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A robust optimization approach for dynamic traffic signal control with emission considerations

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ABSTRACT

We consider an analytical signal control problem on a signalized network whose traffic flow dynamic is described by the Lighthill–Whitham–Richards (LWR) model (Lighthill and Whitham, 1955; Richards, 1956). This problem explicitly addresses traffic-derived emissions as constraints or objectives. We seek to tackle this problem using a mixed integer mathematical programming approach. Such class of problems, which we call LWR-Emission (LWR-E), has been analyzed before to certain extent. Since mixed integer programs are practically efficient to solve in many cases (Bertsimas et al., 2011b), the mere fact of having integer variables is not the most significant challenge to solving LWR-E problems; rather, it is the presence of the potentially nonlinear and nonconvex emission-related constraints/objectives that render the program computationally expensive.

To address this computational challenge, we proposed a novel reformulation of the LWR-E problem as a *mixed integer linear program* (MILP). This approach relies on the existence of a statistically valid macroscopic relationship between the aggregate emission rate and the vehicle occupancy on the same link. This relationship is approximated with certain functional forms and the associated uncertainties are handled explicitly using robust optimization (RO) techniques. The RO allows emissions-related constraints and/or objectives to be reformulated as linear forms under mild conditions. To further reduce the computational cost, we employ a link-based LWR model to describe traffic dynamics with the benefit of fewer (integer) variables and less potential traffic holding. The proposed MILP explicitly captures vehicle spillback, avoids traffic holding, and simultaneously minimizes travel delay and addresses emission-related concerns.

1. Introduction

Traffic signals tend to be the primary focus of urban traffic control and management strategies since they generally serve as the most frequent and restrictive bottlenecks on urban streets. Over time, the implementation of traffic signal control has evolved greatly: from simple fixed-time plans based on historical data and updated infrequently throughout the day to adaptive control systems that update continuously in response to real-time traffic information. The performance of a particular

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strategy depends on several factors: the optimization procedure employed to select signal timings, underlying model used to predict the evolution of traffic dynamics and the objective function considered in the optimization procedure.

Here, we distinguish between two types of optimization procedures: (1) heuristic approaches, such as those developed with feedback control, genetic algorithms and fuzzy logic (Koukol et al., 2015; Zhang et al., 2013) and (2) exact approaches, such as those arising from mathematical control theory and mathematical programming. Although useful for very large and complex optimization problems, heuristic approaches suffer from a failure to provide optimal solutions. Instead, these are more appropriate when exact approaches are computationally intractable. However, exact *mixed integer programs* (MIPs) have been used extensively in the signal control literature and are of particular interest due to their tractable for smaller networks. For example, Improta and Cantarella (1984) formulated and solved the traffic signal control problem for a single road junction as a mixed binary integer program. Lo (1999a,b) formulated the network-level signal control problem as a mixed integer linear program using the *cell transmission model* (CTM) (Daganzo, 1994, 1995). In these papers, time-varying traffic demand patterns were incorporated by adopting dynamic signal timing plans. Such methods were later extended in Lin and Wang (2004) to capture more realistic features of signalized junctions such as the total number of vehicle stops and signal preemption in the presence of emergency vehicles. Building upon this solid foundation that exists in the literature, this MIP approach will be adopted here.

In most works, the model of traffic dynamics is taken as fixed, which is reasonable for models that accurately describe the critical phenomena observed. In this paper, we consider the Lighthill–Whitham–Richards model (Lighthill and Whitham, 1955; Richards, 1956), also known as kinematic wave theory, to describe traffic dynamics on individual links and through signalized junctions. This well-known model is employed as it is one of the most used and trusted traffic flow models currently being used in network optimization procedures today (Aziz and Ukkusuri, 2012; Chitour and Piccoli, 2005; Han et al., 2014b; Lin and Wang, 2004; Liu et al., 2015; Lo, 1999c,b; Zhang et al., 2013). In particular, we employ a *link-based kinematic wave model* (LKWM) proposed in Han et al. (2012) to capture queue dynamics, shock waves and vehicle spillback, while integrating it with signalized junction models. In contrast to the cell-based math programming approaches reviewed above, the link-based approach requires fewer spatial variables and eliminates the problem of *traffic holding* that arises between two adjacent cells (Ziliaskopoulos, 2000) without using additional binary variables (Lo, 1999a). In this way, the resulting mathematical program is more computationally efficient than the more traditional cell-based approach.

As for objective functions, the majority of adaptive traffic signal control schemes update signal timings to minimize total vehicular delays. Representatives of such signal-control systems are OPAC (Gartner, 1983), RHODES (Mirchandani and Head, 2000), SCAT (Sims and Dobinson, 1980) and SCOOT (Hunt et al., 1982). Other control strategies seek to minimize delays to a subset of vehicles; e.g., the goal of transit signal priority strategies is to reduce delays for transit vehicles, often to the detriment of those remaining, see Skabardonis (2000). More recently, a transit signal priority strategy was proposed to minimize total person delay, which essentially considers a weighted average of vehicular delay using the passenger occupancies of each vehicle as the weights (Christofa et al., 2013).

Relatively less attention has been given to vehicular emissions in the optimization of traffic signal timings. The earliest study that includes emissions in signal timing optimization appears to be Robertson et al. (1980), but this work relies on macroscopic simulations that do not accurately account for vehicle dynamics at intersections. The efforts that followed either relied on combining detailed emissions models with outputs from microscopic simulations or models (Stevanovic et al., 2009; Li and Shimamoto, 2011; Lin et al., 2010; Lv et al., 2013) or macroscopic emissions models estimated from data (Aziz and Ukkusuri, 2012; Zhang et al., 2013). The former approach is more accurate, but relies on computationally intensive simulation-based optimization methods. The latter is useful but as pointed out by a survey paper (Szeto et al., 2012) and the literature therein, the environmental considerations typically result in highly nonlinear and nonconvex constraints and objective functions in the mathematical programming formulation, which also imposes tremendous computational burdens. As a result, heuristic methods, such as one found in Ferrari (1995) and Zhang et al. (2013), have been used to solve these types of problems. Classical methods such as the inner penalty technique (Yang and Bell, 1997) and augmented Lagrangian multiplier technique (Yang et al., 2010) have also been used, but well-defined exact approaches that account for these non-linear and (potentially) stochastic relationships currently do not exist.

This paper presents a novel approach to circumvent the aforementioned computational challenges by combining traditional objective functions (i.e., minimizing vehicular delays or maximizing vehicle throughput) with emissions considerations. The latter are incorporated using constraints in the optimization procedure (e.g., maximizing throughput subject to some emissions standard that must be met) and these are reformulated as linear functions through the use of numerical experimentation and robust optimization. This method is made possible by leveraging observed relationships between aggregated emissions rates and vehicles occupancies on a link that arise when certain detailed emission models are employed (e.g., see Shabihkhani and Gonzales (2013)). Such empirical observations are supported by extensive numerical simulations, as we shall demonstrate below. Detailed description of the simulation and synthetic data is presented in Section 3.

Unfortunately, despite the strong correlation between the aggregated emission rate and certain macroscopic traffic quantities (e.g. link occupancy), there are non-negligible errors associated with such approximation. Of course, errors and perturbations to a deterministic model can render an optimal solution in the ideal case suboptimal in implementation. A natural approach to capture uncertainty is by assuming that unknown parameters follow certain probability distributions and by employing the notions and methodologies in stochastic programming. However, such an approach has two main limitations: (1) exact knowledge of error distributions is often difficult to acquire and (2) stochastic programming is recognized as highly

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