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Bus priority at signalized intersections with single-lane approaches: A novel pre-signal strategy

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ABSTRACT

Signalized intersections often represent a major source of bus delays in urban environments. One strategy to mitigate this problem is to dedicate an existing car lane for bus-use only and use an additional signal to help minimize interactions between cars and buses. However, this is physically impossible at approaches where only a single travel lane is available for each direction. To this end, this research explores a novel method to provide priority to buses at signalized intersections with single-lane approaches that (nearly) eliminates bus delays while minimizing the negative impacts imparted to cars. Using additional signals to stop cars on the opposing travel lane, the bus can jump a portion of the car queue using the travel lane in the opposite direction.

This paper theoretically quantifies the delay savings buses can achieve, and the negative impacts imparted onto cars when this pre-signal strategy is applied. The negative impacts are measured as the additional car delays experienced when the intersection signal is under-saturated, and the reduction in car-discharge capacity when the intersection signal is over-saturated. In the under-saturated case, the results show that moderate average bus delay savings (∼5–7 s per vehicle, equivalent to about 25% of the average delay expected at the intersection) are achieved if the pre-signal is always in operation and the total passenger delay is decreased only if bus occupancies are very high. However, if the pre-signal operation is targeted to only provide priority to the buses that would benefit the most, bus delay savings can be more than doubled while reducing the total passenger delay, even if the ratio of bus to car occupancy is relatively modest (greater than about 20). In the over-saturated case, bus delay savings can be much more significant (greater than 30 s per bus), and this delay saving can increase further for longer block lengths (greater than 100 m). However, the capacity of the intersection decreases by up to 25% during each cycle in which a bus arrives to the intersection. Simulation tests confirmed that the general trends and magnitudes of bus delay savings and negative impacts to cars hold for more realistic behaviors. The overall benefits are slightly smaller in the simulations, but nevertheless the strategy seems promising as a bus priority strategy at intersections with single-lane approaches in the field.

1. Introduction

Public transportation is a viable way to combat urban traffic congestion as public transport vehicles (e.g., buses) are able to use urban roadspace more efficiently compared to private vehicles (e.g., cars). However, when buses and cars interact, the operation of both modes could be impaired. This is very evident at signalized intersections, which constitute one of the major

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sources of vehicular delays in urban environments. For example, buses dwelling at stops near a signalized intersection could significantly reduce discharge capacity and this could lead to increased car queues and delays (Gu et al., 2013, 2014). More worrying to public transportation operations is that buses can also get delayed by car queues, leading to more unreliable transit service. Mitigating the impacts of these harmful interactions on transit vehicles is essential to promote public transportation as a solution to urban traffic congestion.

One strategy to minimize negative bus–car interactions at signalized intersections has been to install an additional traffic signal upstream of the intersection to help manage conflicts between the two vehicle types. These additional signals, called pre-signals or bus gates, are used on approaches with dedicated bus lanes. The pre-signals are typically installed at the location where the bus lane ends to help buses transition out of the dedicated bus lane with minimal interruption. The pre-signal stops cars on the mixed-used lanes, which allows a bus approaching on the dedicated lane to bypass any car queues it might otherwise encounter and travel unencumbered by car traffic. The pre-signal intermittently changes the *allocation* of the lane downstream of the pre-signal from mixed-use to bus-use only and only impacts vehicles traveling in the same direction as the bus. Both analytical investigations and field implementations of pre-signals provide evidence that they can yield significant delay savings to buses while adding only modest travel delays to cars (Wu and Hounsell, 1998; Guler and Cassidy, 2012; Guler and Menendez, 2014a,b; He et al., 2015). This strategy has been implemented throughout the world, including in the U.K., Switzerland and Germany.

However, this type of pre-signal operation is only possible at locations with dedicated bus lanes. Unfortunately, bus lanes do not currently exist in many urban environments and expanding the roadway to add a dedicated bus lane is not feasible either due to cost or space restrictions. While an existing lane could be taken away from car traffic to implement a dedicated bus lane, doing so is not viable in situations where only a single travel lane is present. Such single-lane roadways and intersection approaches are very common in urban environments. The only current option available to provide priority for transit vehicles at intersections with single-lane approaches is to implement Transit Signal Priority (TSP) at the main intersection signal, which can provide signal timing benefits to approaches with an arriving bus (Rakha and Zhang, 2004; Stevanovic et al., 2008; Koehler and Kraus, 2010; Christofa and Skabardonis, 2011; He et al., 2014; Ma et al., 2014; AHmed and Hawas, 2015). While this can provide some benefits, TSP still forces buses to mix with cars, which can result in significant bus delays at the intersection.

To this end, this research explores a novel method to provide priority to buses at signalized intersections with single-lane approaches using pre-signals in a way that (nearly) eliminates bus delays while minimizing the negative impacts imparted to cars. The pre-signal that we propose operates differently than traditional pre-signals in several ways: (1) it does not require the existence of a dedicated bus lane; (2) it intermittently changes both the *direction* of vehicle movement and the *allocation* of a travel lane; and, (3) it impacts vehicles traveling in both directions. The idea is to clear cars out of the opposite direction travel lane ahead of an arriving bus, allowing the bus to use this lane to jump a portion of the car queue. To do this, pre-signals are required on travel lanes in both directions. The pre-signal on the opposite direction travel lane allows that lane to clear of cars so that a bus can safely use it as an intermittent bus lane. The pre-signal on same direction travel lane stops cars and allows the bus to merge back onto its original lane without conflict. The details of this dual pre-signal operation are explained in the following section.

The goals of this paper are twofold: (1) to define this new pre-signal operating strategy, and (2) to theoretically evaluate its potential impacts, including both the benefits to buses and the corresponding negative impacts to cars. Only through an exhaustive analysis can a complete understanding of the operation and the bounds of application of this strategy be determined. The benefits to buses are quantified by the delay savings when compared to a no priority strategy. The negative impacts to cars due to the pre-signals are measured differently based on the operating conditions expected at the main signal. If the intersection signal is expected to be under-saturated, the negative impacts are quantified by the additional delays imparted onto cars. In this case, there exists a clear metric that can be used to assess the overall impact of this strategy—change in overall delay of all users in the system. On the other hand, when the intersection signal is expected to be over-saturated, the negative impacts are quantified as the reduction in total throughput (i.e., capacity) at the main signal. Here, the overall impacts are harder to quantify due to the trade-offs between reductions in bus delays vs. reduction in throughput. These trade-offs are best quantified by the relevant transportation agency based on how they value car-moving capacity and transit delays. The theoretical results are then confirmed with tests performed through a micro-simulation.

The remainder of the paper is organized as follows. The details of the pre-signal operation are described in Section 2. Next, theoretical models to analyze the delays and the capacity changes associated with the pre-signals for under-saturated and over-saturated intersections are developed in Sections 3 and 4, respectively. The results of simulation tests and comparisons with theory are presented in Section 5. Finally, some concluding remarks and discussion are presented in Section 6.

2. Description of problem and strategy

We consider here an isolated intersection with single-lane approaches, as illustrated in Fig. 1a. The intersection is assumed to be signalized with a fixed cycle length, L_C [h], and red time, R [h], in both the subject direction (i.e., the direction of bus movement) and the opposite direction. We assume here that the subject and opposite direction share a green phase, however the results can be generalized to cases when different phasing schemes are used (e.g., leading or lagging greens in the opposite direction). Traffic on all approaches is assumed to obey Kinematic Wave Theory (Lighthill and Whitham, 1955;