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A sliding mode controller for vehicular traffic flow

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ABSTRACT

This study proposes a sliding mode controller for vehicular traffic flow based on a car-following model to enhance the smoothness and stability of traffic flow evolution. In particular, the full velocity difference (FVD) model is used to capture the characteristics of vehicular traffic flow. The proposed sliding mode controller is designed in terms of the error between the desired space headway and the actual space headway. The stability of the controller is guaranteed using the Lyapunov technique. Numerical experiments are used to compare the performance of sliding mode control (SMC) with that of feedback control. The results illustrate the effectiveness of the proposed SMC method in terms of the distribution smoothness and stability of the space headway, velocity, and acceleration profiles. They further illustrate that the SMC strategy is superior to that of the feedback control strategy, while enabling computational efficiency that can aid in practical applications.

1. Introduction

Over the past few decades, there has been a lot of focus on capturing the complex mechanisms behind the phenomena of vehicular traffic flow from the microscopic and macroscopic viewpoints. Consequently, various traffic flow models such as cellular automaton (CA) models, car-following (CF) models, lattice hydrodynamic models, and gas kinetic models [1,2] have been proposed. In this context, the optimal velocity (OV) based CF models have been in focus recently to address two important aspects. The first is the descriptive traffic flow modeling, which addresses the underlying mechanisms behind the traffic flow phenomena. The second is the normative traffic flow control, which focuses on congestion mitigation and the smoothness of traffic flow evolution.

From the traffic flow modeling perspective, the CF models can be classified as lane-discipline and non-lane-discipline based models. The lane-discipline-based CF models assume that vehicles follow the lane discipline and move in the middle of the lane without lateral gaps. Bando et al. [3] propose the OV model based on the assumption that the following vehicle seeks a safe velocity determined by the space headway from the leading vehicle. Thereafter, various variations of OV-based CF models have been developed by factoring the surroundings of the following vehicle [4–21], such as generalized force (GF) mode [4], full velocity difference (FVD) model [5], multiple ahead and velocity difference (MAVD) model [6], full velocity and acceleration difference (FVAD) model [7], multiple velocity difference (MVD) model [8], and multiple headway, velocity and

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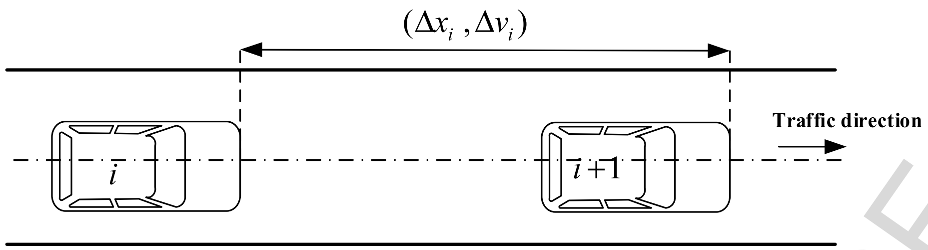

Fig. 1. Lane-discipline-based car-following model.

acceleration difference (MHVAD) model [9]. Results from these CF models show that the stop-and-go waves can be captured effectively. Unlike the lane-discipline-based CF models, the non-lane-discipline-based CF models allow for the scenario that lanes may not be clearly demarcated on a road though multiple vehicles can travel in parallel, or that lane-discipline may not be respected. Jin et al. [22] propose a non-lane-based full velocity difference CF (NLBCF) model to analyze the impact of the lateral gap on one side of the CF behavior. However, the NLBCF model cannot distinguish the right-side or the left-side lateral gaps. Consequently, Li et al. [23] propose a generalized model which considers the effects of two-sided lateral gaps of the following vehicle under the non-lane-discipline environment. Li et al. [24] further study the effects of lateral gaps on the energy consumption for electric vehicle flow under the non-lane discipline. The aforementioned studies also illustrate that CF models can effectively capture the characteristics of traffic flow phenomena in the real world.

From the traffic flow control perspective, control can be used to mitigate traffic congestion or seek the smooth flow of traffic. Konishi et al. [25] simplify the stability condition of OV model under the periodic boundary situation. Konishi et al. [26] propose a decentralized delayed-feedback control mechanism to address traffic congestion based on the OV model. Zhao et al. [27] propose a feedback control approach to reduce traffic jams based on the OV model, where the velocity difference between the leading and following vehicle is designed as the feedback signal. Li et al. [28] propose an acceleration feedback control strategy for traffic jam suppression based on the FVD model. Li et al. [29] propose a delay feedback control strategy of vehicular traffic flow based on the lattice model by considering the difference of the density change rate. The aforementioned studies analyze vehicular traffic flow control using the feedback control strategy. However, the computational time required for enabling smoothness and stability of the space headways and velocities of vehicular traffic flow using such feedback control strategies needs to be reduced given the real-time needs of traffic control. This represents the motivation for the current study which develops a new computationally efficient sliding mode control (SMC) strategy to improve the traffic flow evolution smoothness and stability.

This study focuses on designing a computationally efficient sliding mode controller of vehicular traffic flow based on the FVD model efficiently so as to enable the traffic flow to be smooth and stable. The FVD model is used to capture the characteristics of vehicular traffic flow. The sliding mode controller is designed in terms of the error between the desired space headway and the actual space headway between the leading and following vehicles. The stability of the controller is guaranteed using the Lyapunov technique. Simulation-based numerical experiments are used to compare the performance of the proposed SMC strategy with that of a feedback control strategy. The results indicate that the SMC strategy performs better than the feedback control strategy, in terms of the distribution smoothness and stability associated with the space headway, velocity, and acceleration profiles.

The rest of this paper is organized as follows. Section 2 reviews the FVD model used to model traffic flow in this study. Section 3 designs the sliding mode controller using the Lyapunov technique. Section 4 discusses the numerical experiments to compare traffic profiles with respect to the space headway, velocity, and acceleration profiles. The final section provides some concluding comments.

2. FVD model

As shown in Fig. 1, for the lane-discipline-based scenario in car-following theory, Jiang et al. [5] propose the FVD model to capture the characteristics of vehicular traffic flow by considering both the positive and negative velocity differences between the leading and following vehicles:

$$a_i(t) = k[V(y_i(t)) - v_i(t)] + \lambda \Delta v_i(t), \tag{1}$$

where $x_i(t)$, $v_i(t)$ and $a_i(t)$ represent the position (in m), velocity (in m/s) and acceleration (in m/s^2), respectively, of vehicle i at time t. $y_i(t) \equiv x_{i+1}(t) - x_i(t)$ and $\Delta v_i(t) \equiv v_{i+1}(t) - v_i(t)$ are the space headway difference and velocity difference between the leading vehicle $i+1$ and the following vehicle i. $k > 0$ $(k \in \mathbb{R})$ and $\lambda \geq 0$ $(\lambda \in \mathbb{R})$ are the sensitivity coefficients.

$V(y_i(t))$ is the optimal velocity function [5]:

$$V(y_i(t)) = [\tanh(y_i(t) - x_c) + \tanh(c_c)]v_{\max}/2 \tag{2}$$

where $v_{\max}$ is the maximal speed of the vehicle, x_c is the safe space headway, and $\tanh(\bullet)$ is the hyperbolic tangent function.

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