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A Discrete-Time Nonlinear Optimal Control Mechanism for Monitoring Dynamic Signalized Urban Traffic Networks

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Abstract: Monitoring traffic operations in a detailed manner and at network level, stands for a fundamental component in optimal traffic systems control. Especially the cases of monitoring urban signalized networks, the benefits of accurate and reliable systems monitoring are essential in applying a wide range of control strategies, mechanisms and concepts, among others information provision, signal control and optimal routing. In the current paper, a discrete-time optimal control scheme is developed and tested for monitoring urban signalized networks, augmenting real-time traffic information with a dynamic traffic model. In particular, a detailed representation of network traffic based on the cell transmission model is dynamically calibrated by a quasi-Newton non-linear process able to tackle optimization cases of non-continuous variables by approximating derivatives and performing a line search. An alternative network loading assumption is tested, where the loading process covering all network links' flows, is not relying on complex dynamic equilibrium assumptions that may infer unnecessary estimation inaccuracies, but on the combined estimation of entry flows and turning proportions at each intersection. Results from the application of the proposed framework on a realistic urban network provide encouraging evidence on its value for monitoring realistic urban traffic systems.

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1. INTRODUCTION

Monitoring traffic networks, especially in urban and signalized areas, are of vital importance in applying contemporary ITS strategies. Here, the term monitoring is mainly used for the detailed estimation of network flows, densities and speeds -in dynamics- at each link and intersection level. Though, the estimation of the network loading dynamics stands for a tedious task, due to the complexities involved in estimating an excessive number of important components that effect on the accuracy and robustness of a valuable monitoring system. In the current paper, the network loading process is based on straightforward and robust assumptions regarding the dynamics of traffic operations, trying to relaxing assumptions that may introduce additional complexities in the estimation process.

In detail, the monitoring of network loading and dynamics is based on estimating the inflows and the turning proportions in each intersection, such as to reproduce observed flows at specific locations scattered in the networks. The proposed framework does not involve additional assumptions, such as those concerning route choices and dynamic equilibrium that adds to the estimation complexity/burden, but tries to observe the outcomes of all the above processes.

The structure of the monitoring process is composed of three components; the observation, the modelling and the calibration components. The first component offers point/section-specific information on prevailing traffic condition, the second one offers the spatial and temporal representation of the system, which is based on the discrete-time well-documented cell transmission model-CTM and the third calibrate the network model such as to accurately reproduce observed traffic measurements and thus provide a reasonable estimation on the rest of the network. Then, a calibration mechanism is used for estimating the network loading by estimating an optimal mix/combination of entry network flows and turning proportions at each intersection, resulting in reproducing traffic conditions by minimizing an error metric between observed and simulated flows in predefined locations. The calibration process used here belong to the quasi-Newton nonlinear optimization family of methods, able to adequately treat non-continuous optimization cases by approximating derivatives and perform a line search. The applicability of the proposed framework is tested on a realistic signalized urban network, providing encouraging results on its performance.

The paper structure starts from a brief background review on monitoring mechanisms, commenting on the latest technological advances on the subject. Then, the proposed methodological framework is described, providing its most important parts. Detailed results are presented and discussed offering valuable information of the potential of the proposed mechanism, while the last section concludes.

2. BACKGROUND FRAMEWORK

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The online estimation of network operational characteristics, typically corresponding to a dynamic network traffic model calibration, has been identified as a crucial and vital component in modern urban network optimal control. Various studies demonstrated alternative methods and approaches, but also the potential and limitations of such systems, mainly attributed to the modelling assumptions used for collectively monitoring an extensive and complex phenomenon like flow dynamics at a network level. In the works of Wang, et al. (2006), Antoniou (2007) and Vigos, et al. (2008), the use of alternative optimal control methods based on variants of Kalman filtering have been used, with notable results despite the modelling relaxations used in the traffic representation assumptions. In Aboudolas, et al., (2006) a model-based quadratic programming approach has been presented, taking into consideration traffic dynamics, where systems dynamics have been considered as known. Manolis *et al.* (2015) provided a comprehensive tuning mechanism valuable for ITS purposes, while an optimal control mechanism for multi-lane motorways is presented in Roncoli et al. (2015). Finally, in Dimitriou *et al.* (2006) and in Tsekeris *et al.* (2007), a microscopic traffic model is calibrated by means of Genetic Programming, estimating turning proportions at signalized intersections. As it has been pointed out in all above studies, in order such systems to be useful they should be able to operate in real-time, in order to realistic and accurate the models should be detailed, while in order to be detailed the computational methods are time-consuming. These considerations corresponds to fundamental decisions (and trade-offs) related to the assumptions followed in developing such systems.

A cardinal distinction of the models used stands for the traffic model used and the loading process that will be followed and in particular while the traffic models to be macro-, meso- or micro-scopic and if the loading procedure will be based on network equilibrium assumptions or will follow another descriptive loading process. Here, the monitoring system proposed is based on a dynamic/discrete-time equilibrium-free mesoscopic network model, augmented with an online calibration mechanism. In particular, a network-wide cell transmission model is calibrated in discrete time, by estimating entry flows and turning proportions, providing simulated flows resembling those observed in real time by a surveillance system.

The estimation of turning flows, i.e. proportions of traffic from each entrance going to a given exit at signalized intersections plays a crucial and determinant role in a number of traffic simulation and control procedures of urban networks. The advent of Urban Traffic Control Systems (UTCS), through the on-line, traffic-responsive signal control systems operating on a cycle-by-cycle basis, such as the SCAT, SCOOT (Luk, 1984) and TUC (Diakaki, *et al.*, 2002), and the real-time traffic adaptive control systems, such as the OPAC (Gartner *et al.*, 2001), indicated the importance to automatically estimate intersection turning proportions and flows from traffic detector data.

All the above approaches indicated that the adoption of intelligent computational approaches is promising, while the use of dynamic traffic simulation approaches may offer a better treatment of the problem of network monitoring. In the following section a detailed description of the proposed monitoring mechanism is provided.

3. PROBLEM SETUP

The estimation of entry flows and turning proportions at signalized intersections based on partial traffic counts can be expressed through different types of optimization problems. The problem is the combined estimation of the entry flows (red arrows in Fig. 1) and turning proportions in internal intersections (black arrows in Fig.1).

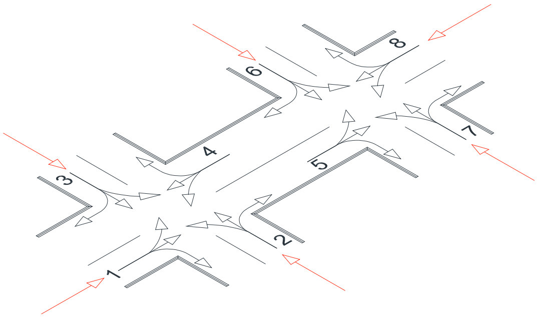

Fig. 1. Turning movements and entry flows on neighboring intersections of two-way streets

The methods used for addressing of such problems include non-recursive (constrained) Least Squares (Cremer and Keller, 1987), recursive Least Squares, Kalman filtering (Nihan and Davis, 1987), iterative maximum likelihood technique (Nihan and Davis, 1989), linear programming (Martin, 1997) and prediction error minimization (Lan and Davis, 1999). The performance of such optimization methods is typically affected by the appropriate selection of time intervals involved in the estimation process (Bell, 1991). The typical limitations are related to the nature of the different types of input data and the natural constraints on the permissible values of the turning proportions (Tian *et al.*, 2004).

In the proposed mechanism, the network topology, flow dynamics and loading process is based on the representation ability of the CTM. CTM has been successfully combined with optimization routines (e.g. Ziliaskopoulos, 2000, Ukkusuri, *et al.*, 2013, Zhang, *et al.*, 2013) due to its straightforward structure. Though, the piece-wise functional of the CTM, introduce a significant burden when using it in network optimization cases. Briefly and without getting into details due to space limitations, in the CTM flow dynamics are calculated by discretizing network links in consecutive cells i while at each time step t the vehicles in each cell are:

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t), \qquad (1)$$

where $n_i(t)$ stands for the vehicles number of cell i while $y_i(t)$ to the entering/exiting cell flows. Additionally, entering/exiting cell flows are estimated as:

$$y_i(t) = \min[n_{i-1}(t), Q_i(t), N_i(t) - n_i(t)], \qquad (2)$$

where, $n_{i-1}(t)$ is the number of vehicles in cell $i-1$ at time t, $Q_i(t)$ is the capacity flow into cell i, and $N_i(t) - n_i(t)$ is the amount of empty space in cell i at time t.

In order to calibrate a network represented by CTM, the flows estimated by the model at specific cells (network locations) can be compared with those collected by a