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Hierarchical perimeter control with guaranteed stability for dynamically coupled heterogeneous urban traffic

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ABSTRACT

Perimeter control based on the Macroscopic Fundamental Diagram (MFD) is widely developed for alleviating or postponing congestion in a protected region. Recent studies reveal that traffic conditions might not be improved if the perimeter control strategies are applied to unstable systems where high demand generates heavy and heterogeneously distributed traffic congestion. Therefore, considering stability of the targeted traffic system is essential, for the sake of developing a feasible and then optimal control strategy. This paper sheds light on this direction. It integrates a stability characterization algorithm of MFD system equations into the Model Predictive Control (MPC) scheme, and features respectively an upper and a lower bound of the feasible control inputs, to guarantee system stability. Firstly, the dynamics of traffic heterogeneity and its effect on the MFD are analyzed, using real data from Guangzhou in China. Piecewise affine functions of average flow are proposed to capture traffic heterogeneity in both regional and subregional MFDs. Secondly, stability of a three-state two-region system is investigated via stable equilibrium and surface boundaries analysis. Finally, a three-layer hierarchical control strategy is introduced for the studied two-region heterogeneous urban networks. The first layer of the controller calculates the stable surface boundaries for the given traffic demands and then determines the bounds of control input (split rate). An MPC approach in the second layer is used to solve an optimization problem with two objectives of minimizing total network delay and maximizing network throughput. Heterogeneity among the subregions is minimized in the last layer by implementing simultaneously a subregional perimeter flow control and an internal flow control. The effectiveness and stability of the proposed control approach are verified by comparison with four existing perimeter control strategies.

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1. Introduction

Urban Traffic Control (UTC) is one of the effective tools for traffic management which is widely used all over the world. The common purpose of UTC is to implement signal timings for minimizing the total vehicular delay in the network with consideration of traffic safety (Keyvan-Ekbatani et al., 2015). With the fast development of cities and increasing number of vehicles, traffic congestion during the peak periods in some metropolitan areas becomes more serious than ever before. At the same time, numerous valuable studies have been carried out in the field of traffic control or traffic timing. For example, adaptive control (Zhang et al., 2013), feedback control (Keyvan-Ekbatani et al., 2015), model predictive control (MPC)

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(Geroliminis et al., 2013) and other control strategies are adopted for improving the efficiency of UTC. Despite these newly developed theoretical models and practical systems, traffic timing in highly congested urban networks with queue spillbacks remains a significant challenge.

The complexity of traffic control for oversaturated large-scale network is due to three aspects. Firstly, the complex network topology has influence on the heterogeneous distribution of traffic demands; moreover, travelers' route choice behavior also increases the uncertainty of traffic flow in the network. Secondly, traditional link-level modeling based optimization may lead to high computational effort, especially for large-scale networks. Finally, instability of traffic flow during oversaturated conditions also contributes to the difficulty of traffic control. Thus, the previous traffic control strategies have limited effect on oversaturated networks with queue spillbacks. For example, Gayah et al. (2014) found that adaptive traffic signals may increase average flows and decrease the likelihood of gridlock when the network is moderately congested, but adaptive signals appear to have little to no effect on network stability and outflows in heavily congested conditions. Recently, perimeter control (or gating) policies have been adopted to handle oversaturated networks (Haddad, 2017a, 2017b). The main idea of perimeter control is to hold vehicles back to upstream of a protected region (PR) and keep the critical accumulation of PR for maximizing flow. For overcoming the complexity of link-based control modeling, Macroscopic Fundamental Diagram (MFD) is introduced in the research of perimeter control, which provides a low-scatter relationship between network vehicle accumulation (veh) or density (veh/km) and network space-mean flow or outflow (trip completion rate) (veh/h).

Daganzo and Geroliminis (2008) and Geroliminis and Sun (2011) studied the existence and properties of MFD, and suggested that the shape of MFD can be simplified as triangular or trapezoid shape in practical applications. Perimeter and boundary flow control strategies that use MFD have been introduced for single-region cities (Daganzo, 2007; Keyvan-Ekbatani et al., 2012), and for multi-reservoir heterogeneous networks (Aboudolas and Geroliminis, 2013; Geroliminis et al., 2013; Kouvelas et al., 2017). Haddad and Shraiber (2014) introduced a robust perimeter controller which is more efficient than a standard feedback controller. However, recent findings revealed that the scatter of an MFD and its shape can be influenced by uneven (in space) or inconsistent (in time) distribution of congestion, which is determined by the topology/structure of the network (Daganzo and Geroliminis, 2008), traffic demand (Haddad and Geroliminis, 2012), traffic signals (Gayah et al., 2014), measurement homogeneity (Buisson and Ladier, 2009), and driver behavior (Gayah and Daganzo, 2011; Leclercq and Geroliminis, 2013). Previous empirical and simulated data also verified the average network flow is consistently higher when link density variance is low for the same network density, and higher densities can create points below an MFD when they are heterogeneously distributed (Leclercq and Geroliminis, 2013; Mazloumian et al., 2010). Furthermore, multi-route network is inherently more unstable as the density decreases than as it increases, and recovery seems to be more unstable than loading (Gayah and Daganzo, 2011). This instability may contribute to the existence of hysteresis loops in MFD (Yildirimoglu et al., 2015), which implies multiple flows for a given value of density.

For investigating the dynamics of heterogeneity in urban regions with perimeter control, Ramezani et al. (2015) introduced two aggregated models (region-based and subregion-based) and proposed a hierarchical control framework for decreasing system delays and congestion heterogeneity. This reference sheds some light on dynamics of heterogeneity and its application in perimeter control. Nevertheless, there are still some challenges on the way of practical application of perimeter control. On the one hand, numerous and detailed empirical analyses using real data are needed, as the shapes of MFD and dynamics of heterogeneity of each urban network are unique. For implementing traffic perimeter control based on MFD, one should also investigate the aforementioned influencing factors and their impacts on MFD respectively with consideration of data availability. On the other hand, the system stability or robustness should be considered in the implementation of dynamic traffic control (Daganzo et al., 2011). It is well known that the optimal strategies derived from perimeter control do not imply stability. That is to say, a heavily congested network with high demand might lead to gridlock even if a so-called optimal control strategy is applied. Haddad and Geroliminis (2012) studied stable characterization of two-region MFDs system by analyzing the dynamic equations of accumulation and equilibrium points of the system. Moreover, an algorithm has been proposed in this reference to derive the boundary between stable and unstable regions considering the phase portraits of the dynamic equations.

In this paper, we extend the control framework in Ramezani et al. (2015) to a three-layer hierarchical control by incorporating the stability analysis. The first layer serves as a stability analyzer to calculate the upper and lower bounds of feasible control input (i.e. split rate between two regions) to ensure system stability. The model predictive control (MPC) approach is applied in the second layer to solve the perimeter flow control (PFC) problem considering the constraints of system stability (i.e. the bounds of feasible split rate). With respect to the third layer, the internal flow control (IFC) is adopted in both the protected region and periphery region to decrease the density heterogeneity of all subregions. In a word, this paper integrates the stability characterization algorithm of the MFD system equations in the MPC scheme, to calculate the upper and lower bounds of the control inputs to guarantee system stability.

The advantages of integrating stability analysis with hierarchical perimeter control are verified by traffic simulation using real data from Guangzhou, China. Five simulation scenarios are designed in Matlab environment which are as follows: (1) no control, (2) MPC + PFC, (3) MPC + PFC + IFC, (4) MPC + PFC considering stability, (5) MPC + PFC + IFC considering stability. Several performance indexes (i.e. accumulation (veh), outflow (veh/s), heterogeneity, etc.) are used to evaluate the efficiency of these control strategies.

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