is gentler than it under angle control. It represents that the system makes it easier for the driver to adjust the trajectory of the vehicle to keep it in the lane; the lateral acceleration and lateral jerk under interactive steering control also fluctuates less under interactive steering control case, and it provides better driving comfort. One thing worth mentioning, by adjusting the TTLC threshold of interactive steering control, the possibility of the vehicle lane crossing reduces.

In conclusion, the interactive steering control system provides better driving experience with less torque demand from the driver. And, it meets well to the limitation of behavior in ISO11270 standard.

Acknowledgment

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References

[1] World Health Organization. Global status report on road safety 2015. Geneva, Switzerland: World Health Organization, 2015.

[2] Rittger, L. and Götze, M., 2018. HMI Strategy – Recommended Action In: K. Bengler, J. Drüke, S. Hoffmann, D. Manstetten and A. Neukum. Eds., "UR:BAN Human Factors inTraffic. Approaches for Safe, Efficient and Stress-free Urban Traffic," Springer, Wiesbaden, Germany, 2018, pp.16 – 20.

[3] S. Winkler, J. Kazazi, M. Vollrath, "How to warn driver in various safety-critical situations – Different strategies, different reactions," ELSEVIER, Accident Analysis and Prevention 117, 2018, pp. 1 - 3

[4] M. S. Netto, S. Mammer, "Lateral adaptive control for vehicle lane keeping," IEEE, American Control Conference, Boston, Massachusetts June 30 - July 2, 2004, pp.2694 - 2696.

[5] H. Du, Z. Man, J. Zheng, A. Cricenti, Y. Zhao, Z Xu and H. Wang, "Robust Control for Vehcile Lane-Keeping with Slifing Mode," Asian Control Conference(ASCC), Gold Coast Convetion Centre, Australia, December 17-20, 2017, pp. 1,5 .

[6] H.M. Fahmy, M. A. Abd El Ghany, IEEE senior Member and G. Baumann "Vehicle Risk Assessment and Control for Lane-Keeping and Collision Avoidance at Low-Speed and High-Speed Scenarios," IEEE Transaction on Vehicular Technology, 2018, pp. 1

[7] A.Y. Ungoren, H. Peng. "An adaptive lateral preview driver model, " Vehicle system dynamics 43.4, 2005, pp.245-259.

[8] J.Y. Hsu, K.L. Ku, T.K. Jhang, H.P. Lin, and C.J. Yeh, "Integration and Implementation of Lane Keeping System with Vehicle Dynamics Control," International Automatic Control Conference(CACS), 2017. pp. 2.

[9] J. L. Wei, "Design of Lane Keeping System Using Adaptive Model Predictive Control," Taipei Tech, graduation paper, 2016, pp.1