Lane Change Behavior Modeling for Autonomous Vehicles Based on Surroundings Recognition

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ABSTRACT: This paper describes an algorithm that determines the reference vehicle trajectory for autonomous lane changing maneuver. The algorithm employs potentially acquired on-board vehicle sensing signals like the velocity of each vehicle, the relative distance between vehicles as variables and estimates the positions of host and surrounding vehicles after finishing lane change maneuver. The lane change timing and reference lateral/longitudinal acceleration are derived theoretically and compared with the data which is obtained from human driver experiments carried out on driving simulator. The longitudinal and lateral accelerations are determined as the reference model. The paper describes algorithm details, following by simulation results which show the feasibility of the proposed algorithm.

KEY WORDS: (Standardized) Safety, Intelligent vehicle, Driving support, (Free) Lane change, Reference model [C1]

1. Introduction

Statistical data of traffic accidents shows that 90% of highway accidents are caused by human errors (1). Especially, lane change maneuver which requires high driver cognitive workload and skills always causes severe traffic accidents because of underestimation of distances and velocities of surrounding vehicles. As to prevent traffic accidents and realize safer driving environments, even though human errors cannot be completely removed, their connection to traffic accidents must be isolated and automatic driving is one of the solutions.

Study on automatic vehicles can potentially improve the safety, traffic capacity and efficiency of transportation systems. For pursuing these benefits, such a field has become one of the most interesting research directions for decades (2) and many researches concerning the functions like lane tracking/changing have been carried out. In several works, a navigation system is developed, which is able to maneuver autonomous lane keeping and lane changing (3). In addition, Ken Schmitt and Rolf Isserman have constructed a model with the function of curved road overtaking based on the estimation of vehicle state (4). Furthermore, a number of algorithms to increase the cornering performance and lane tracking stability based on AFS & DYC have also been proposed (5), (6). Maeda et al. have proposed a reference driver model for lane changing maneuver based on driving simulator experiments which is limited to a traffic circumstance (7). However, to deal with arbitrary conditions of traffic circumstances on highway, the reference driver model for autonomous vehicles as well as lane change assist system is required. A corresponding automatic lane change system is proposed as shown in Fig.1

In this paper, we propose an automated lane change algorithm (block Decision Making Model in Fig.1) based on recognition of surroundings by employing distance and velocity information which can be potentially acquired by on-board LIDAR/radar/image sensors. Furthermore, in the authors’ laboratory, human drivers’ characteristics when making a lane change maneuver were analyzed in detail based on the experiments carried out on driving simulator (7). These are the practical fundamentals of the proposed algorithm. In Section 2, a brief introduction of the previous experiments and the extraction of essential characteristics are presented. The detailed design of the lane change algorithm follows in Section 3. Lastly, simulation is set and the comparison of the experimental data and the simulation results is shown to examine the validity of the proposed algorithm.

Fig.1. Generic overview of automatic lane change system

2. Features Extraction

2.1. Brief overview of previous experiments and scenario

Related experiments were carried out by using TUAT (Tokyo University of Agriculture and Technology) driving simulator (7). The experimental driving situation is shown in Fig.2.

Fig.2 Experimental driving situation
As shown in Fig.2, the host vehicle is travelling with velocity \( V_1 = 70 \) km/h. In the adjacent lane, a platoon is travelling at \( V_2 \) with time gap of 2 seconds. The driver of the host vehicle was instructed to change into the gap behind the marker vehicle. Five drivers were selected, each of them carried out three groups of experiments with \( V_2 \) equals to 80 km/h, 90 km/h and 100 km/h. For every experimental group, 5 times of experiments were executed.

2.2. Extraction of lane change features

The acceleration results of \( V_2 = 100 \) km/h are shown in Fig.3.

![Fig.3 Acceleration data from experiments (\( V_2 = 100 \) km/h)](image)

In Fig.3, the curves are processed to avoid high frequency noises. Comparing with results of other experimental conditions which are not shown here, longitudinal acceleration is always carried out as a trapezoidal shape with different amplitude. The lateral acceleration keeps almost the same shape and amplitude regardless of \( V_2 \).

![Fig.4 General profiles of longitudinal and lateral acceleration](image)

In Fig.4, \( a_{x \text{max}} \) and \( a_{y \text{max}} \) indicate the amplitude of longitudinal and lateral accelerations respectively. \( T_x \) and \( T_y \) indicate the time duration of the two accelerations. \( j_1 \) indicates the jerk (first derivative) of \( a_x \), which has the same absolute value in both acceleration and deceleration processes. \( t \) is the time that is required by longitudinal acceleration to reach \( a_{x \text{max}} \). \( t_0 \) one of the most important parameters, represents the time difference between the starting point of longitudinal and lateral accelerations. Here, the two accelerations are presumed to converge to zero at the same time as the driver finishes the lane changing maneuver. Considering accelerating and decelerating capabilities of real vehicles, the longitudinal acceleration is set as a trapezoid. To fulfill the requirements of lane change maneuver, acceleration procedure should be able to compensate the velocity difference between the original lane and the destination lane. In other words, integration of (the area that is covered by) the longitudinal acceleration should be equal to the velocity difference:

\[
a_{x \text{max}} 
\cdot (T_x - t) = \Delta V_{2-1} \tag{1}
\]

Where, the velocity difference is \( \Delta V_{2-1} = V_2 - V_1 \), and the time duration for reaching \( a_{x \text{max}} \) is defined as

\[
t = \frac{a_{x \text{max}}}{j_1} \tag{2}
\]

and

\[
T_x = t_0 + T_y \tag{3}
\]

Substituting \( t \) and \( T_x \) into Eq.(1) and rearranging the format, the following equation is obtained

\[
a_{x \text{max}} - j_1 = \left((j_0 + T_y) j_1 \cdot a_{x \text{max}} + j_1 \cdot \Delta V_{2-1} = 0 \right. \tag{4}
\]

Solving Eq.(4) and choosing the root which keeps the desired shape of longitudinal acceleration, we get the following expression

\[
a_{x \text{max}}(t_x) = \frac{(j_0 + T_y) j_1 - \sqrt{(j_0 + T_y) j_1}^2 - 4j_1 \cdot \Delta V_{2-1}}{2} \tag{5}
\]

Lateral acceleration is set as a sinusoidal wave, therefore

\[
j(t) = a_{y \text{max}} \sin\left(\frac{2\pi}{T_y} \cdot t\right) \tag{6}
\]

where \( j \) indicates the lateral acceleration. Integrating Eq.(6) with boundary conditions: \( j(0) = 0 \), \( y(0) = 0 \) and \( y(t) = W \), \( a_{y \text{max}} \) can be represented as

\[
a_{y \text{max}} = \frac{2\pi \cdot W}{T_y^2} \tag{7}
\]

in which, \( W \) indicates the lateral displacement of lane change maneuver. In this paper, \( W \) corresponds to the width of the lane.

3. Synthesis of Decision Model

3.1. Design concept

The control objective is to accomplish lane change maneuver automatically with respect to surrounding vehicle situations. To fulfill the demands of such a task, constraints about maneuver safety and host vehicle performance should be understood in the first place. Moreover, an optimized lane change procedure which can mimic human driver behavior best should be chosen as the reference. This paper proposes a decision making model which generates the desired longitudinal and lateral acceleration signals with the appropriate lane change timing. Based on this concept, the synthesis of the model can be divided into the following two steps:

1) Understanding the spatial constraints of lane change maneuver.
2) Selecting the optimal lane change approach.

3.2. Lane change positional constraints

The pictorial diagram of common driving circumstance in highway is shown in Fig.5.

![Fig.5 Common highway traffic situation](image)
The host vehicle is surrounded by cars C1, C2 and C3. C1 and C2 are platoon cars travel at speed \( V_j \), C3 is preceding car, travels at the same speed as host vehicle \( V_j \), \( V_j \geq V_j \). Initial distances between C1, C2, C3 and the host vehicle are represented by \( X_j \), \( X_j \) and \( X_j \). The host vehicle is tending to make a lane change from position A to position B. Position C is the point where vehicle trajectory crosses the lane marker. Longitudinal distances between B, C and A are represented as \( L_1 \) and \( L_2 \).

3.2.1. Constraints by surrounding cars

The lane change maneuver is highly influenced by surrounding cars. A safely accomplished lane change maneuver must keep a safe inter-vehicle distance between the preceding vehicle C1. Constraint 1: after lane change maneuver, the host vehicle should keep a safe inter-vehicle distance with the preceding vehicle C1. Constraint 2: after lane change maneuver, the host vehicle should keep a safe inter-vehicle distance with the rearward vehicle C2. Constraint 3: when the host vehicle reaches the lane marker, it should keep a safe inter-vehicle distance with the preceding vehicle in the original lane C3.

![Fig.6 Surrounding cars constraints](image)

After defining the margins (\( m_1, m_2, m_3 \)) which are used for keeping a minimum safe distance between the host vehicle and the surrounding cars, three equations which express the above mentioned constraints can be obtained as follows

\[
D_1 = X_1 + V_j \cdot T_j - L_1 - m_1 \tag{8}
\]

\[
D_2 = X_1 + V_2 \cdot T_j - L_2 + m_2 \tag{9}
\]

\[
D_3 = X_1 + V_3 \cdot T_j - L_3 - m_3 \tag{10}
\]

In Eqs.(7) - (9), the origin of a vehicle-fixed coordinate system is located on center of gravity (CG) of the host vehicle. \( T_j \) is the time for the host vehicle to travel to the lane marker. \( D_1, D_2, D_3 \) are the predicted distances between the host and the surrounding cars (certain values of margins are included) when the host vehicle finishes lane change maneuver or is right crossing the lane marker. To avoid collision, \( D_1 \) and \( D_2 \) should be kept positive, \( D_3 \) must remain negative.

The longitudinal traveling distance of the host vehicle \( L \) can be expressed as \( L = [a + V_j] \cdot [a + V_j] \cdot [V_j] \). \( L_1 \) is the longitudinal distance that is required by the host vehicle in order to finish the lane change maneuver and is expressed as:

\[
L_1 = \int V_j + \int \Delta V \approx V_j \cdot T_j + S_{AREA} \tag{11}
\]

In Eq.(11), \( S_{AREA} \) is the area of triangle ABE shown in Fig.7.

\[
S_{AREA} = \frac{1}{2} \Delta V_{2-1} \cdot X_1 \tag{12}
\]

Apply Eq.(3) and Eq.(12) into Eq.(11), we can get the following expression

\[
L_1(\tau_o) = V_1 \cdot (T_j + \tau_o) + \frac{1}{2} \Delta V_{2-1} \cdot (T_j + \tau_o) \tag{11'}
\]

With the same principle, \( L_2 \) is the longitudinal distance that is required by the host vehicle in order to reach the lane marker, as a result,

\[
L_2 = \int V_j + \int \Delta V \approx V_1 \cdot T_j + S_{ACDA} \tag{13}
\]

\[
S_{ACDA} = \frac{1}{2} \Delta V_{(C)} \cdot T_j \tag{14}
\]

\[
\Delta V_{(C)} = S_{ACDA} = a_{max} \cdot T_j + \frac{1}{2} a_{max} \frac{a_{max} (t_o)}{f_j} \tag{15}
\]

\[
T_j = \tau_o + \frac{T_j}{2} \tag{16}
\]

Substituting these into Eq.(13), we obtain

\[
L_2(\tau_o) = V_1 \cdot T_j + \frac{1}{2} \left[ a_{max} (t_o) \cdot (\tau_o + \frac{T_j}{2}) - \frac{a_{max} (t_o)}{2 f_j} \right] \left( \tau_o + \frac{T_j}{2} \right) \tag{13'}
\]

Substituting Eq.(11'), Eq.(13'), Eq.(3) and Eq.(16) into Eqs.(8)-(10), we can get the following expressions

\[
D_1(\tau_o) = X_1 + \Delta V_{2-1} \cdot (\tau_o + T_j) - m_1 \tag{8'}
\]

\[
D_2(\tau_o) = X_2 + \Delta V_{2-1} \cdot (\tau_o + T_j) + m_2 \tag{9'}
\]

\[
D_3(\tau_o) = X_3 + \frac{1}{2} \left[ a_{max} (t_o) \cdot (\tau_o + \frac{T_j}{2}) - \frac{a_{max} (t_o)}{2 f_j} \right] \left( \tau_o + \frac{T_j}{2} \right) - m_3 \tag{10'}
\]

![Fig.7 Geometrical approximation of host vehicle travelling distance](image)

3.2.2. Constraints by vehicle performance

Besides the above mentioned constraints caused by surrounding cars, limitations caused by the performance of the host vehicle also play important roles and should be taken into consideration.

In this paper, the friction circle limitation is restricted by setting the maximum longitudinal acceleration and the profile of vehicle accelerating procedure (trapezoid) is formulated by predefining the longitudinal acceleration curve. In Eq.(5), the term inside the square root has to be positive to keep \( a_{max} \) a real number. Furthermore, ensuring the following condition

\[
[t_o + T_j - j_k] > 4 j_k \cdot \Delta V_{2-1} \tag{17}
\]

can also makes \( T_j > 2 r \), that can shape \( a_x \) as a trapezoid. (applying Eq.(1) and Eq.(2) into Eq.(17)). Therefore, after adding two more limitations, the constraints that ensure a safe lane change maneuver can be summarized as shown in Table.1 where \( a_{lim} \) is
the upper limitation of the longitudinal acceleration. The above mentioned constraints are all inequalities concerning $t_o$. In this case, a range of $t_o$ should exist that fulfill all the constraints. In other words, $t_o$ which is inside this range is that which can make the host vehicle change the lane safely.

### 3.3. Selection of the optimized finishing point

Theoretically, all $t_o$ inside the above mentioned range indicated in Eq.(18) can accomplish the lane change maneuver safely. However, human drivers are trying to finish such a maneuver at a safest position. According to the previous experiments, the desired finishing point can be decided as shown in Fig.9. $t_{hw}$ is the symbol of time headway, the desired finishing point located at the point D’ where we leave 0.35$t_{hw}$ with the preceding car. Right before lane change maneuver starts, the initial position of the point D can be expressed as:

$$X_1 - \frac{l_{car}}{2} - 0.35t_{hw} \cdot V_2$$

where $l_{car}$ refer to the length of the vehicle, definition of $X_1$, see Fig.5. To make the host vehicle finishes at the desired position,

$$L_3 = L_1 + X_1 - \frac{l_{car}}{2} - 0.35t_{hw} \cdot V_2$$

Substituting $L_3$ and $L_1$ by Eq.(11') and Eq.(20) and rearranging the format, we can get the following expression

$$X_1 - \frac{l_{car}}{2} - 0.35t_{hw} \cdot V_2 + \Delta V_{2-1} \cdot T_x - L_1(t_o) = 0$$

From Eq.(22), $t_o$ can be derived as

$$t_{o,desired} = \frac{l_{car} + 0.7t_{hw} \cdot V_2 - 2X_1}{\Delta V}$$

Fig.10 shows the relationship of $t_o$ with the change of the relative distance between the platoon car C1 and the host vehicle. According to Eq.(18), only those $t_o$ which are located inside the rhomboid fulfill the demands of the above mentioned constraints.

Among those qualified $t_o$, those which are on the curve $t_{desired}(D_{rel})$ can simultaneously satisfy the requirements that finish the lane change maneuver at a desired position. To keep an appropriate value of $t_o$, and simplify the selection procedure, a $t_o$ threshold line is determined by adding 0.5 seconds to the curve $t_{desired}(D_{rel})$. The first $t_o$ point right after this line is chosen as the output value of $t_o$, see Fig.9, point $t_{output}$.

#### Table 1 Summary of constraints

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Feature symbol</th>
<th>Feature requirements</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constr.1</td>
<td>$D_1$</td>
<td>$D_1(t_o) &gt; 0$</td>
<td>Avoid front collision with C1</td>
</tr>
<tr>
<td>Constr.2</td>
<td>$D_2$</td>
<td>$D_2(t_o) &lt; 0$</td>
<td>Avoid rear collision with C2</td>
</tr>
<tr>
<td>Constr.3</td>
<td>$D_3$</td>
<td>$D_3(t_o) &gt; 0$</td>
<td>Avoid front collision with C3</td>
</tr>
<tr>
<td>Constr.4</td>
<td>$A_{sim}$</td>
<td>$A_{sim}(t_o) = a_{max}(t_o) - a_{lim}$</td>
<td>Ensure friction circle limit</td>
</tr>
<tr>
<td>Constr.5</td>
<td>$Acc_{style}$</td>
<td>$Acc_{style}(t_o)$ = ($t_o$+?)/$\sqrt{t_o^2 + 4 \cdot \Delta V_{2-1}}$&lt;0</td>
<td>Ensure accelerating profile</td>
</tr>
</tbody>
</table>

*Obtained according to Eq.(8'),(9'),(10'),(5) and(17).*
4. Simulation Validation

4.1. Simulation set up

The above mentioned constraints are obtained based on driving situation: one preceding car and two adjacent cars as in Fig.5. However, real highway system will include several cars in the adjacent lane. Therefore, the platoon situation is set the same as the previous experiment (Fig.2). A detection range is implemented on the host to represent the real LIDAR/radar sensor detection as in Fig.11. The host vehicle is travelling at \( V_f \) at the beginning. When starting the simulation, the host begins to perform the lane change and finishes at the same speed as its adjacent lane \( V_s \). The platoon in the adjacent lane keeps the same time headway value \( t_{\text{hw}} \) between each car. The platoon begins to travel from a random set position \( P_{\text{start}} \) right after the simulation started. A detection range is set to the host vehicle with a forward detection distance of 20 meters and a rearward detection distance of 70 meters. Only the information of the platoon cars which enter the detection range is recorded. All the distance mentioned here are the relative distances with the host vehicle (vehicle-fixed coordinated system set on the host). Simulation logic flowchart is shown in Fig.12.

![Fig.11 Set up of simulation conditions](image)

![Fig.12 Simulation logic flowchart](image)

4.2. Simulation results

According to previous experiments, the results \( V_f = 100, 90, 80 \text{ km/h} \) are available. Here, we only presents the results of \( V_f = 100 \text{ km/h} & 80 \text{ km/h} \). In Fig.13 and 14, timestamp “0” is the time instant that the host vehicle reaches the central lane marker. Headway distance is the distance between the host and its preceding car; before reaching the lane marker (time is negative) it indicates the distance between the host and preceding car \( C_3 \); after reaching the lane marker (time is positive), it indicates the distance between the host and the adjacent preceding vehicle \( C_1 \).

From Fig.13, the first graph shows the comparison of lateral acceleration. The amplitude is almost the same, with a value of \( 0.81 \text{ m/s}^2 \). The time duration of the steer that the human driver occupied is around 5.5 seconds including the time for direction adjustment at the end of the procedure (the oscillation appears on the experiment curve when the maneuver is nearly end). The reference \( a_r \) is a sinusoidal curve without any oscillation with period of 5.5 seconds with the amplitude of \( 0.87 \text{ m/s}^2 \). The second graph shows the comparison of the longitudinal acceleration. The amplitude of simulation result is 1.25 \( \text{m/s}^2 \) with the time duration of 9.84 seconds. By calculation of the decision making model, we have \( t_{\text{hw}} = 4.34 \text{ seconds} \), which means the longitudinal acceleration by the accelerator pedal operation starts 4.34 seconds before the lateral acceleration by steering operation. The result of the experiment is that steering starts approximately 4.3 seconds after the beginning of acceleration. The third and the fourth graphs show the change of velocity and the lateral displacement. The time history of simulation and experiment both show that the host vehicle accelerates its velocity from 70 km/h to 100 km/h, and move laterally for 3.9 m. This means the host successfully accomplished a lane change maneuver. The last graph shows the headway distance of the host vehicle to the preceding vehicles in the initial and the destination lanes. Before the acceleration starts, the host keeps a distance around 35 m to its preceding car \( C_3 \). After changing the lane, the headway distance in both the experiment and the simulation maintains steadily at a value around 16.9 m, which takes a portion of 0.35 of the headway distance as the previous design (Fig.9).

From Fig.14, since the finishing speed is lower (velocity difference is lower), the results of the experiment and the simulation show better consistency, especially the response of longitudinal acceleration.

5. Conclusions

The major conclusions to be drawn from the study are as follows:

1. The desired decision making model provides the longitudinal and lateral accelerations as the reference for performing an automatic lane change maneuver on highway traffic circumstances.

2. The decision making model perceives the surrounding cars’ information (relative distances and velocities) to determine the lane change start timing and the amplitude and the time period of the reference accelerations with arbitrary traffic circumstances.

3. By comparison of human driving experiments using the driving simulator and computer simulations based on the
proposed algorithm, the decision making model shows good consistency with the experimental data. Therefore, it is effective to be utilized in realizing the function of the automatic lane change.

In future works, controllers which are able to convert accelerations to actual vehicle control signals such as the accelerator pedal stroke and the steering wheel angle will be developed and the entire system will be implemented on the TUAT driving simulator to validate its feasibility.

Fig.13 Comparison of results when $V_1=70$ km/h, $V_2=100$ km/h (Difference velocity between two adjacent lanes is 30 km/h.)

Fig.14 Comparison of results when $V_1=70$ km/h, $V_2=80$ km/h (Difference velocity between two adjacent lanes is 20 km/h.)

References