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Network traffic flow optimization under performance constraints ☆

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A B S T R A C T

In this paper, a model-based perimeter control policy for large-scale urban vehicular networks is proposed. Assuming a homogeneously loaded vehicle network and the existence of a well-posed Network Fundamental Diagram (NFD), we describe a protected network throughout its aggregated dynamics including nonlinear exit flow characteristics. Within this framework of constrained optimal boundary flow gating, two main performance metrics are considered: (a) first, connected to the NFD, the concept of average network travel time and delay as a performance metric is defined; (b) second, at boundaries, we take into account additional external network queue dynamics governed by uncontrolled inflow demands. External queue capacities in terms of finite-link lengths are used as the second performance metric. Hence, the corresponding performance requirement is an upper bound of external queues. While external queues represent vehicles waiting to enter the protected network, internal queue describes the protected network's aggregated behavior.

By controlling the number of vehicles joining the internal queue from the external ones, herewith a network traffic flow maximization solution subject to the internal and external dynamics and their performance constraints is developed. The originally non-convex optimization problem is transformed to a numerically efficiently convex one by relaxing the performance constraints into time-dependent state boundaries. The control solution can be interpreted as a mechanism which transforms the unknown arrival process governing the number of vehicles entering the network to a regulated process, such that prescribed performance requirements on travel time in the network and upper bound on the external queue are satisfied. Comparative numerical simulation studies on a microscopic traffic simulator are carried out to show the benefits of the proposed method.

1. Introduction

Urban traffic congestion has become a major issue, since it results in – among others – delays, pollutant emissions, higher energy expenditure and accidents (see, e.g., Bigazzi and Figliozzi, 2012 and references therein). Intelligent transportation

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systems via *control* and *estimation* of traffic flows has been of vital importance to support urban traffic management in order to appropriately use finite road capacity under different traffic conditions.

One efficient urban traffic coordination approach is to adapt traffic lights at signalized intersections. To address this problem, several methods has been deployed at different hierarchical levels (ranging from intersection to network level), e.g., Papageorgiou et al. (2003). Among these methods, advanced urban traffic control is one of the most important techniques aiming at describing urban vehicular networks by some traffic models and then based on these mathematical abstractions to develop (optimal) control solutions. Towards this end, the concept of Network Fundamental Diagram, NFD, often called Macroscopic Fundamental Diagram (MFD), has been adopted as a basis for the derivation of traffic control strategies (e.g., Leclercq et al., 2014). The theory was first proposed in Godfrey (1969) and further developed in Daganzo and Geroliminis (2008) and Helbing (2009) (its application to experimental data is analyzed in Mahmassani et al., 1987; Geroliminis and Daganzo, 2008; Ampountolas and Kouvelas, 2015). Geroliminis and Sun (2011) further investigated what the properties that a network should satisfy are, so that an MFD with low scatter exists, by again using data from a field experiment in Yokohama (Japan). It is concluded that if two traffic states from two different time intervals have the same spatial distribution of link density, then the two time intervals have the same average flow. As a result, the assumption that congestion is evenly distributed across the network made by Geroliminis and Daganzo (2008) is relaxed. Daganzo (2007) first used the NFD to synthesize a controller that maximizes the network outflow, thus comprising a starting point for using the NFD theory for controlling traffic flow. Several works followed the developed control strategies based on NFD to maximize the capacity of homogeneous traffic networks. In this case, a single-region model with one NFD represents the dynamics of the network appropriately. The paper by Hajiahmadi et al. (2015) formulates the optimal control problem as a mixed integer linear optimization problem, with two types of controllers: perimeter controllers and a switching controller of fix-time signal plans. However, the solution to the problem cannot be used in real time. For alleviating this problem, a Proportional-Integral (PI) controller is proposed by Keyvan-Ekbatani et al. (2012) for real-time gating, with an application to the network of Chania, Greece. By modeling the dynamics of the external queues, a perimeter problem is solved via a Nonlinear MPC formulation in Csikós et al. (2015). Recently, in Haddad and Mirkin (2016), time delays in MFD related control problems have been addressed by means of adaptive control.

Alternative approaches have been used to forecast changing conditions in transportation systems. Due to the complexity of such systems, however, short term travel time estimation and prediction have been in the spotlight for a few decades; see, for example, Vlahogianni et al. (2014) and references therein. We hereby categorise the available techniques according to (1) the regression technique applied (*methodology*), (2) the type of data (*urban or rural*), and (3) the *source of data collection*. First, in order to describe estimation and prediction techniques for travel time, we may follow the model regression methodologies applied. In this vein, both parametric or non-parametric regression techniques have been already suggested. Second, part of the research has been inclined towards the case of the freeway, e.g., Li and Rose (2011) and some to urban Rahmani et al. (2015), Zhan et al. (2013), Jenelius and Koutsopoulos (2013) travel time estimation, or short time prediction. Third, different data sources have been utilized for travel time estimation and predictions (ranging from fixed or mobile sensors to data fusion), see references inVlahogianni et al. (2014).

The primary goal of the above mentioned works was to inform travellers and hence influence route planning. This means an *indirect* inclusion of the estimated, predicted travel time. *Direct* co-design of travel time estimation/prediction information with urban traffic control solution gives rise to improved transportation service, e.g., Lin et al. (2012) proposes a link travel time minimization in a predictive way. Ensuring performance (e.g., enforced travel time) metrics via traffic control policies is a relevant, non trivial research path, especially in case of large scale traffic networks. In Yildirimoglu et al. (2015), route choice models under dynamical constraint have been included to perimeter flow control decisions. Note that, as reported in Mahmassani et al. (2013),Yildirimoglu and Geroliminis (2014),Kouvelas et al. (2017), route choice effects can influence the trip length distribution of vehicles in the network and thereby approximation of outflow might experience some errors. In Haddad (2017b) optimal control for maximum queue length inclusion on aggregated inter-regional boundary queues is considered. Furthermore, Haddad (2017a) also deals with perimeter control problems for single-region cities, but it focuses on a dynamic model that decomposes the accumulation into two vehicle conservation equations. Optimal control solution to the problem takes decoupled state constraints into consideration.

In this paper, our main contribution is to develop admission control solutions under multiple performance requirements: i.e., provide an upper bound average network travel time and keep the external queue size below a certain threshold. In contrast to recent works Haddad (2017b,a), in our paper these performance requirements are jointly considered and used by rolling horizon capacity maximization where performance requirement are realtime relaxed into changing upper and lower hard constraints for the internal queue dynamics. While perimeter flow control has recently received a lot of attention from a control theoretic perspective, further performance requirements for the system, such as average travel delay in the network, have not been considered. In this work, similarly to the classical perimeter control problem, the objective is to optimize network performance through the maximization of network throughput. However, we additionally include performance requirements, adopting the service indicators of communication networks (see, for example, Klessig and Fettweis, 2014; Liu et al., 2014; Le et al., 2012 and references therein) to (a) keep the travel time spent in the network below a certain threshold, and (b) avoid, if possible, the blockage at the entrance of external queues.

The above performance requirements are incorporated as constraints into the gating design procedure. The problem emanating from our objective and constraints, is first generally formulated as a constrained optimization problem. Furthermore, the general non-convex optimization problem can be transformed to a convex problem for a single step receding horizon