Model Predictive Traffic Control by Bi-Level Optimization

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A bi-level model for traffic signal optimization is developed. The model predictive framework is applied for traffic control in an urban traffic network. The potential of the bi-level formalization is used to increase the space of control influences with simultaneous evaluation of the green light and cycle durations. Thus, the increased control space allows more traffic parameters to be considered, such as vehicles queues and traffic flows. A particular modification of the bi-level control is applied for the synchronization of the traffic lights in the network. The model predictive approach is used for the real-time management of the traffic in the network. The control implementations are constrained by the shortest evaluated cycle.

bi-level optimization traffic control signalized intersections traffic flows queue length

1. Introduction

The topic of traffic behavior improvement in urban areas remains to attract researchers' interests. The problem stays relevant due to the continuous increase of vehicle flows and the enormous breakdowns from traffic jams, increased fuel consumption, negatives from emission pollutions and their consequences to climate changes. In brief, traffic control targets the optimization of the transport flows, resulting in a decrease of vehicle congestions and waiting times, and maximization of the flows crossing the transport network, although this is subject to the construction limitations of the roads.

Different approaches have been investigated for traffic control for a long time [1][2][3]. The control influences, which can be used for the traffic control, are the duration of the green lights per phase, the cycle duration, and the offset between a set of neighbor intersections. Mainly the durations of the traffic lights are applied as control variables in the traffic optimization problems. This causes the control space to be narrow, which restricts the management of the transport system to respect various constraints and/or objectives. If the control space is extended with these three possible influences, the traffic behavior can be improved to respect more requirements for the traffic management. The simultaneous usage of these different control influences in a common optimization problem makes it non-analytically defined and complex for a solution. Due to this complexity, the optimization problems of traffic management apply as control variables only the green lights. Researchers' research targets the modeling of optimal control, which implements both the green lights and cycle durations on the crossroad junctions as control variables and problem solutions simultaneously. The extension of the control set allows more goals for traffic control to be considered for the minimization of queue lengths and maximization of traffic flows. The integration of the two control variables is performed with the usage of a hierarchical definition of a traffic optimization problem. Researchers apply a bi-level formalization, which allows two goal functions to be considered in hierarchical order and to achieve better traffic parameters in comparison with the classical optimization with one goal function. This research hypothesis was tested in a city network in Sofia. The results, presented below, illustrate the positive potential, which the bi-level optimization formalism demonstrates.

2. Traffic Control Approaches and Traffic Signals Control

The traffic control approaches, and traffic signals control have been classified into three types of strategies [2]:

- Control of isolated intersection,
- Traffic light control with fixed time settings,
- Traffic-responsive coordinated and adaptive signal control.

All these strategies implement the traffic lights durations as control influences. The cycles are not considered as tools for adaptive real-time control of the traffic behavior. For the evolution of the traffic signal control, one can refer to [4]. The simplest form of control is applied to isolated intersections under slow fluctuations of the traffic intensity [5]. Such control targets optimal settings in order to decrease the waiting time in front of the crossroad [6]. This isolated crossroad control with complication was applied as fixed time coordination control in a network of junctions. Traffic plans are evaluated off-line for each junction and the light durations are based on historical data about the traffic demands and statistical evaluations of the origin–destination matrices.

The traffic responsible control strategy is implemented in various control systems, which are continuously cited in the references: OPAC (Optimal Policies for Adaptive Control) [5]; SCOOT (Split Cycle Offset Optimization Technique) [7]; SCATS (Sydney Coordinated Adaptive Traffic System) [5]; RHODES (Real time Hierarchical Optimized Distributed Effective System) [8]; PRODYN (the abbreviation comes from the terms Dynamical Programming) [9]; UTOPIA (Urban Traffic Optimization by Integrated Automation) [10]; TUC (Traffic-responsive Urban Control) [11].

The formal relations, which are used for the definition of the optimization problems, are based on the principles and models, which are taken from fluid dynamics, vehicle-following models, and couple lattice models [12]. Attempts to use different models and methods for modeling the traffic behavior, such as the bio-inspired models and hybrid artificial neural network optimization model, are under consideration, respectively, in [13] and [14]. A challenge for the traffic optimization is the lack of analytical relations between parameters such as delays and off-sets [15], as well as the actual throughput as a function of the green time of movement, cycle length, and time, which is obtained with the simulation environment VISSIM [16]. The advances in technology allow to forecast arrival and discharge rates of traffic flows in real time [17].

Researchers' approach follows the analytic descriptions of the traffic behavior and the definition of the traffic optimization problem. An extended overview of the different forms of traffic optimization problems is given in [18]. The provided analysis classifies the content of the traffic control problems about their objectives and constraints. The main control variables and problem arguments are restricted up to the green lights' durations. Researchers' specific place for problem characteristics is the simultaneous application of two objectives for the minimization of cycle length and maximization of traffic flows, which are not presented in this overview. Additionally, researchers extend the control space with both cycle lengths and green durations as arguments in an integrated hierarchically defined optimization problem.

For the definition of researchers' hierarchical optimization problem in this research, researchers apply relations based on the models of fluid dynamics. These models are applicable mainly to freeway traffic control with ramp metering [19] and applications of the store-and-forward approach [20][21]. For relevant applications of ramp metering, one can refer to [22]. The store-and-forward model is intensively exploited and complicated for usage in centralized and or decentralized control schemes [23]. Due to its simplicity, store-and-forward modeling is applied in traffic control algorithms [24][25].

Store-and-forward modeling is applied for obtaining different control gains in traffic optimization. In [26], green wave optimization was the main target of the control. In [27], traffic signal coordination in two-way arterial directions is formalized and solved. The control approaches for traffic management become more complex. A representative for such complications is the model predictive control, which simultaneously applies adaptation of the traffic parameters to each control step [11][28]. Distributed control approaches are implemented in [24][25]. The intelligent transportation approaches started to apply machine learning methods such as reinforcement learning [29]. The stochastic character of the traffic demands is explicitly considered and formalized in the traffic control problem [30].

In general, for the traffic control, there are not many influences: the green lights (or the relative split towards the traffic lights cycle), the cycle duration, which contains all phases of the lights, and the offset as time differences between successive intersections [31]. In the cases of traffic signal control, mostly the green light duration is optimized [19][29][30]. The durations of the traffic cycles are mainly evaluated on statistical considerations, analyzing available historical data of the traffic intensities [32][33].

This research targets the development of such a control strategy, which simultaneously evaluates and implements both types of control influences: the green lights and cycle durations. The extended set of control influences gives the opportunity to optimize more parameters for the traffic behavior. Hence, traffic control is formalized as a bi-level optimization problem. This formalism has the potential to control more than one optimization goal and extend the set of traffic constraints.

For the case of consistent presentation of the bi-level problem definition, here, the roots of store-and-forward modeling are derived and presented. This is needed to prove the ability to incorporate the two control influences: the green lights and cycles in a common optimization problem.

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