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A linear bus rapid transit with transit signal priority formulation

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A B S T R A C T

In this paper, we propose a novel mathematical framework to formulate a unified Bus Rapid Transit (BRT) with Transit Signal Priority (TSP) system for single destination networks, namely, Bus Priority System Optimal Dynamic Traffic Assignment with Signal Control (BP SODTA-SC). This framework considers dedicated bus lanes, bus routes, and priority for public bus transport in mixed bus-car scenarios. Furthermore, this approach assures fairness to all road users. It is *linear* and can be applied to analyze city-size BRT-TSP systems. Our numerical results show that bus priority significantly reduces Total System-wide Passenger Travel Time (TSPT).

1. Introduction

Traffic congestion is a challenging problem around the globe due to the rapid growth in urbanization where a large number of people migrate to live in cities because of better opportunities and lifestyle prospects. Improving public transit is one of the most effective strategies to mitigate the congestion issue (Eichler and Daganzo, 2006; Wu and Hounsell, 1998), and at the same time, to reduce fuel consumption and vehicle discharged emissions (e.g., NO_X,CO) (Ernst, 2005; Satiennam et al., 2006). There are different public transit modes such as high-speed rail, subway, tram, and bus. On one hand, rail, subway, and tram transit modes require large financial investments, overly long construction times, and significant maintenance costs. On the other hand, bus Public Transport (PT), having lower capacity, is slow and unreliable in its current form (Dong et al., 2017). As a result, a smarter public transit system is essential to provide the speed and reliability offered by trains/subways as well as flexibility and economy of buses.

One such solution is Bus Rapid Transit (BRT) which integrates Intelligent Transport Systems (ITS) and Dedicated Bus-only Lanes with Priority (DBLP) to provide rail-like reliable, high-speed, and low-cost transportation service (Deng and Nelson, 2011; Robert, 2013). However, unlike rail or subways, BRT vehicles will compete with other classes of traffic at intersections if no priority or control scheme is implemented. As a result, the BRT operational efficiency can be substantially improved by implementing Transit Signal Priority (TSP) control schemes (Al-Deek et al., 2017; Zhou et al., 2017). A TSP control policy gives priority to the BRT vehicles (i.e., buses) at the signalized intersections to reduce their intersection delay. Furthermore, it increases the reliability of the BRT system and avoids substantial impact on other vehicles in terms of travel time (Ye and Xu, 2017). Due to these facts, BRT with TSP (BRT-TSP) has been deployed in many cities of Asia, Europe, North America, and Australia. A unified mathematical framework will significantly support transit planners and operators to design and assess a BRT-TSP system, transport policies, and management strategies.

Dynamic Traffic Assignment (DTA) framework is widely accepted not only for designing, planning, strategically managing, and determining policies of the BRT-TSP system, but also for evaluating crucial public transit investments (Cheung and Shalaby, 2017). Our proposed computationally tractable framework, namely Bus Priority System Optimal Dynamic Traffic Assignment with Signal

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Control (BP SODTA-SC), enables us to seek the globally optimal routes and traffic signal settings for the combined BRT-TSP system in multi-class traffic networks.

In this framework, the model of DBLP provides bus priority to eliminate the conflict between bus and car movements at the diverging and merging links. In the literature, it was implemented in either mixed-integer (Cheung and Shalaby, 2017; Liu et al., 2015) or non-linear programs (Li and Ju, 2009), which are computationally intractable and difficult to analyze large networks. In one hand, formulating a linear SODTA framework usually relaxes the nonlinear terms of traffic flow propagation rules, e.g., CTM (Daganzo, 1994, 1995), that causes the unwanted vehicle Holding-Back (HB) problem (Mesa-Arango and Ukkusuri, 2014; Ziliaskopoulos, 2000). In the HB solution, vehicles are held back in a link even though there is still available capacity downstream (Aziz and Ukkusuri, 2012b; Carey and Subrahmanian, 2000; Zhu and Ukkusuri, 2013). It is worth noting that the HB problem yields an unrealistic traffic propagation solution (e.g., occupancy and flow) as in real-life traffic conditions, vehicles do not slow-down within the link unless there is congestion. On the other hand, formulating a Non-Holding-Back (NHB) SODTA framework again requires mixed-integer (Doan and Ukkusuri, 2012) or nonlinear programming (Shen and Zhang, 2014; Smaili et al., 2011). As a result, formulating a *linear and NHB* BP SODTA framework is a challenging research problem. In the literature, all the SODTA approaches to formulate BRT framework are mixed-integer or non-linear models. Additionally, almost all the presented BRT formulations do not include either the bus priority on the links or the signal control models in their formulations.

To model TSP in the DTA frameworks, a signal control model that can distinguish between buses and other traffic is required. TSP can be implemented (through an objective function) by maintaining Dedicated Bus-only Lane (DBL) (Li and Ju, 2009) and using the mixed-integer bus indicator variables at the intersections (He et al., 2014). Keeping dedicated bus lanes at the intersections requires a control model that can eliminate intra-phase conflicts. In the Australian phasing convention, an intra-phase conflict would occur between bus and car lanes when the through and left movements are allowed together. This mixed-integer method would impose unnecessary delay to the other vehicle classes due to its on-off nature. Furthermore, it is computationally expensive. Nevertheless, all the presented TSP control formulations for DBLP in the literature were highly complex (i.e., mixed-integer or non-linear) and unsuitable for using in a DTA framework.

To address the above-mentioned shortcomings of the existing DTA models related to BRT and TSP, we propose a Cell Transmission Model (CTM) based BP SODTA-SC mathematical framework to design and analyze the combined BRT-TSP systems. This formulation includes bus routes. In addition, our model supports the give-way behavior between cars and buses at the diverging, merging, and intersection nodes as well as assures the fairness to all the bus and car passengers. We also introduce a control scheme namely *Transit Priority Enabling Signal Control (TPE-SC)* model which enables TSP through the objective function and eliminates intra-phase and inter-phase conflicts at the intersections. To the best of authors' knowledge, this is the only SODTA framework that combines BRT and TSP in a *linear* formulation and can be applied to analyze city-size BRT-TSP systems.

The remainder of the paper is organized as follows. Section 2 discusses the literature relevant to SODTA, BRT, and TSP. Section 3 presents the novel linear-continuous BP SODTA-SC formulation. Our numerical results and analysis of the optimal solutions are discussed in Section 4. Finally, Section 5 summarizes the key outcomes of this paper.

2. Literature survey

In the previous section, we have discussed the issues that are related to formulating BRT-TSP in a mathematical DTA framework as well as the incremental contributions of this paper. In this section, we review the literature relevant to SODTA with and without signal control, BRT, and TSP models.

2.1. Literature related to the SODTA problem

The idea of formulating the traffic assignment problem as a SODTA formulation was first introduced by Merchant and Nemhauser (1978a,b). Since its inception, many researchers have made contributions in this field. Ziliaskopoulos (2000) proposed a linear programming (LP) based approach for the SODTA problem. This formulation considers one class of traffic (i.e., cars) only. In the mentioned approach, the nonlinear equations representing the traffic dynamics in the CTM (Daganzo, 1994, 1995) are relaxed and linearized. Although it provides a correct optimal objective value, this relaxation introduces a new dilemma known as the vehicle HB problem. In the HB formulation, vehicles are held back in a link despite there being capacity available downstream (Carey and Subrahmanian, 2000; Zhu and Ukkusuri, 2013). In real-life, vehicles will always move forward as long as there is space available in the downstream link. Throughout this paper, we call this formulation Ziliaskopoulos (2000) Linear Programming Cell Transmission Model (ZLP-CTM). Similarly, Li et al. (1999) formulated a linear programming based SODTA framework to address single-class traffic assignment problem without resolving the HB phenomena. None of these contributions include traffic signal control in the formulation.

There have been several contributions reported in the literature that addresses the HB problem for single-class traffic scenarios. Nie (2011) proposes an algorithm to solve the issue of HB in a SODTA problem. This algorithm starts with an optimal objective value, then solves a series of subproblems to maximize out-going flows. This post-processing approach complicates the procedure of attaining NHB solution. Furthermore, this approach is unable to guarantee a definite NHB solution (Zhu and Ukkusuri, 2013). Lin and Wang (2004) proposes a CTM-based framework, in which, the objective function is penalized to attain NHB solutions. However, the determination process of these penalty terms is not discussed in the paper as well as no proof is given to show its capability of eliminating the HB problem. Long et al. (2016) includes emission perspective in a Link Transmission Model (LTM) based SODTA framework. In their approach, the authors introduce several mixed-integer constraints to resolve the HB problem. Few more