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Stochastic modeling for vehicle platoons (I): Dynamic grouping behavior and online platoon recognition

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ABSTRACT

A vehicle platoon is a group of vehicles traveling together at approximately the same speed. Traffic platooning is an important phenomenon that can substantially increase the capacity of roads. This two-part paper presents a new approach to stochastic dynamic modeling for vehicle platoons. In part I, we develop a vehicle platoon model with two interconnected components: a Markov regime-switching stochastic process that is used to model the dynamic behavior of platoon-to-platoon transitions, and a state space model that is employed to describe individual vehicles' dynamic movements within each vehicle platoon. On the basis of the developed stochastic dynamic model, we then develop an algorithm for online platoon recognition. The proposed stochastic dynamic model for vehicle platoons also provides a new approach to vehicle speed filtering for traffic with a platoon structure.

1. Introduction

A vehicle platoon is defined to be a group of vehicles traveling together at approximately the same speed. Traffic platooning is an important traffic phenomenon. Tightly spaced platoons will lead to savings in fuel and increased highway capacity. Clearly, when the traffic platooning structure is taken into consideration, the efficiency of traffic management can be enhanced substantially.

The importance of the research on vehicle platoons is reinforced by the rapid development on autonomous driving in the recent decade where considerable research attention has been paid to vehicle platooning formed by a number of automated vehicles that are cooperatively driven. Diakaki et al. (2015) have recently reviewed vehicle automation and communication systems, including platooning systems and cooperative following and merging systems, from a motorway traffic management perspective. Kavathekar & Chen (2011), on the other hand, have provided a survey on vehicle platooning and the relevant technical issues such as inter-vehicle communications, obstacle detection and collision avoidance; See also an interesting case study on vehicle platooning discussed in Bergenhem et al. (2012).

In the literature, the research on traffic platoons can be classified into several broad categories. First, a large body of research on traffic platoon theory focuses on platoon dispersion. In the pioneering model by Lighthill and Whitham (1955), the kinematic wave theory was used to describe the platoon traffic behavior as it travels along a link. Pacey (1956) subsequently proposed a probabilistic model for traffic platoon dispersion, upon which Robertson (1969) developed a recurrence equation to characterize the platoon dispersion phenomena. Robertson's recurrence equation involves a couple of important

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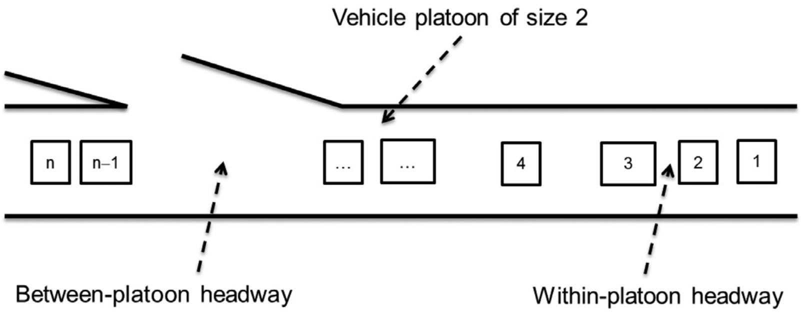

Fig. 1. Illustration of vehicle platoons.

parameters that need to be estimated in practical applications. In recent years, many researchers, e.g., Yu (2000), Farzaneh & Rakha (2006), and Bie et al. (2012), have investigated the calibration of these platoon dispersion parameters for the traffic platoon dispersion model.

The second strand of research on vehicle platoons considers how to identify vehicle platoons and hence how to take advantages of the platoon structure in traffic management. For example, Gaur & Mirchandani (2001) investigated a method for real-time recognition of vehicle platoons. Chaudhary et al. (2006) developed an intelligent traffic control system for identifying platoons at isolated traffic signals on signalized arterials. Jiang et al. (2006) investigated platoon-based traffic signal timing for major-minor intersection types. By minimizing the interruptions to vehicle platoon movements, Jiang et al. (2006) developed an algorithm to reduce traffic delays at intersections.

So far in the traffic literature, there is not much research done for stochastic dynamic modeling of vehicle platoons. The purpose of this two-part paper is to develop a stochastic model to describe the dynamic behavior of vehicle platoons and to investigate various platoon characteristics. In part I, we characterize vehicle platoons by both vehicle speeds and vehicle time headways so that the dynamic nature of the platoon-to-platoon transitions and within-platoon movements can be captured. In contrast, the research on vehicle platoons in the existing literature on platoon classification and recognition (e.g. Gaur & Mirchandani, 2001; Jiang et al., 2006) is solely determined by vehicle time headways, and therefore cannot reflect the platoons' dynamic nature. The developed model in this paper also provides a new probabilistic approach to online platoon recognition and online vehicle speed filtering. Then in part II in Li (2016), we will investigate statistical distribution models for some important platoon characteristics.

This paper is structured as follows. In the next section we propose a dynamic model to describe traffic platoons. Statistical inference, including model estimation, platoon recognition and speed filtering, is considered in Section 3. To illustrate the developed stochastic dynamic model for vehicle platoons, a practical example is discussed in Section 4. Finally, concluding remarks are offered in Section 5.

2. A vehicle platoon model

In this section, we develop a stochastic model to describe the dynamics of vehicle platoons. A vehicle platoon in the literature is defined to be a group of vehicles traveling together at approximately the same speed. We therefore use two microscopic traffic variables, i.e. vehicle speed and vehicle time headway, to identify vehicle platoons and to characterize the dynamic behavior of platoon-to-platoon transitions and within-platoon movements.

2.1. Vehicles and platoons

Consider a traffic flow consisting of a number of consecutive vehicles indexed by $n = 1, 2, \ldots$, as illustrated in Fig. 1. For any vehicle traveling alone, we follow Jiang et al. (2006) and term it as a platoon with size of one. We characterize each individual vehicle n by two microscopic traffic variables, i.e. vehicle speed v_n and vehicle time headway h_n.

We assume that the traffic under investigation involves several velocity modes, indexed by $j \in \mathcal{M}_V = \{1, \ldots, M\}$, where each velocity mode j is associated with a mean speed level μ_j and standard deviation σ_j. Without loss of generality, we restrict $\mu_1 < \ldots < \mu_M$ for identifiability purposes. We use an indicator S_n to represent the velocity mode that a vehicle n is associated with; the velocity-mode indicator S_n takes a nominal level in $\mathcal{M}_V$, i.e. $S_n \in \mathcal{M}_V$.

Next, we turn to consider the other microscopic traffic variable, vehicle time headway. In the literature of traffic studies, vehicle time headway is shown to be in one of the two states: a 'car-following' mode that is associated with the vehicles following its lead vehicle, and a 'free-speed' mode that is associated with the vehicles traveling at a free speed. We define a headway mode indicator $R_n \in \mathcal{M}_H = \{0, 1\}$ to represent the status of the headway of a vehicle n: $R_n = 0$ representing the car-following status and $R_n = 1$ otherwise.

Now we define vehicle platoons. We use two traffic variables, vehicle speed and vehicle time headway, to characterize a vehicle platoon. If two consecutive vehicles belong to the same platoon, they must travel at the same speed level and the temporal gap between them must be small. A natural way to characterize the speed and headway statue of a vehicle