Study on Simulation of Warning Method and Evaluation of Car-following for Intelligent Drive

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Abstract. Car-following behavior is one of the main driving behaviors of drivers in road traffic environment, the simulation experiment for car-following early warning of intelligent driving can provide driver with safe and efficient verification before Real Vehicle Experiments. The focus of the research is how to detect car-following distance by LiDAR and evaluate the car-following warning method under the simulation environment. In this paper, the mathematical model of LiDAR was established in the simulation environment so that we can obtain the Time Headway changing to warn driver to accelerate or not in real time. Next in importance, in Unreal Engine 4 virtual scene, by using the special collision detection box to simultaneously detect the longitudinal and lateral relative positions of the ego vehicle and the front vehicle, we can complete the comprehensive evaluation of car-following behavior in both horizontal and vertical directions. Ultimately, to verify the validity and reliability of this method, hardware-in-the-loop simulation of car-following warning method was realized by connecting the driving simulator. As a consequence, by using the method of this paper, we provide a feasible technical scheme for intelligent driving vehicles in respect of multi-lane car-following warning.

1. Introduction
In recent years, with the rapid development of intelligent driving, the active safety technology of automobile is the core part of intelligent driving automobile. Since car-following behavior is one of the main driving behaviors of drivers in road traffic environment [1], it is very necessary to effectively identify in the current lane, left and right lanes while following cars. Appropriate car-following early warning method can reduce traffic accidents to some extent. At present, there are four principal methods for obstacle avoidance technology, which includes infrared sensor, ultrasonic sensor, laser sensor and visual sensor. For instance, Darmstadt University used Camera and millimeter wave radars successively during the period from 2011 to 2016, and the method of fusing the two sensor measurements was used in it’s latest published article [2-5]. To get along with, Chang’an University and Central South University also made full use of the precise characteristics of radar ranging to get the relative position of obstacles at home. The difference two universities adopt two different kinds of radar, millimeter wave radar [6] and LiDAR [7], respectively. As a safe, efficient and economical method [8], simulation has been paid more and more attention in the verification of various intelligent driving control algorithms [9]. 3D simulation scenario and mathematical model of LiDAR has been established for intelligent driving under UE4(Unreal Engine 4). Therefore, the distance between ego vehicle and preceding vehicle in-lane, left lane preceding vehicle and right lane preceding vehicle could be detected. It is effective to evaluate car-following behavior by comparing the detected distance with the threshold of the car-following algorithm [10].

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2. Multi-lane vehicle following model[10]

The role of driver-following model is to simulate the vehicle control characteristics by the driver in the process of car-following. Numerous studies have shown that the two parameters, Time Headway(THW) and inverse of Time to Collision, are Control Objectives for driving process, especially stable car-following process. Since a lot of research has been done on the frontal collision warning algorithm both at home and abroad [10-16], the multi-lane car-following model in reference [10] was adopted as shown in Formula (1).

\[
RP(k) = \frac{d_{det}(k)}{v_{ego}(k)} = K_d \cdot \left(THW_m'(k) - THW_d\right) + K_v \cdot THW_m(k) \cdot TTC_i(k) \quad (1)
\]

Where, \(k\) is the sampling sequence number of the data. RP, namely risk perception index, is risk perception index defined by forward collision warning algorithm. RP means the ratio of the driver's expected acceleration to the vehicle's speed. Appropriate RP value could be set as the alarm threshold of the forward collision warning system. \(THW_d\) is expected Time Headway of driver, \(K_d\) and \(K_v\) are dynamic parameters relating to the driver's characteristics, \(THW_d = 2.16s, K_d = -0.0012s^{-2}, K_v = 0.065\). And \(THW_m(k), TTC_i(k)\) was calculated by formula (2) and formula (3) respectively.

\[
THW_m(k) = \sum_{i=1}^{n} \rho_i(k) \cdot THW_m(k - n + i) \quad (2)
\]

\[
TTC_i(k) = \sum_{i=1}^{n} \rho_i(k) \cdot TTC_i(k - n + i) \quad (3)
\]

\[
THW_m = \frac{d_m}{v_{ego}} \quad (4)
\]

\[
TTC_i = \frac{v_{rel-m}}{d_m} \quad (5)
\]

\[
v_{rel-m} = \lambda_l \cdot v_{rel-l} + \lambda_h \cdot v_{rel-h} + \lambda_r \cdot v_{rel-r} \quad (6)
\]

\[
d_m = \lambda_l \cdot d_{y-l} + \lambda_h \cdot d_{y-h} + \lambda_r \cdot d_{y-r} \quad (7)
\]

\[
\sum_{i=1}^{n} \rho_i(k) = 1 \quad (8)
\]

Where, \(v_{rel-m}\) is synthetic relative velocity in condition of Multi-lane car following which could be calculated by Formula (6), \(d_m\) in formula (7) is the longitudinal relative distance. \(v_{rel-m}\) and \(d_m\) are calculated by the relative velocity and relative distance of the nearest target in each lane according to the comprehensive weight of the target. \(v_{ego}\) is the speed of the ego vehicle. Weighted-value matrix \(\rho(k) = [0.05 \ 0.1 \ 0.15 \ 0.25 \ 0.45]\) was adopted to simplify the formula (8).

3. Modeling of LiDAR

Before establishing the mathematical model of LiDAR, we should simplify laser beam of the transmitting at first step, then modeling LiDAR by describing main functional parameters. And we modeled LiDAR which is currently used in automatic driving vehicles based on Time of Flight method.

3.1 Prerequisites for modeling

Single beam of LiDAR is an approximate rectangular facula with a certain cross-sectional area, and the laser facula area increases as distance from ego the vehicle increases. The maximum edge length of the facula presented at the maximum detection range of the LiDAR is about cm level. Accordingly, compared to common objects in Driving Environment, the beam of laser radar can be seen as a line without thickness. For this reason, the laser radar beam is abstracted as a ray model which could facilitate the modeling of LiDAR function parameters.

3.2 Modeling of LiDAR function parameters

3.2.1 Detection range and resolution model. LiDAR sensors can identify the details of a few centimeters at more than 100 meters, and its detection range is related to object reflectivity and transmission medium. Therefore, the detection range of LiDAR is the superposition of theoretical detection value and distance error. The theoretical detection value of LiDAR in this paper satisfies the following Formula (9)
\[ R_{\text{true}} = \begin{cases} 0, & \text{No object was detected or less than the minimum detection range} \\ R_{\text{mm}}, & \text{minimum detectable range} \leq \text{distance} \leq \text{maximum detectable range} \end{cases} \] (9)

Here, the detection value of LiDAR is set to 0 under the condition of invalid detection range of LiDAR. When distance between measured object and LiDAR is within the range of effective detection range, that is, between the minimum and maximum detection distance, the normal distribution model is used to simulate the detection capability of LiDAR, as shown in the following formula. (10)

\[ f(R_{\text{msr}}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(R_{\text{msr}} - R_{\text{true}})^2}{2\sigma^2}} \] (10)

Where, \( R_{\text{true}} \) is the theoretical value detected by LiDAR while \( R_{\text{msr}} \) is the practical value, and the units of the above two variables are cm; The standard deviation \( \sigma \) represents the ranging precision in cm. That is to say, the measurement value, theoretical detection value and range resolution of LiDAR satisfy the normal distribution relationship. We can’t solve the equation directly because it belongs to transcendental equation. Therefore, Box-Muller method was used to approximate the solution of the unknown variable \( R_{\text{msr}} \), which can be realized in the simulation software.

3.2.2 Models of horizontal field of view angle, horizontal field of view angular resolution and rotation frequency. Horizontal field of view angle, horizontal field of view angular resolution and rotation frequency of LiDAR are correlated to some extent. As the mechanical LiDAR adopts the cycle scanning mode, horizontal field of view angle range of LiDAR is 360 degrees. The model used in this paper is as formula. (11)

\[ 0^\circ \leq \theta_h < 360^\circ \] (11)

\( \theta_h \) is the horizontal field of view angle in degree.

The rotation frequency is a discrete integer that varies in a certain range, and its relationship with horizontal resolution is described as the following formula (12)

\[ \sigma_h = \frac{N}{C_h} \] (12)

In the formula, \( \sigma_h \) is a horizontal resolution in units of degree; \( N \) is the initial rotation frequency in Hz; \( C_h \) is a constant connecting horizontal resolution and rotation frequency, which is related to the number of transmitting points per second in Hz/degree.

3.2.3 Models of vertical field of view angle, vertical field of view angular resolution and channel number. Multi-channel laser radar usually contains 16 channels, 32 channels, 64 channels and 40 channels, which are finite discrete values. So the number of channels in this paper is an enumeration type.

For the existing LiDAR products, the maximum and minimum field of view angles are not all symmetrical. The model used in this paper is shown as formula (13)

\[ \theta_{v,\text{min}} \leq \theta_v \leq \theta_{v,\text{max}} \] (13)

In fact, the vertical field of view resolution of LiDAR with 16 channels is uniform, and that of LiDAR with more than 16 channels is discrete and non-uniform. The vertical field of view angle model is described as formula (14)

\[ \sigma_v = (\theta_{v,1}, \theta_{v,2}, ..., \theta_{v,n}) \] (14)

Among them, \( \sigma_v \) is the set of vertical field of view angular resolution, \( \theta_{v,1} \) is the minimum field of view angle, \( \theta_{v,n} \) is the sub-minimum field of view angle and \( \theta_{v,n} \) is the maximum field of view angle. \( n \) indicates the channel number of LiDAR, dimensionless.

The above models were embedded in the software and initialized with functional parameters. The instantiated LiDAR model was applied to acquire data in simulation scenario.

4. Construction of simulation environment

In this paper, according to the intelligent driving and car-following scheme, a multi-lane car-following model was selected, and a mathematical model of LiDAR has been established in virtual environment to detect the car-following distance in real time. In order to verify the effectiveness of the proposed
method, Unreal Engine was used to accomplish the simulation and evaluation of multi-lane car-following.

4.1. Modeling of 3D models in intelligent driving simulation environment

Under UE4 Development Environment, typical driving scenarios are built based on real traffic scenarios by utilizing function modules such as UE4 blueprint editor, AI, behavior tree and navigation. Switching of traffic signals and AI Logic in vehicles except ego vehicle were added there. The start-stop, driving, following and lane-changing driving behavior of vehicles that obey the traffic rules were simulated with the blueprints visual script. The LODs (Levels of Detail) algorithm has been adopted for fast rendering complex scenes and optimizing resources.

4.2. Generation of LiDAR point cloud data

High accuracy point cloud data can be obtained by using LiDAR model in the second part. However, the basic research on the organization, management and visualization of point cloud data has always been an important research topic in the field of laser scanning technology since it is an important basis for follow-up analysis and treatment. Real-time vehicle distance detection, which could provide reference data for driver behavior decision-making at intelligent driving, was accomplished by LiDAR model.

In the process of simulation experiment, it requires higher read and write access speed when we want to obtain the detected point cloud data in real time. Shared memory is the fastest form of inter-process communication. Compared with reading file contents from the disk or database in speed of execution, shared memory has an absolute advantage. The operating system maps a memory segment in the address space of several processes, so that several processes can read and write large data quickly in that memory segment without calling operating system functions. It greatly improves the communication speed. Figure 1 illustrates how can we obtain the simulation point cloud data in real time.

4.3. Overall design of simulation scheme

The real-time speed of ego vehicle $v_{ego}(k)$ has been collected at 60 frames per second. In addition, the corrected $\overline{THW}_m(k)$ and $\overline{TTCl}_m(k)$ on multi-lane road were captured by mathematical model of LiDAR. RP(k) was calculated by substituting $\overline{THW}_m(k)$ and $\overline{TTCl}_m(k)$ into the car-following model. If RP(k) is less than 0, deceleration signal will be sent to driver in simulation environment. on the contrary, acceleration signal will be sent. Figure 2 is a flow chart for driving decision-making.

![Figure 1. Obtain point cloud data by simulation](image-url)
Figure 2. Flow chart for driving decision-making

4.4. Hardware configuration of driving simulator

The hardware of driving simulator adopts Logitech G29 force feedback steering wheel pedal suit which includes steering wheel, a manual gear, and a racing pedal with clutch. The steering wheel has 900 degrees steering range, which can simulate real driving behavior to the greatest extent, and also provides programmable keys and direction control keys. Evaluation of Car-following simulation method.

The car-following model used in the preceding paper is mainly aimed at longitudinal direction. In order to evaluate car-following behavior more comprehensively, the longitudinal and lateral relative positions of the ego vehicle and the front vehicle can be judged simultaneously by generating collision detection boxes in the virtual engine. In the simulation scenario, a row of collision detection boxes were generated in the rear of the followed vehicle according to the trajectory and the width of the vehicle body in front. It's convenient that the volume, number, generation interval and disappearance time of collision detection boxes can be customized according to the fine degree of evaluation. Therefore, number of detection boxes collided by ego vehicle showed clearly whether car-following behavior is good or bad.

In the hardware-in-the-loop simulation environment, comparing the $\overline{THW}_{m}(k)$ captured by the mathematical model of LiDAR with $THW_{d}$ all the time, we could remind the driver to control the speed in real time. Figure 3 is the output data of an optional car-following simulation. It is not difficult to see from the Figure 3 that at the beginning of the simulation experiment, the Time Headway $\overline{THW}_{m}(k)$ was much longer than the expected Time Headway $THW_{d}$. The UI interface will prompt the driver to "accelerate properly", as shown in Figure 4. The $\overline{THW}_{m}(k)$ will decrease with the acceleration of the driver, even less than $THW_{d}$. The UI interface will prompt the driver to "slow down", as shown in Figure 5. Due to the continuous evaluation of driver's driving behavior by simulation system, drivers will gradually enter the state of stable car-following.

At the same time, the number of detection boxes collided by the ego vehicle was detected and compared with the total number of detection boxes generated online, the results are shown in Figure 6. From Figure 6, we can see that the number of detection boxes collided by ego vehicle is zero because the $\overline{THW}_{m}(k)$ is much greater than the $THW_{d}$. With the increase of time, the proportion of detection
boxes collided gradually increases, and finally tends to be stable. This also shows the stable car-following situation of Figure 3 from the side.

![Figure 3: Real-time Time Headway of Intelligent Driving Simulation](image)

Figure 3. Real-time Time Headway of Intelligent Driving Simulation

![Figure 4: THW_m(k) was much longer than the THW_d](image)

Figure 4. \( \overline{THW}_m(k) \) was much longer than the \( THW_d \)

![Figure 5: THW_m(k) was less than the THW_d](image)

Figure 5. \( \overline{THW}_m(k) \) was less than the \( THW_d \)
5. Conclusion
With the continuous improvement of artificial intelligence, intelligent driving has attracted more and more attention. However, the complex changes in the traffic system make the safety of intelligent driving face challenges. Aiming at the deficiency of existing research, based on the mathematic model and car-following model of LiDAR, the following work is carried out in this paper: Under the simulation environment of UE4, the vehicle in front is detected by using the mathematical model of LiDAR, so that the $THW_m(k)$ can be obtained and displayed on the UI interface in real time; Comparing the $THW_m(k)$ with $THW_d$ in Car-following Model online, When $THW_m(k)$ is greater than $THW_d$, the driver is prompted to accelerate, conversely, the driver is prompted to decelerate; Furthermore, the unique collision detection box is used to judge the longitudinal and lateral relative positions of the ego vehicle and the front vehicle simultaneously, and the comprehensive evaluation of the horizontal and vertical directions of car-following behavior is completed, which makes up for the deficiency of car-following model. However, there are still some shortcomings in this paper: ignoring the impact of traffic signs, traffic lights and pedestrians on decision-making. In the future, the existing defects will be improved to provide a more perfect and reasonable basis for intelligent driving decision-making system.

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