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Towards mesoscale analysis of inter-vehicle communications

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Abstract

Cooperative traffic systems renew much research interest with the rapid development of communication technologies. This paper considers a finite number of vehicles moving in a single lane from a mesoscale perspective and explores the spectral properties of such a cooperative system, in particular how the communication range and the coupling weights influence the eigenvalues of the global disturbance transition matrix (DTM), i.e., disturbance modes of the traffic system. Dynamics of these vehicles are described by a modified coupled-map car-following model under periodic boundaries with inter-vehicle communications. From a state-space approach, a system DTM is established from a global view and a closed-form solution of its eigenvalues is derived. Linear stability conditions are subsequently obtained. It is found that the eigenvalue distribution of system DTM is essentially dominated by the communication range and the coupling weights, but nearly independent of the system size. By analyzing the magnitudes of the dominant poles, the synchronization of the traffic system is enhanced if the weights of the vehicles within the communication range are more evenly distributed or the communication range is increased. Particularly, it is shown that the optimal communication network tends to be a mean-field network w.r.t. global synchronization, indicating that a communication network emphasizing uniform importance among vehicles within each vehicle's communication range is helpful for improving the synchronizability. Finally, numerical simulations verify the results.

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1. Introduction

In the past five decades, various traffic flow problems have been investigated in the fields of physics and transportation. Many models have been proposed and several techniques have been developed to study the underlying mechanism of traffic congestion as well as its control methods [1–6]. Among them, some car-following models are accepted as they provide reasonable understanding of certain traffic phenomena, such as coupled differential equation models [4], optimal velocity (OV) models [2], coupled-map (CM) models [3], etc. Specifically, the Korteweg de Vries (KdV) equation, a representative differential equation model, originated from the study of water waves, is frequently used to study the linear and nonlinear stabilities of traffic systems [5,6]. The OV model composes of a simple differential equation and an OV function depending on the headway of each car [2]. The CM car-following model is a discrete-time version of the continuous OV model, which is convenient for computer simulations [3].

In recent years, with the rapid development of information and communication technologies, vehicles are allowable to capture the information from their surrounding vehicles and environment. Although the vehicle-to-vehicle and vehicle-to-infrastructure communication frameworks in the intelligent traffic system (ITS) are essentially design plans with little real data available to validate [7], plenty of research has been devoted to studying the properties of cooperative behaviours in traffic systems from the theoretical perspective [6–16]. To evaluate the effects of cooperative behaviours on the performance of traffic systems, one common approach is to modify the traditional car-following model under the assumption that each vehicle can receive information from a number of preceding or following vehicles to update the driver's behaviour. Such consideration has been adopted by many research models. For example, the OV model or the KdV model is improved by taking the next-nearest-neighbor interactions into account in [4], or by considering the headway of any number of vehicles in [8,10]. The CM model has also been improved in [9,11–13] to include both forward and backward-looking information, or to receive multi-hop information from the preceding vehicles within the communication range. Through linear bucking analysis or nonlinear analysis, these efforts reveal that cooperative behaviours among vehicles are helpful for increasing the stability region and stabilizing the traffic flow.

It has been noticed that a common focus in the above investigations is on the stability analysis (including local stability and string stability) for the corresponding cooperative models with a *fixed* communication weight series, which weights the information from vehicles within a vehicle's communication range to update its velocity. Few studies systematically focused on how different communication weights influence the properties of the traffic system [22], especially the temporal performance when a disturbance emerges, i.e., the synchronization performance. These effects were mainly illustrated by numerical simulations [6,11,16]. The simulations in [11] show that the temporal performance of a traffic flow for certain weight series could be better than other ones. A recent paper [16] observes that putting more weight to the second leading vehicle could possibly lead to a more stable traffic flow in a cooperative car-following model, where each vehicle can receive information from its preceding 2 vehicles, but no analytical explanation is given therein.

In this paper, the objective is to investigate how the communication range and weight series influence the spectrum of the disturbance transition matrix (DTM) of the global

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