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A fuzzy logic-based multi-agent car-following model ☆

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ABSTRACT

Most existing analytical car-following models can simulate traffic flow realistically from some aspects, such as stop-and-go, congestion, and nonlinear characteristics, but cannot predict the driving behavior and psychological process as a driver is interacting with preceding vehicles. The reason for that is the difficulty that is generated by the impact of human factor. In this paper, a completely artificial intelligence car-following model, which has no analytical model incorporated, is developed to accurately imitate a human driver. This model comprises the classic stimulus–response framework, an extensive five-layer structure, Perception–Anticipation–Inference–Strategy–Action, and a fuzzy logic-based inference mechanism. A genetic algorithm is employed to calibrate the parameters of this model. The results of experiments, which were conducted by using Next Generation Simulation (NGSIM) dataset to validate the proposed model, indicate that the vehicle trajectories simulated by this model coincide with the actual vehicle trajectories in terms of mean value and deviation. In addition, they show that the proposed model has very good stability.

1. Introduction

Car-following (CF) behavior is an activity in which the following vehicle controls the longitudinal movement in one lane under the influence of the preceding vehicles' driving state without a desire of lane changing. Over the past decades, researchers have proposed various CF models from different perspectives. According to the forms of CF modeling methods, the proposed models can be divided into two categories: the analytical model and the artificial intelligence (AI) model. The analytical model aims to accurately model the CF behavior of a human driver via a mathematical formula. While analytical CF models were developed even further, researchers found that the model complexity and calibration difficulty also increased as the model incorporated human factors, such as recognition ambiguity, estimation error, preference, and distraction. With the rapid development of computer science and AI technology (Negnevitsky, 2011), the AI method was therefore introduced into the study of the CF model by many researchers.

Pipes (1953) and Reuschel (1950) first proposed an analytical CF model corresponding with the California Vehicle Code. Subsequently, Chandler et al. (1958) designed the famous stimulus–response framework-based GHR model that assumes that the response is made by the driver as a result of a stimulus from outside. The general relationship is given as response = sensitivity × stimulus. Initially, the GHR model was a linear model, given by

$$a_n(t) = \lambda \times \Delta V_n(t - t_n) \tag{1}$$

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where $a_n(t)$ is the acceleration of subject vehicle n at time t, $\Delta V_n(t - t_n)$ is the difference in speed between the subject vehicle and the preceding vehicle at time $t - t_n$, λ is the sensitivity parameter of the driver, and t_n is the reaction time. The details of the progression of CF models can be found in various reviews (Brackstone and McDonald, 2005; Saifuzzaman and Zuduo Zheng, 2014; Elefteriadou, 2014). Improved analytical CF models have subsequently been developed by separately inserting human factors into three phases of the control process. The three phases are recognition, decision-making, and action.

The first type of analytical CF models saw improvements in the recognition phase. Gazis et al. (1961) proposed a nonlinear GHR model that combined the space headway due to that the sensitivity of a driver is weaker as the space headway increases. Lee (1966) introduced a memory function into the linear GHR model by assuming that the driver reacts to the relative velocity of the preceding vehicle over a period of time, rather than instantaneously. Wiedemann (1974) used a "perceptual threshold" in the CF model because humans cannot perceive tiny stimuli. Gray and Regan (1998) showed that human drivers cannot accurately estimate the velocity of the preceding vehicle.

The second type of analytical CF models saw improvements in the decision-making phase. Herman and Rothery (1965) established a multiple-vehicle interaction model based on the reality that drivers adjust their driving behavior by observing more than one vehicle ahead. Helly (1959) introduced the concept of desired headway and Treiber et al. (2000) introduced desired velocity.

The third type of analytical CF model saw improvements in the action phase. Ahmed (1999) expanded the GHR model to describe the asymmetry of acceleration and deceleration in reality. Subsequently, on the basis of the other drawbacks of human drivers, such as distraction and being prone to operational errors, Yang and Peng (2010) and Przybyla et al. (2015) established and designed an error-able CF model and a dynamic error-able CF model, respectively.

In the category of analytical CF model, a variety of human factors are studied separately in the stimulus–response framework, but each improved CF model contains only one or two human factors. However, the driver is affected by all of those factors while driving, therefore, a CF model for realistically simulating CF behavior at the microscopic level must contain all the related human factors. But, incorporating these factors in an analytical model is very difficult. As a result, many researchers have begun to study the CF model using AI technology. The AI CF model comprises three sub-classes: the fuzzy logic model, the cellular automata model, and the multi-agent model.

Brackstone et al. (1998) used fuzzy logic to transform the GHR model in order to imitate the uncertainty and ambiguity of human recognition. To make this model more feasible and efficient, Chakroborty and Kikuchi (2003) designed a neural-network based algorithm to calibrate the parameters.

Nagel and Schreckenberg (1992) originally built the famous discrete cellular automata CF model that can simulate the macroscopic characteristics of traffic flow by four simple velocity control rules. In order to simulate CF behavior more realistically, Krauss et al. (1996) developed a continuous version of the cellular automata CF model by incorporating space headway. However, it could only simulate the realistic characteristics of traffic flow at the macroscopic level.

The multi-agent model has been used in the CF model for more than 10 years. Ehlert and Rothkrantz (2001) established a reactive driving agent framework for the purpose of microscopic traffic simulation. The model contains all driving functions, such as car-following, lane changing, and gap acceptance, but the details of the CF model used are not given. Bölöni and Turgut (2005) established a driver simulator, called YAES-DSIM, based on the concept of the agent. Even though the simulator can integrate the CF and lane changing functions, it still uses the analytical models to simulate driving behavior. Luo et al. (2014) used the multi-agent method to model the strategic behavior of drivers for multi-lane highway driving based on the YAES-DISM simulator.

In summary, research on the analytical CF model has reached a peak and many analytical models have been proven to predict well the integrative, long-term parameters of traffic flow, such as throughput and average speed of congested traffic. However, it is very difficult to simulate the driving behavior and the psychological process when the driver is interacting with the preceding vehicles. Further, the AI method is receiving more attention from CF model researchers and has become a new study trend. Although there are currently many cellular automata, fuzzy logic, and multi-agent based CF models, the kernel of these models is still an adoption of the analytical CF model. Consequently, AI CF models simulate traffic flow similar to the analytical CF models and inherit the shortcomings of the analytical CF models.

Consequently, the motivation of this paper is building a new CF model to accurately imitate the CF behavior and driving decision making process of human drivers. And the contributions are:

- We developed a completely artificial intelligence car-following model that has no analytical model incorporated.
- We designed an easy and feasible genetic algorithm to calibrate the parameters of this model.

The results of experiments indicate that the vehicle trajectories simulated by the model coincide with the actual vehicle trajectories very well.

The remainder of this paper is organized as follows. Section 2 presents the architecture of this new multi-agent CF model. Section 3 specifically analyzes the working mechanism and application approach of the sub-models. Section 4 summarizes all the parameters and introduces a genetic algorithm for calibration. Section 5 shows the validity of this model by two examples. Finally, Section 6 concludes this paper.