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Multi-scale perimeter control approach in a connected-vehicle environment

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This paper proposes a novel approach to integrate optimal control of perimeter intersections (i.e. to minimize local delay) into the perimeter control scheme (i.e. to optimize traffic performance at the network level). This is a complex control problem rarely explored in the literature. In particular, modeling the interaction between the network level control and the local level control has not been fully considered. Utilizing the Macroscopic Fundamental Diagram (MFD) as the traffic performance indicator, we formulate a dynamic system model, and design a Model Predictive Control (MPC) based controller coupling two competing control objectives and optimizing the performance at the local and the network level as a whole. To solve this highly non-linear optimization problem, we employ an approximation framework, enabling the optimal solution of this large-scale problem to be feasible and efficient. Numerical analysis shows that by applying the proposed controller, the protected network can operate around the desired state as expressed by the MFD, while the total delay at the perimeter is minimized as well. Moreover, the paper sheds light on the robustness of the proposed controller. This multi-scale hybrid controller is further extended to a stochastic MPC scheme, where connected vehicles (CV) serve as the only data source. Hence, low penetration rates of CVs lead to strong noises in the controller. This is a first attempt to develop a network-level traffic control methodology by using the emerging CV technology. We consider the stochasticity in traffic state estimation and the shape of the MFD. Simulation analysis demonstrates the robustness of the proposed stochastic controller, showing that efficient controllers can indeed be designed with this newly-spread vehicle technology even in the absence of other data collection schemes (e.g. loop detectors).

1. Introduction

Real-time traffic control strategies at the aggregated level have been receiving significant research attention, in particular the perimeter control (also known as gating). The basic concept is to restrict the incoming flow through traffic signals at the boundaries of a pre-defined region to prevent congestion inside. The controllers of this type are typically designed based on the Macroscopic Fundamental Diagram (MFD), also known in the literature as the Network Fundamental Diagram (NFD). Examples of such control strategies can be found in Keyvan-Ekbatani et al. (2012), Geroliminis et al. (2013), Haddad et al. (2013), Aboudolas and Geroliminis (2013), Haddad (2015), and Ramezani et al. (2015).

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The concept of an MFD or NFD was initially proposed in Godfrey (1969) and followed in Mahmassani et al. (1987) and Daganzo (2007). The demonstration of the existence of the MFD with dynamic features from field data was firstly reported in Geroliminis and Daganzo (2008), showing that traffic in urban single-mode regions exhibits an aggregated relationship between the space-mean network flow (traffic throughput) and the network density (traffic accumulation). During the past decade, plenty of research efforts have been devoted to further investigate the properties and develop approximations of the MFD model. An interested reader could refer to Yildirimoglu and Geroliminis (2014) and Leclercq et al. (2014) for a review of recent developments in MFD. For the control research field, the most important contribution of the MFD model lies in the fact that the model features the so-called critical accumulation of the network, which serves as the control goal and facilitates the design of various control schemes for traffic signals in real time. It has been shown in the literature that MFD-based control strategies are effective in regulating the global traffic performance; examples for single-mode networks can be found in Haddad and Geroliminis (2012), Keyvan-Ekbatani et al. (2012), Keyvan-Ekbatani et al. (2015), and Haddad (2015).

As the network-wide control has increasingly gained relevance, alternative and more complex concepts have been developed. For example, approaches have been proposed to partition heterogeneous networks (where congestion levels are unevenly distributed) into a small number of homogeneous regions, and to apply perimeter control to the inter-regional flows along the boundaries between those regions. This is known as multi-region control (see Aboudolas and Geroliminis, 2013; Ramezani et al., 2015; Kouvelas et al., 2016). The inter-transferring flows are controlled at the intersections located at the border between regions, so as to distribute traffic in an optimal way and minimize the total travel costs of all regions. This type of control can be viewed as a high-level regional control scheme and may be combined with other strategies (e.g. local or distributed controllers) in a hierarchical control framework (Kouvelas et al., 2016). Recent advances towards this direction are reported by Daganzo (2007), Keyvan-Ekbatani et al. (2012), Geroliminis et al. (2013), Aboudolas and Geroliminis (2013), Ramezani et al. (2015), and Kouvelas et al. (2016). Furthermore, some studies have extended the network-wide control to multimodal networks. Ampountolas et al. (2014) developed perimeter control strategies for a bimodal network, recognizing buses have larger transport efficiency than cars, therefore certain amount of buses should operate in the system to optimize passenger throughput. Chiabaut (2015) looked at the MFD model of arterial roads from a passenger flow perspective, and developed optimization strategies for bus operations. These last two references provide approaches for optimizing the passenger mobility through real-time control.

Regardless of what type of algorithms are applied, the optimal flow allowed to enter the network has to be distributed to the local intersections. In other words, as long as the controllers determine the total flow, the flow should be allocated to each individual perimeter intersection through the control of the traffic signals. Nearly all the existing studies have emphasized that delay may be caused at local intersections when applying perimeter control (Keyvan-Ekbatani et al., 2012; Geroliminis et al., 2013; Haddad et al., 2013; Aboudolas and Geroliminis, 2013; Hajiahmadi et al., 2015; Haddad, 2017). However, to the best of our knowledge, no work has quantitatively and systematically treated the delay at these intersections when designing the controllers for network-wide applications. Considering detailed performance of the local intersections may complicate the dynamics of the system, and consequently the optimization problem. Thus, given its challenging complexity, controllers treating specifically the intersections are rarely reported in the literature. Although some initial efforts have been made (e.g. combining adaptive traffic signal settings inside the network Kouvelas et al., 2016, and considering the queue length at the perimeter Keyvan-Ekbatani et al., 2016; Haddad, 2017), the interaction between the network level perimeter control and the local level intersection control has not been fully considered.

Motivated by the discussion above, this paper proposes a novel perimeter control approach that aims at improving the global traffic performance while simultaneously accounting for new technologies in transportation. Specifically, we propose and design control algorithms that work efficiently in a connected vehicle environment. The connected vehicle technology has been attracting increasing attention in the traffic control field, thanks to its capability of detailed and anticipative information provision. This information can be used not only to measure the current traffic situation, but also to predict traffic states in the future. This facilitates the application of the Model Predictive Control (Garcia et al., 1989) (MPC), which takes the predicted information and current states as inputs to optimize the current control actions while taking into consideration the future performance. Given its ability to handle complex and dynamic system models, MPC-based approaches have been studied for traffic control (see for example, Geroliminis et al., 2013; Hajiahmadi et al., 2015).

The contributions of this paper are twofold. (1) We develop a multi-scale control algorithm that optimizes traffic performance at the network level, and at the local level (i.e. perimeter intersections). Although extensive work has focused on either the network control or the intersection control, this paper is among the first pioneers that unify the control of the two levels. This is a challenging problem, as two competing control objectives are coupled into an integrated multi-scale control scheme. We will show that by applying the proposed multi-scale controller, the protected network can operate around the desired state as expressed by the MFD, while the total delay at the perimeter is minimized as well. (2) We apply the proposed controller in a connected-vehicle environment, for which the robustness of the control is enhanced. Although connected vehicle technology has attracted much attention in managing simple intersections (Guler et al., 2014; Yang et al., 2016), this work, to the best of our knowledge, is the first attempt to develop a network-level methodology using such technology. Evidently, using also traditional data sources such as loop detectors, video cameras and probe vehicles would be helpful to measure traffic accumulations (e.g. see Ambühl and Menendez, 2016) for control purposes. However, loop detectors are only expensive but also inflexible in location which results in biased estimation, while video cameras are be sensitive to weather and coverage conditions. In comparison, the data provided by connected vehicles is richer, more diverse and detailed. These advantages make CV environment exclusively suitable for developing multi-scale control. On the other hand,