Adaptive Lane Keeping Assistance System design based on driver's behavior

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Abstract

The lane keeping assistance system can reduce the risk of lane departure effetely, but the control parameters in the existing system are fixed and single warning algorithm is hard to adapt to different drivers. And the decision-making logic for lane keeping intervention is relatively simple, and cannot be self-optimized according to the driver's behavior. In view of the above problems, this paper proposes an LKA system based on driver's behavior habits and the road condition so that to improve the driver's confidence to use the system.

Around the function, system structure, key technology and experiment verification, the following work was carried out:

First, launched the driving tests to collect the driver's real lateral driving behavior. The differences of the driving parameters when driver has different driving intentions, i.e. lane keeping or not, are funded. These provide a design basis to the control decision layer. Then, proposed a joint-warning algorithm for TLC and FOD. On this basis, an adaptive adjustment method with two databases of driver profiles and lane keeping scenes are constructed. In the next step, the paper optimized the decision-making layer of LKAS. It includes 3 parts: Activation condition judgement, Driver operating status judgement and whether the system should intervene. At last, an active control algorithm based on EPS control was proposed and verified the algorithm by Simulink / Carsim.

Keywords: Lane keeping assistance control; Lane departure warning; Driver behavior

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Chapter I. Introduction

1.1 Background

In recent years, with the increasing number of cars, the total number of traffic accidents has been rising. Driving safety issues have become a major concern in the social transportation and automotive sectors. According to the WHO's global status report on road safety 2018, the number of deaths on the world's roads remains unacceptably high with 1.35 million people dying each year. As shown in Figure 1.1, despite the increase in absolute numbers, the rate of road traffic deaths has separately constant at around 18 deaths per 100,000 population over last 15 years. [1].

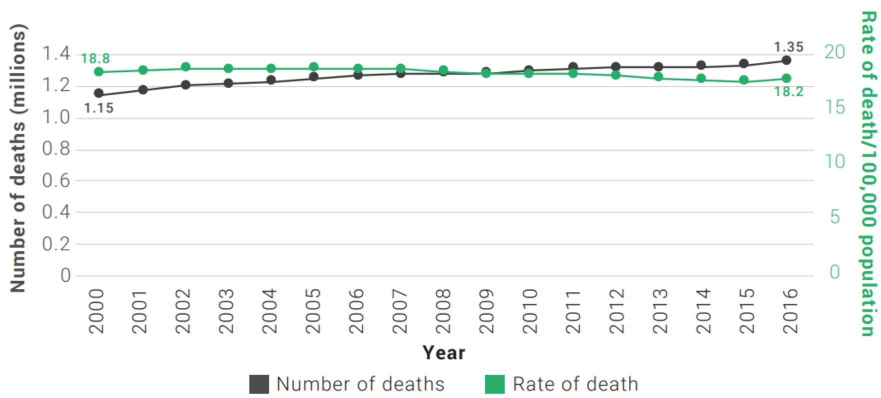


Figure 1-1 Number and rate of road traffic death per 100,000 population: 2000-2016

Relevant departments in Europe and the United States have investigated traffic accidents and found that about 80% of the accidents that occurred in the traffic accidents were related to the driver. The traffic accidents caused by the driver's energy dispersion accounted for a large proportion [2]. Through investigation and analysis of the causes of traffic accidents, it is found that a large part of traffic accidents is caused by improper behavior of drivers, such as rear-end collision, long-time driving, and vehicles leaving the scheduled lanes [3]. According to the statistics of the National Highway Traffic Safety Administration of the United States, about 30% of traffic accidents are caused by rear-end collisions, and about 20% of traffic accidents are caused by vehicles leaving the scheduled lanes [4]. In 2008, the US Federal Highway Administration reported that nearly 50% of major traffic accidents were related to the vehicle leaving the original lane [5]. In addition, the departure of the vehicle from the original driving lane is also one of the important incentives for the vehicle rollover.

Therefore, in order to improve driving safety and reduce driver's driving burden, Advanced Driving Assistance Systems (ADAS) has been extensively studied and gradually applied [2]. As the main branch of ADAS, the vehicle's lateral driving assistance system has many forms, such as Lane Keeping Assistance System (LKAS, also known as Lane Departure Prevention/Avoidance, LDP/LDA)、Lane Change Assist (LCA, also known as Blind Spot Warning/Intervention, BSW/BSI), Collision Avoidance (FCA), etc. [3-4]. Among them, LKAS is designed for the driver's lane departure caused by fatigue or lack of concentration, and one of the typical lateral driving assistance systems that help the driver to suppress the lane departure tendency by the steering assist control to keep the vehicle in the original lane.

There are several different forms of lane keeping assistance that are distinguished from the assist mode. One type of lane keeping assistance method is limited to alerting the driver to the danger of lane departure, in the form of shoulder belt vibration or machine vision-based Lane Departure Warning (LDW) [5]. Another type of lane keeping assistance can actively intervene in lane departure behavior, which is called semi-autonomous driving assistance, and is also an auxiliary method used by the usual lane keeping assistance system. At present, the research on lane keeping assistance technology is mainly aimed at the latter. The lane keeping assistance system that meets the basic functional requirements has been introduced as an optional configuration on medium and high segments of major auto brands such as Volkswagen, Toyota and Nissan. Existing research reports on traffic accidents in Europe show that if all vehicles are equipped with lane keeping assistance systems, it can reduce road traffic accidents by about 12% [6].

However, there are still some shortcomings in LKAS products. The unnecessary intervention due to the lack of adaptability to driver behavior and intentions is the main point.

First, LKAS with fixed parameters is difficult to apply to different drivers with individual differences. Different drivers are accustomed to keeping the vehicle in different position ranges, and the risk perception of lane departure is affected by road type, lane position, lane line type and surrounding vehicles. For example, a driver is used to driving to the left in the leftmost lane, if LKAS frequently starts the intervention of the driver on the left side according to the fixed parameters, it will cause unnecessary interference to the driver and reduce the system's acceptance, also reduce the comfort of the driver during driving. Therefore, in order to improve the acceptance of the system, the driver's driving behavior habits under different working conditions should be designed to flexibly adjust the lane departure intervention threshold, to ensure the intervention under real dangerous conditions and reduce the unnecessary intervention which may influence driver's acceptance.

Second, the existing LKAS is based on the cornering signal to determine whether the driver's pressure line is for the purpose of lane change or insufficient attention or mismanagement. The criterion is relatively simple. However, according to the research results of driver's lane change behavior, the average cornering signal usage rate of Chinese drivers during the lane change process is 54.88% [7], and the driver lacks standard operation awareness in this aspect. Therefore, when the driver changes lanes without using the indicator, the LKAS will start after the tires approached the lane mark, which will give the driver unnecessary intervention. Especially if the vehicle urgently changes the lane mark due to avoiding obstacles in front, improper intervention will lead to more serious danger. Therefore, how to identify the driver's intention of change lanes as efficiently and accurately as possible is an important research topic.

In addition, the existing LKAS will only be activated after predicting the lane departure, which the control loop time is short and the degree of assistance is limited. At present, the higher level of automation assistance has become the main trend, and the automatic driving technology can be realized under some road conditions and driving conditions [8-9]. However, due to imperfect regulations, limited environmental awareness of all working conditions, and difficulty in achieving seamless connection between human-machine interfaces, the fully autonomous driving technology cannot be matured currently. From the perspectives of laws and regulations, technical difficulty and the degree of acceptance by the drivers, the development of the driver assistance system is an important stage from the manual driving to the autonomous driving, and is more feasible in the present [10-11]. To this end, based on the traditional lane keeping system, Toyota has proposed a co-pilot system to avoid the technical reliability of the current autonomous driving and the accompanying problems of human-machine interface (Copilot) [12]. Collaborative control by the driver and the auxiliary controller, taking advantage of both sides and avoiding their respective drawbacks, becomes a feasible solution. Therefore, applying this idea to the design of LKAS can extend the traditional LKAS, and the assist mode with higher automation level will further reducing the driver's operation pressure.

In summary, in order to improve the driver's acceptance of the assist control, avoid the conflict between the assist control system and the driver's intention, reduce the operational pressure of the driver during the driving process, and adapt the LKAS to the driver's behavior habits, is the major requirement for further development and enhancement of LKAS technology. In order to meet the above requirements, this paper proposes and establishes the Adaptive Lane-Keeping Assistance System (ALKAS), which is based on the driving behavior habits and intentions, as the supplementary program of the traditional Lane Departure Prevention (LDP). In this mode, the assist controller and the driver work together so that the vehicle is always close to the desired position during the lane keeping process. When the driver temporarily loses control or the assist system temporarily loses the working ability, it will seamlessly transit the control to the other one to ensure the driving safety and reduce the driving risk. This mode can be applied under both current legal conditions and environmental awareness technology levels, which can further reduce the driver's operation pressure and avoid the problems of uncoordinated human-machine interface.

In order to realize the adaptive control function of driver characteristics and different assist modes of LKAS, this paper focuses on the analysis of driver's characteristics of lane keeping behavior, departure warning algorithm, decision-layer logic and active control methods. Firstly, the real road test is completed, and the driver behavior characteristics of lane keeping are analyzed. Based on that, multi-modes warning algorithms and the adaptive adjustment logic are proposed to provide support for the design of LKAS decision parameters and achieve the self-adaptation of LKAS to drivers' behaviors and habits. Then, the paper optimizes the decision-making layer of

LKAS and conducts a case analysis. Finally, an active control model of LKAS is established based on EPS. And the co-simulation test of CarSim and MATLAB/Simulink was carried out to verify the functions of the system. The research in this paper is a further expansion of LKAS, providing an effective way to improve the coordination and adaptive ability of LKAS with drivers and improve their automation level.

1.2 Research Status of LKAS' Control Algorithm

SAFELANE, a sub-project of the European PreVENT research project [13], proposed a LKAS which can adapt to different road conditions, including the environmental awareness layer, decision-making layer, and execution layer [14], as shown in Figure 1.2.

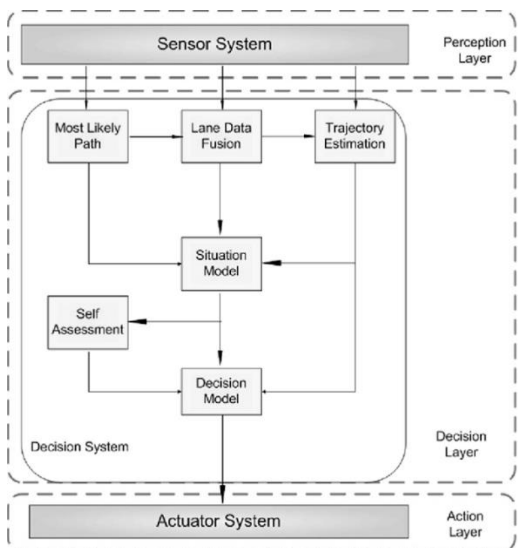


Figure 1-2 Structure and modules of the SAFELANE system.

The main functions of each part are as follows:

(1) The environmental awareness layer, i.e. the information acquisition system, includes various sensors and image processing modules, which are the source of LKAS lane mark signals and vehicle status signals.

(2) The decision-making layer is mainly composed of the lane departure warning algorithm, the driver operation state identification algorithm and the lane keeping active control algorithm. The layer determines whether to send a command to the execution

layer by judging the motion state of the vehicle and acquiring the vehicle position information, which determines the working status of LKAS.

(3) The executive layer executes the decision-making layer command, uses the steering system or braking system to control the vehicle motion, and corrects its motion trajectory to return it to the original driving lane.

The decision-making layer is the core of LKAS. It determines the working state of LKAS through driver operation state identification algorithm, deviation warning algorithm and active control algorithm. The LKAS warning algorithm is used for determining the relative position between the vehicle and the lane to determine the deviation state of the vehicle, and determining whether to send a command to the deviation warning execution module according to the driver operation state identification result; the driver operation state recognition module determines whether the driver participates in the current driving activity, if the driver does not take corrective action after the warning, the LKAS active control algorithm will send an active control command to the execution layer.

The executive layer consists of two parts: the deviation warning execution agency and the active control execution agency, which respectively accept the commands from the lane departure warning algorithm and the lane keeping active control algorithm to realize the purpose of reminding the drivers and prompting them to take corrective actions in time. If the driver does not implement the corrective action, LKAS will take the initiative to take corrective action to improve the active safety of the vehicle. Among them, warning execution agencies are divided into three types: visual warning, auditory warning and tactile warning. Among them, tactile warning is the most efficient. There are two forms of active control actuators: steering actuators and brake actuators. There are three common control technologies:

(1) Active steering technology, control of vehicle steering systems such as Electric Power Steering (EPS) and Steer-By-Wire (SBW) creates additional corners that are superimposed on the steering wheel to change the vehicle's trajectory.

(2) Differential braking technology, which controls vehicle braking systems such as the Electronic Stability Program (ESP), performs differential braking control on the

left and right wheels, and uses the generated yaw moment to return the vehicle to the original lane.

(3) The active torque distribution technology, on the all-wheel drive vehicle, makes the driving torques distributed to the respective wheels, and controls the vehicle trajectory by controlling the yaw motion of the vehicle.

As shown in Figure 1.3, the solution adopted by Nissan's LDP system is to generate the yaw moment by assigning different braking forces to the left and right wheels to control the yaw motion of the body [24]; Volkswagen's Lane Assist system and Honda's LKAS system generate torque to assist the vehicle back to the center of the lane via EPS [25-26].

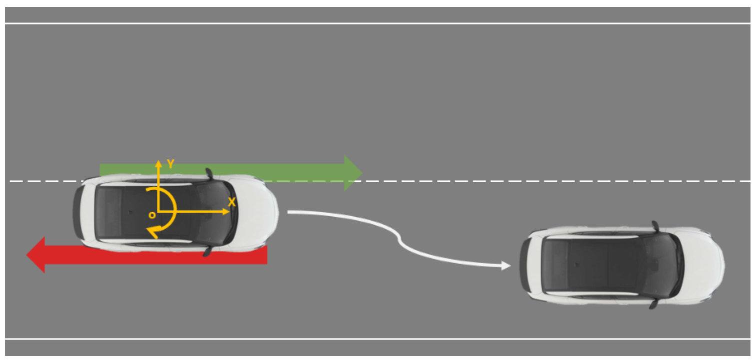


Figure 1-3 LKAS based on EDB

In recent years, the functionality of the LKAS system has been extended in some products and research to support coordinated assist control with other driver assistance systems, such as Emergency Lane Assist (ELA) proposed by Eidehall A. On the basis of observing the traffic dynamics of the adjacent lanes, the steering assistance intervention in the emergency case is carried out [29]. Bosch's Integrated Cruise Assist (ICA) inherits vertical ACC and horizontal LKAS [11]. Toyota’s CADAS proposes a multi-mode driver assistance system for urban road conditions, combined LKAS, ACC and Pre-Crash System (PCS) [30].

1.2.1 Control theory of LKAS

Lane Keeping Assistance is a semi-automatic driving assistance system, there are two difficulties in the design of its control method. First, the vehicle dynamics model and the driver model have nonlinear characteristics. Linear approximation processing will result in large state prediction errors, and the control performance cannot be optimal. Secondly, when using the model to predict the state in the predicted-time domain, there are uncertainties in vehicle parameters, driver behavior, and road environment. The controller design needs to be able to ensure the stability of the controlled object when these uncertainties exist. As the degree of automation increases, the duration of the assistance control intervention increases, and the requirements for control performance are higher.

Some common control algorithms are used in the controller design of LKAS. These control algorithms include state feedback control [31-33], optimal control [35], H2 predictive optimization control [36-37], and model prediction control [38], robust feedback control based on state invariant set theory and Lyapunov equation [39]. However, the above research has made the assumption that the lane keeping assist control is in the linear region of the tire model during most of the working time. Therefore, the design of the control algorithm can ignore the nonlinear characteristics of the controlled object and use the linear model for approximate estimation. It has also been studied to use the segmentation affine method [40] and the sliding mode control method [41] to deal with the nonlinear characteristics of the controlled object. Hedrick J K et al. established a nonlinear model predictive control law and solved it to obtain the optimal control [42-43].

For the second difficulty mentioned above [44-45], based on the invariant set theory and Lyapunov equation, and using the LMI method to solve the state feedback control [46-47], the self-correcting regulator [48] and other methods were used to solve the problems of robust stability caused by uncertainties such as vehicle model, road curvature, road surface attachment parameters, and windward resistance. In order to deal with the technical limitations of lane recognition, Lee J et al. designed a double-deck lane-maintaining auxiliary controller. The first layer controller performs lane-maintaining assistance based on lane mark recognition, and when lane mark and curve curvature are limited and the first layer controller fails, the GPS-based second layer controller is used for correction and intervention to ensure basic security [49].

Due to the large randomness of the driver's behavior, the error caused by the driver's behavior prediction needs to be considered in the controller design. In response to the uncertainty of driver's behavior, the following studies propose different solutions. Based on the design of the anthropomorphic driver model [20], Saleh L et al. used the structural singular value μ analysis method to further explore the design of robust stability of the H2 predictive optimization controller when the driver model parameters are bounded uncertain [28]. A study by Chen L et al. shows that there is a significant difference between the behaviors of different drivers, which will result in the stability of the model predictive controller based on a single driver model. Therefore, the author nests the time-varying driver model in the controller, and the model parameters are estimated online using the autoregressive state based on the recursive least squares method through the model identification method, thus establishing a variable. As shown in Figure 1.4, the Variable Structure-Model Reference Adaptive Controller (VS-MRAC), used to construct a suitable Lyapunov equation to obtain a control solution that guarantees the stability of the Robust system [21-22].

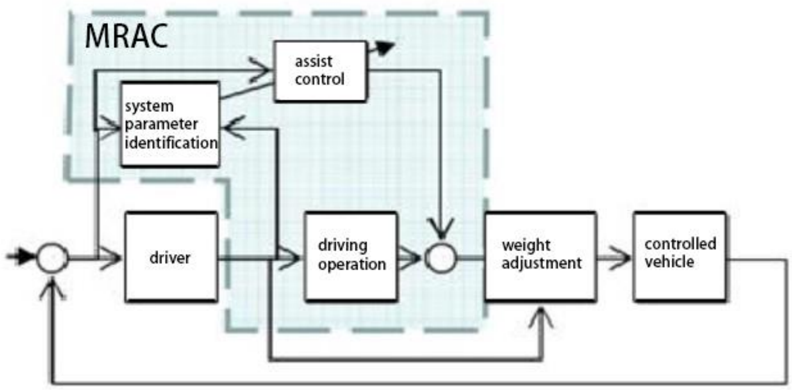


Figure 1-4 The Variable Structure-Model Reference Adaptive Controller (VS-MRAC)

Liu C et al. considered the vehicle-driver system as a linear system in the study, and designed the Robust Model Predictive Control (RMPC) control law for model uncertainty [33-34]. Among them, method 1 uses a driver model with uncertainty and a linear vehicle model to form a closed-loop structure when building the model. The system is based on the feedback control law of the Linear Quadratic Regulator (LQR). The robust invariant set is used as the input and state constraint in the control law of RMPC, so as to ensure that the system state can satisfy the constraint condition when the driver behavior is uncertain. In the second method, a closed-loop structure composed of a random driver model with a normal distribution form and a linear vehicle model is used to calculate the distribution range of the vehicle trajectory in the predicted time domain, and the error constraint is used in the form of probability, using the principle of Chebyshev inequality, probabilistic constraints are transformed into common linear inequality constraints.

Summarizing the existing research, the model predictive control method has the following advantages: (1) It can process the state and input and output constraints explicitly, so it is relatively simple to adjust the constraint interval online; (2) its rolling time domain optimization characteristics, the target is optimize the control problem of system state in the future period. Therefore, this method is widely used in the controller research of the lane keeping assist system.

1.2.2 Human-machine Cooperation Mode of Lane Keeping Assistance System

In the interaction between LKAS and the driver, there are many feasible solutions for human-machine cooperation. The work objectives can be roughly divided into two categories, one type of collaborative approach to the driver for the purpose of reducing steering power, or the application of reverse steering torque to intervene, can be called tactile lane departure intervention, such systems include a system startup/shutdown policy switching module predicts whether an unintentional lane departure will occur based on the driver's state and the relative motion state of the vehicle, and makes a decision to initiate or cancel the intervention control. The other type of intervention is relatively automated, so that the lateral position of the vehicle does not exceed the lane keeping boundary or the vehicle is strictly required to follow the planned trajectory as a control target to optimize the steering wheel angle, apply torque on the steering column, or directly yaw control. This will constantly adjust the driver's handling behavior of the vehicle. Such systems typically do not require a mode switch that is activated or deactivated, but rather a co-driver assistance system that shares control with the driver at all times.

Depending on the control objectives, there is also a difference collaboration strategy between the assist system and the driver. At present, most of the lane keeping assistance systems that have been applied in the products adopt the first type of design ideas, while for the second type of system design schemes, the system normally open state puts forward higher reliability requirements for environmental identification, driver's intention identification, and controller design. Therefore, it has not yet matured the product application, but it has received more attention in the research field. Regardless of the control target, in order to achieve good control transition or switching, an important issue is to design the control right switching strategy in the system design, to make the assist system and the driver share the control right without conflict [60]. The following study also pointed out this problem and proposed some specific technical solutions.

The LKAS designed in the SAFELANE research project [13] has a clear switching control strategy, if and only if the tendency of lane departure is detected and the driver does not have special steering intentions (such as cornering, lane change, overtaking) performs steering assist control. The lane departure intervention system proposed by Volvo includes three layers of assist sequence, which are alarm, brake assist, and differential brake-based steering assist [11]. Hyundai and Kia have proposed an active lane keeping assist system that can switch between two assist modes, including lane departure intervention and automatic lane keeping control. The switching of the assist mode is implemented by the driver through the human-machine interaction system [33]. The design that drivers and assist controllers have the control right at the same time, in addition to improving the accuracy and reliability of technologies such as environmental awareness, the key points to be considered in the design of the controller are: first, if conflicts occur in collaborative control, the driver will not trusting the assist system, even bringing security problems due to control conflicts; secondly, if the control of the system is too concentrated, it will lead to excessive trust and dependence on the system.

Cerone V et al. designed a strategy for switching control between the automatic lane keeping system and the driver. When the driver expresses the intention of overtaking or avoiding steering, the control is handed over to the driver. After the steering control is over, it continues to be controlled by the lane keeping controller, and the intermediate transition is safe and smooth [28].

The above scheme only considers the working condition in which the driver actively exhibits the intention of changing the lane, and does not consider whether the driver can maintain the attention, and makes a reasonable lane change decision according to the driving condition. For example, when the driver's attention is not concentrated and the lane change is required, it is not guaranteed that it can take over the vehicle in time. Researchers at Georgia Tech and General Motors have validated the problem by designing a Limited Ability Autonomous Driving System (LAADS) with integrated Adaptive Cruise Control (ACC) in automatic lane keeping. The driver's ability to use the system was tested. The lane automatic alignment function of LAADS does not normally require the driver to participate in the steering wheel control, but requires the driver to be in a state of supervising the system at all times. When the working capacity of the system is limited, the driver should be able to take over the control tasks of the vehicle in time. Experimental studies have shown that compared to using only the ACC system, when using a LAASS with basic functions and can be trusted most of the time, the driver will perform more behaviors that are not related to the driving task. The length of time that the line of sight leaves the road ahead increases by an average of 27%, which is difficult to guarantee the ability of the driver to take over in an emergency.

Griffiths P et al. studied the effect of the driver's and assist systems operating the lane keeping assist system of the steering mechanism. The study used a driving simulator with a motor on the steering wheel to provide operational feedback resistance, simulating the steering control of the SBW. The driver can select the operation of the compliance controller by means of torque superposition or choose to overcome the operational behavior of the controller. By setting up straights, bends, and conical obstacles in the middle of the road, the driver's ability to complete lane keeping and obstacle avoidance tasks when the LKAS system is turned on is verified. The experimental results show that after using the lane keeping assistance system, the average distance of the vehicle from the centerline of the lane is significantly reduced, but the frequency of collisions with obstacles is significantly increased [25-26].

The study by Katzourakis D et al. of Volvo once again demonstrates this conclusion, comparing the safety impact of two LKAS-assisted forms under emergency collision avoidance conditions. One of the assist forms is the driver's ability to have direct contact perception (Haptic Feedback, HF). When predicting a lane departure hazard, the driver will feel the steering wheel steering resistance increased, thereby reducing the tendency to deviate from the lane. Another form is the SBW-based lane keeping assistance, which decouples the linear relationship between the angle of the driver's steering wheel and the front wheel angle of the vehicle. The angle control increment calculated using the system is superimposed with the steering wheel angle applied by the driver to become the determined amount of the actual vehicle angle. When the vehicle suddenly encounters an obstacle located in front of the lane, it needs emergency steering to avoid collision. During the collision avoidance process, the vehicle will have a great possibility of deviating from the original lane. The assist control of LKAS may have a negative effect on the collision avoidance of the vehicle. The data obtained by 30 drivers participating in the driving simulator showed that the assist control in the form of HF could not effectively prevent the driver from deviating from the lane under such conditions. The active intervention control causes the driver to fail to grasp the relationship between the vehicle motion and the steering wheel angle under emergency conditions, resulting in collisions. The above two studies prove that in the cooperative control, if the driver and the controller are in conflict, it may lead to the safety problem of improper vehicle control.

Summarizing the above research, a perfect human-machine collaboration method of sharing control rights should not only reduce the driving burden, but also ensure driving safety. Most studies suggest that the driver should be in vehicle control in case of sudden or complicated conditions, and if the driver is not in the ring, the efficiency of the takeover may be reduced. Conversely, if the driver is in the ring, the efficiency of full takeover can be improved and ensure safety. In addition, in the existing human-machine cooperation mechanism, the driver's main role is generally not emphasized, the driver and the co-drive assist controller each have independent decision-making and control processes. The control amount of the two is proportionally coupled by the decision result of the control right, which causes the driver to have no final control over the vehicle, and the feedback on the vehicle control is not so good. Therefore, in this paper, when designing lane maintaining assist control, it is clear that the driver is the main body. The control system matches the driver's driving habits and performs assist control in accordance with the driver's intention and the driver's control target.

1.3 Research Status of Driver Characteristics for Driving Assistance Technology

Due to the strong interaction between the driver assistance technology and the driver in the actual application process, in order to improve the driver's trust and acceptance of the driving assistance technology, more and more driving assistance technology research takes the driver characteristics factor into account [72]. Existing research indicates that improper driving assistance technology may lead to driver's “negative behavior adaptation”. Taking LKAS as an example, premature alarm timing and auxiliary control will lead to excessive driver dependence, and once the system fails, a missing alarm or intervention may result in an increase in lateral positional offset and an increase in the severity of the collision hazard caused by lane departures [33]. Therefore, improving safety is also one of the important reasons for the study of driver assistance technology to consider the characteristics of the driver. More advanced driving assistance should be able to adapt the driver's personal behavior characteristics or driver type adaptation for different driver individuals or groups. The ability to provide different levels of assistance for different driving styles is called general adaptive capability, such as the Human-Machine Interface (HMI), which provides several alarm threshold gear options. Based on a certain model learning method, the system operating parameters can be adjusted to suit individual drivers, so that each driver's individual experience of the system is optimal, called user adaptation [33].

In the design of the driver assistance system, there are three design issues related to driver acceptance: whether to intervene, when to intervene, and how to intervene. Whether the intervention problem needs to consider whether the assist system will interfere with the driver's normal driving behavior after the intervention, that is, the decision of the system needs to adapt the driver's control intention. The question of when to intervene needs to consider whether the timing of intervention is just in line with the driver's needs, that is, the timing of the intervention of the system needs to adapt the driver's cognitive characteristics to danger. How to intervene needs to consider whether the control mode of the system is consistent with the driver's usual behavior, that is, the control behavior of the system needs to adapt the driver's steering behavior. Therefore, the driver characteristics study applied to the driving assistance technology can be divided into two parts: one is the analysis and application of the driver's risk perception and steering control behavior habits; the other is the identification of the driver's intention.

1.3.1 Driver Behavior Habit Analysis and Application

The study of driver behavior habits is of great significance for the design of driver assistance systems. Because the driver's longitudinal driving behavior is relatively simple, his behavior habits are easier to analyze and learn, and the vertical driving assistance system, such as Forward Collision Warning/Assistance (FCW/FCA). The environmental recognition technology on which the ACC system relies is more mature, and the research and application time of the horizontal driving assistance system is longer. Therefore, the current driver behavior characteristics are widely used in the research of longitudinal driving assistance technology. Some products have the ability to adapt to the driver's driving style. For example, if there are multiple gears for FCW/FCA alarm or intervention timing, ACC's following distances may be selected, or different modes of acceleration may be provided by Audi and Subaru.

Figure 1-5 Audi's multi-mode ACC

The driving assistance system designed by Onken R et al. in 1997 was the earliest proposed alarm system for adaptive driver behavior, and the driver's behavior was learned in real time based on the fuzzy artificial neural network method [25]. Jiménez F et al. provide a solution for adaptive driver behavior for intelligent speed control systems, online learning driver's speed control behavior, reaction time and braking habits in corners, and applying it to controller design for intelligent vehicle speed adaptive systems

[26]. Hirose T et al. proposed the concept of customized driving assistance system, which was divided into three functions: brake assist, steering assist and acceleration assist. Using the real driving data after clustering to build a driver model with neural network structure, and using the driver model as the control basis of the driving assistance system [17].

In the study, Yi K et al. proposed a follow-up distance control method for adaptive driver personal driving habits for the ACC system [27]. Professor Nagai M and others proposed a driving assistance system framework based on multiple methods of adaptive driver characteristics, and applied it to the design of forward collision warning and collision avoidance systems [39]. For example, the longitudinal driving conditions are divided into five common working conditions according to the presence or absence of the preceding vehicle, the traffic light, and the degree of danger. There are five kinds of braking and acceleration control models corresponding to the five working conditions [39]. The online working condition identification is carried out by the BSLM (Boosting Sequential Labeling Method) method, and then the corresponding model is used to adaptively adjust the assist control strategy parameters of the system. Other studies have designed adaptive driving assistance systems for specific users and special conditions that have an impact on driver behavior. For example, analyzed the characteristics of the response time and braking habits of the elderly driver to the alarm function, and designed an warning assistant system for adaptive driving habits of the elderly; research considering the slippery road to the driver [44], considers the influence of the slippery road surface on the driver's driving behavior, and adaptively adjusts the alarm timing according to the adhesion of the tire road surface.

By comparing the non-adaptive FCW with the adaptive FCW based on the driving simulator, the results show that the driver shows a higher acceptance study for the adaptive system. The same conclusion is also true for the establishment of LDW, indicating that not only the vertical driving assistance system needs to consider the behavioral characteristics of the driver, but also the lateral driving assistance system. The adaptation of the lane departure warning technology to the driver's driving behavior habits is mainly reflected in how to make the warning timing meet the driver's perception and judgment of danger. In the algorithm design of LDW, the concept of virtual boundary is generally accepted to reflect the safe lateral position boundary of the driver's subconscious.

In the early stage, Kim S et al. considered the driver characteristics factor in the design of the LDW system, and used the TSK fuzzy model to construct the lane departure risk level judgment model. The model uses the lateral offset and TLC as inputs and the hazard level as the output. In order to make the algorithm adapt to the individual characteristics of the driver, the driver's driving data samples are used to evaluate the algorithm, and the variable weights of the fuzzy system are iteratively optimized to find the weight value that best matches the driver's risk perception habit.

The PreVENT project in Europe took the lead in considering the driver's various driving behavior habits in the design of LKAS. According to the driver's driving habits under different working conditions, the adaptive multi-condition control strategy was designed [10]. The strategy adaptively adjusts the lateral position of the vehicle according to the operating conditions of the adjacent lanes. As shown in Figure 1.6, if it is detected that the lateral distance between the adjacent lane vehicle and the EGO car is small, then, the safe lateral area of the EGO car is moved in the opposite direction, and the lane keeping assist control is performed according to the adjusted safety area [13].

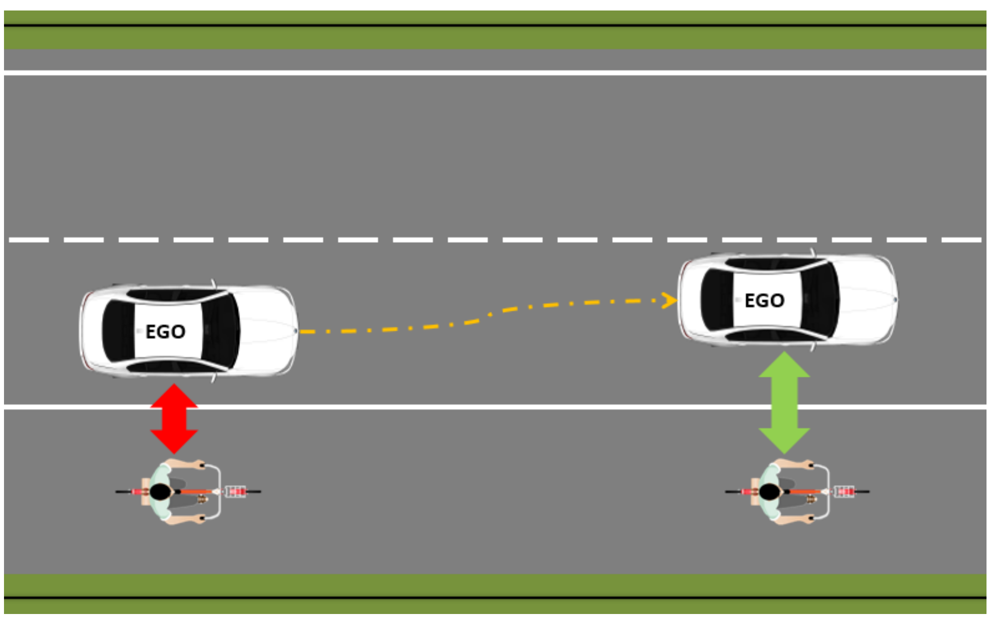


Figure 1-6 Adaptive adjustment of lane keeping based on driving conditions

Yi K et al. designed the control strategy of the lane keeping assist system according to the driver's control habits of trajectory and lateral acceleration, and divided the process of correcting lane departure into two stages as shown in Figure 1.7. The trajectory characteristics of the driver in the lane changing behavior and the distribution relationship of the corner-lateral acceleration are studied. The law obtained by the study is set to the reasonable yaw angular velocity control target in phase 2 to meet the driver's comfort requirements. Anderson S J et al. also pointed out that the control method of the lateral driving assistance controller should learn the operating habits of individual drivers or different types of drivers to improve the driver's acceptance of the system.

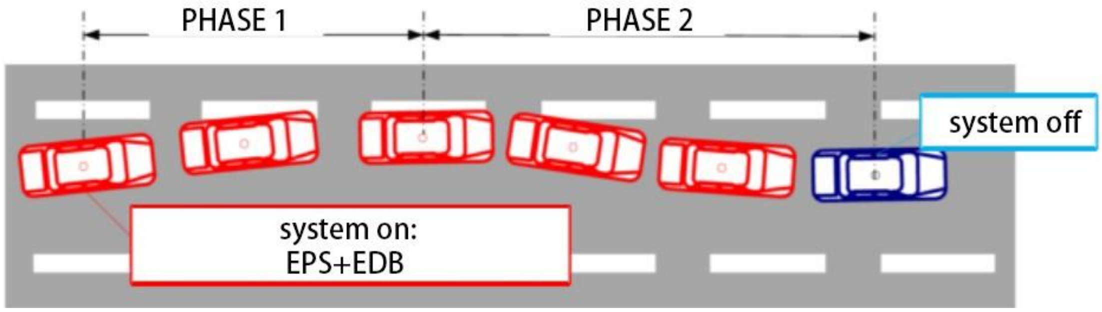


Figure 1-7 Stages of Lane Departure Control

Hyundai-Kia Motors' Active Lane Keeping Assist (Active-LKAS, ALKAS) applies driver characteristics to the timing of system intervention. According to its analysis, the current LKAS deficiency includes: (1) The timing of intervention should be flexibly adjusted according to different road curvature radius, longitudinal speed/acceleration, and driver status; (2) Different drivers have different perceptions of lane departure risk, and warning system should also set different intervention areas. An optional mode that provides the driver with multiple intervention times.

The existing driver lane keeping model is basically based on two ideas. The early driver model assumes that the driver's behavior can be described by a linear time-invariant dynamic system, mostly based on the error compensation control for single-point preview. It is proposed that the transfer function is generally used for expression. Another type of driver lane keeping model is collectively referred to as a prediction model, represented by the pre-targeting time domain optimal control model proposed by Macadam C. The driver is assumed to be an optimal pre-shooting controller with response delay. The cost function of the optimal control is a function of the trajectory following error in the preview time domain.

On this basis, with the increasing attention of the driver's characteristics, more and more researches are aimed at the driver's lateral driving model design, and the problems and solutions for adjusting the model parameters according to different driving styles and driving habits are proposed. The adaptive lateral preview model proposed by Peng H et al. uses yaw deviation as a measure of trajectory tracking performance in another preview time domain, in addition to using lateral position error. The model adjusts the weight values of the components in the performance optimization function to adapt to different driving styles [34].

In addition, several studies have proposed adaptive lateral driver models for different types of drivers, such as different lateral driving models for drivers with lower and higher driving skills [10]. The study concludes that low-level drivers' understanding of vehicle control is linear, and that feedback control of positional offset can be simulated by simple PID control methods. High-level drivers have a good understanding of the nonlinear characteristics of the vehicle at high vehicle speed or high lateral acceleration, and can adjust the control of the vehicle according to the vehicle dynamics characteristics accordingly. Therefore, the high-level driver model is based on the above PID model, but the PID parameter is no longer a constant, but a dynamic value that varies with error and control, and is self-adjusting according to the adaptive mechanism [10].

However, the above research on the driver's lateral driving behavior characteristics is mainly applied to two aspects: (1) the design of the lane keeping assistance system considering the driver's behavior characteristics. For this purpose, there are few studies to adjust the control parameters according to the driver's personal habits and working conditions. (2) The modeling and prediction of driver's direction control behavior can be used for various simulations, but the driver direction control behavior model designed on the premise of ideal trajectory cannot simulate the unsafe random behavior that may occur under certain possibilities. In addition, most of the studies use the driver behavior experimental data obtained based on the driving simulator, which lack actual road test data as the basis of analysis that can hardly reflect the driver's control habits in the actual traffic environment.

1.4 Summary of Research Status and Research Content of This Paper

1.4.1 Summary of Research Status

According to the above research and analysis, in order to make the lane keeping assistance control have better control effect, meet the driver's habits and intentions, and meet the driver's need to further reduce the driving pressure, there have been a lot of researches on the control methods, assist forms, driver habit's analysis and application, driver lane change intention identification, etc. But there are still some unresolved problems, including:

(1) Lane keeping assistance with fixed parameters is difficult to apply to different drivers with individual differences. With the development of driving assistance technology, the driver's acceptance has been paid more attention. Adaptive driver behavior is a trend toward improved driving assistance technology. In the lateral driving assistance system represented by the lane keeping assistant, although the research has proposed a method of adjusting the lane keeping assisting parameters according to the driver's behavior characteristics, this type of research has not yet provided the driver with the lanes under various working conditions. There is also no complete solution for how to make parameter design and adaptive adjustment through the driver's driving behavior database. Therefore, it is necessary to solve the problem, so that the lane keeping assistance system can ensure the safety, make the control timing and the control target in accordance with the driver's behavior, reduce the invalid intervention, and improve the driver's acceptance.

(2) In the current lane keeping assist system, only relying on the turning signal to identify the driver's map change, so the criterion is single and there is no guarantee that the assist strategy will be switched in time when changing lanes. The improvement of this problem in various studies is limited to the intentional identification of the characterization parameters of the driver's steering behavior and the characterization parameters of the vehicle's motion. In order to improve the accuracy of the algorithm, the general input parameters are not single. With the increase of input parameters, the nature of the input parameters determines that the method can accurately identify the driver's

intention only after the lane change behavior continues for a period of time. Therefore, it is necessary to collect scenes in which the driver's behavior is inconsistent with the system lane keeping, so that the driver's operation behavior can be predicted with higher efficiency.

(3) The design of the controller needs to balance the computational complexity with the model's uncertainty factors and the control performance caused by the interference. In the solutions proposed by the existing research institutes, at least one of the following problems exists. First, the method of directly ignoring the system modeling error is not conducive to obtaining optimal control because the model is not accurate enough. Second, the common control method for nonlinear structures and systems with uncertain components has high computational complexity which weakens the real-time control. When the driver is in the ring for a long time, the uncertainty of his behavior is greater, making the first point above more prominent. Therefore, it is necessary to select a suitable control method for the design of the lane keeping assistance controller to improve the control effect.

1.4.2 Research Content of This Paper

In view of the above problems, this paper proposes a lane keeping assist system that adapts to driver characteristics based two aspects: driver behavior profiles and scenarios learning. Around the function, system structure, key technology and experiment verification, the following work was carried out:

(1) Analysis of Driver's Lateral Driving Behavior Based on Real Road Test

The analysis of the driver's lateral driving behavior parameters is based on the data of the real road experiment. The behavioral rules and influencing factors of the driver during the lane keeping process are obtained. In a meanwhile, the differences in the distribution of the driving parameters when driver has different driving intentions are funded. These provide a design basis to the control decision layer.

(2) LKAS Departure Warning algorithms and Adaptive Adjustment Scheme

First, this chapter studies the common LDW algorithms in the world. A multi-mode TLC warning algorithm with driver selection is designed for high departure risk condition, and a flexible FOD warning algorithm with dynamic adjusted virtual boundary is designed for low departure risk. On this basis, an adaptive adjustment scheme combining driver behavior habit learning and lane keeping scenarios learning is proposed, and two databases of driver profiles and lane keeping scenes are constructed.

(3) Optimized decision-making layer and case study

In this part, the paper optimizes the decision-making layer of LKAS and conducts a case analysis. First, the state decision strategy is studied in deep. It includes 3 parts: Activation condition judgement, Driver operating status judgement and whether the system should intervene. All the judgements are analyzed with specific case. Finally, the decision flow chart was realized by using Simulink.

(4) Control algorithm of LKA system based on EPS

LKAS active control can effectively reduce the possibility of a traffic accident caused by the vehicle leaving the lane due to the driver not taking any operation. This paper establishes an EPS-based LKAS active control model, and the CarSim vehicle model outputs the actual lateral position of the vehicle. The deviation of the actual and target lateral position can be processed by the path model to obtain the desired steering wheel target angle. The difference between the target steering angle and the actual rotation angle of the EPS assisted motor is processed by the EPS-based LKAS active control model to obtain the target parameters of the EPS assisted motor. The target parameters control motor driving the movement of the mechanical steering system to change the trajectory of the vehicle.

Chapter II. Analysis of Driver's Lateral Driving Behavior Based on Real Road Experiment

In order to propose the description method of the driver's lane keeping behavior characteristics, and select the effective feature parameters with the degree of discrimination to identify the driver's intention, this chapter studies the driver's lateral driving behavior based on the real road experimental data. Taking the open driving test road in Beijing as the experimental site, the data collection experiment of free driving behavior based on real road is carried out. Based on the data preprocessing and the selection of effective road segments, the characteristics of the driver's lane keeping behavior are analyzed from the two aspects: the overall distribution of the characteristic parameters in the lane keeping process and the influence of the traffic environment factors on the lane keeping behavior. The variance analysis was used to compare the distribution of driving behavior characteristic parameters under different driving intentions. In order to meet the LKAS design requirements, a dynamic lane keeping boundary for describing driver lane keeping behavior and its adaptive adjustment scheme are proposed. The rationality of the description method is verified by modeling and simulating the driver lane keeping behavior mechanism based on the dynamic lane keeping boundary.

2.1 Driver's Natural Driving Behavior Data Collection and Processing

Compared with the simulation experiment based on the driving simulator and the directional working condition experiment on the design site, the real vehicle experiment in the real road environment has high realism and high working condition, and the driver behavior data and non-experimental conditions are obtained. The difference in natural driving behavior is small. The analysis results obtained from such data can basically reflect the driver's natural driving behavior characteristics. Therefore, this paper uses BMW's existing experimental vehicles and its integrated data acquisition platform to carry out the data collection experiment of the driver's natural driving behavior under the road conditions of automatic driving test in Beijing. The recorded data includes vehicle motion status, environmental data, and driver operational behavior data. On the basis of data preprocessing, effective road segment selection is carried out to distinguish between two lanes to be analyzed and lane change conditions, which provide data support for lateral driving behavior analysis under different working conditions. On the basis of data preprocessing, effective road segment selection is carried out to distinguish two types of conditions to be analyzed: lane keeping and lane changing, which provide data support for lateral driving behavior analysis under different working conditions.

2.1.1 Experiment and Data Collection Scheme

During the experiment, a 2018 BMW G12 vehicle equipped with ACC, LDW and other driver assistance systems was used as the platform, and the driving behavior collection system shown in Figure 2.1 was used to record and synchronize the required vehicle CAN bus data, FlexRay data, 4 channel video, and GPS location information.

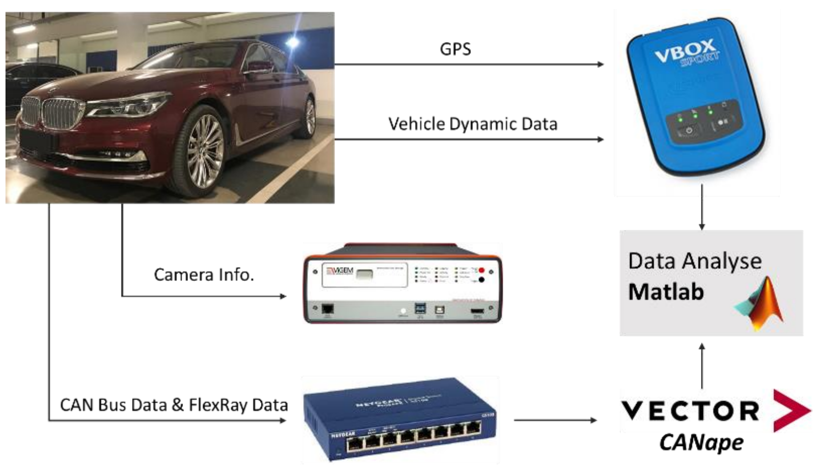


Figure 2-1 The driving behavior collection system

Among them, the vehicle CAN bus and FlexRay bus can provide information such as driving speed and steering wheel angle of the ego car, and also provide information such as the front distance and lane position sensed by the sensors of the driving assistance system such as ACC and LDW; 4 channel video includes the driver's facial image, front road image and rear road image, and KAFAS camera information. The bus digital signal is used for the calculation of characteristic parameters of driving behavior, and the video image and GPS position information are used to assist in the selection of analysis conditions.

The components of the information collection platform include the Vbox device, the Vector diagnostic device, the camera and the power module. The installation of the equipment is shown in Figure 2.2. The Vbox is responsible for recording GPS signals, vehicle trajectories and basic motion parameters. The Vector diagnostic device can read all of the vehicle's CAN bus and FlexRay data as needed. The Vigem recorder is primarily responsible for recording 4 channel videos. The digital signal sampling frequency is 10 Hz, and the sampling frequency of the video signal is 30 Hz.

Figure 2-2 Main experimental equipment

Consider the data requirements of different analysis contents and based on the China automatic driving test road classification regulations, select the three different characteristics of the route shown in Figure 2.3 for experiments. 24 test roads, totaling 74.4 kilometers, covering various road traffic environments such as urban main roads, secondary roads, and branch roads.

Route 1 is the circular section of Ludong District. The starting and ending point is Kechuang 10th Street. It runs clockwise and has a total length of 7.7 kilometers, including R1 and R2 roads. On the west side, the east side of the two-way six-lane main road is a two-way four-lane branch road with fewer vehicles, smoother traffic and higher average speed. The driving behavior data collected on the route is used to analyze the driver's lane keeping behavior characteristics in the main road.

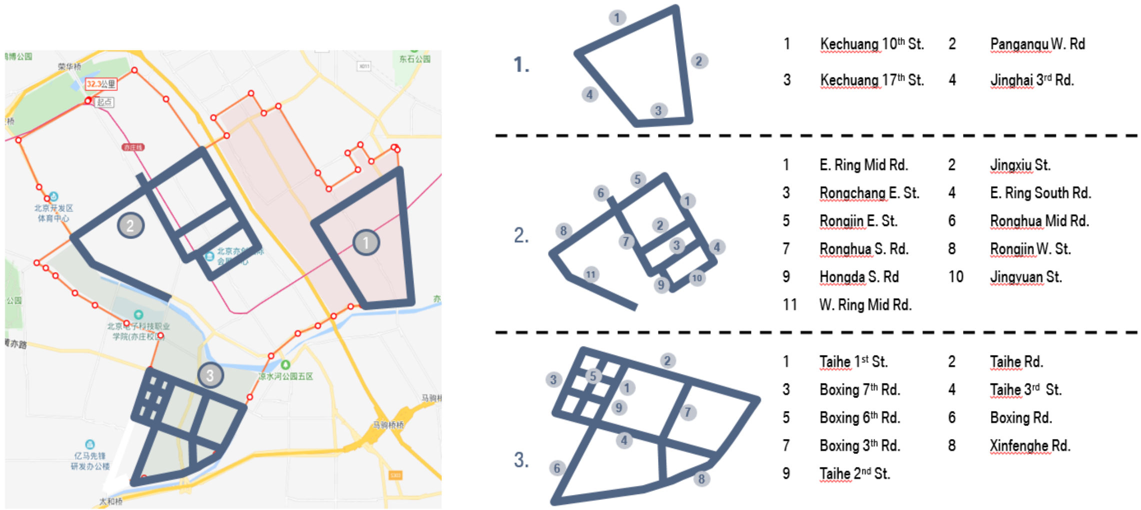
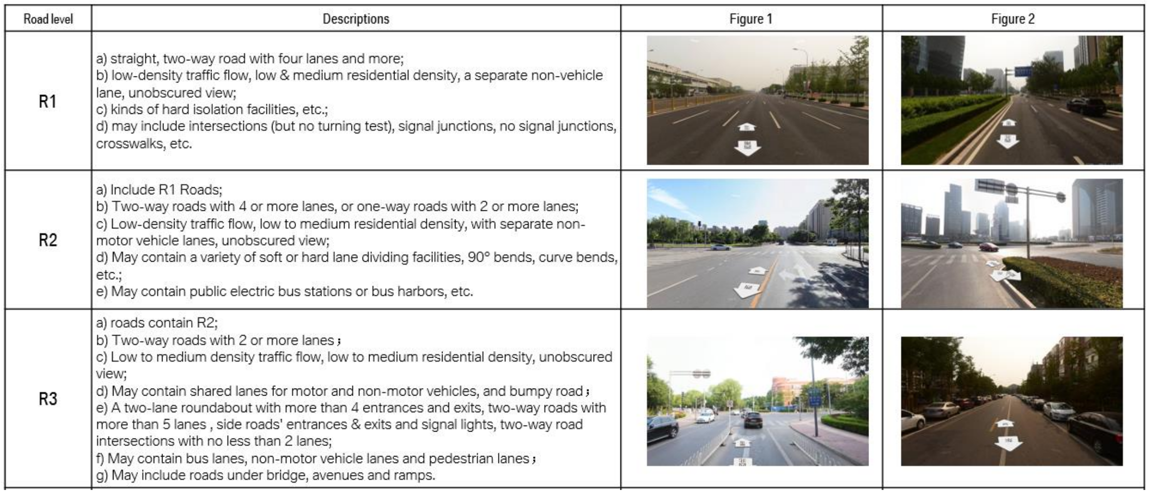


Figure 2-3 Test road information

In the figure, Route 2 is the section of the core area. The starting and ending point is Tongren Hospital of Xihuan Middle Road. It runs counterclockwise. The road is mainly main road (R2 level road), including some branch roads (R3 level road), about 17.8 km. The roads are relatively smooth, the traffic volume is large, and the average speed is medium. The data collected by the West Ring Road can be used to analyze the driving characteristics of the corners. Route 3 is located in the Hexi test area. The west side of the section is a community road (R3 level road), about 10.3 kilometers, with a low speed. The east side belongs to the express road (R2 level road), about 8.1 kilometers, which the speed is high. The driver's behavioral habits on this section are different from those on ordinary highways. The test data of the three routes will be used together to analyze the driver's lane change decision-making factors and optimize the performance of the vehicle maintenance system on the urban road, which is of great significance for the future development of low-speed lanes.

The road’s complexity level is described in Figure 2-4. R1 is the simplest road condition.



Road level	Descriptions	Figure 1	Figure 2
R1	a) straight, two-way road with four lanes and more; b) low-density traffic flow, low & medium residential density, a separate non-vehicle lane, unobscured view; c) kinds of hard isolation facilities, etc.; d) may include intersections (but no turning test), signal junctions, no signal junctions, crosswalks, etc.		
R2	a) Include R1 Roads; b) Two-way roads with 4 or more lanes, or one-way roads with 2 or more lanes; c) Low-density traffic flow, low to medium residential density, with separate non-motor vehicle lanes, unobscured view; d) May contain a variety of soft or hard lane dividing facilities, 90° bends, curve bends, etc.; e) May contain public electric bus stations or bus harbors, etc.		
R3	a) roads contain R2; b) Two-way roads with 2 or more lanes； c) Low to medium density traffic flow, low to medium residential density, unobscured view; d) May contain shared lanes for motor and non-motor vehicles, and bumpy road； e) A two-lane roundabout with more than 4 entrances and exits, two-way roads with more than 5 lanes , side roads' entrances & exits and signal lights, two-way road intersections with no less than 2 lanes; f) May contain bus lanes, non-motor vehicle lanes and pedestrian lanes； g) May include roads under bridge, avenues and ramps.		

Figure 2-4 Road’s complexity level information

In order to make the drivers participating in the experiment have a certain randomness, which reflects the natural differences between the individual drivers, when selecting the experimental subjects, the drivers are tested in terms of gender, age, driving age, driving frequency, occupation, etc. A total of 28 subjects participated in the experiment, including 24 males and 4 females, aged between 24 and 59 years old, with a driving age of 4 to 23 years. Thirteen of them have never used the lane keeping function, three people may use it once a month, and four people use it once a week, and eight people use the lane keeping function every day. For the main information of specific experimental objects, please refer to Table 2.1.

Table 2.1 Main information of test drivers

Driver’s number	Gender	Age	Driving experience	Function using frequency
1	Male	31	12	Weekly
2	Female	36	10	No
3	Male	51	9	Every day
4	Male	29	10	No
5	Male	50	20	Every day
6	Female	54	20	No
7	Male	35	16	No
8	Male	46	14	Per month
9	Female	36	10	Every day

10	Male	29	6	Weekly
11	Male	48	10	No
12	Male	36	18	Every day
13	Male	37	8	Every day
14	Male	30	10	No
15	Male	59	20	Weekly
16	Female	51	20	Weekly
17	Male	26	8	No
18	Male	26	6	No
19	Male	50	20	Every day
20	Male	30	7	No
21	Male	44	13	Per month
22	Male	48	10	Per month
23	Male	45	15	No
24	Male	42	20	Every day
25	Male	33	10	No
26	Male	44	23	No
27	Male	43	20	Every day
28	Male	24	4	No

2.1.2 Data Preprocessing and Effective Data Selection

The signals that can be recorded in real time during the experiment are shown in Table 2.2. By using the UTC timeline, the data collected by the Vbox and CANape is synchronized with the data collected by the Vigem recorder.

Table 2.2 Key parameters from the measuring equipment

Symbol	Descriptions	Unit	Data recording method
t	Time	s	Vbox
Lat	Latitude	°	Vbox
Long	Longitude	°	Vbox
Lo	Latera offset	m	Vbox
S_{light}	Turning signal		Vector
P_{left}	Left lane mark position	cm	Kafas Camera
P_{right}	Right lane mark position	cm	Kafas Camera
DTF	Front car spacing	m	Vector
V_{rel}	Relative speed	m/s	Vector
V	Ego car speed	kph	Vbox

$V_{departure}$	Lateral offset speed	m/s	Vbox
δ_{sw}	Steering wheel corner	°	Vector
$\dot{\psi}$	Yaw rate	°/s	Vbox
Fnum	Video frame number		Vigem
ρ	Road curvature	m^{-1}	Vbox

Some parameters in the subsequent data analysis need to be obtained through post-processing calculation, such as vehicle lateral position offset, vehicle relative road lateral speed, and time to lane crossing (TLC). These are shown in Table 2.3.

Table 2.3 Post-processing data

Symbol	Descriptions	Unit
TLC	Time to lane change	s
$\dot{\delta}_{sw}$	Angular velocity of steering angle	°/s
X_v	Longitudinal position in the Global coordinate which converted from latitude and longitude	
Y_v	Lateral position of the Global coordinate which converted from latitude and longitude	

Based on the above measured or already obtained data, the lane changing conditions, lane keeping conditions, and special moments are selected as the basis for the analysis of the driver's lateral driving behavior characteristics.

<u>Selection of lane changing conditions</u>

In order to study the difference in control behavior of the driver under different intentions, the lane changing condition is selected for subsequent analysis. When selecting the lane changing conditions, the collected data needs to meet the good road conditions, low traffic flow, high average speed. And the driver's lane change process is natural, and the frequency is high. The specific scene can be divided into lane change without car and lane change with the car. Taking the left lane change as an example, the selection process is as follows:

First define the mid-point of the lane change i.e. the moment when the vehicle's mass center crosses the lane mark. At this time, the position value of the lane mark will be abruptly changed, and the mid-point of the lane change will be selected by using the mutation. According to China's "Urban Road Traffic Planning and Design Specification" GB 502220-95, the urban lane width is mainly 3.5m, considering the lateral motion of the vehicle, the sampling time interval and the lane mark identification error, etc. When the value of the distance between the one-sided lane mark at a certain time and the distance of the same lane mark at the next moment changes by more than 2 m, it is considered that the moment is the centroid crossing time. Therefore, if the ***i***-time and the one-side lane mark position $\boldsymbol{P_{left}}$ at the previous moment satisfies the mutation law shown in the equation (2-1), the time point is the mid-point of the lane change.

$$\left|P_{left/right}(i) - P_{left/right}(i-1)\right| > 250\ mm \tag{2-1}$$

Secondly, define the starting point of the lane change, and trace back from the mid-point of the lane change. The first time point found that meets the following conditions is the starting point of the lane change: 1) the center of mass of the vehicle is between the centerline of the original lane and the target lane, and the distance from the centerline of the original lane is greater than a set threshold; 2) the driver's steering wheel turns to the target lane direction. Considering that the vehicle center of mass is not absolutely at the center of the lane during the lane keeping process before the lane change, the driver often has different lateral position control habits, which are shifted to the left by 0-0.5m, and 0.5m is selected as the distance threshold in condition 1).

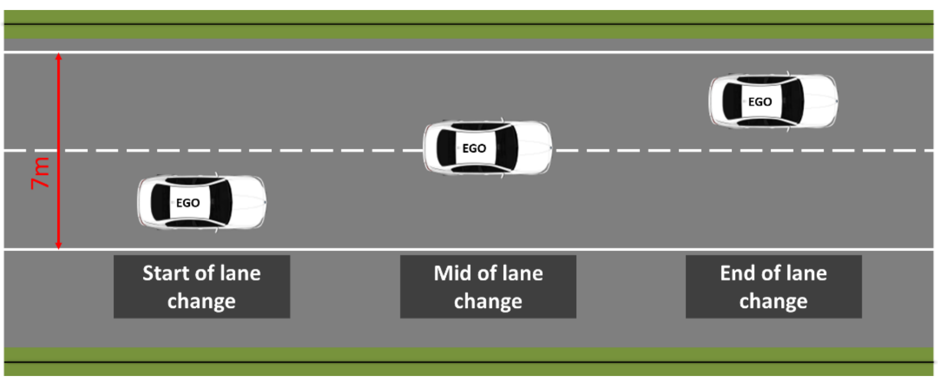


Figure 2-5 Schematic diagram of the lane change process

Finally, the end point of the lane change is defined, and the point is traced backward from the mid-point of the lane change. The first time point found at the same time meets the following conditions is the end of the lane change: 1) The vehicle center of mass is between the target lane centerline and the target left lane line, the distance from the target lane centerline is less than the set threshold; 2) the vehicle has a lateral velocity component in the direction of the original lane. Similarly, the distance threshold in condition 1) is chosen to be 0.5m.

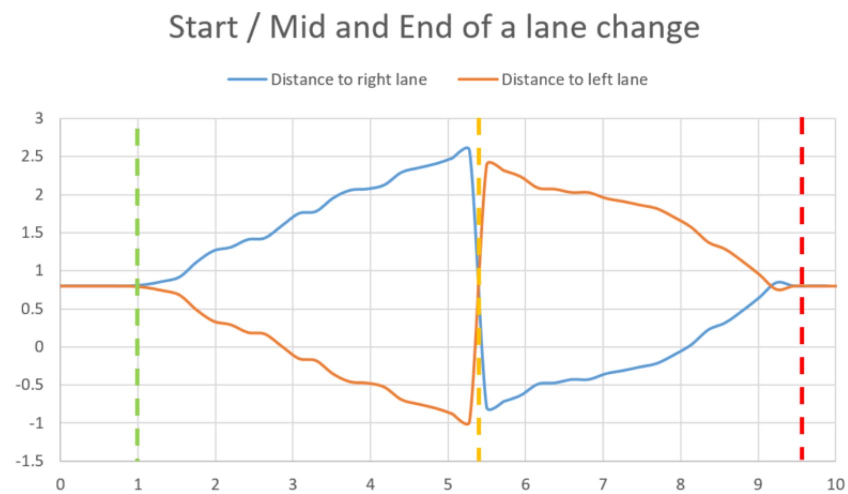


Figure 2-6 Define the lane change process

<u>Selection of lane keeping conditions</u>

The lane keeping condition is the main object of the driver behavior research in this paper. Excluding the lane changing conditions selected above, the following two cases are excluded, and the remaining data is defined as the lane keeping condition.

First exclude the situation that the driver initially had the intention to change lanes and had a lane change behavior, but eventually canceled the lane change. If any of the following two conditions is met, it is determined that the driver has the intention to change the lane but does not complete the lane change behavior. In the first case, the driver turns the turning signal on during the lane keeping but does not perform the lane change, eliminating the time when the turning signal is turned on. The second case is: after the time of the cross-track, the vehicle does not completely enter the target lane, and finally returns to the original lane, using the same algorithm in (1) above to find the mid-point of the lane change and the starting point as the failure. After the starting point of the lane change, and after finding the time of the cross-track, the time when the vehicle center crosses the center line of the original lane for the first time, as the end point of the failed lane change, the time period from the start point to the end point of the failed lane change is excluded.

2.2 Analysis of Characteristic Parameters of Lateral Driving Behavior

After pre-processing and selecting the working conditions of 28 drivers' behavior data, the driver behavior habits in the lane keeping process are studied from the aspects of the overall rule of the parameters in the lane keeping process and the influence of the traffic environment factors on the driver's lane keeping behavior. The variance analysis method was used to study the distribution difference between vehicle motion parameters and driver control behavior parameters under different driving intentions.

2.2.1 Analysis of Lateral Characteristic Parameters during Lane Keeping

In order to prove that individual habit difference and working condition difference have an impact on the driver's lane departure risk perception, and provide support for establishing a dynamic characterization method, the driver's driving behavior in the lane keeping process is studied from the following two aspects: on the one hand, it analyzes the overall law of the driver's behavior habits and the individual differences between the drivers; on the other hand, it analyzes the parameter distribution characteristics of the driver at the special moment of turning back to the punctual point. In the lane keeping process, the most representative parameters are the vehicle position lateral offset (Lo) and the cross-track time TLC. Therefore, this section analyzes the two characteristic parameters of the driver in the whole process and the steering back to the point, to understand the driver's behavior.

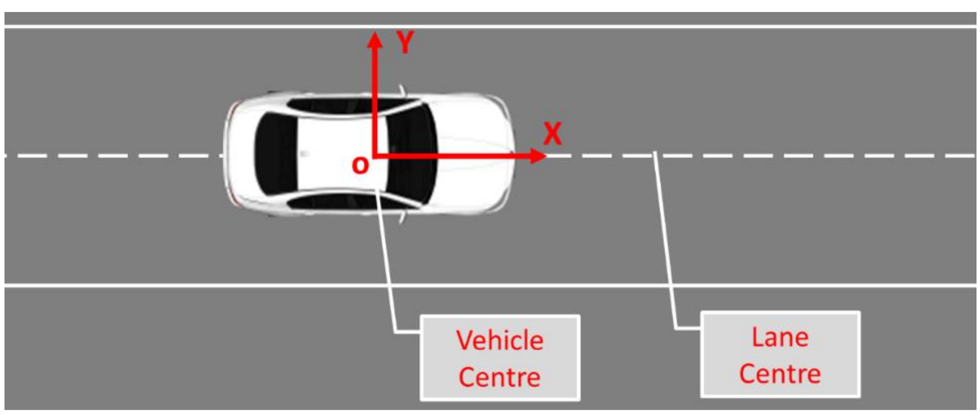


Figure 2-7 Lateral offset (LO), coordinate system

The distribution of characteristic parameters and individual differences

The lateral offset (***Lo***) of the vehicle is a direct parameter to show the driver's control. Taking the driver No. 1 as an example, the distribution frequency and cumulative frequency of ***Lo*** are shown in Figure 2.8. It can be concluded from the distribution in the figure that during 90% of the lane keeping operation, Lo concentrates between -0.35 and 0.60 m, and the overall distribution is biased to the left of the lane centerline.

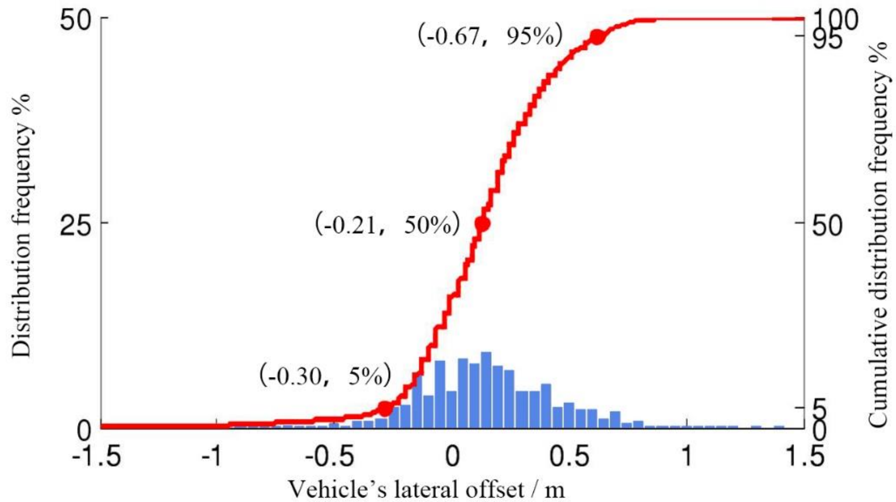


Figure 2-8 Lateral offset's distribution frequency and CDF of the driver 1

Table 2.4 shows the statistical results obtained from data analysis of 28 drivers' driving behavior. It can be seen from the results that different drivers have large differences in the control of the lateral offset of the vehicle position. Some drivers are used to drive to the right of the centerline, such as drivers 7, 21 and 23, the average lateral displacement of the vehicle is negative and the absolute value is high. Some drivers have higher tolerance for lane departure. The sensitivity to lane departure risk is low, like drivers 3, 11, 15, and 27, Lo has a higher variance. As can be seen from the overall cumulative distribution function, most drivers show the habit of driving to the left of the centerline.

Table 2.4 Lateral offset statistic results of all drivers

Driver	Mean	Variance	5% CDF	50% CDF	95% CDF
1	0.18	0.07	-0.30	0.25	0.65

2	0.08	0.08	-0.24	0.25	0.61
3	-0.19	0.37	-0.28	0.31	0.57
4	0.45	0.03	-0.32	0.17	0.61
5	0.15	0.07	-0.26	0.25	0.65
6	-0.12	0.37	-0.40	0.27	0.57
7	-0.32	0.40	-0.28	0.29	0.71
8	0.05	0.20	-0.30	0.35	0.69
9	0.05	0.24	-0.32	0.19	0.61
10	0.08	0.37	-0.34	0.31	0.55
11	0.05	0.54	-0.32	0.23	0.71
12	0.35	0.40	-0.20	0.17	0.67
13	0.35	0.54	-0.38	0.31	0.69
14	0.28	0.26	-0.20	0.21	0.69
15	-0.22	0.58	-0.28	0.33	0.55
16	0.48	0.10	-0.32	0.25	0.71
17	0.01	0.17	-0.38	0.23	0.67
18	-0.12	0.44	-0.36	0.31	0.67
19	0.31	0.27	-0.40	0.21	0.61
20	0.35	0.14	-0.36	0.21	0.69
21	-0.29	0.40	-0.36	0.29	0.59
22	0.11	0.34	-0.26	0.19	0.67
23	-0.28	0.18	-0.20	0.29	0.63
24	0.41	0.37	-0.28	0.23	0.61
25	0.41	0.34	-0.24	0.21	0.69
26	0.15	0.54	-0.34	0.35	0.69
27	-0.09	0.57	-0.30	0.33	0.71
28	-0.02	0.40	-0.26	0.35	0.61

Time to Lane Change (TLC) is a predictive parameter for the risk of lane departure. It is assumed that the movement of the vehicle relative to the lane remains unchanged, and the crossing time is the time from the current time to the wheel touches lane mark.

According to the value of TLC, all lane keeping processes can be divided into four working conditions: $TLC \geq 15$ means that there is no risk of lane departure in a short time. $0<TLC<15$ means that the vehicle is currently facing a potential hazard that may deviate from this lane within 15s. $TLC \leq 0$ means that the wheel touched the lane mark. According to the direction of velocity, it is divided into lane departure to left and lane departure to right.

The percentage of four operating conditions varies with vehicle speed as shown in Figure 2.9 It can be observed from the figure that as the vehicle speed increases, the proportion of lane departures of the vehicle increases, and the proportion of lane departure tendency (TLC ≥ 15) does not decrease in a short period of time; meanwhile, the frequency of the lane departure to the left is significantly lower than The frequency at which the lane departure to the right.

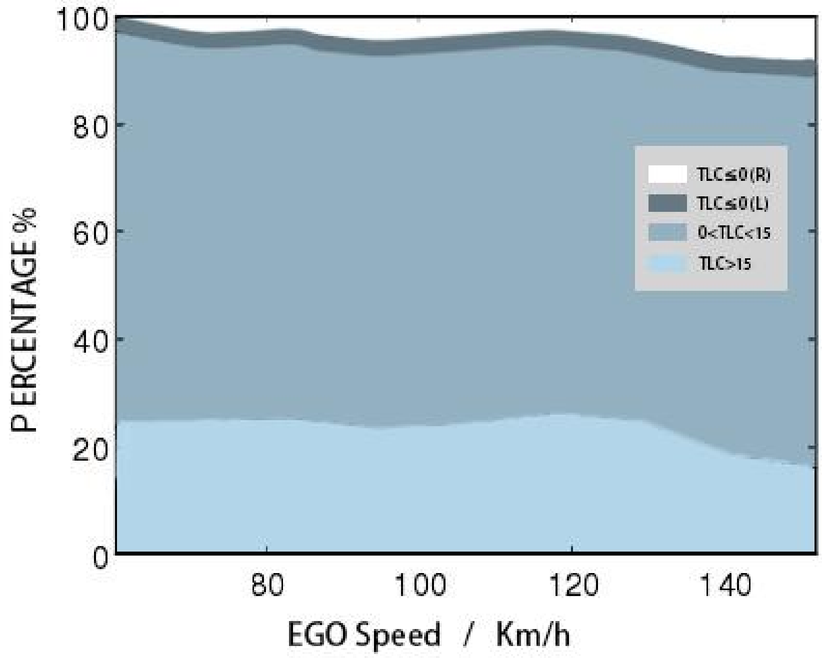


Figure 2-9 The percentage distribution of TLC at different vehicle speeds.

By analyzing the statistical results of TLC, we can find that drivers have large differences in the control of the lateral offset of the vehicle position. Some drivers have a higher tolerance for lane departures, and the time when the wheel touches lane mark close to or exceeds 10%. Some drivers pay more attention to the control of the lateral position, and the time of wheel pressing lane mark is less than 5%. Some drivers have a clear perception of the risk of lane departure from different sides. The frequency of the departure to the right is 5 to 10 times that of the departure to the left.

<u>The distribution of steering reverse point</u>

Steering Reverse Point (S.R.P.) is the turning point when the driver reverses the steering wheel. To define the S.R.P., taking the lane departure to the left as an example:

During the lane keeping process, when the lateral speed of the vehicle relative to the lane is to the left, and the steering wheel begins to return to the right, that is, the moment when the steering wheel angle is the maximum value to the left. As can be seen from its physical meaning, the S.R.P. represents the range boundary of the driver's ideal lane keeping behavior. Once the vehicle exceeds the S.R.P. boundary means that there is a potential lane departure risk. Analyzing the parametric characteristics of the S.R.P. helps to understand the lateral position area that the driver expects.

Considering that most people's driving style is gently driving, the performance of the first driver is taken as a representative. The differences in driver behavior in different lane departure directions were studied. Among them, when car at the S.R.P., the distribution of the lateral offset of the vehicle position is shown in Figure 2.10 and Figure 2.11.

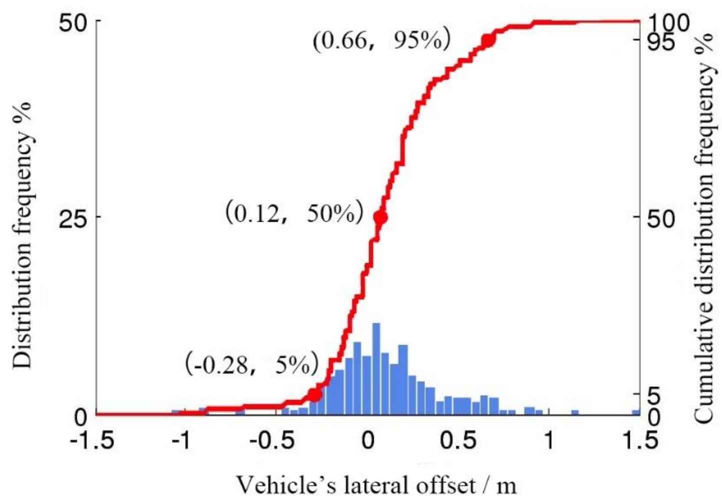


Figure 2-10 S.R.P. on the left side

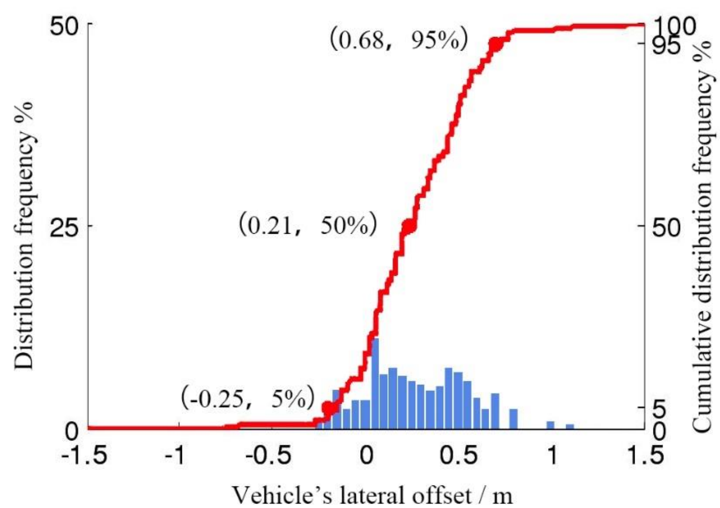


Figure 2-11 S.R.P. on the right side

If the S.R.P. are on the right side, it is clear that the lateral offset position distribution is significantly far from the zero point.

Generally speaking, the driver is considered to be more sensitive to the potential danger on the left side, and often takes a steering back operation when it is relatively safe; while it is more common that ignoring the potential lane departure to the right. Thus, the following conclusions can be drawn: (1) The driver is more tolerant of the lane departure to the right; (2) the driver is less likely to notice the lane departure to the right.

2.2.2 The influence of traffic environment factors on driver's lane keeping behavior

During the lane keeping process, the traffic environment factors have a certain influence on the driver's steering control. In this section, the influence of the lane position factor and the surrounding traffic flow factors on the driver's lane keeping behavior is discussed.

<u>Analysis of the influence of lane position factors</u>

The source of the data used in this section is the city's two-way six-lane fast-way. The left lane of the three-lanes is the overtaking lane, the middle lane is the driving lane, and the bus lane on the right side. Taking the first driver as an example, the distribution of driver's travel time in the lane is counted. The conclusion is:

The leftmost lane is mostly overtaking lane. Due to heavy vehicles (such as large operating vehicles: buses), the vehicle speed for rightmost lane is much slower. More than 80% of the time, the driver is in the middle lane.

Figure 2-12 Road information

The distribution of lateral offset of the vehicle position on different lanes is shown in Figure 2.13 and Figure 2.14. It can be seen that in the left lane, the vehicle tends to departure to the right for most of the time, while on the middle lane, it tends to keep with the centerline. The reason is that since the left lane is closer to the road fence, the driver's desired trajectory is affected by it and is trend to the right. The middle lane is not directly constrained by the guardrail on the road boundary, and also there is a bus lane on the right side, so the driver can guarantee a better lane keeping behavior.

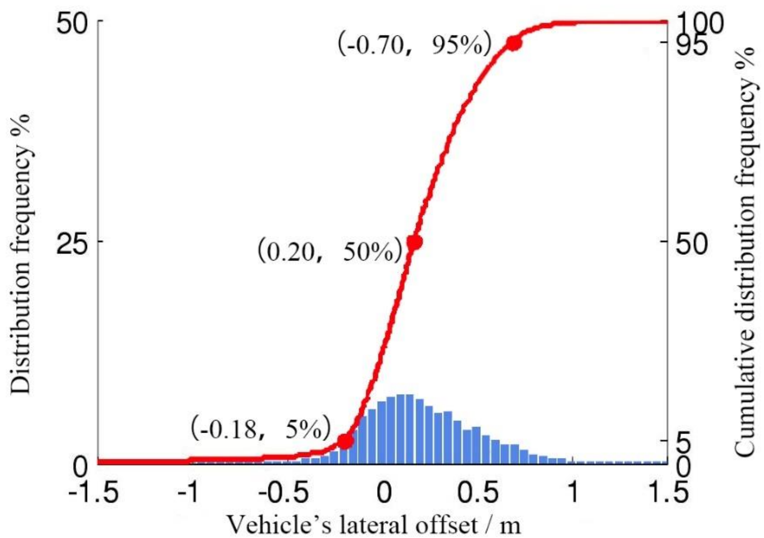


Figure 2-13 Statistical results of lateral offset when driving on the leftmost lane

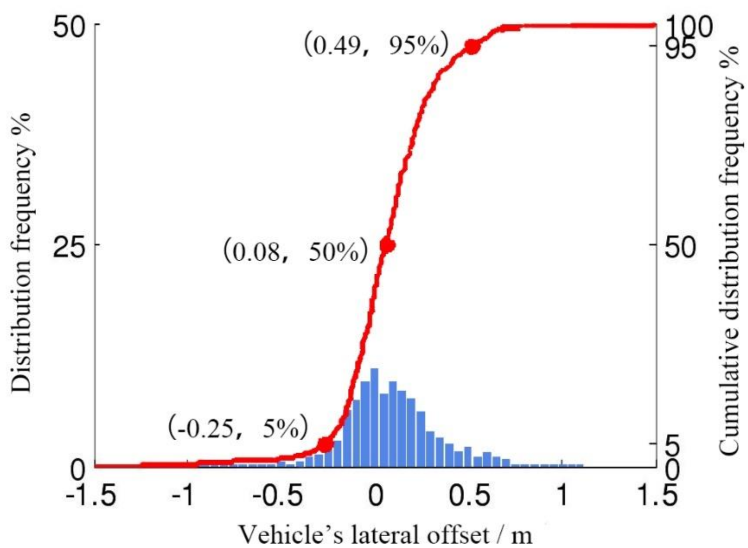


Figure 2-14 Statistical results of lateral offset when driving on the middle lane

Since the first driver can keep in the lane for most of the time, the TLC data between 0 and 15 s of him is analyzed. The results are shown in the figures 2.15 and Figure 2.16.

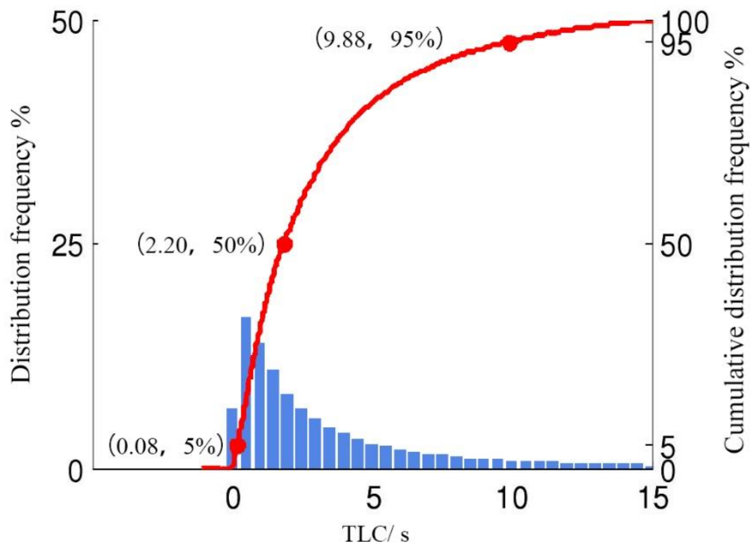


Figure 2-15 Statistical results of TLC when driving on the leftmost lane

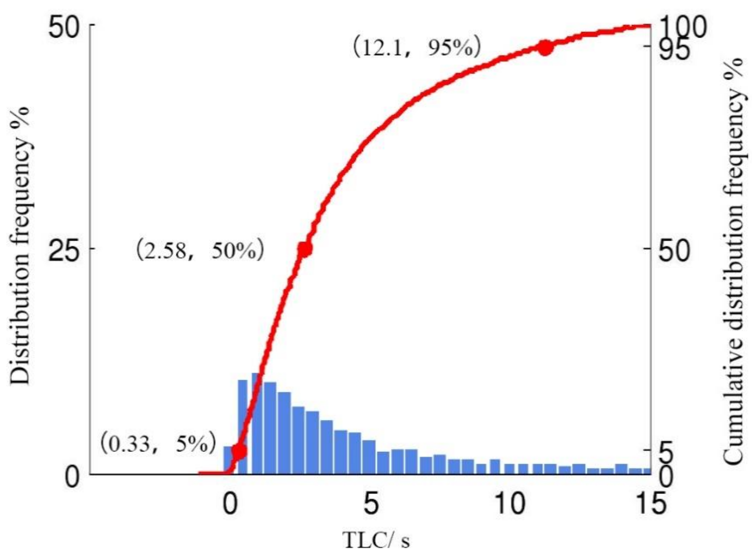


Figure 2-16 Statistical results of TLC when driving on the middle lane

From the comparison of the two figures, it can be seen that for all the conditions with the risk of lane departure, the TLC value on the left lane is smaller than the TLC value on the middle lane. This means that the driver's lane keeping behavior on the left lane is more aggressive and the probability of lane departure is higher.

The K-S test method was used to verify whether there was a significant difference between the two sets of TLC distributions. The original assumption was that the lane position had no significant effect on the TLC distribution. The data processing results show that the probability of this hypothesis is p=4.77×10-43. When the significance level is α=0.05, it can be considered that there is a significant difference in the distribution of TLC when driving on the left and middle lanes.

Analysis of the influence of surrounding traffic factors

Interference in adjacent lanes is a common factor for the driver's lane keeping behavior, especially in the case of there are road constructions or heavy vehicles in the adjacent lane.

In this section, to understand the influence of surrounding traffic factors on driver behavior, 168 overpassing data of first driver from the No.2 test route is analyzed. Among them, 61 groups have cars in the adjacent lanes on the left side and 107 groups have cars in the adjacent lanes on the right side.

The progress of overpassing can be divided into three periods. Two of the key moments are shown below:

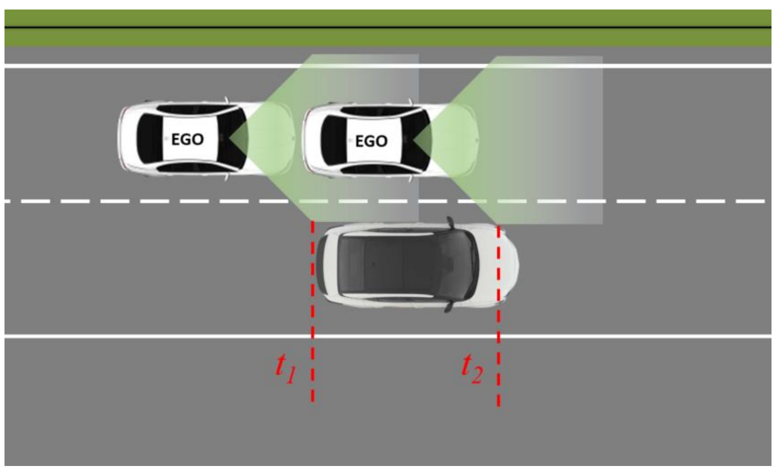


Figure 2-17 Schematic diagram of the two key moments

(1) At time t_1, the moment when the tail light of the adjacent car disappears from the front camera.

(2) At time t_2, the moment when the headlight of the adjacent car disappears from the front camera. Since the car has not completely overtook the adjacent car at time t_2, the time of $t_2+0.5s$ is selected as the overpassing end point. Take the length of each segment

as $p_{eriod} = t_2 - t_1 + 0.5s$. Then, three stages can be selected for sampling and calculation of parameters:

Stage (1) before passing the adjacent car: t_{period} before t_1;

Stage (2) when passing the adjacent car: t_1 to $t_2+0.5s$ time period;

Stage (3) after passing the adjacent car: t_{period} after $t_2+0.5s$.

Connect these three time periods to draw the trajectory of the car during overpassing, as shown in the figures below.

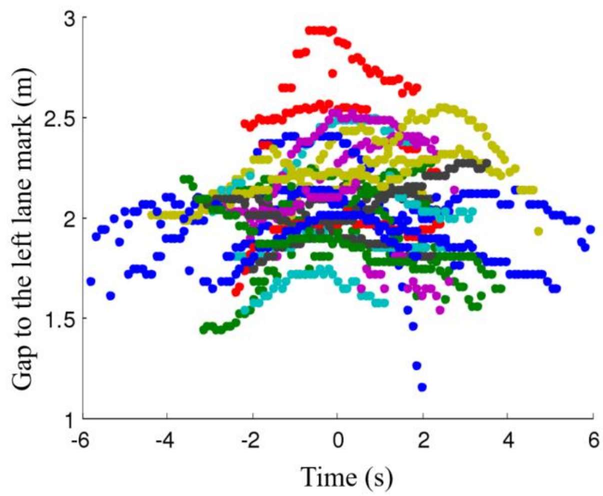


Figure 2-18 Trajectory when pass the target car on the left

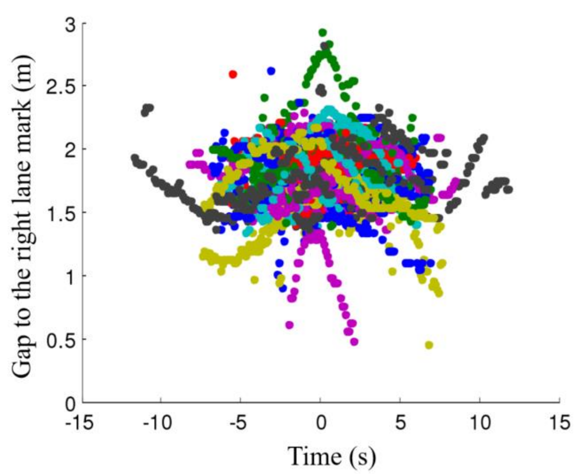


Figure 2-19 Trajectory when pass the target car on the right

It can be seen from the change process of the trajectory in the figure that when the vehicle passes the target vehicle in the adjacent lane, the lateral motion trajectory of the self-vehicle presents a general rule of moving away from the target vehicle and then returning back to the normal lateral position.

2.2.3 Differences in distribution of characteristic parameters under different intents

In order to select effective parameters to identify the driver's lane change intention, the actual vehicle experimental data of the 28 drivers collected on route 2. They are used to analyze the differences between parameters of lateral motion under driver control behavior. The parameters include lateral motion parameters as well as lateral control parameters. The lateral motion parameters include the lateral speed of the vehicle relative to the lane ($\boldsymbol{V_{departure}}$) and the yaw rate of the vehicle ($\dot{\psi}$). The driver's lateral control parameters include the steering wheel angle (δ_{sw}) and the changing rate of the steering wheel angle ($\dot{\boldsymbol{\delta}}_{\boldsymbol{sw}}$).

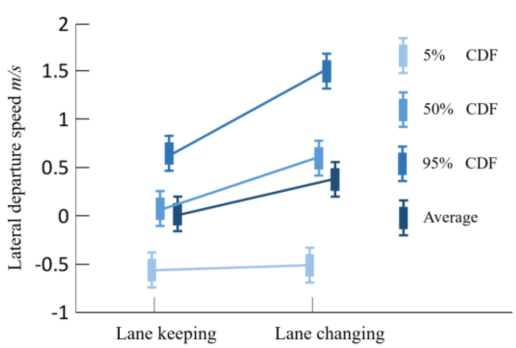


Figure 2-20 The comparison of $\boldsymbol{V_{departure}}$

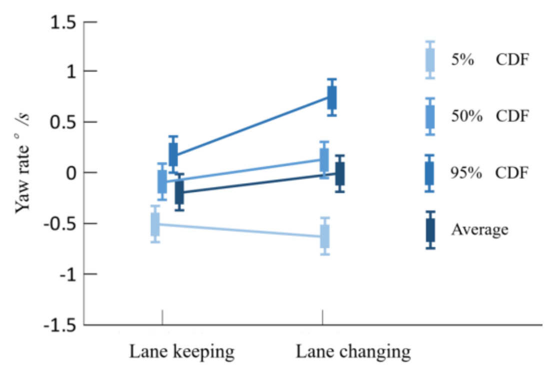


Figure 2-21 The comparison of $\dot{\psi}$

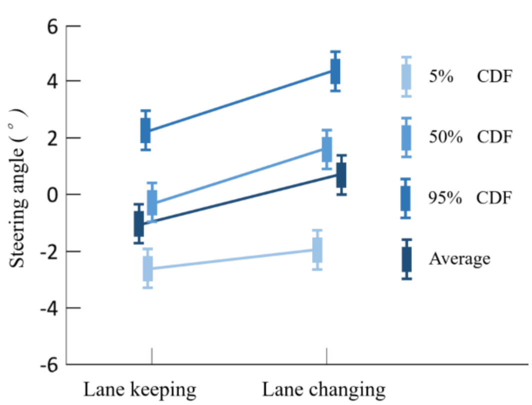


Figure 2-22 The comparison of the δ_{sw}

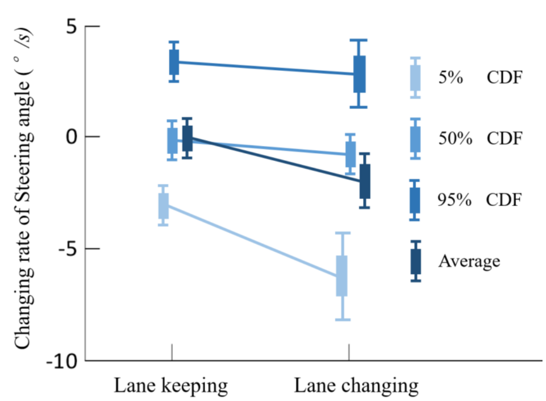


Figure 2-23 The comparison of $\dot{\boldsymbol{\delta}}_{\boldsymbol{sw}}$

According to the above analysis of the motion parameters and the control behavior parameters, the relative lateral speed of the vehicle, the yaw rate of the vehicle, the steering wheel angle and the changing rate of the steering wheel, most of the parameters have a significant difference between lane keeping and lane changing.

2.3 Summary of this chapter

This chapter takes the Beijing A.D. Test Road as the experimental route. Carried out the real vehicle experiment, collected the driver's natural driving behavior data, and analyzed the driver's lateral driving behavior characteristics under specific working conditions. Through the research in this chapter, the following main conclusions are obtained:

1. Through the analysis of the driver's lateral driving behavior characteristics, it is clear that different drivers have obvious differences in the control habits of the vehicle's lateral offset and movement during the lane keeping process;

2. During the lane keeping process, different working conditions, such as lane position and overpassing behavior, have certain influence on the driver's lateral position control habit during the lane keeping process.

Therefore, it is necessary to adaptively adjust the LKAS warning strategy and control target according to the driver's behavior characteristics when design the lane keeping assist system, so that the LKAS can meet the driver's cognitive habit of lane departure risk.

Chapter III. LKAS Departure Warning algorithms and Adaptive Adjustment Scheme

Establishing a reliable description method with considering driver behavior's difference and randomness and integrating multiple effect factors has a great significance for adaptive LKAS design. Based on the above analysis of driver behavior during the lane keeping process, this section first reviews the current lane departure warning algorithm, and then proposes a lane departure judgment mechanism for various conditions under TLC algorithm and FOD algorithm. The concept of variable departure warning parameters is used to describe the driver's different perceptions of lane departure risk, thus reflecting the lane keeping behavior mechanism which can adapt to driver driving characteristics.

3.1 Overview of lane departure warning algorithm

The camera and radar system detect the relationship between the vehicle position and the lane mark and then send this information to the lane departure warning algorithm. The algorithm integrates sensors' information, the GPS position information and the vehicle state information.

Most of the published literature on LDWS and LKAS uses visual sensors to obtain lane line information, and combined with warning decision algorithms to identify whether the vehicle has a tendency to departure from the original lane. The lane departure warning algorithms used by various research institutions are basically divided into two categories, one is the combination of road structure model and image information, and the other is only using image information. There are eight types of departure warning algorithms that are currently used commonly: TLC algorithm, FOD algorithm, CCP algorithm, instantaneous lateral displacement algorithm, lateral velocity algorithm, Edge Distribution Function (EDF) algorithm, and Time to Trajectory Divergence (TTD) algorithm and Road Rumble Strips (RRS) algorithm [31]. The RRS algorithm belongs to the combination of road structure and image information, which requires the installation of vibration bands or constructing new roads.

In the existing road, a 15cm~45cm groove is placed on the shoulder of the road. If the vehicle deviates from the lane and enters the groove, the tire will rub against the groove due to contact, and the sound of the friction will remind the driver the departure from the original lane. The seven departure warning algorithms except RRS belong to the algorithm using only image information. In order to clearly understand the advantages and disadvantages of various algorithms, and to guide the study of the lane departure warning algorithm, the comparative analysis of the above eight warning algorithms is shown in Table 3.1:

Table 3.1 Comparison of the eight warning algorithms

Algorithms	Pros	Cons
TLC	Long warning time	Fixed parameters
FOD	Multiple warning thresholds	Limited reaction time for driver
CCP	Based on real-time position	High precision sensors
Lateral Velocity	Easy to define	High false rate
TTD	Always follow lane center	Complex algorithm and works bad in bend
Instantaneous Lateral Displacement	Simple algorithm and easy to realize	Ignored the vehicle trajectory, relatively high false rate
EDF	No need for camera	Complex algorithm
RRS	Effective alert	High cost

From the above analysis, it is clear that each algorithm has different advantages and disadvantages. The eight common departure warning algorithms have certain limitations and the algorithm does not change once it is determined. But factors such as age, gender, and driving age make each driver almost have their own driving habits. Therefore, the efficient and practical warning algorithm must not only have higher precision, but also should adapt to the driving habits of different types of drivers.

Among the above methods, TLC has simple using conditions and high precision, and is the most widely used in LDWS and LKAS related products. FOD considers driving habits when setting the lane virtual boundary line, but the accuracy is limited. Therefore, in order to make LKAS adapt to different types of drivers to the maximum extent, this paper improves the existing TLC and FOD algorithms—establishing TLC and

FOD algorithms with selectable mode and multiple working conditions and based on them, and proposes the concept of dynamic warning boundary and warning parameters.

3.2 Multi-mode TLC warning algorithm with selectable driving style

The TLC algorithm assumes that the vehicle maintains its current state of motion and calculates the time it takes to move from the current position to the left front wheel or the right front wheel to touch the lane boundary.

TLC working principle: If the calculated TLC value is less than the set threshold, the vehicle has the potential of driving departure of the original lane. LKAS or LDWS will send a warning signal to the driver to remind the driver to take over in time to correct the vehicle movement. There are many different methods for estimating TLC, and each method differs in accuracy due to its complexity. When the vehicle deviates from the original lane to the wheel touches the lane boundary line, the vehicle travels a certain distance in both the longitudinal and lateral directions. The TLC can be calculated from the lateral cross-track distance. The TLC can also be calculated from the longitudinal cross-track distance. The lateral TLC algorithm assumes that the lateral velocity and yaw angle of the vehicle are unchanged in a short time, and the cross-track time is calculated by using the lateral distance and the lateral velocity. The advantage is that the algorithm is simple, the parameters are easy to measure, and the warning time is early, so that the driver has enough time to correct vehicle motion. The disadvantage is the low accuracy. The longitudinal TLC algorithm takes into account road geometry parameters and vehicle state parameters. The calculation assumes that the vehicle's heading angle remains constant during the deviation process [45]; its advantage is that the accuracy is higher than the lateral TLC algorithm, and the TLC value of each moment can be obtained. The driver is reserved for a certain reaction time to correct the vehicle movement; the disadvantage is that additional sensors are required to collect vehicle state parameters compared to the lateral TLC. This paper selects the longitudinal TLC algorithm according to the LKAS function and characteristics. The formula is as shown in Equation 3.1:

$$\mathrm{TLC} = \frac{d_x}{V_x} \tag{3-1}$$

$\boldsymbol{d_x}$ is the length of the motion trajectory when the vehicle touches the lane boundary line, and $\boldsymbol{V_x}$ is the longitudinal motion speed of the vehicle.

The lanes are divided into straight roads and curved roads according to the center line type. The trajectory of the vehicle from the lane is divided into straight lines and curves. The deviation direction is divided into a leftward deviation and a rightward deviation. So, there are 8 possibilities when the vehicle deviates from the lane on any road, as shown in the following Table 3.2:

Table 3.2 Possibilities of deviating working condition

Road Type	Straight Line	Curved Line	
Straight Roads	1	2	Departure to Left
	3	4	Departure to Right
Curved Roads	5	6	Departure to Left
	7	8	Departure to Right

In this paper, the two conditions: vehicles in the straight road deviate to the left with the curve trajectory (working condition 2) and the vehicle on the curved road deviate to the right with a straight trajectory (working condition 3) will be taken as examples to analysis the longitudinal TLC algorithm model. The analysis methods of the other six cases are consistent with these two cases.

3.2.1 Calculation method of vehicle deviating to the left with a curved trajectory on a straight road

Since the road surface has a certain lateral slope and the presence of lateral wind and other lateral interferences, the driver must constantly adjust the steering wheel to keep driving in the straight line. Therefore, even if the vehicle is driving on a straight road, the steering wheel angle cannot be maintained at zero position. Assuming that the yaw angle does not change during the vehicle deviation, the vehicle's motion trajectory is similar to a circular curve, as shown in Figure 3.1.

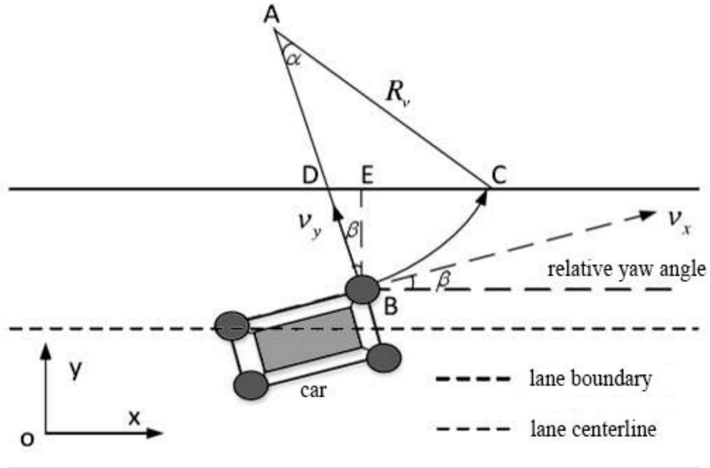


Figure 3.1 The vehicle on the straight road deviates to the left with a curved trajectory

In Figure 3.1, a plane rectangular coordinate system is established. The positive direction of the x-axis is positive with the longitudinal direction of the vehicle. The y-axis is positive to the left. Point B represents the left front wheel of the vehicle. Point C is the intersection of the trajectory and the road boundary when the vehicle deviates from the lane in the current state. So, the calculation of TLC is to calculate the length of the trajectory of the vehicle when it deviates from the lane, that is, the length of BC. From the basic principle of geometry, it is clear:

$$d_x = BC = R_v \cdot \alpha \quad (3\text{-}2)$$

In the formula, $\boldsymbol{R_v}$ is the radius of curvature of the vehicle's motion trajectory. $\boldsymbol{\alpha}$ is the central angle experienced by the vehicle from the current position to the intersection of the motion trajectory and the boundary line. According to the law of uniform circular motion, $\boldsymbol{R_v}$ is as shown in Equation 3.3:

$$R_v = \frac{V_x}{w} \quad (3\text{-}3)$$

$\boldsymbol{V_x}$ is the longitudinal speed of the vehicle and $\boldsymbol{w}$ is the yaw rate of the vehicle.

$\boldsymbol{V_x}$ and $\boldsymbol{w}$ can be obtained from the vehicle state sensors. The radius of curvature $\boldsymbol{R_v}$ of the vehicle's motion trajectory can be obtained by simple calculation, so in fact the calculation of dx is to calculate the central angle $\boldsymbol{\alpha}$. Use the trigonometric function to get the formula 3.4:

$$BD = \frac{BE}{\cos\beta} \tag{3-4}$$

BE is the vertical distance from the left front wheel to the road boundary. $\boldsymbol{\beta}$ is the yaw angle of the vehicle relative to the coordinate system $\boldsymbol{xoy}$. The BE is obtained by the lane width $\boldsymbol{W_{width}}$ and the left front wheel's ordinate values $\boldsymbol{y_f}$ as shown in Equation 3.5:

$$BE = \frac{W_{width}}{2} - |y_f| \tag{3-5}$$

So, according to the Law of Cosines, $\boldsymbol{\alpha}$ is

$$\cos\alpha = \frac{AD^2 + AC^2 - BC^2}{2AD \cdot AC} = \frac{2{R_v}^2\cos^2\beta + BE^2 - 2R_v \cdot BE \cdot \cos\beta - CD^2 \cdot \cos^2\beta}{2{R_v}^2\cos^2\beta - 2R_v \cdot BE \cdot \cos\beta} \tag{3-6}$$

And

$$AD = AB - BD = R_v - \frac{BE}{\cos\beta} \tag{3-7}$$

In triangle ACD, you get CD by the law of cosines

$$CD = R_v * \cos(90 + \beta) + \sqrt{AC^2 - (AD * \cos\beta)^2} \tag{3-8}$$

So far, all the unknowns in the calculation formula of central angle α have been solved by using the cosine theorem. Since we know the value of α, the TLC time is clear.

3.2.2 Calculation method of vehicle deviating to the right with a straight trajectory on a curved road

The following is an example to illustrate the TLC calculation method when vehicles on curved roads deviate to the right in a straight trajectory. The principle is shown in Figure 3.2. Point A represents the center of the curve road. Point B is the front right wheel of the vehicle. Point C represents the intersection point between the departure trajectory and the road boundary when the vehicle deviates from the lane. Point D represents the intersection of line AB with the road boundary. Point E represents the foot of a perpendicular from the center A to the BC line. The radius of curvature of the road Rr can be the length of line segment AC. Angle β represents the relative yaw Angle of the vehicle. The distance between vehicle right front wheel and road boundary is y_{rr}. Since road curvature radius Rr is much larger than y_{rr}, y_{rr} can be used to approximately replace line segment BD.

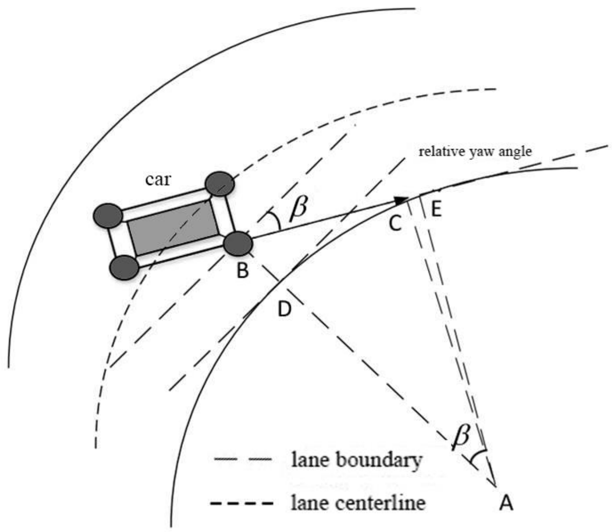


Figure 3-2 The vehicle on the curved road deviates to the right with a straight trajectory

It is clear to know, in triangle ABE:

$$BE = AB * \sin\beta = (R_v + y_{rr}) * \sin\beta \tag{3-9}$$

$$CE = \sqrt{AC^2 - AE^2} \tag{3-10}$$

So

$$BC = BE - CE = (R_r + y_{rr}) \cdot \sin\beta - \sqrt{{R_r}^2 - [(R_r + y_{rr}) \cdot \cos\beta]^2} \tag{3-11}$$

TLC time is

$$TLC = \frac{BC}{v} = \frac{(R_r + y_{rr}) \cdot \sin\beta - \sqrt{{R_r}^2 - [(R_r + y_{rr}) \cdot \cos\beta]^2}}{v} \tag{3-12}$$

When driving on a curved road and near the left boundary line, if the driver does not control the steering wheel due to distraction or dozing, the vehicle may also exit the lane from the left boundary line of the road in a straight trajectory as shown in Figure 3.3.

In this case, the calculation method of the deviation time TLC is similar with the vehicle exiting the lane from the right boundary line, and will not be described here.

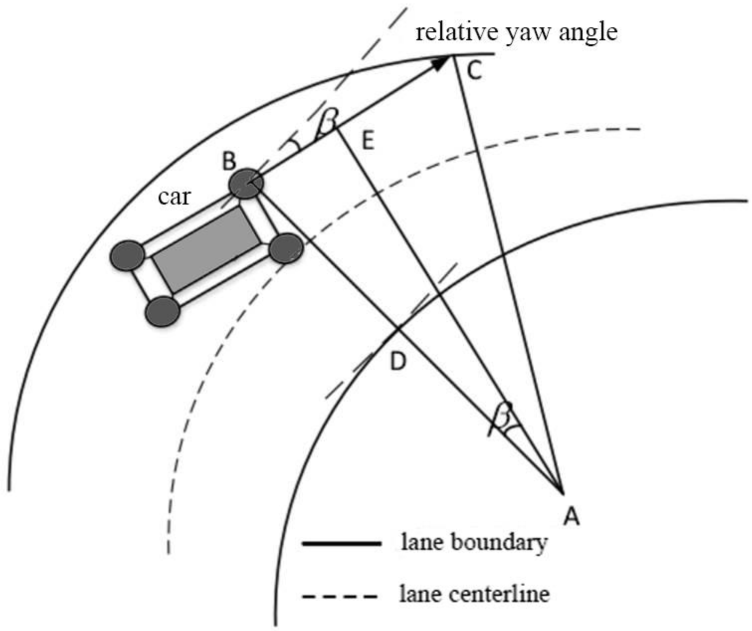


Figure 3-3 The vehicle on the curved road deviates to the left with a straight trajectory

3.2.3 Multi-mode TLC warning algorithms

In order to adapt to the diversification of driver types, reduce the false alarm rate of LKAS and improve the accuracy of warning algorithm, this paper develops a multi-mode TLC algorithm. The algorithm contains two layers: the first layer is different types of drivers correspond to different warning modes. The second layer corresponds to different warning algorithms for same driver but under different working conditions. Besides the accuracy of the algorithm, the warning threshold is also an important factor affecting the false alarm rate of LKAS. It directly relates to the driver's human-machine experience of LKAS. The actual road test data in the second chapter shows that drivers can be divided into three categories: strict, standard and free. But the driver's type is not always unchanged. If the environment and driving conditions change, the driver is likely to change from one type to another. To judge which type a driver belongs to is the result of probability statistics. In this paper, the LKAS warning algorithm sets dynamic warning thresholds to suit different types of drivers. For the strict driver LKAS, the warning time is early, the driver is reminded for a certain time before the vehicle deviates from the lane center, and the active control time is earlier than the other two types of drivers. LKAS actively controls the vehicle to return to the original before the wheel touches the lane boundary line to avoid causing driver panic. For standard drivers, the LKAS warning time can be later than the stricter driver, sending a warning signal to the driver when the wheel touches the lane boundary, and the active control function is activated when the wheel touches the latest warning boundary. For the free-type driver, LKAS warning time and active control time, compared with the other two, are the latest under the same working condition. The warning function can be started when the wheel is close to the last warning boundary line. And the active control function is delayed. It will be activated after the wheel get to warning line.

In the design of the warning boundary, this paper refers to China's standard for the earliest warning boundary and the latest warning boundary. The earliest warning boundary for a strict driver is a varied which is determined by the speed of the vehicle and the yaw angle. The free-type driver's latest warning boundary should not exceed 0.3m outside the lane mark. The standard driver's warning boundary is somewhere in between of other 2 driver’s. The driver can choose the appropriate LKAS working mode and warning boundary based on personal driving habits and the experience of using LKAS. Although in most cases a driver belongs to a fixed type, the states of vehicle deviates from the lane under different conditions. In addition, under different vehicle speeds and different yaw angles, the vehicle’s departure time is quite different. Therefore, the use of a fixed warning boundary clearly does not accommodate the various departure situation of the vehicle. Since the LKAS warning boundary directly affects its false alarm rate and missed alarm rate, this paper sets different earliest warning boundaries for the same type of driver. The dynamic boundary is related to vehicle status information and the relative position of the vehicle and the lane. The relationship of the warning boundary and its relative position with the lane boundary are shown in Figure 3.4:

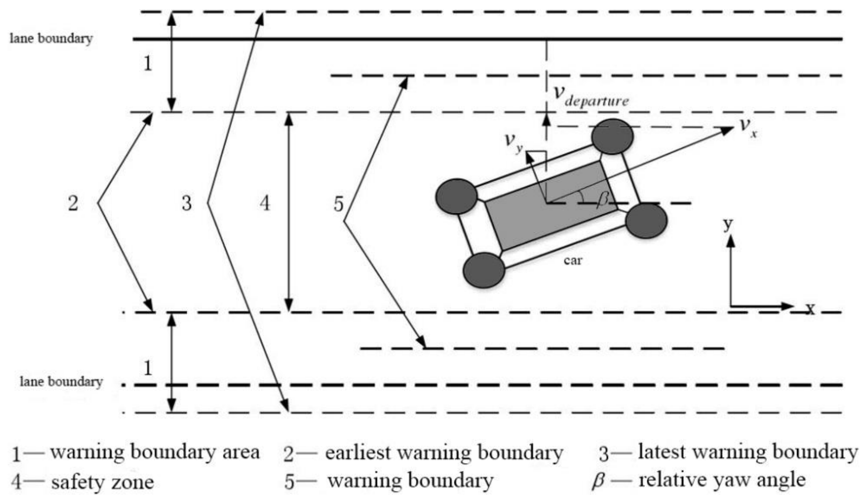


Figure 3-4 The warning boundary and its relative positional with the lane boundary.

The vehicle speed and yaw angle determine the lane departure time, in another word, the potential that the vehicle will deviate from the lane. If the lane departure time is long, the time reserved for the driver to correct the vehicle trajectory is longer, so that the vehicle is less likely to deviate from the lane; conversely, the possibility of the vehicle deviating from the lane is greater. The width of the lane is generally fixed. For example, the standard lane width of a Chinese urban road is 3.5m, and the lane width is relatively small, so in most cases the vehicle departures from the lane in a very short time. In order to measure the urgency level of the lane departure, this paper introduces the physical quantity-departure speed $\boldsymbol{V_{departure}}$ (as shown in Figure 3.4) as an indicator. On one hand, the lager the departure speed of the vehicle is, the shorter the time required for the wheel to touch the lane boundary line will be, that is, the greater the tendency of lane departure. On another hand, the longer time the wheel takes to touch the lane boundary, the smaller tendency of lane departure.

Departure speed is defined as the speed perpendicular to the lane boundary when the vehicle deviates from the lane. The value is determined by Equation 3.13:

$$V_{departure} = V_x \cdot \sin\beta + V_y \cdot \cos\beta \tag{3-13}$$

LKAS is a derivative of LDWS with the same departure warning algorithm. China's traffic regulations regulate the earliest warning boundary and the latest warning boundary for LDWS. This paper refers to this rule to set the mathematical relationship between the earliest warning boundary of LKAS and the vehicle's departure speed. As shown in Equation 3.14:

$$D = \begin{cases} 0.75, & V_{departure} \in (0,0.5] \\ 1.5 \times V_{departure}{}^{a}, & V_{departure} \in (0.5,1.0] \\ 1.5, & V_{departure} \in (1.0,+\infty] \end{cases} \qquad (3\text{-}14)$$

$\boldsymbol{D}$ is the maximum distance of the earliest warning boundary line within the lane boundary, in meters. $\boldsymbol{V_{departure}}$ is the lane departure speed of the vehicle in m/s. $\boldsymbol{a}$ is the shortest distance between the left front wheel or the right front wheel and the edge of the lane, in meters.

3.3 FOD algorithm with dynamically adjusting boundary

3.3.1 FOD algorithm

The FOD algorithm is also called the virtual roadside vibration band algorithm, and the principle is similar to the RRS algorithm. As shown in Figure 3.5, the roadside vibration band of the RRS algorithm is replaced by the virtual lane boundary. FOD allows the vehicle to deviate from the lane before reaching the virtual boundary line. Compared to RRS, FOD considers the influence of the driver's usual lateral offset on the warning boundary position when setting the virtual boundary, which is more adaptive with the actual diversified driving habits. It can effectively reduce the false alarm rate of the system and improve the driver's acceptance of LKAS. If the false alarm rate is high, it will interfere with the driver's judgment of the correct warning, which also affects the accurate implementation of the LKAS function. Although RRS can significantly reduce the false alarm rate, the position of the vibration band is difficult to change after being built, and the response time left to the driver is short. The position of the virtual lane boundary in FOD algorithm can be adjusted according to driving habits and reserve a certain response time for the driver.

The FOD algorithm structure is simpler than other early warning algorithms. There are two main parameters: the look-ahead time, $\boldsymbol{T_{lookahead}}$ and the virtual lane boundary position, $\boldsymbol{L_{virtual}}$. The FOD algorithm predicts the lateral position $\boldsymbol{L_T}$ of the vehicle after the look-ahead time (as shown in Equation 3.15) and compares it with the virtual lane boundary position $L_{virtual}$. If $L_{virtual} < L_T$, then the front wheel of the vehicle near the lane boundary has a tendency to touch the virtual lane boundary. A warning signal will be sent to the driver.

$$L_T = L_{current} + T_{lookahead} \cdot V_{departure} \tag{3-15}$$

$L_{current}$ is the distance between the wheel and the virtual boundary in real-time. $V_{departure}$ is the lateral departure velocity, $T_{lookahead}$ is：

$$T_{lookahead} = \frac{L_{virtual} - L_{warning}}{V_{departure}} \tag{3-16}$$

$L_{warning}$ is desired warning trigger position. From the equation, it is clear; once the virtual lane boundary, $L_{virtual}$ and the desired warning trigger position $L_{warning}$ are determined, the different lateral speeds $V_{departure}$ correspond to different look-ahead time $T_{lookahead}$, i.e. there are numerous pairs of $T_{lookahead}$ and $V_{departure}$ corresponding to $L_{virtual}$ and $L_{warning}$ (as shown in Figure 3.6). If $T_{lookahead}$ and $V_{departure}$ satisfy Equation 3.16, they will trigger an alert at the same location $L_{warning}$, but the performance of the warning system is different under different $T_{lookahead}$ and $V_{departure}$ conditions, i.e. the sensitivity of the system is different, so the driver's human-machine experience is different.

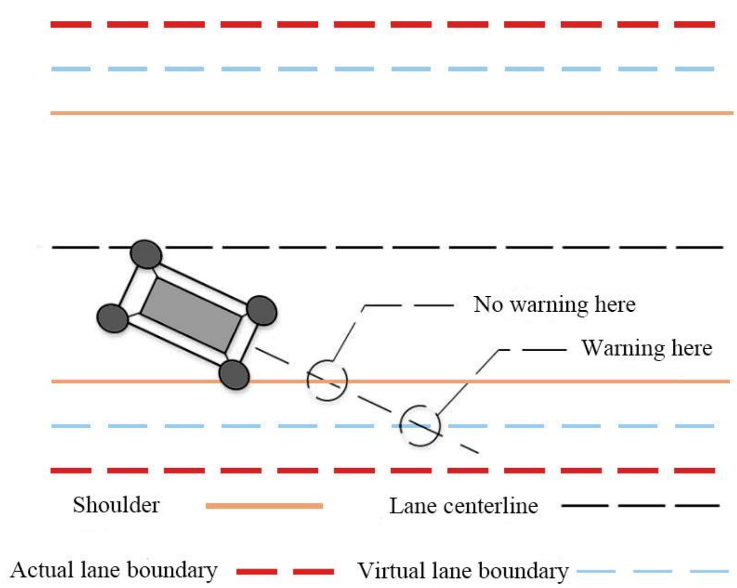


Figure 3-5 Schematic diagram of FOD algorithm

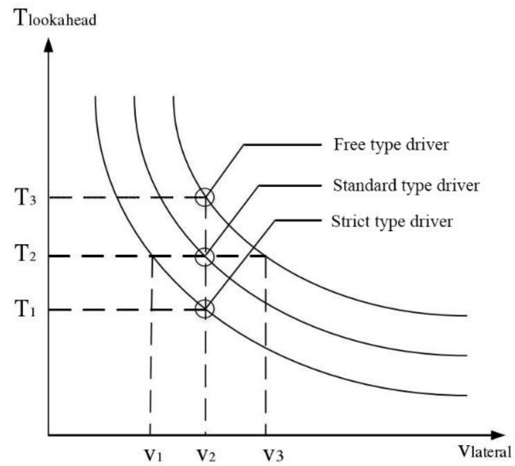


Figure 3-6 Schematic diagram of FOD algorithm with different types drivers

For strict-type drivers, if the virtual boundary is set outside the actual lane boundary and the look-ahead time is long, the vehicle has already driven out of the lane when the warning is activated, which will cause a panic. So that now, moving the boundary inwardly into the actual lane boundary and reduces the forward-looking time, increasing the sensitivity of the system to accommodate the driving habits of strict drivers

For free-type drivers, if the virtual lane boundary is set inside the actual lane boundary and the system's look-ahead time is short, a false alarm will occur. So that to accommodate the habits of free-type drivers, the virtual lane boundary should be moved outward to the actual lane boundary and increasing the look-ahead time, reducing the sensitivity of the system.

The standard-type drivers correspond to a moderate degree of sensitivity in the LKAS, and the virtual lane boundary can coincide with the actual lane boundary, and the look-ahead time is between the strict type and the free type.

3.3.2 Dynamically adjusted virtual boundaries

Due to the driver's random behavior, during the lane keeping behavior, the driver does not use the center line of the lane as the target trajectory. First, the driver generates a desired virtual boundary in the mind based on the observed boundary of the road ahead and the surrounding vehicle driving state. The scope of the boundary reflects the driver's understanding of safety, and is affected by various factors such as the lane position and the interference factors in the adjacent lane. And thus, the boundary is dynamically changed.

The parameters of the dynamic virtual boundary include a safety boundary which representing the maximum acceptable deviation and an idea lateral position center of vehicle. The safety boundary represents the maximum lateral displacement of the vehicle that is acceptable to the driver. Beyond this boundary, steering back is required to ensure safe driving. The desired lateral position center is the safest and most comfortable location for the driver to stay. The parameters of the dynamic virtual boundary are affected by working conditions such as road shape, lane position, and surrounding vehicles.

The LKAS uses the virtual boundary as the intervention decision threshold; and the ideal lateral position center is the target of vehicle position control. In addition to the adaptive adjustment of the working conditions, the parameter design of the boundary should be different from person to person. By adjusting the sensitivity of the FOD warning system, the system can be adapted to the driving behavior.

The Figure 3.7 shows a case of dynamic adjustment. When the vehicle in the adjacent lane is closer to the lane where the EGO car is located, according to the driver's behavior studies in Chapter 2, the desired virtual boundary should be dynamically adjusted. On the one hand, the lane keeping based on the dynamically adjusted virtual boundary design makes the operation of the system more trustable and acceptable for the driver, and on the other hand, the driving safety is also guaranteed.

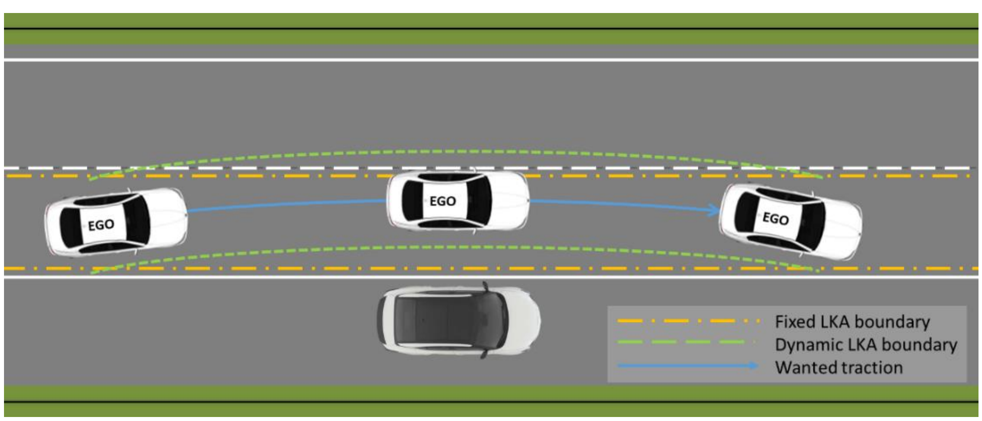


Figure 3-7 A case of dynamic adjustment

The FOD algorithm originally matched driver habits by setting different virtual lane boundaries. The design of this paper considers the impact of the surrounding traffics, and is more adaptive with diverse driving habits. The driver can choose the appropriate LKAS working mode and warning boundary based on personal driving habits and the experience of LKAS.

3.4 Joint Warning Algorithm

The lane departure situation is generally summarized as two types: one is that the vehicle is closer to the lane boundary, and the driver may cross the lane easily; the other is that the vehicle is deviating with a large velocity, that is, the vehicle is approaching the lane boundary line quickly. In the two cases, the former describes the relative positional relationship between the vehicle and the lane based on the space, while the latter is based on the time description.

The single warning algorithm is difficult to take care of all the deviation conditions. Therefore, different warning algorithms need to be selected according to different deviation conditions to ensure that the LKAS warning decision is working in time and has a low false alarm rate. In this paper, the vehicle operating state is used to identify the driver's operating state, and the position of the vehicle and the lane is predicted based on the vehicle's information. Based on the surrounding conditions of the road, the deviation condition is determined, and then the appropriate LKAS warning algorithm is selected.

(1) When the departure velocity $V_{departure}$ is greater than 0.7 m/s, the vehicle is approaching the lane boundary at a large speed, using the multi-mode TLC algorithm.

(2) When the departure velocity $V_{departure}$ is less than 0.7m/s, it indicates that the vehicle is near the lane boundary speed, and the multi-mode FOD algorithm is used.

(3) While LKAS is in normal working condition, it is in a servo state before reaching the warning threshold. It receives information such as vehicle status parameters and relative position of vehicles and lanes in real time, in order to prepare for the warning.

3.5 Adaptive Adjustment Scheme of the LKAS' parameters

For LKAS applied to adaptive driver 's characteristics, the lane keeping boundary needs to achieve dynamic adaptive adjustment. The adaptive adjustment scheme is based on two aspects: The first one is a driver profile database which classify the driver's driving behavior, and collect the parameters under different road environment conditions. Among them, the warning boundary is obtained by analyzing the data of the steering reversal point, and the lateral offset distribution center is obtained by analyzing the lane keeping behavior data. The second is to record the operation results of the driver and the LKAS according to the working conditions of the road, and establish a scenarios lane keeping database. Through the combination of the above two ways, the dynamic parameters of the predicted lane keeping boundary are realized.

A database of driver behavior and lane keeping scenarios is constructed using the process shown in Figure 3.8. First, to judge the working condition. The current working condition information, such as the surrounding traffic state, road curvature and lane position, will be collected continuously through machine vision or V2X communication. Then, move to LKAS on/off module. If the LKAS is not activated, the collected data is marked as free driving data and stored in the driver profile database. If the system is activated, the real-time driving scene is further compared with the operation schemes of the scenarios database. If there is no similar scenario, it will be stored in the database. If it exists, proceed to the next step - lane keeping operation. The parameters of lane keeping are controlled by both databases. Finally, the driver's real-time operation will be compared. If there is a conflict between driver's intention and system operation, the data will be updated to the databases.

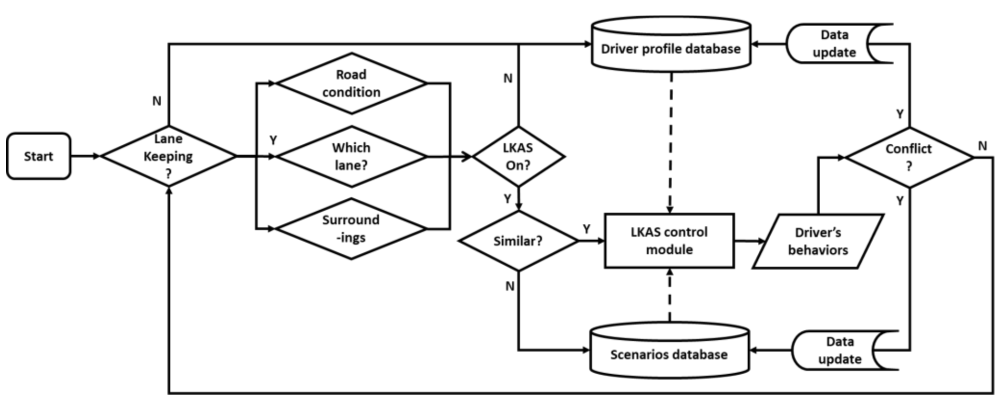


Figure 3-8 Adaptive Adjustment Scheme

Among them, the parameters when steering are stored in the driver profile database, as shown in Table 3.3.

Table 3.3 Parameters in the driver profile database

Num.	Parameters	Road	Lane type	Surroundings
1	Left SRP	Straight	High speed	Clear
2	Right LO	Curved	Mid	With car in left
…	…	…	…	…

The decision result of the driver in this scenario is recorded in the scenarios database. For example, during working of the LKAS, when the system attempts to correct the lane departure behavior in the form of an alarm or steering control, the driver overcomes the operation of the assist control. The data of the process is recorded in the database and used to select valid data when the parameter is updated. As shown in the Table 3.4.

Table 3.4 Lane keeping scenarios database

Num.	Departure	Conflict?	Road	Lane type	Surroundings
1	Left	Yes	Straight	High speed	Clear
2	Right	No	Curved	Mid	With car in left
…	…	…	…	…	

3.6 Summary of this chapter

This chapter mainly studies the LKAS departure warning algorithm. The main contents are as follows:

(1) Contrasting and analyzing the advantages and disadvantages of the existing departure warning algorithm. Then improving the TLC algorithm and FOD algorithm. Considered the diversity of driver types and LKAS functional requirements, establishing a multi-mode TLC warning algorithm with optional driver style and a FOD warning algorithm with dynamically adjusting boundary.

(2) The adaptive adjustment logic of the dynamic lane keeping control parameters is established, which can be actively adjusted according to the driving behavior of the driver, the driving scenarios and the real-time road condition.

Therefore, the control parameters of LKAS based on this logic can make LKAS have the ability to adapt to the driver's behavior habits.

In addition to the deviation from the warning function and the active control function, the most important thing for LKAS is the accurate decision logic. The figure 4.1 shows the details of the decision-making layer and execution layer and the control algorithm loop we exploit in this project. The decision-making layer is consisted of SDM (State Decision Module) and PEC (Path Error Controller). The SDM contains functions such as suppression request and driver priority etc., so that enabling LKAS to improve active safety and ergonomics.：

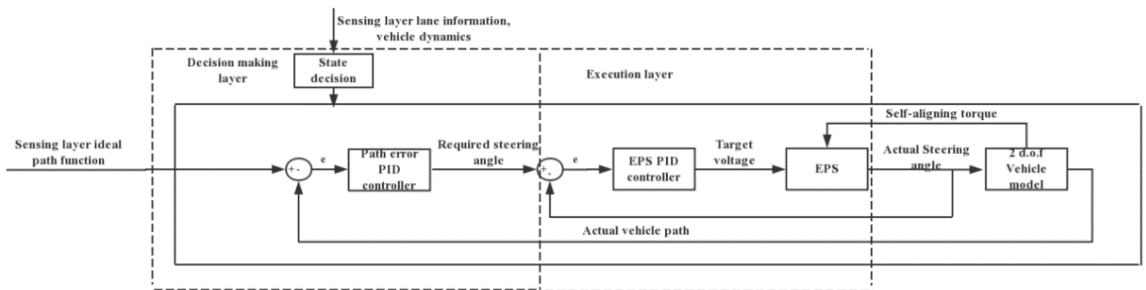


Figure 4-1 The structure of the decision-making layer

To identify lane lines, LKAS generally uses cameras and combine the vehicle status information to determine the relative position of the vehicle to the lane mark. If the vehicle has a risk of deviating from the lane and the LKAS does not receive a suppression request, the warning device sends a warning signal to the driver; if the driver turns on the turning indicator, LKAS considers that the current state of the vehicle is the result of its conscious control, then suppresses the request of the warning. The driver has the highest priority when LKAS actively controls the return of the vehicle. Once the driver intervenes, even if the active control process has not been completed, it will stop immediately and the driver will take over the vehicle.

4.1 State decision strategy

The LKA system has three states which are OFF, Standby, and Intervention. The state transition is decided based on the LKA activation condition and the intervention condition. Here, the activation condition coefficient α and the intervention condition coefficient β are introduced, and the auxiliary coefficient γ is the logical sum of α and β. That means, when the opening condition and the intervention condition are simultaneously satisfied, γ=1 (intervention state) is taken, otherwise γ=0 (standby or shutdown state). The coefficient γ directly affects the torque that the lane keeps the auxiliary controller output. Figure 4.2 shows the State Decision Strategy.

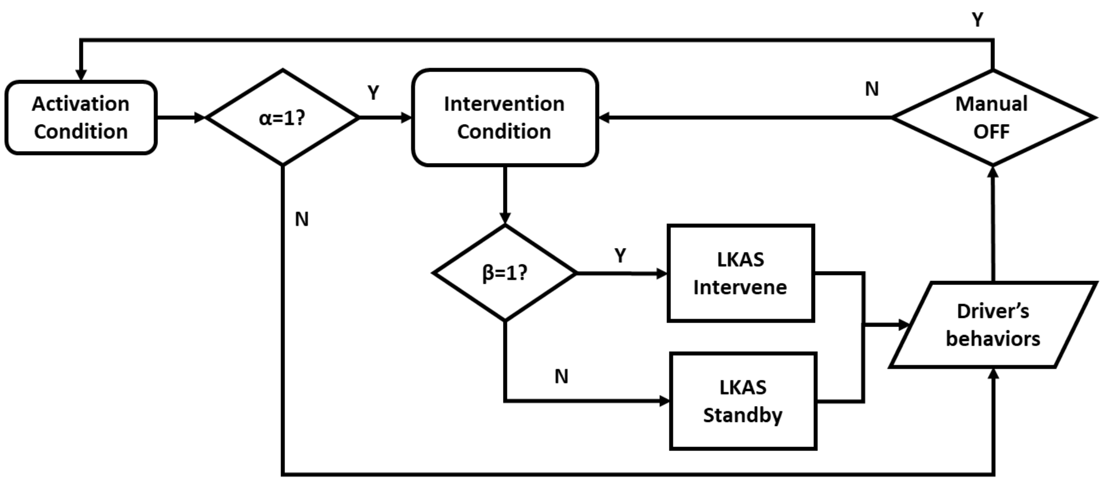


Figure 4-1 State Decision Strategy

4.1.1 Activation condition judgement

In the State Decision Strategy, two parameters should be evaluated. First one is the activation condition coefficient α which is used to judge whether the system should be activated or not. For estimating the value of α, three conditions should be taken into consideration. Figure 4.3 is the flowchart for judging the activation condition.

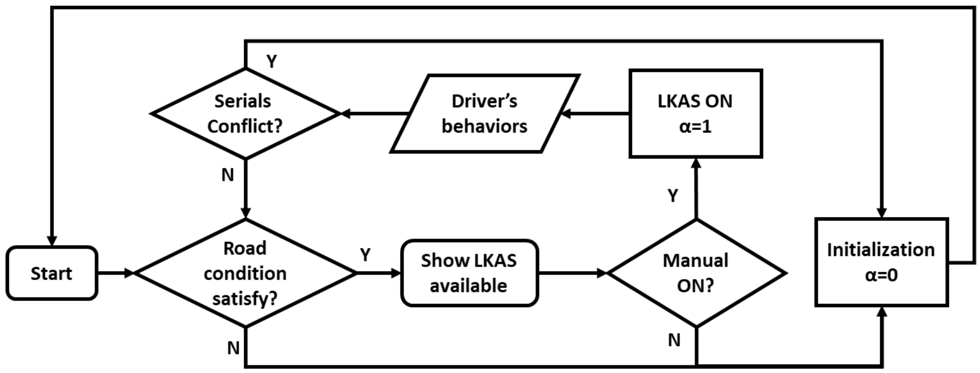


Figure 4-3 Activation condition judgement

The first condition is the acquisition of the road condition information. The input from the sensors would be processed by the system. Is the lane mark clear enough for the camera? If it finds out that the system cannot detect a clear lane, the system would not be activated. This is designed due to the bad quality of the actual lane lines at some time and the limited detection capability of the sensor. Sometimes the system loses the lane information in a short-term. It happened from time to time especially when the road is in a bad condition. Sometimes the road line is coved by snow, leaves or mud. Sometimes the road is under construction. The simple LKA system cannot work on these situations. A Car-following ACC may be help for this condition. Besides the lane marking problems, the system also needs to take consideration of the surroundings. Will there is a car cut in from the side lane suddenly? Continuous detection of valid and safe road condition is a prerequisite for activating LKA. Once the road conditions are satisfied, a clear reminder will show on the instrument cluster: LKAS is available.

The second condition is the status of the LKA system switch. The LKA system needs to have a switch interface to ensure that the driver can turn the system on or off at any time, to avoid continuously interference to the driver or even causing an accident. The switching signal of the LKA system is received from the human-machine interaction device, and if the driver turns off the LKA system, the activation condition coefficient $\alpha = 0$.

The third condition is to ensure that there are no serials conflicts between driver and LKA system. For example, the driver is not intending to change lane for preventing interference. If the driver wants to change lane, the LKA system should not interfere the operation. Otherwise, it would bother the driver and even cause danger. Therefore, we must avoid this situation.

4.1.2 Driver operating status judgment

Generally, there are four kinds of driving states during driving: following the road shape, changing lane to overtake, avoiding adjacent objects intentionally, and departure from this lane unconsciously. The first driving state is normal driving. The vehicle stays in first state for the longest time when driving. The second driving state is that the driver intentionally leaves the lane and enters the target lane according to the driver's needs, which usually occurs when the speed of the car in front is much lower than the set speed of the EGO car. The third kind occurs in situation that the adjacent lane has obstacles, temporary construction, huge vehicles etc. The fourth is that the driver's distraction, such as dozing off or answering the phone, causes the vehicle deviate from the lane center and approaching the edge of the lane slowly. Before executing the departure-warning command or the active control command, LKAS should identify the driver's operating state and determine whether the current deviating state of the vehicle is intentional by the driver, so that avoid causing driver-vehicle conflict and lowering the human-machine friendliness of the system.

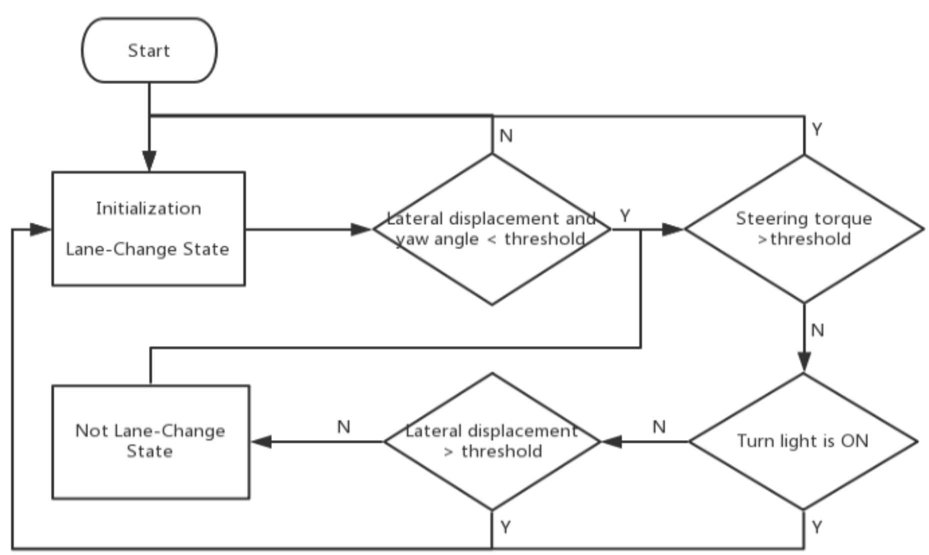


Figure 4-4 Lane-change state judgement

In order to achieve this goal, according to the study of chapter 2, the steering torque applied to the steering wheel by the driver and the lateral displacement of the vehicle are the key information to distinguish the driver behavior. In addition, the status of the turning indicator should be also taken into consideration. Figure 4.4 is the flow chart for judging whether the vehicle is in lane-change state or not.

From Figure 4.4, we can notice that when the LKA system start, it is in lane-change state by default for safety reasons. Then, it starts to judge the lateral displacement and the yaw angle. If they are bigger than threshold, the vehicle is considered in lane-change state. Otherwise, the system would continue to judge the steering torque and turning indicator status. If all the conditions are satisfied, the system would shift to Not-Lane-Change state.

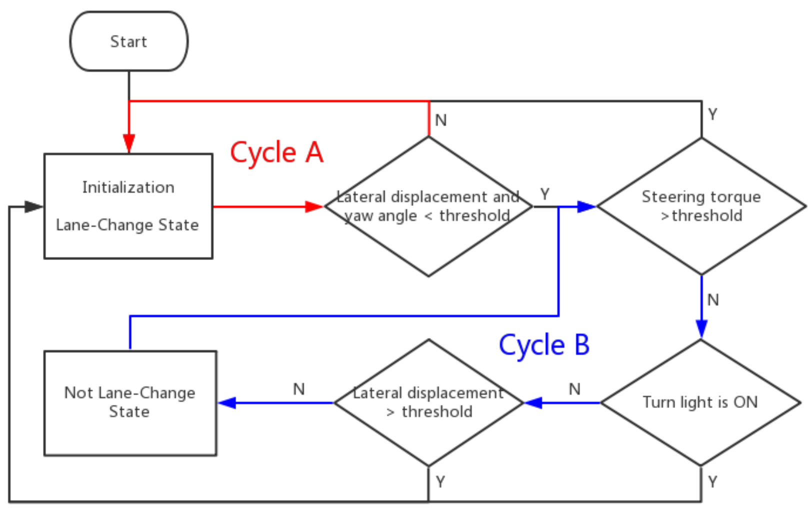


Figure 4-5 Case study of lane-change state judgement

In order to further explain the logic of the chart flow, a special case is introduced for better understanding. The strategy for lane-change judgment can be seen as two loops which are called cycle A and cycle B as shown in Figure 4.5. When the system activates, the default state is in lane change state so that the LKA system is not activated. Then, according to the judging criteria, the system would shift between these two cycles.

The Figure 4.6 shows an example, we assume that the LKA system is active at the beginning which means the system is working in cycle B in the not-lane-change state. Then driver suddenly discover that there is an obstacle in front. At time t1, the driver turns the steering wheel so that applied a torque to the steering wheel. The system find that the steering torque is above the threshold and then it will shift to cycle A and shift to the lane-change state. So that the LKA will not interfere the driver's operation. The system stays in the cycle A. Until time t2, when the lane-change maneuver is about to finish, the lateral displacement and the yaw angle are both below the thresholds. Then, the LKA system will shift to cycle B and activate again.

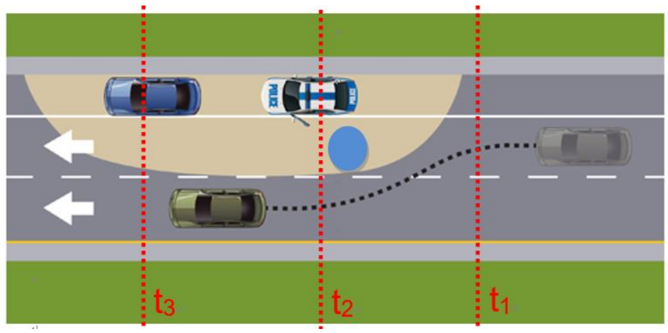


Figure 4-6 Lane change example

The lateral displacement and yaw angle of the vehicle should be compared with specific threshold. The threshold should be designed according to the width of the lane and the width of the vehicle. Thus, the threshold is different depend on the car models and different countries' lane standards. Based on adaptive adjusting logic, all the variable threshold can be found in the scenarios database and driver profiles database.

The judgement for steering torque is made according to the following equation:

$$\int_{t-\Delta t}^{t} |T_{driver}(t)|dt > MT_{threshold} \tag{4-1}$$

The status of the turning indicator is available from the CAN bus. When driver is focused on driving, ON state of turning indicator indicate that the driver wants to change lane while OFF state does not indicate the opposite situation. Sometimes driver forget to turn on the turning indicator while changing lane and sometimes after lane changing the driver may forget to tur off the turning indicator. So, the state of turning indicator is just an auxiliary judgement signal.

4.1.3 Intervention condition judgement

Finishing the evaluation of the activation condition coefficient α, we now should consider the evaluation of the intervention condition coefficient β. It is critical to judge when the LKA system should intervene and turn the vehicle back to the center of lane. This task is done following the logic show in Figure 4.7.

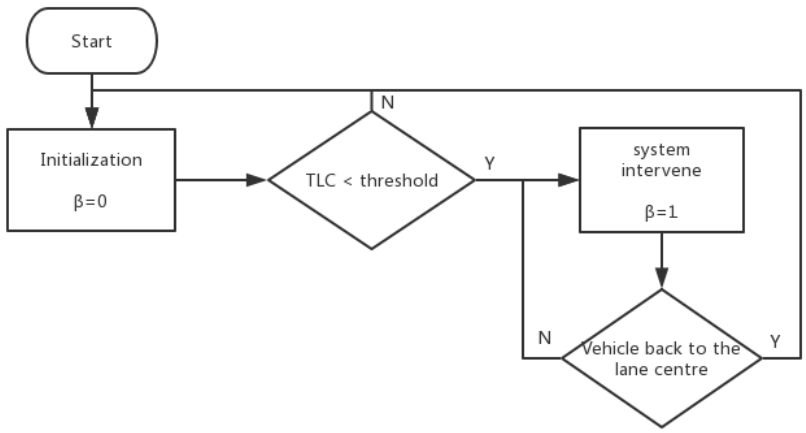


Figure 4-7 Intervention condition judgement

For safety reason, when the system starts, the system is not intervened by default which means the default value of β is 0. Since we had already discussed warning algorithms in chapter 3, in this part, we just use TLC algorithm as an example.

If the TLC is smaller than the threshold, the system would consider that the vehicle has risks of touching the lane. Then, the LKA system should step in to turn the car back to lane center.

Here, we should notice that, once the LKA system start working, it would not stop until the vehicle turn back to the lane center or until the driver taking control, even though the TLC is bigger than the threshold. This design is for preventing the LKA system from frequently turn on and turn off in some situations. Especially when the car is running on a corner.

Imagine the situation if it is not designed in this way. Assuming that the driver is sleeping so that the LKA system is fully controlling the vehicle. When the car is running on a corner, TLC firstly drop below threshold. Then, LKA start working and the vehicle start to turn. A very short time after that, TLC increase above threshold and LKA stop working. Again, short time after turning LKA off, TLC would again drop below threshold It would be a loop like this so that the LKA system turn on and turn off continually with a high frequency. This is not acceptable. Therefore, it would be better to let the LKA system continue working until the car back to the lane center.

The method for judging whether the vehicle has been back to the lane center is monitoring the lateral displacement and the yaw angle. If these two parameters are all smaller than the thresholds, the vehicle is considered to be back to the lane center.

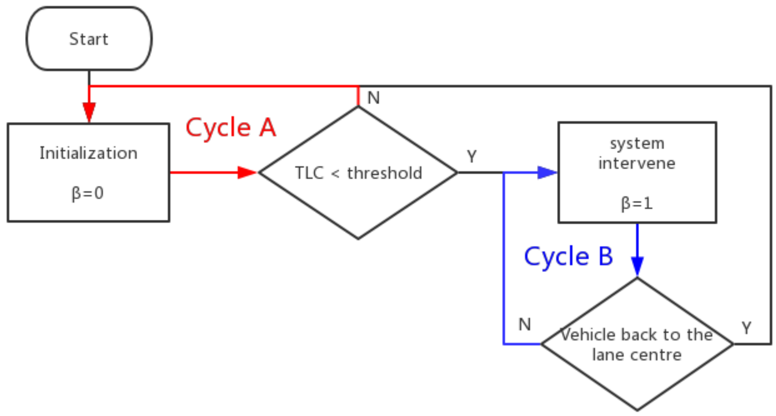


Figure 4-8 Intervention condition judgement

Similarly, the flowchart of the intervention condition judgement can be also considered as two cycles. The system continually shifts between these two cycles and two states. Cycle A means TLC< threshold and LKA system doesn't interfere, while cycle B means TLC>threshold and LKA system is interfering.

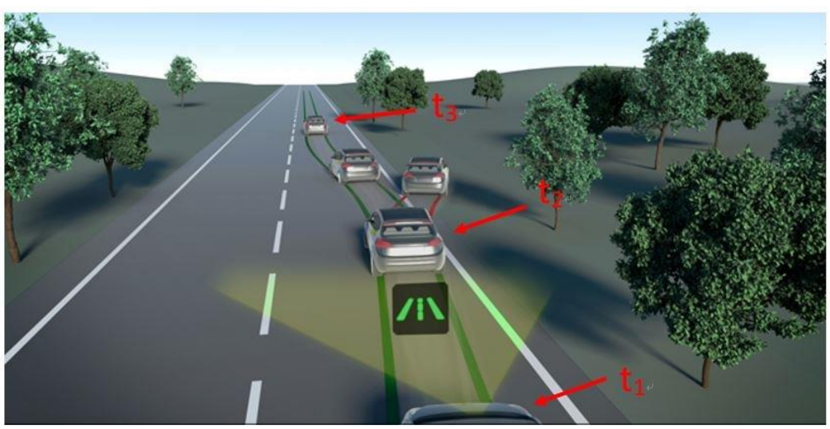


Figure 4-9 Example of intervention condition judgement

Let us take the situation shows in Figure 4.9 as an example. This time, we assume that the driver is sleeping so that the LKA system start taking fully control of the vehicle during the whole process. At first, the vehicle is running in a straight line. The system is working in cycle A which the system is not step in.

At time t_1, the vehicle turns which is not caused by the driver but by an external disturbance, for example a strong lateral wind or a bump. Short time after that, the system detect that TLC drop quickly below the threshold and the driver do nothing. The system will shift to Cycle B and start intervene the vehicle motion. Once the system enters the cycle B, the judgment criterion changes to “vehicle back to lane center”. It means that, once the LKA start intervention, it will not stop until the vehicle back to the lane center. Therefore, in the interval between t1 and t_3, the LKA system keep working even if the TLC become much bigger than the threshold. The system will stop the intervention after t_3 when the vehicle has back to the center.

4.2 Flow chart realization using State flow of Simulink

It's quite convenient to construct the flow chart using the state flow of Simulink. It's shown in following Figure 4.10,

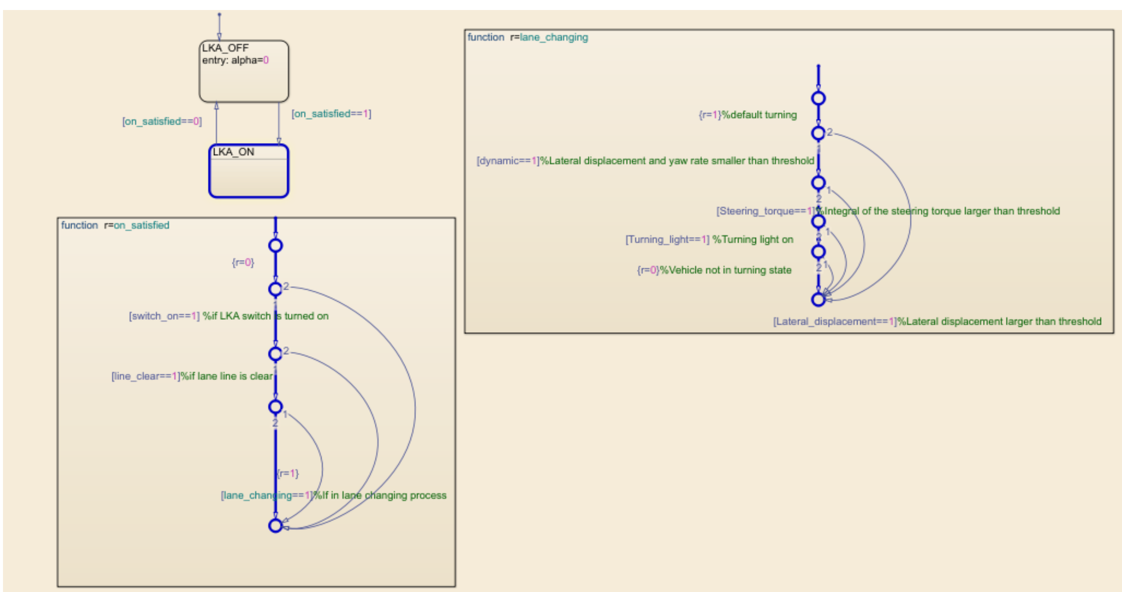


Figure 4-10 LKA on condition judgment

In this figure the blue line means indicates the logic flow of the flow chart. LKA_ON state is also highlighted by the blue line which means that all the conditions are satisfied and the lane keeping assistance system is turned on.

Inside LKA_ON state there are two sub-states which are LKA_INTERFERE AND LKA_WAITING, now the interfere condition are satisfied which means LKA system starts to interfere, it's shown in Figure 4.11

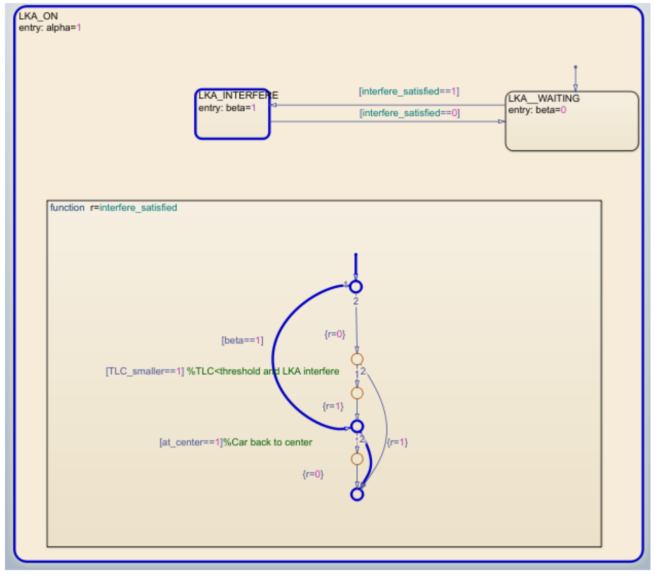


Figure 4-11 LKA interfere condition judgment

Now if we switch on the turning light, which means the driver wants to turn and thus the LKA should be suppressed, we can see that the turning light condition is not satisfied and so the LKA system is switched-off, it's shown in the following figures.

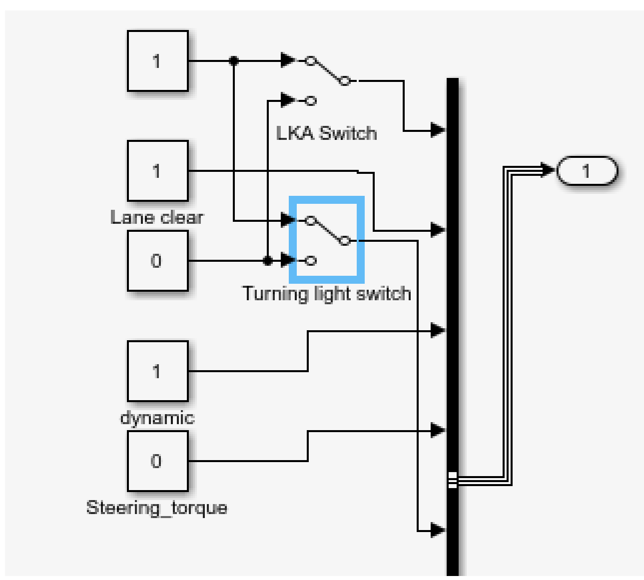


Figure 4-12 Virtual switches of turning light switch

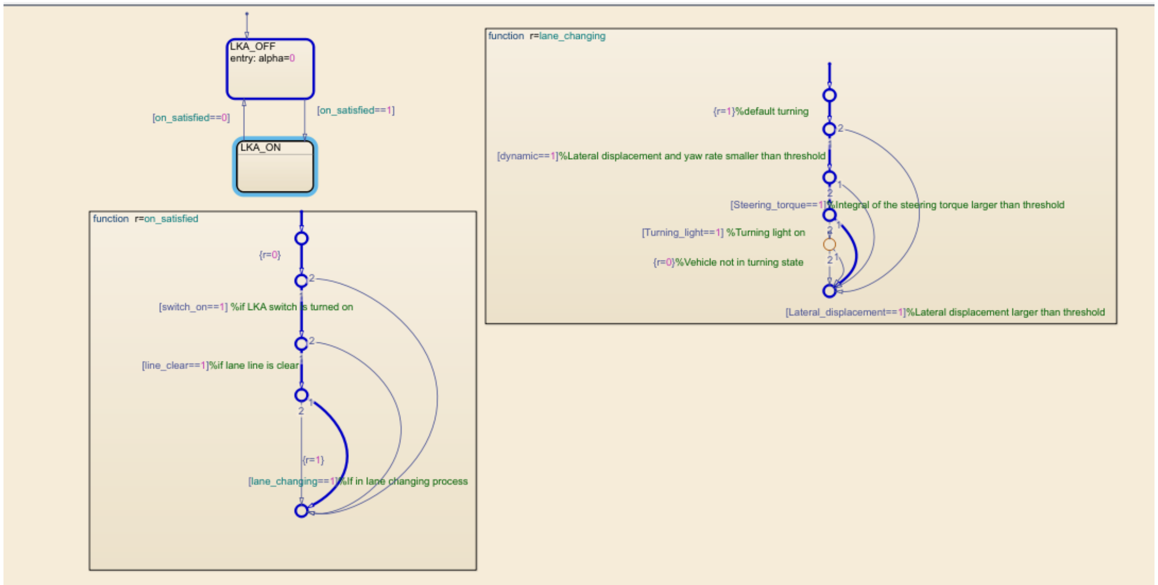


Figure 4-13 LKA off condition judgment

4.3 Summary of this chapter

In this chapter, based on the vehicle status signals and driver behaviors, a driver operating state identification model is established to determine whether the current deviation state of the vehicle is the driver's intention. If the current deviation state of the vehicle is the driver's intention, the LKAS warning function is suppressed; if not, the LKAS sends a warning signal to the driver; if the warning signal is sent for a certain period of time, the driver's operation state identification model determines that the driver has not made In any response, LKAS will actively control the vehicle to return to the original lane. If the vehicle is running normally, but the steering wheel steering torque continues to fall below a certain threshold, the driver's operating state identification model determines that the steering wheel is in the disengaged state, and the LKAS will remind the driver to take over the steering wheel.

Chapter V. Control algorithm of LKA system

5.1 Establishing control model for LKA system

5.1.1 Two degree of freedom vehicle model

If we neglect the self-aligning torque and aerodynamic, we can obtain a simplified version of vehicle 2.d.o.f model [51], it's shown as follows,

$$\dot{x} = \begin{bmatrix} \dot{\beta} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -\frac{C_1 + C_2}{mV} & \frac{C_2 b - C_1 a}{mV^2} - 1 \\ \frac{C_2 b - C_1 a}{J_Z} & -\frac{C_1 a^2 + C_2 b^2}{J_Z V} \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_1}{mV} \\ \frac{C_1 a}{J_Z} \end{bmatrix} [\delta] \tag{5-1}$$

$$y = \begin{bmatrix} \beta \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} [\delta]$$

In which input is steering angle at the wheel, output is the side slip angle and yaw rate of the vehicle.

5.1.2 Tire model

In this case it's necessary to introduce the tire model since we need to derive the self-aligning torque so that we could solve the dynamic equation of the steering system and determining the angular position of the steering system. From the dataset of Carsim we obtain self-aligning torque $\boldsymbol{T_{sa}}$ as a function of side slip angle $\boldsymbol{\alpha_1}$. Considering the side slip angle of a vehicle travelling on a highway is small, so we assume that the tire works in the linear region and we obtain the following equation,

$$T_{sa} = M_{z(\alpha)}\alpha \tag{5-2}$$

In which $\mathbf{M_{z(\alpha)}}$ is a function of vertical force $\boldsymbol{F_z}$. By linear interpolation using F_{z1} which is the vertical force on the front axle and Carsim dataset we obtain,

$$M_{z(\alpha)} = 1606.6 Nm/rad$$

In order to obtain $\boldsymbol{T_{sa}}$ the next step is to estimate the side slip angle using the vehicle dynamic parameters. The equation is shown as follows,

$$\alpha_1 = \beta + \frac{a \cdot r}{V} - \delta \tag{5-3}$$

Then we are able to derive the self-aligning torque $\boldsymbol{T_{sa}}$ and solve the dynamic equation of the steering system.

5.1.3 Electric power steering model

Introduction of EPS

A general structure of the EPS is shown as Figure 5.1. For power assistance model, controller request a certain torque front the electric motor according to the torque on the steering wheel. However, in LKA system the EPS enters active steering mode, the controller should control the angular position of the electric motor rather than the torque. Here we should notice that there is a transmission ratio between the electric motor angle and the angle of the steering wheel, and another transmission ratio between the angle of the steering wheel and the front wheel angle.

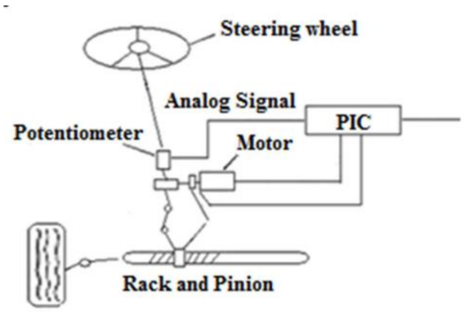


Figure 5-1 Structure of EPS

Establishing model for EPS

The equivalent circuit of DC brush motor is shown in the following figure 5.2.

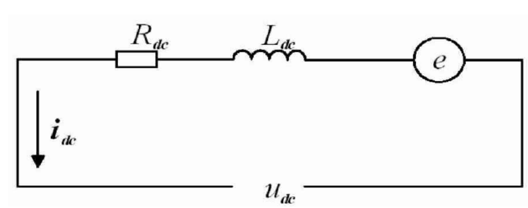


Figure 5-2 Equivalent circuit of DC brush motor

Which consists of a resistance, inductance and electric motor. From which we can write the following equation,

$$Le\frac{dI_e}{dt} + R_eI_e + U_e = U \tag{5-4}$$

$$U_e = K_U\frac{d\theta_e}{dt} \tag{5-5}$$

$$T_e = K_TI_e \tag{5-6}$$

In order to simplify the model, we assume that the steering mechanism is a rigid body. We don't consider the deformation, damping and friction of the steering mechanism. So, the dynamic equation of the steering system is as follows [2],

$$J_{Jtot}\,\ddot{\theta}_e = T_e - \frac{T_{sa}}{K_e \cdot K_{sw}} \tag{5-7}$$

Now we can derive the state space equation of the electric motor from the above equation. The state $[I_e\ \theta_e\ \dot{\theta}_e]^{\mathrm{T}}$ are respectively the current, angle position, angular speed of the electric motor.

$$\dot{x} = \begin{bmatrix} \dot{I}_e \\ \dot{\theta}_e \\ \ddot{\theta}_e \end{bmatrix} = \begin{bmatrix} -\frac{R_e}{L_e} & 0 & -\frac{K_U}{L_e} \\ 0 & 0 & 1 \\ \frac{K_T}{J_{tot}} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_e \\ \theta_e \\ \dot{\theta}_e \end{bmatrix} + \begin{bmatrix} \frac{1}{L_e} & 0 \\ 0 & 0 \\ 0 & -\frac{1}{G_eG_{sw}J_{tot}} \end{bmatrix} \begin{bmatrix} U \\ T_{sa} \end{bmatrix}$$

$$y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_e \\ \theta_e \\ \dot{\theta}_e \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} U \\ T_{sa} \end{bmatrix} \tag{5-8}$$

5.2 Design of active control algorithm

5.2.1 Controller of the EPS system

The EPS active control is different from EPS power assistance control. The previous one means without steering torque from the driver, EPS controller is able to adjust the steering angle of the steering system. The closed loop control is based on the error between the required steering angle and actual steering angle. While EPS power assistance need to generate a required steering torque which is proportional to the steering torque from the driver so that the driver can have a correct feeling of the side slip angle. Which means the close loop is based on the error between the required torque and actual torque.

So, the control block is shown as follows:

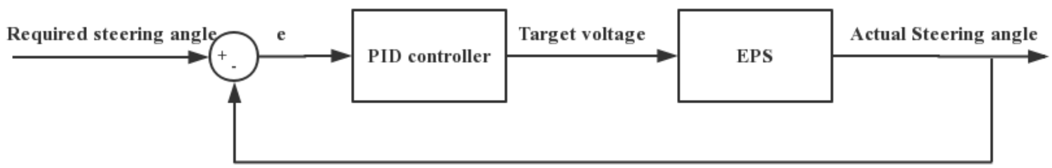


Figure 5-3 Control block of EPS controller

Here we implement a simple P control, which means the target voltage of the EPS is based on the error between the required steering angle and actual steering angle.

$$U = K_p \cdot e \tag{5-9}$$

The voltage can be controlled using PWM control.

We can specify the value of $\boldsymbol{K_p}$ based on Ziegler-Nichols theory [51], first find out $\boldsymbol{K_u}$ so that the closed-loop system oscillate with a constant amplitude. Which means the closed loop system is at the critical point between stable and unstable. And we can find K_u according to Nyquist stability criterion [52], we could adjust $\boldsymbol{K_u}$ so that the curve on the Nyquist diagram of the open loop system passes the critical point (-1,0). Then define $\boldsymbol{K_p}$ =0.5$\boldsymbol{K_u}$. Also, we should adjust $\boldsymbol{K_u}$ taking into consideration of the whole control loop to make sure that the system is stable. Larger is $\boldsymbol{K_u}$ shorter is the response time of the electric motor while higher is the oscillation. In this case since the rising time plays a critical role in terms of the stability of whole control loop. So, it's important that the electric motor has a short response time.

5.2.2 Controller of the path

Since the information of the road centerline can be derived from the camera. So, in this project we assumed that the function of road centerline in the global reference system is known. In this case we implement the proportional control, which means the required steering angle is based on the error between the road centerline and actual vehicle path. However, if we determine the required steering angle based on the current lateral displacement, the vehicle will have stability problems. So, we design the path error controller taking the preview driver model as a reference [54]. Which means the required steering wheel angle is not based on the current lateral displacement, but based on the predicted lateral displacement after a preview distance.

In this case the preview distance is set as 20 meters. The process of determining the predicted lateral displacement is shown as follows,

First, we need to convert the longitudinal and lateral speed in vehicle reference system $\boldsymbol{V_x}$, $\boldsymbol{V_y}$ into the speed in the global reference system $\boldsymbol{V_X}$, $\boldsymbol{V_Y}$. The equation is shown as follows,

$$V_x \approx V \tag{5-10}$$

$$V_y \approx V \cdot \beta \tag{5-11}$$

$$V_X = V\cos(\psi) - V \cdot \beta \sin(\psi) \tag{5-12}$$

$$V_Y = V\sin(\psi) + V \cdot \beta \cos(\psi) \tag{5-13}$$

Yaw angle is the integration of yaw rate $\boldsymbol{r}$,

$$\psi(t) = \int_0^t r(t)dt \tag{5-14}$$

Then we calculate the preview time which equals to preview distance $\boldsymbol{L_{pre}}$ divided by longitudinal speed $\boldsymbol{V_x}$,

$$t_{pre} = \frac{L_{pre}}{V_X} \tag{5-15}$$

Finally, the predicted lateral displacement after the preview distance is calculated as follows,

$$Y_{pre} = Y_{current} + V_Y \cdot t_{pre} \tag{5-16}$$

And the current lateral displacement $\boldsymbol{Y_{current}}$ is the integration of the speed in Y direction $\boldsymbol{V_Y}$, the equation is shown as follows,

$$Y_{current}(t) = \int_0^t V_Y(t)dt \tag{5-17}$$

Since that in this case the road condition is a straight road, so the target road function is,

$$Y_{target} = 0 \tag{5-18}$$

Now we can specify the road path error controller as,

$$\theta_{target}=K_{y}*(Y_{target}-Y_{pre}) \tag{5-19}$$

The Simulink function block is shown as follows:

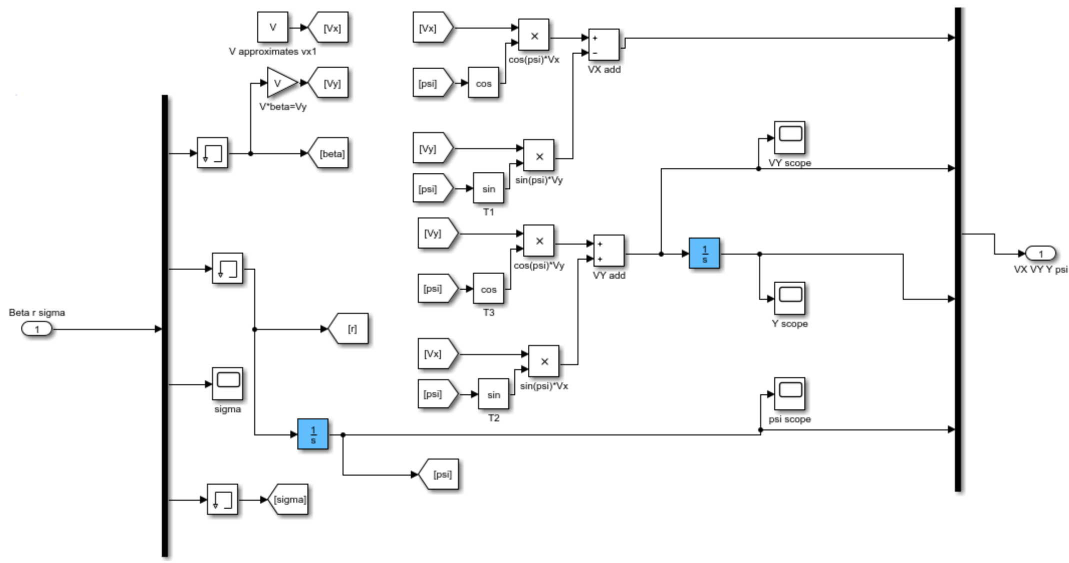


Figure 5-4 Converting V_x, V_y into V_X, V_Y

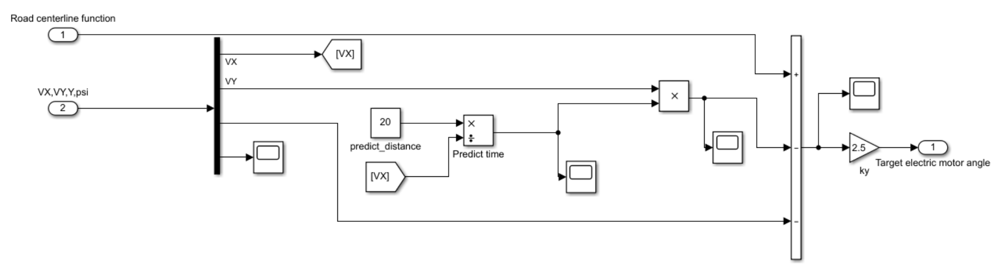


Figure 5-5 Path error controller

5.3 Verification of the algorithm

5.3.1 Specifying the test condition

Considering that on a highway, the curvature of the road is small. Also, because the main function of the lane keeping assistance system is to keep the vehicle in the road lane not following a curve. So we only consider that the vehicle is on a straight road, and we apply a disturbance to the steering system. Then let the lane keeping assistance system control the vehicle and return to the road center.

The vehicle speed is at 60km/h, the simulation lasts 10 seconds. At 1 second we apply a steering of the steering wheel with 0.2radian≈11.5deg and lasting 1 second as the disturbance.

5.3.2 Verifying control algorithm using 2.d.o.f vehicle model in Simulink

The loop of the whole system is shown as follows,

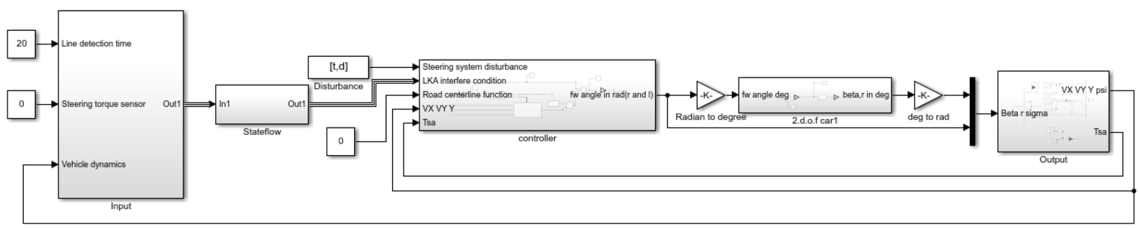


Figure 5-6 Model in loop

The vehicle lateral displacement in the global reference system and yaw angle as a function of time is shown in Figure 5.7.

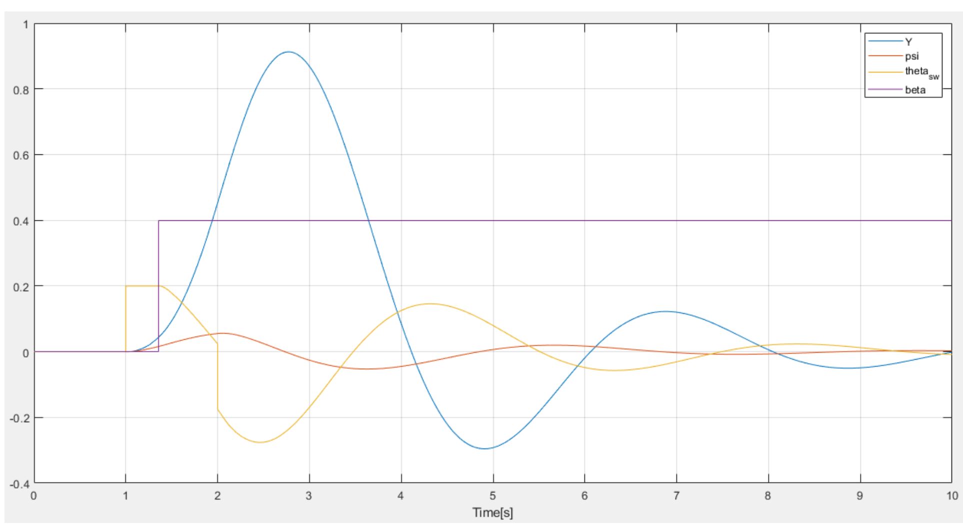


Figure 5-7 Lateral displacement, yaw angle, steering wheel angle, LKA intervention conditions variation

From which we could see that after 1 second under the disturbance at first the vehicle deviated from the road center (the function of which is *Y=0*) due to the disturbance which applied to the steering system at 1 second. After with the correction of the lane keeping assistance the vehicle will finally be able to return to the road center. The point at which ψ=0 corresponds to the maximum lateral displacement which is the starting point that vehicle moves close to the centerline. The yellow line indicates the angular position of the steering wheel. At 1 second it suddenly becomes 0.2 due to the disturbance and starts to make correction after the interference of the LKA assistance. The purple line indicates beta, when it at high level, it means that the LKA system starts to interfere. It's also corresponding to the point that the steering angle starts to decrease, which means the EPS system starts to correct the steering wheel.

The required electric motor angle and actual electric motor angle is shown in Figure 5.8,

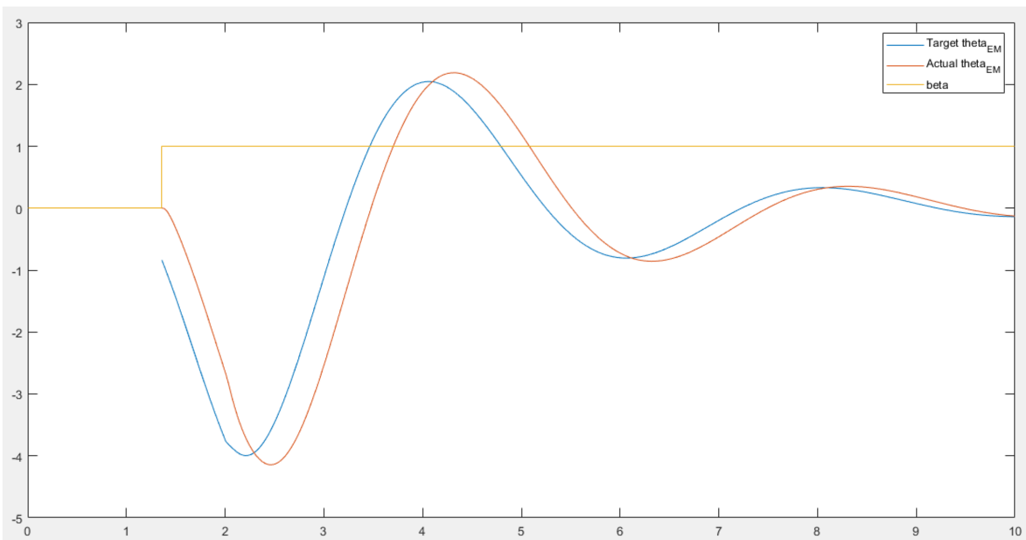


Figure 5-8 Target and actual electric motor angle

From Figure we can see that when beta enters high level which means LKA starts to interfere, the controller requires an electric motor angle from the EPS module which is indicated using the blue curve. Then the red curve indicates the actual electric motor angle. The actual electric motor angle is delayed compared with the target EM angle due to the response time of the electric motor. The absolute value of the peak of actual EM angle is also large than target EM angle. The reason is that in order to have a short response time we need to increase the proportional gain of the EM PID controller K_{P_EM}, which has a penalty of overshoot. In this case what matters is a short response time, so a small overshoot is accepted.

5.3.3 Verifying control algorithm using S-Function imported from CarSim

First, we select the car model, which is a B-class Hatchback car and modify the parameters to be the same as the 2 d.o.f model built in Simulink. And specify the input and output variables of the S-Function. The input is the steering angle at the front wheel $\boldsymbol{\delta_1}$ and the output is side slip angle $\boldsymbol{\beta}$ and yaw rate r of the vehicle. We send the S-Function to the simulink and substitute the 2 d.o.f model with the S-Function, it's shown in Figure 5.9.

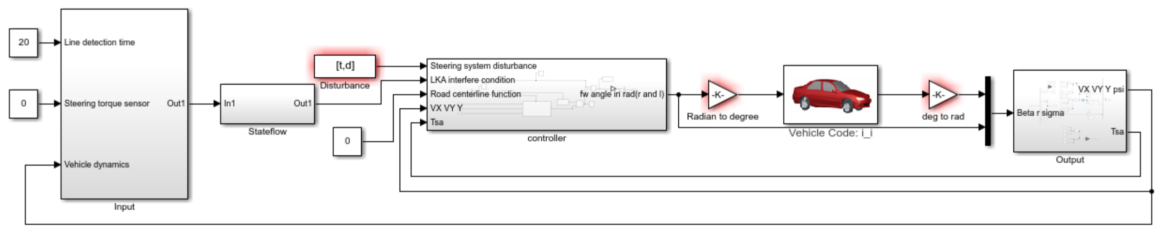


Figure 5-9 CarSim S-Function in loop

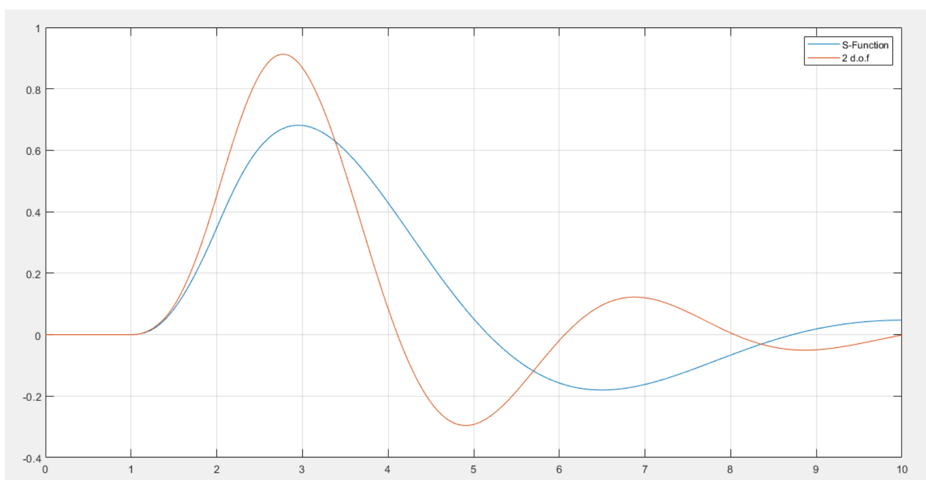


Figure 5-10 Lateral displacement of vehicle using 2 d.o.f model or CarSim S-Function

By comparing the Lateral displacement between the results obtained by S-Function and 2 d.o.f model we can see that the trend of the curve is generally the same. But due to the reason that 2 d.o.f model is less precise than CarSim S-Function, we can see there is the difference between the two curves. The curve of S-Function is more damped and has longer rising time.

5.4 Summary of this chapter

This chapter mainly studies the LKAS active control algorithm and carries out the CarSim/Simulink joint simulation to verify its accuracy. The main contents are as follows:

1. Establish a 2 d.o.f. vehicle model, a tire model, and an EPS-based LKAS active control algorithm. The 2 d.o.f. vehicle model and the tire are used to predict the lateral position of the vehicle. The CarSim vehicle model outputs the actual lateral position of the vehicle. The EPS controller obtains the LKAS correction signal according to the deviation between the vehicle target lateral position and the actual lateral position. The LKAS correction signal is the target angle of the steering wheel. And it is the target value of the LKAS active control algorithm and the EPS assist motor. The difference between the angle of the assist motor and the target angle of the steering wheel let the EPS driving the steering mechanism to change the vehicle movement track.

2. Perform a joint simulation experiment between CarSim and Matlab/Simulink. The simulation results show that the LKAS can send a warning signal in time when the driver leaves the original lane due to the driver's distraction, and can actively control the vehicle when the driver does not correct the vehicle movement in time. Returning to the original lane, the validity of the LKAS warning algorithm and active control algorithm is fully verified.

Chapter VI. Final summary and outlook

The role of vehicle active safety technology in reducing traffic accidents has become more and more important. The ADAS has attracted much attention for its ability to significantly improve the active safety of vehicles. As a subsystem of ADAS, LKAS has a significant effect because it avoids the vehicle departure and causing traffic accidents due to the driver's distraction.

In order to improve the driver's acceptance of the LKAS and avoid the conflict between the system control and the driver's decision, this paper proposes an adaptive lane keeping assist control method which based on the driver profile database and scenarios database. Analyzed the working principle and characteristics. And the LKAS warning algorithm and active control algorithm are studied in detail. Finally, the joint simulation is carried out to verify the accuracy and effectiveness of the two algorithms. This article mainly studies several aspects:

1. The analysis of driver's lane keeping behavior characteristics reflects the differences between different drivers and the influence of specific driving conditions on their behavior. In the lane keeping behavior, different drivers have different control habits for vehicle position and TLC, which reflects the differences of drivers' cognitive in lane departure risk. In addition, the specific working conditions such as overtaking have a significant influence on the driver's vehicle lateral position control habits. The results of the variance analysis show that under the two intentions of lane change and lane keeping, the steering wheel angle control parameters of the driver and the distribution of vehicle lateral motion parameters are significantly different.

2. In view of the current high false warning rate of LDWS and LKAS and easy to be turned off by drivers, this paper considers the diversity of driving habits, establishes a multi-mode TLC algorithm with selectable style and FOD algorithm with dynamic adjustable virtual boundary. Different types of drivers correspond to different warning thresholds, and personalize the LKAS algorithm according to Driver profile database and driving scenarios database. So far, there is no any algorithm that is highly accuracy for

any working conditions. A single mode warning algorithm is difficult to achieve high accuracy under various departure conditions. Therefore, in this paper, the established joint warning algorithm, based on different operating conditions, can combine the advantages of TLC and FOD and make up for the shortcomings of both. The accuracy is higher than that of single mode TLC algorithm and FOD algorithm.

3. A decision logic is established for the LKAS. When the vehicle departures from the lane, if the driver does not use turning indicator or the torque value acting on the steering wheel is below a certain threshold, it indicates that the driver is not controlling the steering wheel; otherwise, the driver is focusing on controlling the steering wheel. When LKAS actively controls the vehicle to return to the original lane, if the driver's torque on the steering wheel is still lower than the threshold, the driver's operating state identification model determines that the driver has taken off the steering wheel at this time to ensure the safety of the vehicle. LKAS will remind the driver to take over the steering wheel.

4. Even the LKAS to send a warning signal after a certain time, the driver may not take any correction operation, so that the vehicle still moves out of the lane. This paper established the LKAS active control algorithm to actively control the vehicle to return to the original lane. The difference between the target value and the actual value of the vehicle's lateral position is processed by the path controller. And the target angle of the LKAS active control steering system is obtained. The EPS controls the difference between the steering wheel target angle and the actual motor angle to obtain the control EPS. The target current and voltage of the motor control the steering mechanism to change the direction of the wheel movement so that to achieve control of the direction of motion of the vehicle. In order to verify the accuracy of LKAS active control algorithm, the joint simulation experiment of CarSim and Matlab/Simulink is carried out. The experimental results show that the LKAS active control algorithm is effective under road conditions. LKAS can accurately correct vehicle deviation motion when driver is not correcting vehicle movement in time.

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