The Car-Following Model Based on Fuzzy Inference Controller

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Abstract. Many existing researches mostly establish a theoretical car-following model from a perspective of statistical physics, but the vehicle driver is the decision-maker of driving behaviors. When modeling the micro-behavior of the vehicle, the driver's driving intention and decision-making basis need to be considered. In order to consider human factors more in microscopic traffic simulation, this paper uses fuzzy inference technology as the basis, selects the headway distance, ideal speed difference, and reasonable spacing difference as the input variables of the control system, considering the free running and car-following state of the vehicle, constructs fuzzy rules and establishes a car-following model.

1. Introduction
This paper mainly studies the free driving behavior and car following driving behavior under single-lane driving conditions. It determines the influencing factors of the following state according to the headway distance and the reasonable distance, and provides support for the decision of the vehicle following behavior.

Since the 1950s, Pipes had explained the car-following behavior from the dynamic point of view, marking the beginning of the car-following theory, and thus building a bridge between micro-traffic behavior and macro-phenomena of traffic flow[1]. In the past 60 years, many experts have made contributions in this field. According to different perspectives, the car-following models can be divided into optimal speed model (Optimal Velocity Model, OV[2]) ,intelligent driving model (Intelligent Driver Model, IDM[3]), artificial intelligence model[4], stimulus-response model[5], etc. Above models based on different factors such as distance and velocity, is in some way to explaining the macro mechanism of all kinds of transport phenomena in traffic flow. However from a microscopic point of view, the actual driving behaviors are the result of a combination of psychological and physiological factors of the driver.

Logic is the basis of human rational decision-making, and fuzzy logic through reasoning of decision-making strategies can effectively describe driving behaviors that cannot be expressed by accurate mathematical models. In this paper, the three variables of the headway distance, the ideal speed difference and the reasonable spacing difference are used as the input of the inference system to construct the decision model of the following behavior.

Kikuchi[6] first proposed the model based on the fuzzy controller. They fuzzed the classic GM model and used relative velocity, relative distance, and leading vehicle's acceleration as model input variables.
If the relative distance is reduced by one level for each fuzzy set, the acceleration is reduced by a fixed value $\phi$. In addition, some other scholars have established similar car-following model based on fuzzy logic[7-8].

2. Model Elements

There are three inputs in the vehicle speed decision model: (1) the headway distance $T$; (2) the ideal speed difference $\Delta v$; (3) the reasonable spacing difference $\Delta d$. The output of the model is the acceleration of the vehicle.

The ideal speed difference refers to the difference between the speed of the following vehicle and the ideal speed or the speed of the preceding vehicle. When the headway distance is greater than or equal to 4, the speed difference refers to the difference between the speed of the following vehicle and the ideal speed, and when the headway distance is less than 4, the speed difference is between the speed of the following vehicle and the speed of the preceding vehicle. The ideal speed is based on current road conditions such as weather conditions, traffic congestion, road speed limit and other factors, and is the highest safe driving speed that can be achieved.

The reasonable spacing difference is the difference between the current distance and the reasonable spacing.

\[
\Delta d = d_i(t) - d_{\text{ideal}}(t)
\]

\[
d_{\text{ideal}}(t) = \max(d_{\text{safe}}(t), d_{0.5}, d_{\text{min}})
\]

\[
d_{\text{safe}}(t) = \frac{v_2^2(t) - v_1^2(t)}{2a} + \delta * v_2(t)
\]

\[
d_{0.5}(t) = 0.5 * v_2(t)
\]

\[
d_{\text{min}} = 3
\]

The linguistic variables and scope can be seen in the table 1.

| Variable | Symbols | Scope   |
|----------|---------|---------|
| $T$/s    | PS      | [0,2]   |
|          | M       | [1,3]   |
|          | PB      | [3,8]   |
|          | FR      | [5,10]  |
|          | NB      | [-30,0] |
| $\Delta v$/($m$/s) | M      | [-3.3]  |
|          | PB      | [0,30]  |
|          | NB      | [-25.0] |
| $\Delta d$/m | M      | [-3.3]  |
|          | PB      | [0.25]  |
|          | NB      | [-4.2]  |
|          | NM      | [-3.1]  |
|          | NS      | [-2.0]  |
| $A$/($m$/s$^2$) | M      | [-1.1]  |
|          | PS      | [0,2]   |
|          | PM      | [1.3]   |
|          | PB      | [2.4]   |
2.1. Fuzzy membership function
With the help of appropriate membership function and correct control rules, the fuzzy controller has good adaptability, stability and fault tolerance, and is suitable for nonlinear, time-varying and incomplete systems. The control strategy of the entire system is based on the setting of the membership function. When setting the membership function, a key point is that adjacent fuzzy sets need to overlap each other, so that the system can smoothly transform when performing fuzzy reasoning, so that the output of the system is stable.

The figure 1 is for membership function.

![Membership functions](image)

**Figure 1.** Membership functions for all the variables.

2.2. Fuzzy rules
The fuzzy rule is based on the driving strategy to derive the optimal decision in different driving conditions. These rules maintain the stability of the traffic flow and road capacity at macro view, safety and comfort at micro perspective. The fuzzy rules are shown in table 2.

| Number | T  | Δv | Δd | A  |
|--------|----|----|----|----|
| 1      | FR | NB | PB |    |
| 2      | FR | M  | M  |    |
| 3      | FR | PB | NS |    |
| 4      | PS | NB | NB |    |
| 5      | PS | M  | NB |    |
| 6      | PS | PB | NM |    |
| 7      | M  | NB | NB | NS |
| 8      | M  | M  | NB | NM |
| 9      | M  | PB | NB | NB |
| 10     | M  | NB | M  | PM |
| 11     | M  | M  | M  | PS |
The above rules are based on an analysis of the driver's behaviors under different situations. Driving state can be divided into free driving state and car following state without considering lane change. In the free driving state, the driver wants to meet the requirements of ensuring safety and speed and adjusts to the optimal speed as soon as possible. The ideal speed is based on current road conditions such as weather conditions, traffic congestion, road speed limit, and other factors, and is the highest safe driving speed that can be achieved.

In the car following state, the speed of the preceding vehicle and the distance between the cars will have a direct impact on the state of the following vehicle. When the speed of the preceding car is smaller than that of the following car, and the smaller the car spacing, the greater the deceleration of the car. If there is still a distance from the optimal distance at this time, the braking force can be adjusted appropriately considering the comfort of passengers.

When the headway is at PS, due to the difference in the drivers' response at high speed and low speed, we introduce reasonable spacing to regulate the following behavior of the vehicle. When the headway is at PB, the following car is in the transition stage that accelerates to the ideal speed. We need to adjust the acceleration slightly.

In the state of free driving, the driver hopes to adjust the speed to the ideal speed as soon as possible and revise the value of the ideal speed with the change of driving condition. In the car following state, the following vehicle needs to seek the optimal acceleration value according to the speed of the preceding vehicle and the distance between the vehicles. The ultimate goal is to ensure that the speed of the following vehicle is at an optimal value while the distance between the vehicles is safe and stable.

3. Simulation experiment

The following model is built by Matlab Simulink app, and simulation experiments are carried out to verify the rationality of the established inference rules and the stability of the car-following model. In this paper, Lilian's[9] experimental scheme was adopted, and the experimental results were used as a control group. The scheme is as follows: Assume that the lane is a single lane straight line of infinite length. The starting point of the leading vehicle is 200 m, the starting point of the following vehicle is the origin, and the initial speed of the rear car is 0 m/s. Speed change of the leading vehicle is shown in equation (6).

\[
v = \begin{cases} 
15 + \frac{4}{9}t, & 0 \leq t < 45 \\
55 - \frac{4}{9}t, & 45 \leq t \leq 90 \\
15, & 90 < t \leq 120 
\end{cases}
\]

The leading vehicle running curve is divided into three phases: firstly, it accelerates uniformly from the initial speed of 15 m/s to 35 m/s. Then evenly decelerate to 15 m/s, and finally drive at a constant speed for a while. It can be predicted from the previous analysis that, firstly, the leading vehicle will be in the free driving state and then will accelerate to the ideal speed as soon as possible. If the distance between the vehicles is gradually shortened, the following vehicle is going to step into the car following state. Whether the following vehicle can maintain the car following state and whether the
traffic flow can keep stable will be the basis for judging the rationality of membership functions and fuzzy inference rules. The simulation model is shown in figure 2.

**Figure 2.** This figure shows the entire experimental model

### 4. Simulation results

As shown in figure 3, the experimental vehicles are in the free driving state at the beginning of the simulation. The experimental vehicles accelerate from the initial speed to the ideal speed within 5 s and then entered the car following state. In the period of 20-90 s, in all the experimental plans, the speed of the following vehicle closely follows the speed of the leading vehicle.

According to the results, these experiment plans are stable, and the speed curves of the various plans are quite different. The speed curve of the IDM model is almost perfect, and it is almost impeccable in terms of safety, curve roundness and state transition stability. However, it can be seen that the biggest disadvantage of the numerical calculation models that IDM belongs to is unrealistic. In less than 1 s from the start of the experiment, the speed of the following vehicle rapidly increases from 20 m/s to 33 m/s. The acceleration could be hundreds.

Compared with the model proposed by Li Lian, the proposed model in this paper has little difference between the free driving stages. When the leading vehicle accelerates, the FV1 closely fits the speed curve of the preceding vehicle with a certain delay, while the FV2 stabilizes at 30m/s. When the leading vehicle decelerates, the speed curve of FV2 has a steep cliff-like drop at the 70s. While FV1 adopts a slow deceleration strategy to ensure greater safety and comfort while following the speed of the preceding vehicle.
5. conclusions
The fuzzy following model established in this paper considers the characteristics of free driving behavior and car-following behavior of vehicles, and establishes a complete control system to measure and evaluate the driving environment. The perception layer converts the determined value of the input quantity into the corresponding fuzzy variable value by fuzzification. The inferring layer and the driving strategy layer make the acceleration and deceleration decisions based on current state through fuzzy inference and obtain the accurate value of the acceleration through defuzzification. In the experimental simulation, the system simulates the driving behaviors of the actual vehicle and improves the driving efficiency under the premise of considering safety and comfort.

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