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A rolling-horizon quadratic-programming approach to the signal control problem in large-scale congested urban road networks

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ABSTRACT

The paper investigates the efficiency of a recently developed signal control methodology, which offers a computationally feasible technique for real-time network-wide signal control in large-scale urban traffic networks and is applicable also under congested traffic conditions. In this methodology, the traffic flow process is modeled by use of the store-and-forward modeling paradigm, and the problem of network-wide signal control (including all constraints) is formulated as a quadratic-programming problem that aims at minimizing and balancing the link queues so as to minimize the risk of queue spillback. For the application of the proposed methodology in real time, the corresponding optimization algorithm is embedded in a rolling-horizon (model-predictive) control scheme. The control strategy's efficiency and real-time feasibility is demonstrated and compared with the Linear-Quadratic approach taken by the signal control strategy TUC (Traffic-responsive Urban Control) as well as with optimized fixed-control settings via their simulation-based application to the road network of the city centre of Chania, Greece, under a number of different demand scenarios. The comparative evaluation is based on various criteria and tools including the recently proposed fundamental diagram for urban network traffic.

1. Introduction

Urban road network congestion has been a problem of most municipalities around the world for several decades. Several measures have been proposed and partly implemented to reduce the traffic demand in urban areas, such as road pricing, access restrictions of various kinds, dedicated lanes and signal priority of public transport vehicles, bicycle lanes, etc. On the supply side, there is usually hardly any possibility (or political support) for road infrastructure extension; this calls for operational signal control strategies that exploit the available infrastructure in the best possible way, particularly under peak period congestion.

It is generally believed that real-time signal control systems responding automatically to the prevailing traffic conditions, are potentially more efficient than clock-based fixed-time control settings. On the other hand, the development of optimal network-wide real-time signal control strategies using elaborated network models is deemed infeasible due to the combinatorial nature of the related optimization problem (see e.g. Papageorgiou et al., 2003); as a consequence, any real-time feasible signal control strategy design must include some simplification, either in its modeling approach, or in its optimization algorithm, or in its extent of network coverage.

SCOOT (Hunt et al., 1982; Bretherton et al., 2004) and SCATS (Lowrie, 1982) are two well-known and widely used traffic-responsive strategies that function effectively when the traffic conditions in the network are undersaturated, but their

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performance was reported to deteriorate under congested conditions. Other field-operational elaborated model-based traffic-responsive strategies such as PRODYN (Farges et al., 1983) and RHODES (Mirchandani and Head, 1998; Mirchandani and Wang, 2005) employ dynamic programming while OPAC (Gartner, 1983) employs exhaustive enumeration; due to the exponential complexity of these solution algorithms, the basic optimization kernel is not real-time feasible for more than one (or few) junctions and hence, interconnections between junctions must be addressed separately. More recently, a number of further research approaches have been proposed employing various computationally expensive numerical solution algorithms, including genetic algorithms (Abu-Lebdeh and Benekohal, 1997; Lo et al., 2001), multi-extended linear complementary programming (De Schutter and De Moor, 1998), and mixed-integer linear programming (Lo, 1999; Beard and Ziliaskopoulos, 2006); in view of the high computational requirements, the network-wide implementation of these optimization-based approaches might face some difficulties in terms of real-time feasibility.

A different design avenue for network-wide signal control is based on the store-and-forward modeling paradigm. Store-and-forward modeling of traffic networks was first suggested by Gazis and Potts (1963) and has since been used in various works, notably for road traffic control. This modeling philosophy describes the network traffic flow process so as to circumvent the inclusion of discrete variables and hence it allows for efficient optimization and control methods with polynomial complexity to be used for signal control of large-scale congested urban networks. On the other hand, the introduced modeling simplification allows only for split optimization, while cycle time and offsets must be delivered by other control algorithms, see Diakaki et al. (2003). A recently developed strategy of this type is the signal control strategy TUC (Diakaki et al., 2002) that has been successfully field-implemented in large networks of five cities in four different countries, see Kosmatopoulos et al. (2006) for recent field results.

TUC is based on a very convenient and simple Linear-Quadratic (LQ) multivariable regulator design approach with a posteriori consideration of the cycle-time and minimum-green constraints which is likely to reduce the achievable control performance. An extended approach that incorporates the constraints in the optimal control problem formulation was shown to lead to an open-loop quadratic programming problem (Aboudolas et al., 2009) with potential benefits over the simpler LQ control. For online application, the quadratic programming problem must be cast in a rolling-horizon framework, similarly to other aforementioned strategies (PRODYN, OPAC, RHODES). The purpose of this paper is to investigate the efficiency of the rolling-horizon quadratic programming control (QPC) and to compare it with TUC and with optimized fixed-time control via simulation-based application to the road network of the city centre of Chania, Greece, under a number of different scenarios. The comparative evaluation is based on a number of criteria including the recently developed notion of a fundamental diagram for urban road networks.

2. Fundamental diagram of two-dimensional networks

The notion of a fundamental diagram (e.g. in the form of a flow-density curve) for freeways was recently found to apply (under certain conditions) to two-dimensional urban road networks as well; see Gartner and Wagner (2004) for simulation-based experiments; Geroliminis and Daganzo (2008) for real-data based investigations; Daganzo and Geroliminis (2008) and Farhi (2008) for analytical treatments. In fact a fundamental-diagram-like shape of measurement points was first presented by Godfrey (1969), but also observed in a field evaluation study by Dinopoulou et al. (2005), see Fig. 6 and the related comments therein.

Fig. 1 displays the typical shape of a fundamental diagram (FD) for urban road networks, where the y-axis reflects the total network flow (i.e. the sum of flows exiting the network links) or the total flow of vehicles reaching their respective des-

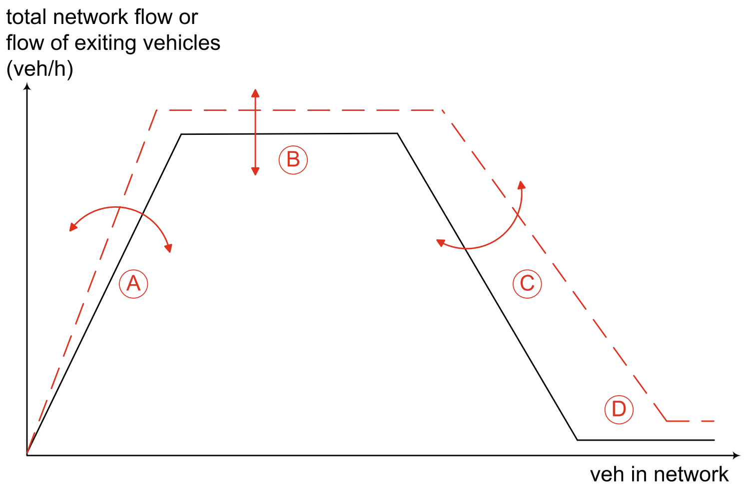

Fig. 1. Fundamental diagram for urban road networks.