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Modeling the information flow propagation wave under vehicle-to-vehicle communications

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ABSTRACT

Vehicle-to-vehicle (V2V) communications under the connected vehicle context have the potential to provide new paradigms to enhance the safety, mobility and environmental sustainability of surface transportation. Understanding the information propagation characteristics in space and time is a key enabler for V2V-based traffic systems. Most existing analytical models assume instantaneous propagation of information flow through multi-hop communications. Such an assumption ignores the spatiotemporal relationships between the traffic flow dynamics and V2V communication constraints. This study proposes a macroscopic two-layer model to characterize the information flow propagation wave (IFPW). The traffic flow propagation is formulated in the lower layer as a system of partial differential equations based on the Lighthill-Whitham-Richards model. Due to their conceptual similarities, the upper layer adapts and modifies a spatial Susceptible-Infected epidemic model to describe information dissemination between V2V-equipped vehicles using integro-differential equations. A closed-form solution is derived for the IFPW speed under homogeneous conditions. The IFPW speed is numerically determined for heterogeneous conditions. Numerical experiments illustrate the impact of traffic density and market penetration of V2V-equipped vehicles on the IFPW speed. The proposed model can capture the spatiotemporal relationships between the traffic and V2V communication layers, and aid in the design of novel information propagation strategies to manage traffic conditions under V2V-based traffic systems.

1. Introduction

1.1. Background

Advances in information and communication technologies enable new paradigms for connectivity involving vehicles, infrastructure and the broader road transportation system environment. They provide the potential for developing innovative and sustainable solutions to enhance traffic safety and mobility. In this context, vehicle-to-vehicle (V2V) communications under the aegis of the connected vehicle are being leveraged for novel applications related to traffic safety, management and control, which lead to a V2V-based traffic system. For example, traffic safety applications (Biswas et al., 2006; Palazzi et al., 2010; Benedetto et al., 2015; Liu and Khattak, 2016) primarily provide advisories and warning for drivers to avoid potential collisions. Traffic management and control applications (Leontiadis et al., 2011; Monteil et al., 2013; Feng et al., 2015; Guler et al., 2014; Gueriau et al., 2016) focus on

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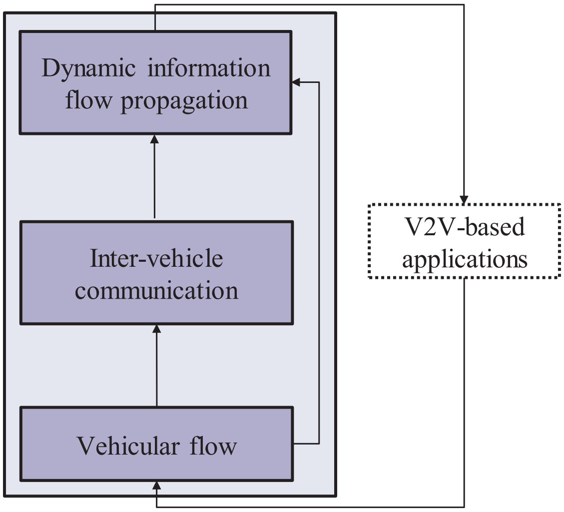

Fig. 1. Components of a V2V-based traffic system.

improving mobility by assisting the driver to manage speed for smooth driving or fostering informed decision-making by providing information on alternate routes. These applications can be developed based on vehicle operational information (such as vehicle position, speed, and direction) and road condition information (such as hazardous locations on roads, slippery sections, and potholes).

A V2V-based traffic system consists of the vehicular traffic flow, inter-vehicle communication, spatiotemporal information flow, and V2V-based applications. The relationships between these components are characterized by nonlinearity, interdependencies, and a feedback loop, as illustrated in Fig. 1. In this study, we use the term "information flow" to denote the flow of a single unit of traffic data (for example, traffic condition information or safety alert information) between vehicles. The dynamics of the vehicular traffic flow (such as the travel direction, location, speed, and the density of equipped vehicles) determine the occurrences of inter-vehicle communication. The traffic flow dynamics and the communication occurrences lead to the dynamics of information flow propagation. Based on the information propagated, a V2V-based application provides an audio or visual message to a driver, which he/she uses to determine the future speed or an alternative route to take. This impacts the traffic dynamics, as illustrated by the feedback loop in Fig. 1.

Within the proposed V2V-based traffic system framework, this study focuses on understanding how information propagates in space and time, as highlighted by the shaded box in Fig. 1. This is because V2V-based applications require timely and reliable information delivery. However, the real-world environment for implementing a V2V-based application can be constrained by the characteristics and phenomena associated with the interactions involving traffic flow dynamics and V2V communication constraints. Hence, a critical question is how information propagation is impacted by the traffic flow dynamics and V2V communication constraints.

To address the aforementioned question, there is the key need to develop realistic models that can: (i) capture the relationship between traffic flow and information flow propagation, (ii) incorporate realistic V2V communication constraints related to range, data communication frequency, and transmission power, and (iii) generate closed-form solutions for the information flow propagation speed, so as to provide insights on its qualitative properties.

This paper seeks to develop an analytical model, which characterizes the relationship between V2V communications and traffic flow dynamics, to determine the information flow propagation speed. In this context, we derive a closed-form solution of the information flow propagation speed under certain traffic conditions. Reliable knowledge of the information flow propagation and corresponding closed-form solutions serve as the enabling foundation for the reliable and practical design of V2V-based applications. This underlines the importance of developing realistic, yet easy-to-use, models to capture the dynamics of information flow propagation.

Previously, analytical microscopic models have been developed to describe the dynamics of information flow propagation. These models can be classified into two groups based on the underlying assumption of V2V communications. The first group of analytical models (Jin and Recker, 2006; Wang, 2007; Ukkusuri and Du, 2008; Wang et al., 2012; Yin et al., 2013; Wang et al., 2016) rely on the assumption of instantaneous multi-hop to characterize the propagation of information flow. They assume that information propagation is instantaneous with respect to vehicle movement to establish an end-to-end multi-hop communication path between vehicles. Based on the distribution of vehicle location, the probabilities for information to travel to and beyond a vehicle are computed (Jin and Recker, 2006). Therefore, these models account for the randomness in the locations of equipped vehicles and derive the expected coverage of information. By contrast, the proposed study seeks to understand the information propagation characteristics in space and time. It explores how information propagation is impacted by the traffic flow dynamics and communication constraints in a V2V-based traffic system.

The second group of studies (Wu et al., 2009; Jacquet et al., 2010; Zhang et al., 2011; Du and Dao, 2015; Du et al., 2016) are

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