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Optimal perimeter control synthesis for two urban regions with aggregate boundary queue dynamics

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A B S T R A C T

Perimeter control policies for urban regions with Macroscopic Fundamental Diagram (MFD) modeling have been presented in previous works. The control policies might meter the number of transferring vehicles from one region to another, resulting in queueing vehicles at regional boundaries. Concentrated vehicles at boundaries might affect the existence of well-defined MFDs. Most previous works neglect the effect of the boundary concentrated vehicles on the traffic flow dynamics, and do not explicitly consider their effect on the perimeter control policy.

This paper introduces a new MFD-based model for two-region networks with aggregate boundary queue dynamics. The dynamic flow characteristics for the two urban regions are modeled by the MFD functions, while aggregate boundary queue dynamics for both regions are modeled by input-output balance differential equations. Maximum lengths are imposed on the aggregate boundary queues, that aim at maintaining the existence of well-defined MFDs and their dynamics.

Based on the developed model, the optimal control policy to maximize the total network throughput is found. Analytical solutions for the optimal perimeter control problem, with constrained perimeter control inputs and constrained lengths of aggregate boundary queues, are derived. The optimal synthesis for principal cases are found and verified by numerical tests. The numerical results demonstrate the effect of aggregate boundary queues on the optimal perimeter control policy.

1. Introduction

Perimeter control is the idea to manipulate the transfer flows at the perimeter borders of an urban region in order to obtain the desired number of vehicles in that region. Several perimeter control strategies for large-scale urban road networks have been studied recently in Daganzo (2007), Haddad and Geroliminis (2012), Geroliminis et al. (2013), Hajiahmadi et al. (2015), Haddad et al. (2013), Aboudolas and Geroliminis (2013), Keyvan-Ekbatani et al. (2012), Knoop et al. (2012), Zhang et al. (2013), and others. These strategies have been designed utilizing aggregate network models, that have similar mathematical representations: (i) relying on vehicle conservation equations, and (ii) the network space-mean flow or outflow

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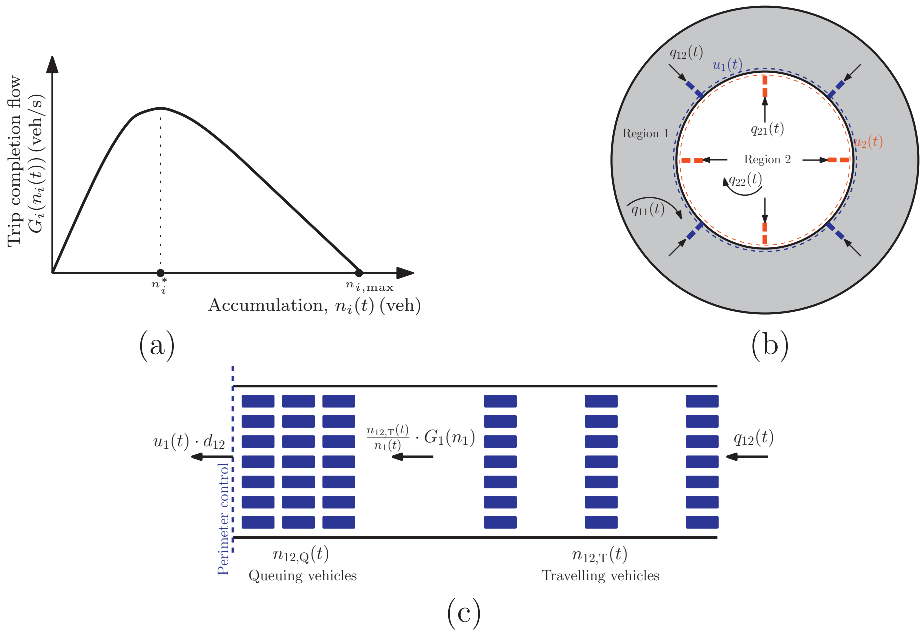

Fig. 1. (a) A schematic MFD which is concave, twice differentiable, non-negative, and strictly unimodal function, (b) A schematic urban network consists of two urban regions with internal demands $q_{11}(t)$, $q_{22}(t)$, external demands $q_{12}(t)$, $q_{21}(t)$, perimeter control with inputs $u_1(t)$, $u_2(t)$, and boundary queues, (c) A schematic description for the aggregate boundary queue dynamics in region 1.

(veh/hr) is given as a static function of the network vehicle density (veh/km) or accumulation (veh), i.e. by the Macroscopic Fundamental Diagram, see Fig. 1(a). It was shown that utilizing aggregate MFD-based models can model large urban regions, if congestion is uniformly distributed (Geroliminis and Daganzo, 2008).

Empirical and simulation studies have provided observation and theoretical elements for the existence of well-defined MFDs for homogeneous urban networks with small variance of link densities (Buisson and Ladier, 2009; Daganzo, 2007; Daganzo et al., 2011; Geroliminis and Daganzo, 2008; Geroliminis and Sun, 2011b; Godfrey, 1969; Mahmassani et al., 1987; Mazloumian et al., 2010; Olszewski et al., 1995). On the other hand, heterogeneous networks might not have a well-defined MFD, mainly in the decreasing part of the MFD, as the scatter becomes higher as accumulation increases and hysteresis phenomena has been found to exist (Buisson and Ladier, 2009; Daganzo et al., 2011; Geroliminis and Sun, 2011a; Xie et al., 2016). One approach to handle the scatter is to partition heterogeneous networks into “more homogeneous” regions with small variances of link densities MFD (Ji and Geroliminis, 2012; Ji et al., 2014). Another approach is to consider that the shape of MFD is not exactly known and located in some interval, i.e. interval function of MFD, see Laval and Castrillón (2015), Haddad and Shraiber (2014) and Haddad (2015b). Modeling the dynamics of heterogeneity with a parsimonious model has been developed in Ramezani et al. (2015) and Mahmassani et al. (2013).

MFD-based perimeter control has been proposed for single-region cities in Daganzo (2007), Keyvan-Ekbatani et al. (2012), Haddad and Shraiber (2014), and for multi-region cities in Haddad and Geroliminis (2012), Geroliminis et al. (2013), Aboudolas and Geroliminis (2013), Hajiahmadi et al. (2015) and Haddad et al. (2013). In Haddad et al. (2013), different levels of coordination between freeways and urban roads have been proposed. Another type of controllers, i.e. the switching signal timing plans controller, together with the perimeter controllers, has been introduced to manage and control a large-scale urban network in Hajiahmadi et al. (2015). Moreover, route guidance strategies with the utilization of MFD have been studied in Knoop et al. (2012), Gayah and Daganzo (2011) and Yildirimoglu et al. (2015), while in Xiong et al. (2016) modeling agents’ en-route diversion behavior under information provision has been introduced, where the dynamic behavioural responses and network performance are represented by MFDs. In Zhang et al. (2015) integrating a Cell Transmission Model with the MFD for urban networks is proposed, while the relations between route patterns within a network and the related aggregate traffic dynamics is investigated in Leclercq et al. (2015). Recently, control design for perimeter and gating control in presence of time-delay in urban road network have been developed in Haddad and Mirkin (2016), Keyvan-Ekbatani et al. (2015) and Mirkin et al. (2016). Simulation results in Xue et al. (2016) have revealed that the designed control and the resulted control performance highly depend on the system modeling.

Different control approaches have been used to solve the perimeter control problems, e.g., Model Predictive Control (MPC) approach has been used to solve the optimal control problems in Geroliminis et al. (2013), Haddad et al. (2013), Hajiahmadi et al. (2015) and Ramezani et al. (2015), while a classical feedback control approach has been implemented in Keyvan-