Design of an Automotive Lane Keeping System Based on the Structure of Electric Power Steering

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Abstract—The objective of this research is to develop a lane keeping control system for vehicle, which bases on the structure of electric power steering (EPS). The lane keeping system (LKS) can actively control the vehicle steering to help driver keep his car within its lane, and prevent driver from the unintentional lane departure. A vision-based lane departure detection unit is used as the main input for this system to detect the position between the vehicle and its lane in real-time. The lane keeping control strategy was designed in accordance with the vehicle dynamic model for figuring out the appropriate steering angle and torque, and further controlling the electric power steering system. In this research, the electronic control unit (ECU) of LKS has been implemented with an embedded hardware and made cooperative control with EPS ECU. The simulation and on-vehicle test results show the proposed lane keeping control algorithm can work appropriately, and offer active control within the center area of the lane.

Keywords —roadway image sensing unit, lane keeping control, electric power steering

I. Introduction

Within the last few years, due to the increasing awareness of automotive safety and the considerable progress in automotive key technologies, many advanced safety systems have been implemented and commercialized. The well-known applications are vision-based driver assistance systems, like blind spot detection system (BDS), lane departure warning system (LDWS) and forward collision warning system (FCWS) [1,2] shown as Figure 1. However, although these systems can provide early warnings with sound and indicated light, but driver still has to control the steering or brake by himself for traffic accident avoidance. For promoting these assistance systems from passive warning to constructive control, active vehicle control systems for reducing the driver's burden through the control of steering and brake have gradually become the main advanced technology in vehicle safety improvement.

Lane keeping (LK) system is one of the important technologies in the development of advanced safety vehicle (ASV). This system uses a front-view camera to acquire roadway image, and recognize lane markings through a series of image processing process for obtaining road features and the position relation between the vehicle and its lane. According to the recognition result, the vehicle can be controlled to track the target lane center. The lane keeping control was implemented on a column-type EPS in an actual vehicle. EPS is a new steering system used for replacing the traditional hydraulic power steering (HPS). Instead of the complex and fuel-guzzle HPS mechanism, EPS only comprises motor, sensors and electric control unit as shown in Figure 2. By an appropriate motor torque (current) control, EPS can be used to save fuel, improve initiative security and the steering feel. Since the steering is capable of being controllable by EPS, the lane keeping function can be implemented by controlling the motor on EPS. A steering control method was used in this research can make the flat road like a cambered surface to keep the host vehicle around the center area of the lane steadily, and always reserve the highest priority for the driver's conscious operations of overriding.

There have been many methods for lane keeping control [3,4], but most of them used only the steering wheel angle as the control input that was difficult to permit driver's intervention in the steering control loop[5]-[7]. Therefore, the focus of this research is to develop an interactive lane keeping system based on original EPS structure by adopting both of steering angle and torque as the inputs. In the following sections, we will describe the design concept of the lane keeping control, which includes system modeling, controller design, simulation and experimental results.

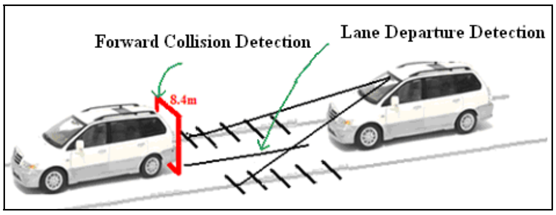


Fig.1. Vision-based safety application for vehicle

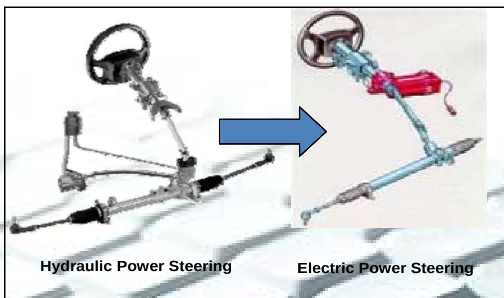


Fig.2. The structure comparison for HPS and EPS

II. System Overview

Figure 3 shows the overall configuration of the lane keeping (LK) system. This LK system mainly comprises three parts, i.e., lane departure detection, lane-keeping control algorithm and electric power steering system. The module for lane departure detection can extract the lane information, including lane position and road curvature by image processing processes and then send these data to the LK ECU. According to the calculated results from LK control algorithm, the control current for EPS will achieve the steering angle and torque control to help the driver keep the vehicle in the current lane.

The lane detection module of the LK system uses a CCD camera mounted on the windscreen behind the rearview mirror to take roadway image in front of the car. Furthermore, these images are processed by the pattern recognition hardware to extract the lane marking and build the essential lane model such as lateral displacement and curvature. The relation between the world coordinates and the camera image coordinates is shown in Figure 4. Since the system has to locate lane markings and the preceding vehicle in the image coordinates, the processed 2D image should be transformed into 3D space information through the inverse perspective mapping in order to obtain the lane positions in the real space. Fig.5 shows the lane detection results under various environments.

By the above lane departure detection, system will obtain the vehicle position in its lane and the relative parameters of the road. LK controller will take these inputs and calculate the steering angle and torque value through lane keeping control algorithm. Finally, the motor of electric power steering will be control according to the steering angle and torque command.

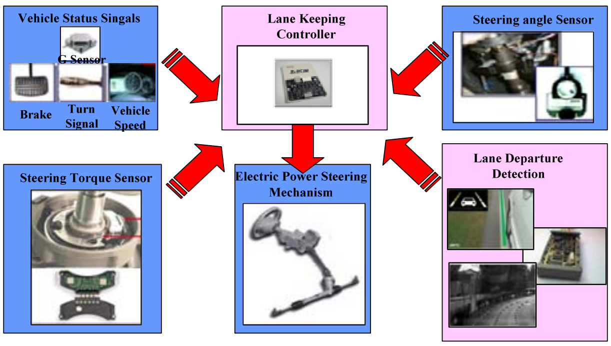


Fig.3. Structure of the LKS

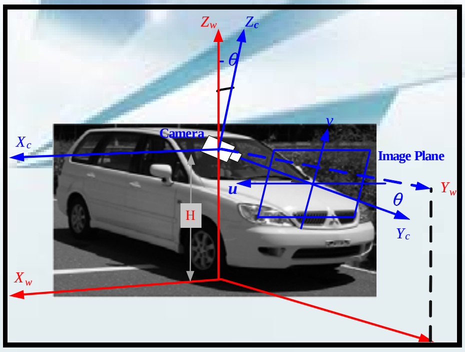
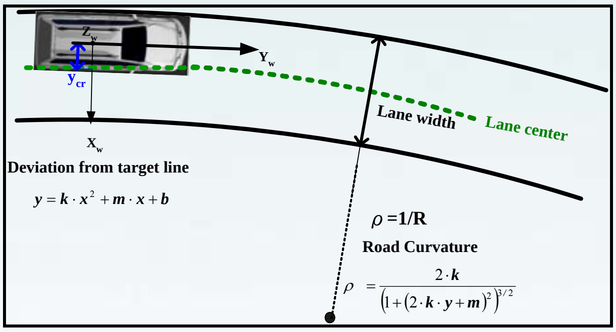
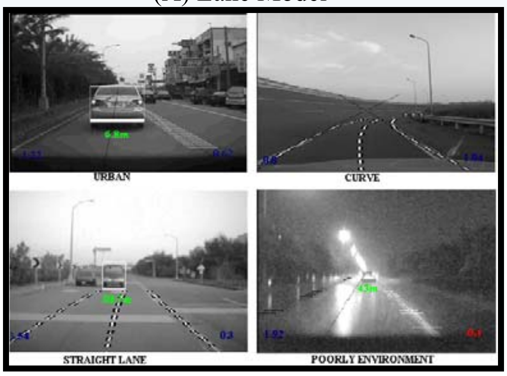


Fig.4. Coordinates System



(A) Lane Model



(B) Lane Recognition Results (with FCW functions)

Fig.5. Road Model and Lane Recognition Result

III. System Modeling

This research utilizes the co-simulation technique to develop the control logic. This needs to build up the mathematic model to describe the system dynamics and take this mathematic model to verify the effects of LK system and reliability of the lane keeping control algorithm before the on-vehicle test.

A. Steering System Model

The schematic diagram of the EPS system is shown in Fig. 6. The typical column-type EPS system consists of a torque sensor, an electric motor, a reduction gear, a column and a rack–pinion mechanism. In order to model the steering system behavior for the control logic design, it can obtain the equations of motion of the EPS system according to the Newton's Law. The equations are shown as fallowing:

$$T_h - K_t(\theta_{sw} - \theta_{sc}) - B_{sw}\dot{\theta}_{sw} = J_{sw}\ddot{\theta}_{sw}\,. \tag{1}$$

$$T_{mn} + T_f - B_{sc}\dot{\theta}_{sc} + K_t(\theta_{sw} - \theta_{sc}) - k_r(\theta_{sc} - \frac{x_r}{r}) = J_{sc}\ddot{\theta}_{sc} \tag{2}$$

$$\frac{k_r}{r}(\theta_{sc} - \frac{x_r}{r}) - F_r - b_r\dot{x}_r = m_r\ddot{x}_r\,. \tag{3}$$

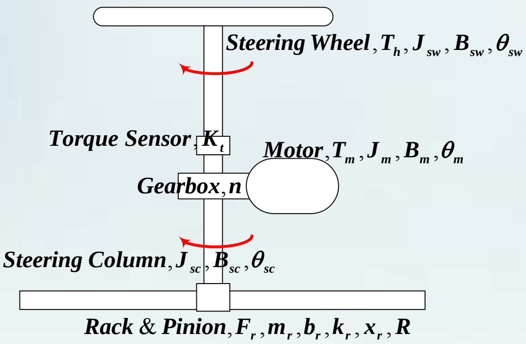


Fig.6 Schematic diagram of EPS

B. Vehicle Motion Model

Instead of complex vehicle dynamic model, this research utilizes the simplified two-wheel bicycle model as shown in Fig.7 and uses the front wheel steering angle δ as the input of vehicle motion. Equation (4) and Equation (5) express the yaw motion and lateral motion related to the recognized lane feature model that we mentioned in preceding section. Due to the main effects on vehicle motion are based on ground plane, rolling and pitching motions are disregarded in this research.

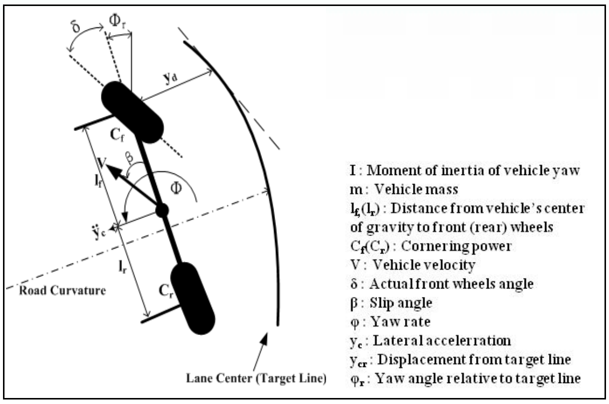


Fig.7. Two-Wheel Bicycle Model

In addition, the vehicle steering model is shown in Fig. 7. This steering model is used to work out the assist control current supplied by the EPS motor according to the inputs of vehicle lateral deviation, speed, road curvature and driver's torque. The block diagram for computing the assist torque command is shown in Fig. 6.

$$I\ddot{\psi} = l_f C_f(\delta - \frac{l_f}{V}\dot{\psi} - \beta) - l_r C_r(\frac{l_r}{V}\dot{\psi} - \beta) \tag{4}$$

$$m\ddot{y}_c = mV(\dot{\psi} + \dot{\beta}) - C_r(\frac{l_r}{V}\dot{\psi} - \beta) - C_r(\frac{l_r}{V}\dot{\psi} - \beta) \tag{5}$$

$$I_s\ddot{\theta} + C_s\dot{\theta} = N_a K_T i - \xi K_p C_f(\frac{1}{N}\theta - \frac{l_f}{V}\dot{\psi} - \beta) + T_d \tag{6}$$

These lateral dynamic models are used to control a vehicle to stay in the center of its lane. By summarizing Equation (1)-(6), the following expression is obtained as equation of state of the vehicle model that is based on the target line given by the road curvature.

$$\dot{x}_v = Ax_v + B_1 u + P[T_d \quad \rho] \tag{7}$$

Where $x_v = [y \quad \dot{y} \quad \psi \quad \dot{\psi} \quad \theta \quad \dot{\theta}]$, $u = [i]$ and A, B_1 are the parameters matrixes of vehicle motion, steering system and road model. A block diagram shown in Fig.8 presents the relation among the vehicle motion, steering system and road model. In this block diagram a_1~a_8 must be obtained from system identification process like the motion step response and the frequency response of steering system during slalom driving. Since each car model owns different characteristics, these parameters were got from the real driving measurement.

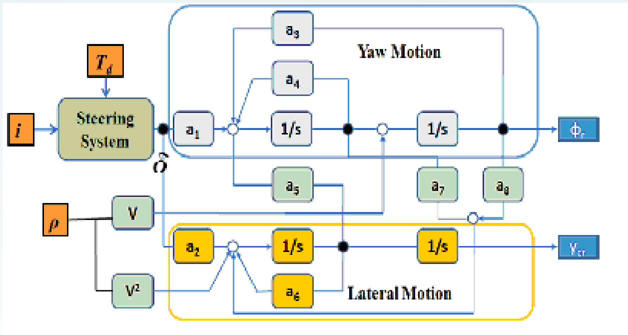


Fig.8. Block Diagram Based on the Target Tracking

IV. Controller Design

After finishing the system modeling, this section will describe how to design a state feedback controller for lane keeping control. Since lane deviation and yaw angle error are necessary inputs for the state feedback controller, the state variables in equation (7) have to be changed into error-oriented variables for tracking the desired path i.e. the lane center. If we assume that the radius of the vehicle path changes slowly, then the rate of change of orientation of the vehicle (i.e. $\dot{\psi}_{des}$) must be equal to the angular velocity of the vehicle. The relation among vehicle speed, road radius and yaw rate can be expressed as

$$\rho V^2 = V\dot{\psi}_{des} \tag{8}$$

According to the state-space equation (7) and equation (8), the state feedback control model for the lateral dynamics of the vehicle can be presented as

$$\dot{x}_e = Ax_e + B_1\delta + B_2\dot{\psi}_{des} \tag{9}$$

Where $x_e = [e_1 \dot{e}_1 e_2 \dot{e}_2]$, e_1 is the lateral deviation from the lane center and e_2 is the yaw angle difference between the vehicle and target line (lane center). $\dot{e}_1$ and e_2 can be calculated through equation(10) and equation (11) . Matrices *A* B_1 *and* B_2

$$\ddot{e}_1 = (\ddot{y} + V_x\dot{\psi}) - \frac{V_x^2}{R} = \ddot{y} + V_x(\dot{\psi} - \dot{\psi}_{des}) \tag{10}$$

$$e_2 = \psi - \psi_{des} \tag{11}$$

The block diagram of state feedback controller is expressed as Fig.9. The steering angle input is

$$\delta = -\boldsymbol{K}\boldsymbol{x}_e = -\boldsymbol{k}_1\boldsymbol{e}_1 - \boldsymbol{k}_2\boldsymbol{e}_2 - \boldsymbol{k}_3\boldsymbol{e}_3 - \boldsymbol{k}_4\boldsymbol{e}_4 \tag{12}$$

Where $\boldsymbol{e}_3 = \dot{\boldsymbol{e}}_1 ; \boldsymbol{e}_4 = \dot{\boldsymbol{e}}_2$

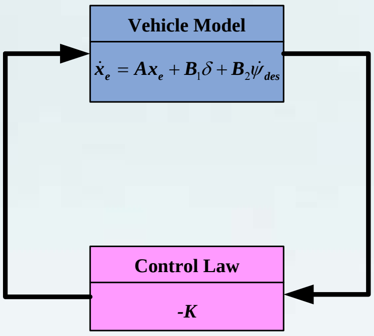


Fig.9. State Feedback Control Block Diagram

For solving the SISO problem, Ackerman Formula can be utilized for the closed-loop matrix *(A - BK)* to be placed at any desired locations. The closed-loop system using this state feedback controller is

$$\dot{\boldsymbol{x}}_e = (\boldsymbol{A} - \boldsymbol{B}_1\boldsymbol{K})\boldsymbol{x}_e + \boldsymbol{B}_2\dot{\psi}_{des} \tag{13}$$

In this research, Eigenvalues were placed at *[- 6 - 3 j - 6 + 3 j - 6 – 11]* for leading the LKS to be a stable system. The measured vehicle parameters shown in Table 1 will be used for controller design, and the calculated matrix *K* for state feedback control *is [0.1568 0.0339 1.262 0.1625]*, and this state feedback matrix will always make the lane keeping system in a stable and convergent situation.

Table 1 Vehicle Parameters

Name	Symbol	Value
Mass	*m*	*1640kg*
Distance from C.G. to front wheel	l_f	*1.1m*
Distance from C.G. to rear wheel	*lr*	*1.58m*
Inertia	*I*	$650kg.m^2$
Cornering Force	C_f	*5500N/rad*
Cornering Force	C_r	*4500N/rad*

In order to avoid the conflict between the driver and system, the LK system can detect the driver's operations, such as braking and lane changing, to determine whether the system shall be deactivated or not. Moreover, the assist torque generated by the LK system is set at a threshold that can be overridden by the driver readily. In other words, the driver's operation is the top priority for controlling the vehicle. In this study, the signals of the blinker (turning switch), brake pedal steering angle, torque and G (lateral acceleration) sensors are used to judge the timing for LK system deactivation, as listed in Table 2. The system has taken the cooperative driving strategies into consideration through analyzing the driving status signals. By taking these strategies, the unnatural feeling between the driver and the system is capable of being eliminated.

Table 2 LK system deactivated conditions

Condition	Detection
Emergency	Brake signal
Lane Change	L/R Turning signal
Forced Steering	Steering torque
Hands On	Steering torque/Angle frequency distribution
Over Turning	Lateral G

V. SYSTEM SIMULATION AND VALIDATION

Due to the active lane keeping control will involve the vehicular safety concern, the simulation works are necessary to be done before the system on-vehicle test. For observing the system accuracy and reliability, the relative model of vehicle motion and the designed controller were built by taking advantage of SIMULINK & CARSIM software validation tool. The simulation results for the stability validation of the designed controller are shown in Fig.10 and Fig. 11, and the vehicle was driven with orientation and position errors from the target lane centers. Both of the simulation results show the proposed LK controller has a good performance to converge the orientation and position errors between the current pose of the vehicle and the target lane centers, and control the vehicle under stable and safe driving.

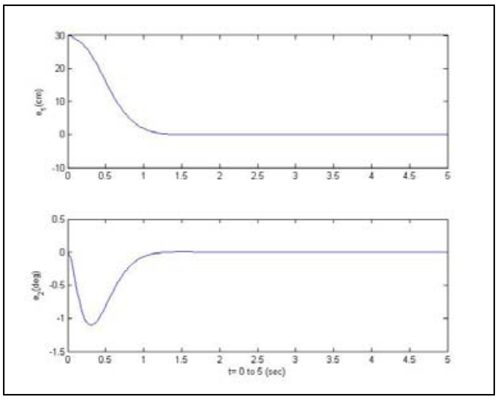


Fig.10. Lane keeping control simulation with position error =30cm and orientation error = 0 degree

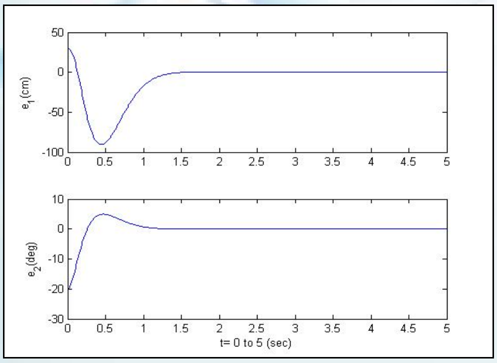
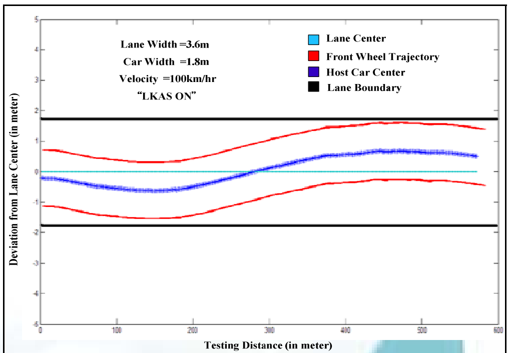


Fig.11. Lane keeping control simulation with position error =30cm and orientation error= –20 degree

The simulation results for driving with and without lane keeping activation are shown in Fig. 12 and Fig. 13. Apparently, it can be seen in Figs. 12 and 13 that, under the hand-free driving with the LKS activation the vehicle can be effectively kept within the lane. On the contrary, the vehicle without the lane keeping activation gradually drifted out of the lane until the driver took over the control. Figure 14 shows the vehicle responses of wheel steering angle, yaw rate and lateral acceleration during the LKS operation. It can be observed from Fig. 14 that the reaction frequency of vehicle yaw rate is quite low and the G acceleration is less than 0.05G, meaning that the system would always offer an appropriate and continuous lane keeping force for the host vehicle.

(A) CARSIM Simulation



(B) Vehicle trajectory with lane keeping control
Fig.12 Lane keeping control simulation

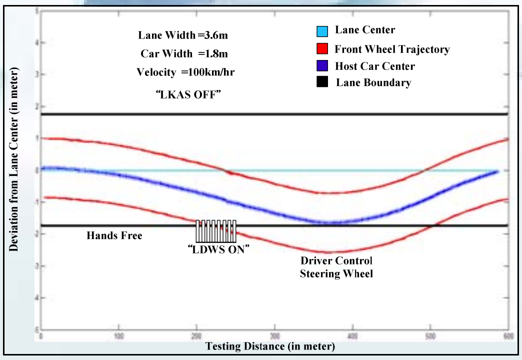


Fig.13. Vehicle trajectory without lane keeping control

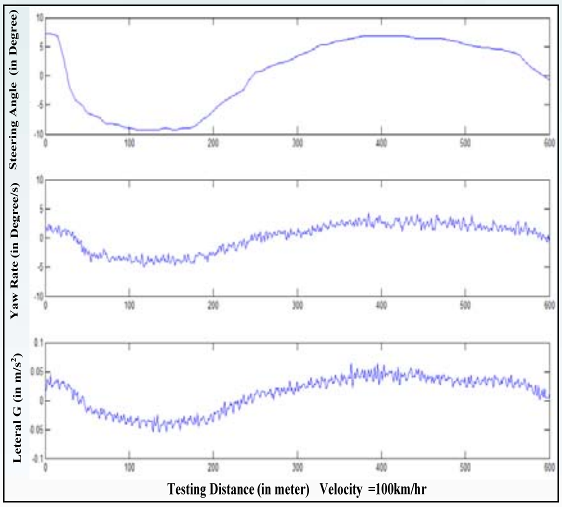


Fig.14. Vehicle response simulation results as LKS is acting

VI. EXPERIMENTAL RESULTS

The LK system incorporating with the function of lane departure warning established in this research is shown in Fig. 15. The LK system was tested on the test tracks of the ARTC proving ground to validate its performance. Figure 15 shows the testing results of the LK system performed on the straight test track for 3.5 km with a vehicle speed of 100 km/hr. It can be seen in Fig. 11 that the vehicle can be kept within the lane by the LK system similar to that of the aforementioned simulation result, and the frequency of the pendulum motion and the lateral acceleration are, respectively, below 0.02 Hz and 0.05 G indicating stable keeping control.

Figure 17 shows the testing results of the LK system performed on the curved track of a curvature of 1/250 m with a vehicle speed of 100 km/hr. From Fig. 12, it can be seen that the vehicle can still be controlled to stay within the lane. However the frequency of the pendulum motion and the lateral acceleration are obviously increased. In order to avoid the instability of vehicle motion, the lateral acceleration is limited to a maximum of 0.2 G for deactivating the LKS operation as shown in Fig. 13. By observing the experimental results, we can summarize three points as follows:

(1) This system can work normally under expressway and highway road environment, and vehicle speed interval between 60km/hr and 110km/hr is

suggested for safety consideration.

(2) On the condition that the range of visibility for lane detection is above 150 m, the lane departure warning and lane keeping control can be activated even the system is operated in bad weather condition, e.g. nighttime, rainy day, fogged day and so on.

(3) Once the intentional lane change, preceding emergency and unexpected errors occurred, driver can override the system easily i.e. driver always owns the highest priority.

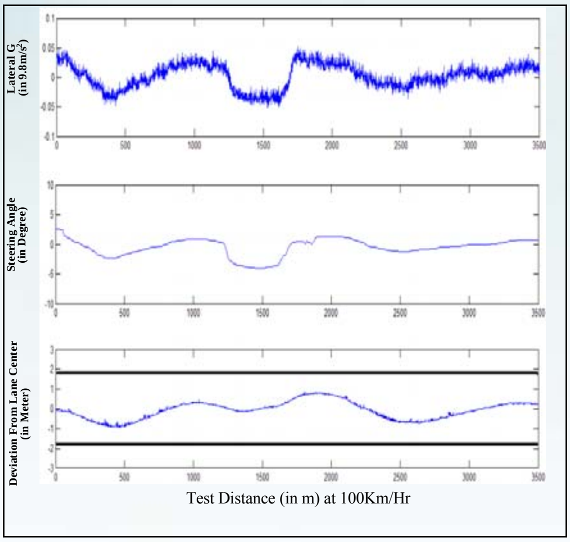


Fig.15. LKS performance testing on a straight track

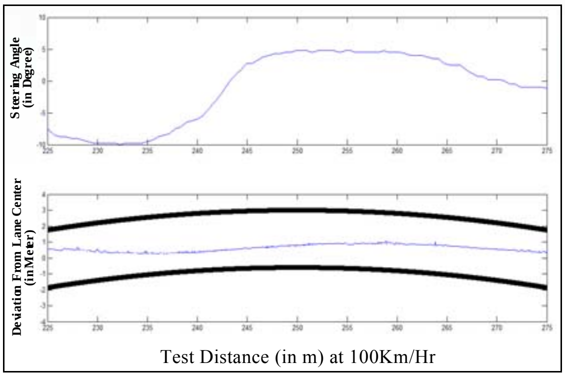


Fig.16. LKS performance testing on a curve track (Road curvature=1/250)

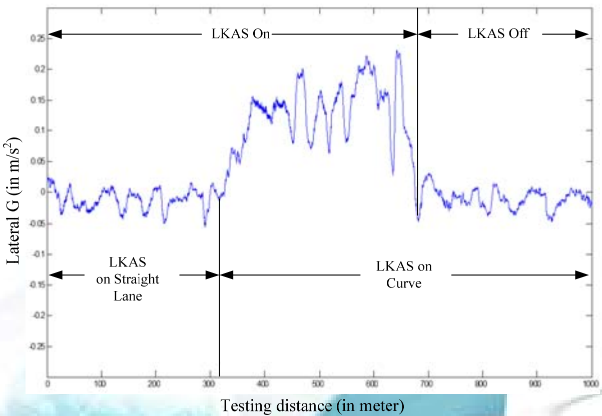


Fig. 17. Threshold of lateral acceleration for activating LKS.

VII. CONCLUSION

This research has successfully developed a lane keeping system based on automotive electric power steering, and this system has been validated through software simulation and the on-vehicle tests in the ARTC proving ground. The test results show the system can keep the vehicle driven within the lane center area, and furthermore prevent the driver from the traffic accidents caused by the unintentional lane departure. In order to avoid generating the unnatural steering feeling to the driver while the system acts, the system also took cooperative driving strategy into consideration in the design stage. Moreover, the control force generated by the LK system is set under a threshold that can be overridden by the driver easily, i.e., the driver's steering is the top priority for the vehicle steering control.

Fig.18 shows the system configuration in ARTC ASV learning car, and it was implemented on two embedded modules with the lane departure warning and the lane keeping control function. Base on the current achievement, our group will continuous to strengthen the design of failure safety mode including the over current detection, over heat protection, rollover prevention, self-diagnosis and so forth for EPS actuator and vehicle. In the next few years, the developed LK system will be sufficiently capable of being used in Taiwan's expressway and freeway by the enhancement of the system's reliability and stability.

Fig.18. The developed lane keeping system on ARTC ASV learning vehicle

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