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Controller Design for Gating Traffic Control in Presence of Time-Delay in Urban Road Networks

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Abstract

Recent studies demonstrated the efficiency of feedback-based gating control in mitigating congestion in urban networks by exploiting the notion of macroscopic or network fundamental diagram (MFD or NFD). The employed feedback regulator of proportional-integral(PI)-type targets an operating NFD point of maximum throughput to enhance the mobility in the urban road network during the peak period, under saturated traffic conditions. In previous studies, gating was applied directly at the border of the protected network (PN), i.e. the network part to be protected from over-saturation. In this work, the recently developed feedback-based gating concept is applied at junctions located further upstream of the PN. This induces a time-delay, which corresponds to the travel time needed for gated vehicles to approach the PN. The resulting extended feedback control problem can be also tackled by use of a PI-type regulator, albeit with different gain values compared to the case without time-delay. Detailed procedures regarding the appropriate design of related feedback regulators are provided. In addition, the developed concepts are also exploited to test and compare (for the first time in the related technical literature) the impact of increased sample times on the gating performance. A large part of the Chania, Greece, urban network, modelled in a microscopic simulation environment under realistic traffic conditions, is used as test-bed in this study. The reported results demonstrate a stable and efficient behaviour and improved mobility of the overall network in terms of mean speed and travel time.

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Keywords: Over-saturated urban networks; network fundamental diagram (NFD); time-delayed feedback gating control

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1. Introduction

The notoriously increasing economic and social activity and increasing number of vehicles in metropolitan areas result, on a daily basis, in over-saturated and highly congested traffic conditions at some network parts during the peak periods. The network service quality is deteriorated drastically, and the average travel times are raised accordingly. Provision of new infrastructure is not deemed to be a sustainable solution. Thus, the efficient utilization of the existing infrastructure is a crucial ingredient towards sustainable urban mobility. Traffic management is an efficient tool for enhanced capacity and improved mobility network-wide. Up to now, numerous valuable studies have been carried out in the field of urban traffic control (UTC). However, despite a number of achievements, the negative effects of congested traffic networks, such as excessive delays, environmental impact and reduced safety, persist or even increase; hence, introducing improved traffic signal control methods and techniques continues to be a vital issue.

Many different real-time UTC strategies have been proposed up to now, but due to the reduced efficiency of the strategies (e.g. SCOOT (Hunt et al., 1982) and SCATS (Lowrie, 1982)) in saturated traffic conditions, there is still space for further developments. Some other recently proposed UTC concepts employ computationally expensive algorithms, which might render the network-wide implementation of these optimization-based approaches difficult in terms of real-time feasibility; see e.g. Lo et al., 2001, for genetic algorithm application; and Putha et al., 2010, for colony optimization applications. TUC (Diakaki et al., 2002) is a noteworthy and practicable UTC strategy for saturated traffic conditions; see also (Aboudolas et al., 2010). Chang and Sun (2004) used a bang-bang like concept for control of an urban network with oversaturated intersections. However, these methods may allow the traffic to enter into the network part to be protected from over-saturation and act after the congestion starts occurring; hence, the methods should be specifically tested for highly congested urban road network parts.

Gating or metering is a practical tool, frequently employed against over-saturation of significant or sensitive links, arterials or urban network parts (Wood et al., 2002; Bretherton et al., 2003; Luk and Green, 2010). The idea is to hold traffic back (via prolonged red phases at traffic signals) upstream of the links to be protected from over-saturation, whereby the level or duration of gating may depend on real-time measurements from the protected links. Gal-Tzur et al. (1993) proposed a strategy which employs the concept of metering for small congested networks with one critical intersection. Gating is usually employed in an ad hoc way (based on engineering judgment) regarding the specific gating policy and quantitative details, which may lead to insufficient or unnecessarily strong gating actions.

Recently, the reproducible relationship between flow and density occurring at the network level under certain conditions (e.g. homogeneous spatial distribution of the congestion), known as network fundamental diagram (NFD), has gained increased popularity. The notion had been initially proposed by Godfrey (1969); see (Gartner and Wagner, 2004) for simulation-based experiments; (Geroliminis and Daganzo, 2008) for real data based investigations; (Daganzo and Geroliminis, 2008; Farhi, 2008; Helbing, 2009) for analytical treatments. Other interesting studies related to network level relations for simulated and real networks can be found in (Buisson and Ladier, 2009; Ji et al., 2010; Gayah and Daganzo, 2011; Knoop et al., 2013). Keyvan-Ekbatani et al. (2015) showed that production and variance of accumulation in the network are inversely correlated. This means a smart demand distribution may address the variability of link densities to keep the network production at a higher level. Gayah and Gao (2014) showed that in an extremely congested network adaptive traffic signals might have little to no effect on the network or NFD due to downstream congestion and queue spillbacks. Hence, under this traffic conditions, other strategies should be used to mitigate the instability, such as gating (or perimeter) control or adaptively re-routing drivers to avoid locally congested regions. Although the NFD notion is still under investigation in various aspects, it can be exploited as a fruitful basis for derivation of urban signal control approaches. In particular, NFD is useful to introduce elegant perimeter traffic signal control strategies, as details of individual links are not needed to describe the congestion level and its evolution.

Daganzo (2007) used the NFD concept to propose a control rule that maximizes the network outflow; however, the proposed rule cannot be directly employed for practical use in urban networks. Based on the NFD, Zhang et al. (2010) developed a bang-bang control strategy to optimize the accumulated vehicular number. Other works (Strating, 2010; Geroliminis et al., 2012) pursued a model-predictive control (MPC) approach. However, MPC calls for sufficiently accurate model and external disturbance predictions, which may be a serious impediment for practicable control. Lia et al. (2012) introduced a fixed-time signal timing perimeter control by exploiting the NFD, albeit