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A car-following model considering asymmetric driving behavior based on long short-term memory neural networks

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A B S T R A C T

Asymmetric driving behavior is a critical characteristic of human driving behaviors and has a significant impact on traffic flow. In consideration of the asymmetric driving behavior, this paper proposes a long short-term memory (LSTM) neural networks (NN) based car-following (CF) model to capture realistic traffic flow characteristics by incorporating the driving memory. The NGSIM data are used to calibrate and validate the proposed CF model. Meanwhile, three characteristics closely related to the asymmetric driving behavior are investigated: hysteresis, discrete driving, and intensity difference. The simulation results show the good performance of the proposed CF model on reproducing realistic traffic flow features. Moreover, to further demonstrate the superiority of the proposed CF model, two other CF models including recurrent neural network based CF model and asymmetric full velocity difference model, are compared with LSTM-NN model. The results reveal that LSTM-NN model can capture the asymmetric driving behavior well and outperforms other models.

1. Introduction

Over the past six decades, numerous car-following (CF) models have been developed to describe the longitudinal interactions of vehicles, including mathematical CF models (Chandler et al., 1958; Herman et al., 1959; Helly, 1959; Newell, 1961; Gipps, 1981; Bando et al., 1995; Helbing and Tilch, 1998; Treiber et al., 2000; Jiang et al., 2001; Gong et al., 2008, Tordeux et al., 2010; Xu et al, 2013; Liu et al., 2017) and data-driven CF models (Panwai and Dia, 2007; Khodayari et al., 2012; Wei and Liu, 2013; Zheng et al., 2013; Z. He et al., 2015; Wang et al., 2018). Mathematical CF models mathematically describe drivers' behavior in the context of varying traffic conditions, while data-driven CF models precisely mimic the CF behavior based on a mass of empirical data without manual intervention. For both types of CF models, human behaviors (e.g. asymmetric driving behavior, distractive driving behavior) are critical in describing real traffic flow. However, only a few studies have incorporated human driving behaviors (e.g. asymmetric driving behavior) in CF modelling (Krauß et al., 1997; Zhang and Kim, 2005; Gong et al., 2008; Tordeux et al., 2010; Xu et al., 2013, 2015; Wei and Liu, 2013).

The asymmetric driving behavior, which means that drivers are more attentive in deceleration than in acceleration, is closely related to the well-known traffic hysteresis phenomenon (Zhang, 1999). This study attempts to model CF behavior and investigate the related characteristics of asymmetric driving behavior: (1) hysteresis: drivers are used to keeping a larger headway when accelerating than decelerating given the same speed (Wei and Liu, 2013); (2) discrete driving: the acceleration and deceleration in CF are not consecutive (Yeo, 2008); (3) intensity difference: the response intensity of drivers to the positive and negative relative speed are

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different though driving at the same condition, e.g., the same magnitudes of the relative speeds, the same speed, the same gap between the leading and following vehicles. (Zhang, 1999; Wei and Liu, 2013).

In addition, Toledo (2007) pointed out that driver's decisions are always dependent on the historical driving behaviors and the past traffic states. In human driving process, the historical information usually have a fading effect which means that the memory is not always constant. Other researchers also demonstrated that CF models taking driving memory into account can describe the traffic flow characteristics better (Lee, 1966; Treiber and Helbing, 2003; Peng et al., 2016). Therefore, it is necessary to model the historical driving behaviors and fading memory effect. However, since it is difficult for mathematical CF models to consider a relative long-period and varying memory, a data-driven model is thus needed for modeling the CF behavior.

The Long Short-Term Memory (LSTM) neural networks (NN) proposed by Hochreiter and Schmidhuber (1997) is used for CF modeling in this study due to its advantages on considering massive historical information and fading memory effect. With NGSIM data (FHWA, 2008), the LSTM-NN model is optimized and analyzed. Meanwhile, the three characteristics of asymmetric driving behavior (i.e. hysteresis, discrete driving and intensity difference) are investigated to validate the efficiency of proposed CF model. In addition, one data-driven model (recurrent neural network (RNN) based CF model), and one mathematical model (asymmetric full velocity difference (AFVD) model (Gong et al., 2008)) are compared with the LSTM-NN model in terms of the simulated trajectories and asymmetric driving behavior characteristics.

The remaining part of this paper is organized as follows: Section 2 reviews the studies about asymmetric driving behavior, and the development of data-driven CF models; Section 3 proposes the structure of LSTM-NN model; Section 4 optimizes the LSTM-NN model and other two CF models in terms of simulated trajectories; Section 5 discusses in detail the characteristics of the asymmetry driving behavior and the comparison with RNN model and AFDV model; Section 6 studies the ability of proposed CF model on reproducing stop-and-go wave and Section 7 summarizes main conclusions and discusses the future study.

2. Literature review

2.1. The asymmetric driving behavior

Asymmetric driving behavior, which is a critical characteristic of human driving behaviors and has a significant impact on traffic flow, has been observed and verified by many studies. As early as 1960s, the asymmetry in acceleration and deceleration has been observed from the real traffic (Forbes, 1963; Foote, 1965; Edie, 1965; Newell, 1965). Among these studies, Newell (1965) is the first one who gave a theoretical explanation for the asymmetric phenomenon, believing that drivers tend to maintain different gaps from the leading vehicle in accelerating and decelerating and proposed two speed-gap curves with different jam spacings for acceleration and deceleration respectively. The spacing in accelerating is always larger than that in decelerating.

Later, Treiterer and Myers (1974) found the traffic hysteresis phenomenon on macroscopic level. They concluded that the asymmetric driving behavior in acceleration and deceleration causes the hysteresis loops. Additionally, by using the CF model proposed by Gazis et al. (1961), they testified that drivers increase awareness on speed and space when decelerating than accelerating, which is consistent with Newell (1965). To testify the asymmetric reaction time in acceleration and deceleration, Ozaki (1993) proposed a piecewise function for reaction time and calibrated the model with observed data. Zhang (1999) is the first one that proposed a mathematical model for the hysteresis phenomenon from macroscopic level based on the analysis of three groups of observed data respectively representing different traffic conditions: acceleration, deceleration and equilibrium. Daganzo et al. (1999) proposed a possible explanation for the phase transitions considering the feature of asymmetric driving behavior. They also pointed out that the lane changing behavior contributes to counter-clock hysteresis loop.

Recently, Yeo (2008) investigated the asymmetric driving behavior thoroughly and found three characteristics in asymmetric driving behavior: traffic hysteresis, intensity difference and discrete driving. Tordeux et al. (2010) found that driving behaviors in acceleration and deceleration are different by analyzing the NGSIM data. Khodayari et al. (2012) testified that the reaction time in acceleration is different with that in deceleration. Li and Chen (2017) pointed out that the right-skew feature of headway distributions which has been found by many researchers, results in asymmetric driving behavior.

2.2. CF models considering asymmetric driving behavior

To further investigate the asymmetric driving behavior, many CF models incorporating asymmetric driving behavior have been proposed and are demonstrated to describe the traffic flow well. A summary of representative studies on these CF models are presented in Table 1.

2.3. Data-driven CF models

For CF modeling, Adeli (2001) pointed out that data-driven model can capture the features from data (the examples or experiences) automatically, even though the input data has noise (error, incomplete, etc.). Due to these advantages, many researchers proposed data-driven CF models based on conventional Neural Networks (NN). e.g. Panwai and Dia (2007), Khodayari et al. (2012), and Zheng et al. (2013). All the studies have proved that the data-driven CF model outperform the mathematical models. Wei and Liu (2013) modeled the driving behavior based on Support Vector Machine (SVM) and pointed out that the performance of data-driven method is better than mathematical models in capturing the asymmetric driving behavior. However, the feature of intensity difference in Wei and Liu (2013) is inconsistent with the observed data.