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Optimization of vehicle and pedestrian signals at isolated intersections

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ABSTRACT

In most traffic signal optimization problems, pedestrian traffic at an intersection receives minor consideration compared to vehicular traffic, and usually in the form of simplistic and exogenous constraints (e.g., minimum green time). This could render the resulting signal timings sub-optimal especially in dense urban areas with significant pedestrian traffic, or when two-stage pedestrian crosswalks are present. This paper proposes a convex (quadratic) programming approach to optimize traffic signal timings for an isolated intersection with one- and two-stage crosswalks, assuming undersaturated vehicular traffic condition. Both vehicle and pedestrian traffic are integrated into a unified framework, where the total weighted delay of pedestrians and vehicles at different types of crosswalks (i.e. one- or two-stage) is adopted as the objective function, and temporal and spatial constraints (e.g. signal phasing plan and spatial capacity of the refuge island) are explicitly formulated. A case study demonstrates the impacts of incorporating pedestrian delay as well as geometric and spatial constraints (e.g., available space on the refuge island) in the signal optimization. A further analysis shows that a two-stage crosswalk may outperform a one-stage crosswalk in terms of both vehicle and pedestrian delays in some circumstances.

1. Introduction

With rapid urbanization and moterization especially in developing countries, daily commuters in dense urban areas suffer from heavy traffic congestion that leads to delays, environmental deterioration, and economic loss (Koonce et al., 2008). As reported in National Transportation Operations Coalition (NTOC) (2012), delays at traffic signals in road networks are estimated to be 295 million vehicle-hours. Improving traffic signal operation has a significant impact on the efficiency of transportation systems in dense urban areas, potentially more effective than any other operational measure in the traffic engineering toolkit (NTOC, 2012).

Abundant studies on signal optimization have been conducted at isolated intersections, along corridors, or at network levels. A comprehensive literature review of off-line traffic signal optimization methods is provided in Wong et al., (2005). Conventionally, signal optimization are stage-based (Allsop, 1981; Webster, 1958) or group-based (phase-based) (Heydecker, 1992; Silcock, 1997). Compatible traffic movements are grouped and move together in the same time window, called a stage, in the stage-based approach. Green time is then allocated to each stage. In contrast, there is no need to specify a

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stage structure in the group-based approach. Green time is directly allocated to each movement. Obviously, the group-based approach is more flexible and potentially more efficient. More recently, it has been reported that signals could be optimized together with lane markings to further improve traffic conditions (Wong and Heydecker, 2011; Wong and Wong, 2003a, b). These various approaches adopt similar optimization objectives; that is, the minimization of vehicle delay and maximization of intersection throughput with undersaturated and oversaturated vehicular traffic, respectively.

Based on the signal optimization for isolated intersections, signal coordination for multiple intersections along corridors is investigated. MAXBAND (Little et al., 1981) and MULTIBAND (Stamatiadis and Gartner, 1996) are proposed to signalize intersections along arterial roads. The stage-, group-, and lane-based methods were extended to the optimization of area traffic signals (Li and Gan, 1999; Wong and Wong, 2002; Wong and Yang, 1999). In addition, relatively new methods (e.g., fuzzy approaches and reinforcement learning algorithms) are applied to cope with complicated models and address computational burdens in signal optimization problems (Murat and Kikuchi, 2008; Ozan et al., 2015).

Moreover, additional concerns such as traffic flow uncertainty and vehicle-derived emissions are taken into consideration in signal optimization. The real-world traffic flows are time-varying and stochastic in nature (Cascetta et al., 2006; Szeto and Lo, 2005), even for the same time period across days of the same category (Yin, 2008). In general, robust signal optimization and on-line (adaptive) signal control are available to address flow uncertainty and influence traffic in an adaptive manner. Using robust optimization, signal parameters (e.g., cycle lengths and green splits) are predetermined, for example, by a scenario-based model using historical data in order to maintain satisfactory performance under flow fluctuations (Yin, 2008; Zhang et al., 2010). Robust optimization has also been applied to handle uncertainties in emission estimation arising from a macroscopic traffic modeling approach (Han et al., 2016). On the side of on-line optimization, real-time traffic measurements and prediction of future demands are utilized to dynamically adjust signal plans (Liu et al., 2015; Tong et al., 2015). With growing attention to the negative impacts of traffic on air quality and public health, sustainable traffic control measures have gained much attention. Minimization of vehicle emissions is regarded as one of the objectives in the signal optimization, mainly by means of analytical models (Khalighi and Christofa, 2015; Ma and Nakamura, 2010) and traffic microsimulations (Mascia et al., 2016; "Brian" Park et al., 2009; Zhang et al., 2013). In addition, signal prioritization for emergency vehicles and public transportation is also investigated (Head et al., 2006).

The numerous studies reviewed above focus on vehicles and their delays, with little or no attention given to crossing pedestrian traffic. In fact, most of these studies only implicitly consider pedestrians by imposing constraints such as minimum green time and pedestrian clearance time. Pedestrian delay is not included in the objectives of the signal optimization problems. This seems reasonable in situations where vehicular traffic dominates pedestrian traffic, and the former receives far greater priorities. However, this does not apply to dense metropolitan areas with significant pedestrian traffic. Indeed, very limited studies have provided insights into this issue. Li et al., (2010b) propose a traffic signal optimization strategy that considers both vehicular and pedestrian traffic. Vehicle and pedestrian delays are calculated by a deterministic queuing model. Wang and Tian (2010) develop a model in an analytical form to estimate pedestrian delay at a two-stage crosswalk. Ma et al., (2014) model pedestrian delay in the optimization of signal timing for an isolated intersection with exclusive pedestrian phases. In these studies, however, vehicle and pedestrian delay models are nonconvex, and global optima cannot be guaranteed. Moreover, only one-stage crosswalks have been investigated so far. Notably, two-stage crossings become increasingly popular and preferred by traffic engineers when a crosswalk at an intersection is long and a safe median refuge island is available. For example, in MOHURD (2011) a refuge island is requested when a crosswalk is longer than 16 m. However, the limited space on the refuge island is usually ignored. Insufficient space on the island may impose restrictive constraints to the signal optimization problems, while raising safety concerns. Although the extended cell transmission model in Zhang and Chang (2014) may provide a potential way to address these issues, their optimization problem is solved with heuristic methods, which does not guarantee global optimality and may be computationally expensive. Therefore, a rigorous and effective signal design framework for intersections with two-stage crosswalks is needed to minimize vehicle delay as well as provide a high level of service for pedestrians.

In order to address this gap, this paper presents a convex (quadratic) programming approach to optimize fixed signals for vehicles and pedestrians at an isolated intersection with one- and two-stage crosswalks with undersaturated vehicular traffic.[1] A unified signal timing optimization framework is developed, in which the delays of both vehicles and pedestrians are explicitly accounted for. The impacts of spatial and temporal constraints, including space limitation of the refuge island and the occupancy of the island, are explicitly captured and modeled through linear formulae. Next, a series of quadratic formulae are derived to approximate vehicle and pedestrian delays at the signalized intersection with one- and two-stage crosswalks. The feasibility of the proposed delay model is validated. The signal optimization problem is decomposed into a series of quadratic programming problems, which guarantees global optimality and maintains computational tractability, allowing computationally intensive tasks such as real-time signal control and signal coordination to be subsequently developed. The proposed model can be readily solved by many existing commercial solvers efficiently, which serves well the purpose of practical applications. The effectiveness of the proposed model is validated by numerical examples.

[1] The model is built assuming undersaturated vehicular traffic condition as vehicle delay is part of the objective to be minimized. In case of oversaturation, maximization of intersection capacity tends to be used as the objective. In this latter case, all of the proposed linear constraints remain effective, and the signal optimization problem can be formulated as a linear program when the reserve capacity is adopted (Wong and Heydecker, 2011; Wong and Wong, 2003a, b).