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Enhancing model-based feedback perimeter control with data-driven online adaptive optimization

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ABSTRACT

Most feedback perimeter control approaches that are based on the Macroscopic Fundamental Diagram (MFD) and are tested in detailed network structures restrict inflow from the external boundary of the network. Although such a measure is beneficial for the network performance, it creates virtual queues that do not interact with the rest of the traffic and assumes small unrestricted flow (i.e. almost zero disturbance). In reality, these queues can have a negative impact to traffic conditions upstream of the protected network that is not modelled. In this work an adaptive optimization scheme for perimeter control of heterogeneous transportation networks is developed and the aforementioned boundary control limitation is dropped. A nonlinear model is introduced that describes the evolution of the multi-region system over time, assuming the existence of well-defined MFDs. Multiple linear approximations of the model (for different set-points) are used for designing optimal multivariable integral feedback regulators. Since the resulting regulators are derived from approximations of the nonlinear dynamics, they are further enhanced in real-time with online learning/adaptive optimization, according to performance measurements. An iterative data-driven technique is integrated with the model-based design and its objective is to optimize the gain matrices and set-points of the multivariable perimeter controller based on real-time observations. The efficiency of the derived multi-boundary control scheme is tested in microsimulation for a large urban network with more than 1500 roads that is partitioned in multiple regions. The proposed control scheme is demonstrated to achieve a better distribution of congestion (by creating “artificial” inter-regional queues), thus preventing the network degradation and improving total delay and outflow.

1. Introduction

Real-time traffic management is deemed to be an efficient and cost effective way to ameliorate traffic conditions and prevent gridlock phenomena in cities. Although many methodologies have been developed for real-time signal control over the last decades (see e.g. Papageorgiou et al., 2003 for a good review), the design of efficient control strategies for heterogeneous large-scale urban networks that can deal with oversaturated conditions (where queues spill back to upstream links) remains a significant challenge. Local adaptive strategies that are widely used around the world are based on heuristic optimization techniques and are not efficient when the network faces congestion propagation phenomena and queue spillbacks.

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Other traffic responsive strategies (Gartner, 1983; Mirchandani and Head, 1998) use complex optimization methods, which make their online application to large-scale urban networks difficult due to high computational requirements.

More recently, a practicable network-wide control strategy (TUC) has been developed (Diakaki et al., 2003; 2002) that tries to deal with oversaturated conditions by minimizing the variance of relative occupancies of the network links; this strategy has been tested in simulation but also in various field implementations (see e.g. Aboudolas et al., 2010; Kouvelas et al., 2011b). Another conception, which has been recently proposed for regulating urban traffic and is based on a decentralized approach of the problem, is the max-pressure controller (Kouvelas et al., 2014; Varaiya, 2013). This distributed control law, which was originally applied to production processes and communication networks and has lately gained a lot of attention in traffic control, acts locally in coupled intersections and has been proven (under certain conditions) to stabilize the queues of the network. In the same direction, Muralidharan et al. (2015) studied the network stability under fixed-time control; this analysis provides useful insights about simple network traffic instances (i.e. the demand is assumed to be "feasible" – can be accommodated by the signals) and can potentially lead to analytical derivations of performance measures (i.e. total travel time, total delay). Note, however, that in the case of heterogeneous networks with multiple pockets of congestion and heavily directional demand flows such an analysis is not straightforward (due to the lack of spillback modelling and infeasible demand[1]) and this type of control (i.e. TUC, max-pressure) may not be optimal or the stabilization of the system in a reasonable time period might not be feasible.

An alternative approach for real-time network-wide control for heterogeneous urban networks that is steadily gaining momentum is the perimeter flow control, which adds an additional layer of a more aggregated approach for modelling and control. While a global optimization framework for all controllers in the city may sound impossible (due to both computational burden and model uncertainty and unpredictability), identifying some critical intersections and regulating them effectively can significantly alleviate the level of congestion (and even make more efficient the local strategies). The basic concept of such an approach is to partition the heterogeneous network into a small number of homogeneous regions and apply perimeter control to the inter-transferring flows along the boundaries between regions. The input flows to a region (which are also output flows for the neighbouring regions) can be controlled at the intersections located at the borders of the region, so as to maximize the total throughput of the system. Perimeter control (or gating) policies have been introduced for single-region homogeneous networks (Daganzo, 2007; Keyvan-Ekbatani et al., 2012) and multi-region heterogeneous networks (Aboudolas and Geroliminis, 2013; Geroliminis et al., 2013 and many other works) using different control methodologies. The key modelling tool that is used by all the aforementioned strategies is the Macroscopic Fundamental Diagram (MFD), which provides a concave, low-scatter relationship between network vehicle accumulation (veh) or density (veh/km) and network production (veh·km) or circulating flow (veh/h). The concept of a network MFD was firstly introduced in Godfrey (1969), but the empirical verification of its existence with dynamic features is quite recent (Geroliminis and Daganzo, 2008).

Evidently, the stability of the MFD shape faces two main challenges that are (a) the hysteresis phenomena that appear at the onset or offset of congestion (Buisson and Ladier, 2009; Gayah and Daganzo, 2011a; Geroliminis and Sun, 2011a; Saberi and Mahmassani, 2012), and (b) the heterogeneity of traffic in urban networks (Geroliminis and Sun, 2011b; Knoop et al., 2012; Mazloumian et al., 2010). Essentially, heterogeneous networks do not exhibit a well-defined MFD, especially in the congested regime. Partitioning such a network into homogeneous regions (i.e. areas with compact shape that have small variance of link densities) can result in well-defined MFD as shown in Ji and Geroliminis (2012). Nevertheless, the MFD concept constitutes a useful tool for designing control policies, as it provides aggregated relationships between macroscopic traffic variables and reduces the complexity of traffic flow dynamics (i.e., there is no need for tracking the state of each individual link of the network).

Despite the vast literature related to empirical observations, modelling and control with MFDs, there are still multiple challenges in this growing field of research. In this work, we address 3 main challenges related to modelling, control and applicability of methodologies in real situations. First, (a) we reformulate the system dynamics developed in previous works in a way that the derived controllers can be implemented with limited data from inductive loop detectors. Second, (b) in the experimental studies all the controlled queues are internal to the simulated network and interact and influence the rest of the traffic and (c) an online data-driven approach is utilized to optimize the controller parameters.

With respect to (a) previous works have developed and described nonlinear dynamics of MFD systems with multiple regions (see e.g. Ramezani et al., 2015 for a detailed description). Nevertheless, these equations include state variables for vehicle accumulations n_{ij} (where i is the current region of vehicles and j the destination region) and proper information about OD demand d_{ij}. If n_{ij} and d_{ij} can be measured with a decent level of accuracy, then the model predictive control approach developed in these works can properly solve the problem. However, there are some difficulties in estimating these variables without vehicle trajectories (i.e. only by using loop detector data). Thus, our current work does not contribute per se in the modelling of MFD dynamics, but rather adjusts previous formulations in a way that is very useful for control purposes without knowledge of n_{ij} states. Regarding contributions (b) and (c) the work of Aboudolas and Geroliminis (2013) (for multiple regions) and Keyvan-Ekbatani et al. (2012) (for single region) specify set points $\hat{n}_i$ for each region i, which are integrated in the control framework. The specification of $\hat{n}_i$ for monocentric networks with clear attractions of destinations

[1] This is a demand where one can prove mathematically that no feasible control can prevent congestion. One pathway to deal with this is demand management strategies (e.g. congestion pricing), but if this is not the case one can try to manage congestion in an efficient way for the system.