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Linear-quadratic model predictive control for urban traffic networks ☆

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ABSTRACT

Advancements in the efficiency, quality and manufacturability of sensing and communication systems are driving the field of intelligent transport systems (ITS) into the twenty first century. One key aspect of ITS is the need for efficient and robust integrated network management of urban traffic networks. This paper presents a general model predictive control framework for both centralized traffic signal and route guidance systems aiming to minimize network congestion. Our novel model explicitly captures both non-zero travel time and spill-back constraints while remaining linear and thus generally tractable with quadratic costs. The end result is a central control scheme that may be realized for large urban networks containing thousands of sensors and actuators.

We demonstrate the essence of our model and controller through a detailed mathematical description coupled with simulation results of specific scenarios. We show that using a central scheme such as ours may reduce the congestion inside the network by up to half while still achieving better throughput compared to that of other conventional control schemes.

1. Introduction

Increasing population and economic activities in modern societies have led to a significant rise in the demand for mobility and transportation. Consequently, urban road networks are becoming frequently congested which creates severe economical, social, and ecological challenges. Research into traffic management systems aims to make a better use of existing network infrastructure to improve traffic conditions. Nowadays, traffic control centers receive data from remote sensors and apply control policies that respond to the prevailing traffic conditions. While real-time signal control systems responding to traffic conditions can help in alleviating congestions, optimal network-wide control strategies remain a challenge due to the combinatorial nature of the related optimization problems (see e.g., Papageorgiou et al., 2003).

Historically, the SCOOT Hunt et al. (1982) and SCATS Lowrie (1982) systems were among the earliest efforts to develop adaptive traffic control systems in the 1970s. These well-known and widely-used traffic-responsive control systems are based on heuristic optimization algorithms. In the 1980s, new optimization methods for traffic control were introduced based on rolling horizon optimization using dynamic programming – the prominent examples include OPAC Gartner (1983), PRODYN Farges et al. (1983) and RHODES Mirchandani and Head (1998) or backtracking search on complex decision tree implemented in ALLONS-D Porche et al. (1996). The more recent works on traffic control systems have adopted results

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of modern control theory. In particular, the TUC system (Diakaki et al., 1999; Diakaki et al., 2002) applies a multivariable feedback regulator approach to calculate in real time the signal control plans (splits) as a linear-quadratic (LQ) optimal control problem. This approach is based on the store-and-forward model of traffic network which was first proposed by Gazis and Potts (1963). While its simplicity enables efficient algorithms for split optimization, cycle time and offsets must be delivered by other control algorithms (Diakaki et al., 2003). Abdul Aziz and Ukkusuri (2012) recently presents an optimal control framework which is based on the cell-transmission-model. The model assumes discrete time, discrete space and linear relationship between density and flow. Another linear programming approach is the work of Waller and Ziliaskopoulos (2006). Their model provides robust solutions while explicitly considering constraints, however, it only focuses on single destination networks.

Early works on traffic control systems based on the theory of Model Predictive Control (MPC) focused on the problems of ramp metering and variable speed limit control in freeway traffic management (Bellemans et al., 2002; Hegyi et al., 2003) where a free way link is geometrically divided into segments. Each segment is characterized by traffic density, mean speed and flow. Although the prediction model provides a comprehensive expression of fundamental traffic diagram on each link, its non-linearity feature is impractical in large urban networks. Aboudolas et al. (2009), Aboudolas et al. (2010)) and many others such as Tettamanti et al. (2008), Tettamanti et al. (2010), Tettamanti and Varga (2010) investigate an MPC-based approach to urban traffic control. In their approach, the store-and-forward traffic modeling is employed to represent the states of the links in an urban road traffic network. The objective of the control system is to reduce the risk of congestions by balancing the number of vehicles between links. However, their approach focuses on long term converged states of links rather than the rapid evolution of traffic phenomena inside link, e.g. the wave of congestion or vehicles speed; and the travel time in the roads between intersections is ignored. Another MPC-based approach introduced by Lin et al. (2011) considers vehicles speed by estimating the time of travel through links by a non-linear non-convex prediction model. In order to overcome computational complexity this model assumes constant delay and thus leads to the model inaccuracy in light traffic.

Our paper proposes an urban traffic control strategy to coordinate the green time split and turning fractions at intersections aiming to minimize the number of vehicles in the controlled area. The model is designed to predict the queuing dynamics through links while retaining the linearity of state evolution equations. Retaining linearity is important since the main idea behind the MPC approach is to repeatedly solve optimization problems on-line to find a near-optimal control strategy for a large network. To this end, we describe and emulate real traffic behavior in the proposed MPC framework using only linear dynamics and constraints. In our framework, the roads are modeled as series of queues where the nonuniform characteristics of links are captured by different queue parameters. Travel time on the link is effectively taken into consideration by modeling the vehicles' movements from queue to queue. The turning fractions of vehicles between queues are treated as control variables, assuming full compliance from drivers with our centralized controller. The route guidance without concerning about drivers' preferences is applicable in the emergency scenarios such as disaster evacuation or in traffic scenarios with heavy congestion where exiting the controlled area is drivers' first priority. In contrast to store-and-forward models, our model can essentially adapt to changes of link conditions due to increased traffic, accidents or other disturbances. In short, our approach improves on the above approaches in three aspects: we explicitly consider spill-back constraints and travel time in the road between intersections; our model unifies traffic light control and route guidance; the state prediction equation in our proposed MPC framework is linear so the model is capable of handling large network in real time control.

The main contribution of this paper is thus a novel framework for real time control of urban traffic networks. It allows for optimization of network wide conditions by jointly considering traffic control and route guidance. The numerical comparison of our model with other control schemes shows that in general our model is superior in reducing congestion.

The remainder of the paper is organized as follows. Section 2 describes our discrete time MPC framework. Section 3 discusses the simulation and results. We conclude in Section 4.

2. Discrete time MPC framework

MPC is a multi-variable control method that is usually used to optimally control complex systems while explicitly considering constraints. The system dynamics are represented by a discrete time predictive model where the next state is a function of the current state, current demands (disturbance) and the current control vector with constraints. In each time instance, the optimal control problem is solved online based on the measured (estimated) current state (at time $n = n_0$) and the predictive demands over a N step finite horizon (at time $n = n_0, \dots, n_0 + N - 1$). The result of the optimization is a sequence of control vectors over time $n = n_0, \dots, n_0 + N - 1$ but only the first control vector (at time $n = n_0$) is applied to the system. In the next state (at time $n = n_0 + 1$), the optimal control problem is solved again for time horizon $n = n_0 + 1, \dots, n_0 + N$ then only the control vector at time $n = n_0 + 1$ is applied and so forth. Section 2.1 below describes our predictive model while Section 2.2 presents our optimal control problem in detail.

2.1. A general controlled network model

Below is a technical definition of our network model to be used as part of the MPC controller. The main attribute of the model is that it evolves in time, synchronous with traffic light cycles (similarity to a cellular automaton model), yet the