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Joint optimization of tram timetables and signal timing adjustments at intersections

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ABSTRACT

This paper explores at the planning level the benefits of coordinating tram movements and signal timings at controlled intersections. Although trams may have dedicated travel lanes, they mostly operate in a mixed traffic environment at intersections. To ensure tram progression, pre-set signal timings at intersections are adjusted by activating Transit Signal Priority (TSP) actions, which inevitably add delays to the auto traffic. A mixed integer program is proposed for jointly determining tram schedules for a single tram line and modifying signal timings at major controlled intersections. The objective is to minimize the weighted sum of the total tram travel time and TSP's negative impacts on other traffic. A real-world case study of Line 5 of the Shenyang Hunnan Modern Tramway shows that by extending the dwell time or link travel time we can significantly reduce the TSP's negative impacts on the auto traffic while only slightly increasing tram travel times.

1. Introduction

The tram mode has gained enormous popularity in some medium-sized cities in China in the past few years. While megacities, such as Beijing, Shanghai and Guangzhou, are implementing their unprecedented heavy rail transit plans to satisfy ever increasing public transit needs, smaller cities, such as Shenyang and Xuzhou, find tram appealing after benefit/cost analysis. Since heavy rail transit systems have exclusive rights-of-way (ROW), those services are undisrupted by the auto traffic and can serve heavy passenger flows at high levels of service. Compared to heavy rail transit, tram has a lower capacity and its capital cost is also considerably lower, because it usually requires no tunnels or elevated structures (which are much more expensive than at-grade travel lanes). When tram has dedicated travel lanes, it has advantages in capacity, travel speed and service reliability over bus transit. For medium-sized cities, the projected ridership hardly justifies the extensive capital investment in heavy rail transit. Therefore, at least 10 newly built tram systems are operating in China as of 2016, with more under construction. In these cities, a few heavy rail lines can still be planned to cover the urban core, while tram lines connect suburban areas to major hubs.

As in other rail services, a timetable, which details the arrival and departure times at each station for each train run, plays a vital role in managing and operating complex rail systems (Zhou and Zhong, 2007). The timetabling problem attracts considerable attention from both practitioners and researchers, such as Jovanović and Harker (1991), Higgins et al. (1996), Kroon and Peeters (2003), Goverde (2007), Liebchen (2008), and Sparing and Goverde (2017). Common considerations in these

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optimization models include restrictions on dwell times, link travel times, passenger transfers, and headways. While most studies adopt objectives such as profit maximization or delay minimization, some emerging studies are starting to pursue energy consumption minimization (Gupta et al., 2016).

In general, right-of-way is the defining characteristic of public transit modes. There are three ROW types:

(1) *Exclusive:* Transit vehicles operate on fully separated and physically protected ROW. Tunnels, elevated structures, or at-grade tracks are such examples. This ROW type offers very high capacity, speed, reliability and safety. All heavy rail transit systems, such as the Metrorail of the Washington Metropolitan Area Transit Authority, belong in this category.
(2) *Semi-Exclusive:* Transit ways are longitudinally separated from other traffic, such as motor vehicles, pedestrians, and bicycles. However, streets can cross dedicated transit ways at some intersections. Transit vehicles operating on this ROW type may be largely isolated from congestion. Light rail transit (LRT) systems, such as the Lynx Blue Line in Charlotte, North Carolina, and most newly built tram systems in China, usually have this ROW type.
(3) *Fully-Shared:* Transit vehicles share ROW with other traffic. This ROW type requires the least infrastructure investment, but operations are relatively unreliable due to roadway congestion.

In a physically isolated transit system (exclusive ROW), timetables can be determined without considering other traffic. Most trams (English term) and streetcars (U.S. term) operate on semi-exclusive or fully-shared ROW, implying that the potential conflicts between trams and other traffic should be resolved through signal timing adjustments at intersections. Usually, adjustments are made to grant priority to transit over other traffic. For example, Fig. 1 illustrates three types of Transit Signal Priority (TSP) actions, with further explanations as follows:

(1) *Green extension.* When a tram is approaching, the signal is green but the remaining time is insufficient for the tram to proceed through the intersection. In this situation, a green extension action can be activated. Green extension is one of the most effective TSP actions and the least disruptive to non-transit traffic, because additional clearance intervals are not required.
(2) *Early green.* Early green, also called red truncation, is used to shorten the conflicting phase when a tram arrives near the end of a red phase.
(3) *Phase insertion.* Compared with green extension and early green actions, phase insertion is much more disruptive, because a green phase for the approaching tram is inserted into the active red phase. This tactic is used only when a tram arrives in the middle of the red phase.

There is a major stream of studies (e.g., Furth and Muller, 2000; Skabardonis, 2000; Currie and Shalaby, 2008; Islam et al., 2016) on selecting proper TSP control measures to favor transit operations. In the literature, the timetable problem and TSP-related studies are quite separated. However, as shown in Fig. 2, coordination in adjusting train schedules and modifying signal timings at intersections could be very beneficial.

According to the existing tram schedules, three trams run from station 1 to station 7 crossing three intersections. To ensure the progression of trams, a number of signal timing adjustments at a series of intersections are made, as shown in Fig. 2(a). Both the phase insertion and green extension actions are used twice. In Fig. 2(b), dwell times are slightly increased

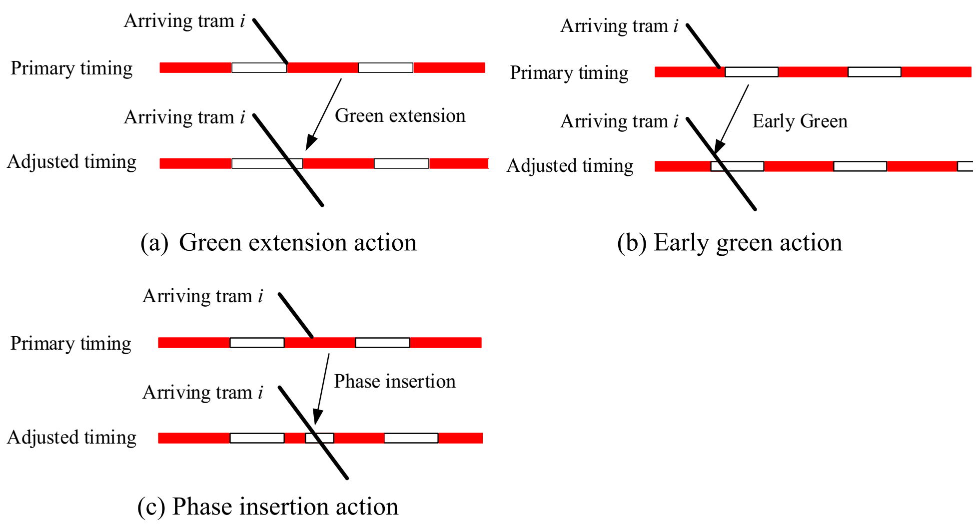

Fig. 1. Illustration of three common TSP actions.