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Cooperative traffic control of a mixed network with two urban regions and a freeway

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A B S T R A C T

Currently most optimization methods for urban transport networks (i) are suited for networks with simplified dynamics that are far from real-sized networks or (ii) apply decentralized control, which is not appropriate for heterogeneously loaded networks or (iii) investigate good-quality solutions through micro-simulation models and scenario analysis, which make the problem intractable in real time. In principle, traffic management decisions for different sub-systems of a transport network (urban, freeway) are controlled by operational rules that are network specific and independent from one traffic authority to another. In this paper, the macroscopic traffic modeling and control of a large-scale mixed transportation network consisting of a freeway and an urban network is tackled. The urban network is partitioned into two regions, each one with a well-defined Macroscopic Fundamental Diagram (MFD), i.e. a unimodal and low-scatter relationship between region density and outflow. The freeway is regarded as one alternative commuting route which has one on-ramp and one off-ramp within each urban region. The urban and freeway flow dynamics are formulated with the tool of MFD and asymmetric cell transmission model, respectively. Perimeter controllers on the border of the urban regions operating to manipulate the perimeter interflow between the two regions, and controllers at the on-ramps for ramp metering are considered to control the flow distribution in the mixed network. The optimal traffic control problem is solved by a Model Predictive Control (MPC) approach in order to minimize total delay in the entire network. Several control policies with different levels of urban-freeway control coordination are introduced and tested to scrutinize the characteristics of the proposed controllers. Numerical results demonstrate how different levels of coordination improve the performance once compared with independent control for freeway and urban network. The approach presented in this paper can be extended to implement efficient real-world control strategies for large-scale mixed traffic networks.

1. Introduction

Metropolitan transportation networks have a hierarchical structure which essentially consists of freeways and urban roads providing the interrelated infrastructure for mobility and accessibility. The freeway and the urban network are inherently coupled, but they have dissimilar traffic flow dynamics which challenge the traffic control of mixed networks of two interconnected (urban and freeway) traffic control entities. Although integrating the two entities through an effective mixed control policy could enhance the network performances during heavy congestion conditions, lack of coordination among the urban and freeway network jurisdictions and/or limited means of traffic monitoring and data communication might impede

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such mixed traffic network ideal goal. To overcome such deficiency, cooperative decentralized or if possible centralized control schemes can be developed as potential solutions, which oblige us to inquire into the traffic dynamics and control of the freeway and urban network to model the mixed traffic network.

Currently most optimization methods for urban transport networks (i) are suited for "toy" networks with simplified dynamics that are far from real-sized networks or (ii) apply decentralized control, which is not appropriate for heterogeneously loaded networks with short links and spillbacks or (iii) investigate good-quality solutions through detailed micro-simulation models and scenario analysis, which due to computational complexity make the problem intractable in real time. In principle, traffic management decisions for different sub-systems of a transport network (urban, freeway) are controlled by operational rules that are network specific and independent from one traffic authority to another. In some cases, the operational decisions of two sub-systems turn out to be competitive. For example, a ramp metering strategy to retain high flows of the freeway sub-system can create long queues in the access ramps that propagate and block the center of the city. In this paper, several control structures with different levels of coordination between the freeway and the urban network control entities are introduced and elaborated for traffic control of the mixed urban-freeway network. Our objective is to investigate how restrictions in coordination among different controllers (e.g. lack of communication or data) can affect the mobility levels of a city. Nevertheless, optimizing in real time all controllers of a city (traffic lights, variable message signs, on-ramps, etc.) in a coordinated way is an infeasible solution due to the computational burden of a very complex model, needed to represent traffic dynamics. Our objective is to integrate realistic aggregated models of urban and freeway traffic with efficient control approaches that will allow for coordinated traffic management.

Recently, a large effort for the development of Integrated Corridor Management (ICM) has been promoted by Federal Highway Administration, with many case studies around US metropolitan areas. Most of the implementations and case studies mainly perform scenario analysis and considers alternative routes under extreme events, e.g. accidents, while it is expected that a more formal optimization approach could lead to a better system performance.

In freeways, ramp metering is the most commonly used controller to manipulate the flow entering the freeway from its urban surrounding roads. Local and coordinated control strategies were proposed and implemented for ramp metering. In local control strategies, the control law for an on-ramp is determined according to the traffic conditions downstream and upstream of the on-ramp (e.g. ALINEA controller in Papageorgiou et al. (1991)). In coordinated strategies, the control law for multiple on-ramps are determined based on the traffic conditions in multiple areas including several on-ramps and sections in the freeway. The coordinated ramp metering is in fact a multi-regulator controller as all ramp meterings attempt to regulate the freeway traffic conditions near the desired densities. Overviews of local and coordinated ramp metering controllers are presented in Papageorgiou and Kotsialos (2002), Papageorgiou et al. (2003), and Geroliminis et al. (2011). The ramp metering approach (even in the coordinated case) might not efficiently operate in case of downstream bottleneck restrictions, e.g. a high demand off-ramp queue spillbacks in the freeway which blocks mainline lanes. Also, in case a freeway ends inside a congested city center, ramp metering might not be able to increase the outflow. In these cases, the freeway and urban network should be controlled in an integrated manner.

For urban networks, the Macroscopic Fundamental Diagram (MFD) aims to simplify the urban traffic micro-modeling, where the collective traffic flow behaviors of subnetworks capture the main characteristics of traffic dynamics, such as the evolution of space-mean flows and densities in different regions of the network. The MFD provides a unimodal, low-scatter relationship between network vehicle density (veh/km) and network space-mean flow or outflow (veh/h) for different network regions, if congestion is roughly homogeneous in the region. Alternatively, the MFD links *accumulation*, defined as the number of vehicles in the region, and *trip completion flow*, defined as the output flow of the region. Urban region flow or trip completion flow increases with accumulation up to a critical point, while additional vehicles in the network cause strong reductions in the flow. The physical model of MFD was initially proposed by Godfrey (1969) and observed with dynamic features in congested urban network in Yokohama by Geroliminis and Daganzo (2008), and investigated using empirical or simulated data by Buisson and Ladier (2009), Ji et al. (2010), Mazloumian et al. (2010), Daganzo et al. (2011), Gayah and Daganzo (2011), Zhang et al. (2013) and others. Earlier works had looked for MFD patterns in data from lightly congested real-world networks or in data from simulations with artificial routing rules and static demands (e.g. Mahmassani et al. (1987); Olszewski et al. (1995) and others), but did not demonstrate that an invariant MFD with dynamic features can arise. Control strategies utilizing the concept of the MFD have been introduced for single-region cities in Daganzo (2007) and later a linear control approach applied for a micro-simulation environment by Keyvan-Ekbatani et al. (2012). These strategies provide some useful insights towards system coordination, but might not operate in an efficient manner and might be far from optimal if congestion is heterogeneously distributed or if many trips have destinations outside the area of analysis, which is the case in many congested cities. Moreover, route guidance strategies with the utilization of MFD have been studied in Knoop et al. (2012) for grid networks.

In case of link density heterogeneity in an urban network, a possible solution to have a well-defined MFD is to partition the heterogenous network into a number of homogeneous smaller regions with small variance of link densities, see Ji and Geroliminis (2012). Recently, Geroliminis et al. (2013) introduced an elegant perimeter control approach to improve traffic conditions in an urban network which has been partitioned into two regions with well-defined MFDs (for stability analysis of the perimeter control see Haddad and Geroliminis (2012)). These results encourage us to utilize the MFD and the perimeter control approach for the mixed urban and freeway network.

All of the above approaches provide a first proof of concept that coordinated real-time control strategies with parsimonious models can create a new generation of smarter cities and improve their mobility. But, still congestion governance in