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Analytical formulation and empirical evaluation of pre-signals for bus priority

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ABSTRACT

One of the major causes of bus delays in urban environments are signalized intersections. A commonly used solution to give priority to buses at signalized intersections is to dedicate a lane for bus-use only. However this strategy can waste valuable green time at signals and impose additional delays to cars, especially when bus flows are low. Overall, the total person hours of delays in the system (i.e., buses and cars) can increase due to excessive delays experienced by car users. To this end, an additional signal upstream of the main signal, called a pre-signal, can be used to better utilize the capacity of the main signal while still providing bus priority to reduce the system-wide person hours of delays.

The aim of this research is to analytically quantify and empirically evaluate the delays encountered by cars and buses with the use of pre-signals. The ultimate goal is to provide domains of applications for the proposed strategy. The paper presents analytical formulations to compute bus and car delays using queuing theory. The analytical models show that for a wide range of cases pre-signals can minimize the system-wide person hours of delays, as compared to dedicating a lane for bus-use only or operating buses and cars completely mixed. The analytical model is validated with empirical data collected at an existing pre-signal, which shows that the delay predictions of the model closely follow reality.

1. Introduction

In urban areas, to provide faster and more reliable bus service, priority to buses is often given by dedicating a lane for bus-use only. When bus flows are low, an underutilized bus lane running through a bottleneck can significantly reduce total discharge flows from the bottleneck. These reduced discharge flows can increase car delays and cause car queues to grow and spill back to other bottlenecks (or intersections in the case of an urban network). Therefore, the total person hours of delay in the system can increase when dedicated bus lanes are applied. However, it is possible to improve the system without harming buses by allowing cars to share the space between buses only at bottlenecks.

These types of dynamic bus lane allocations have been previously investigated. On signalized arterials the use of intermittent bus lanes (IBL) was proposed by Viegas and Lu (2001, 2004). In this strategy, cars are banned from using a section of a lane residing downstream of an advancing bus. This allows for the bus to travel without being impeded by cars. However, when buses are not present, cars using this lane can increase the discharge flow from the arterial. Cars are alerted of the lane change restriction with the aid of electronic signs and signals. In this strategy, cars do not vacate their present lane when the restriction is activated. Field experiments conducted in Lisbon, Portugal, showed that intermittent bus lanes can increase

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bus speeds by 15–25% as compared against buses and cars traveling mixed on the same lanes. A variation of intermittent bus lanes was also field tested in Melbourne, Australia, in 2001 (Currie and Lai, 2008). Even though travel time improvements to buses were observed in Melbourne as well, the authors found that these improvements were not as significant as in the case of Lisbon. On a variation of this idea named bus lanes with intermittent priority (BLIP), cars are required to vacate their present lane in advance of an approaching bus (Eichler and Daganzo, 2006). In this theoretical study, the authors found that the application of BLIPs reduces the interaction between buses and cars, and this can significantly reduce bus delays. More recent work has explored the domains of application of shared bus lanes (Guler and Cassidy, 2012). By using traffic flow theory tools, their work analytically determined the bus flows for which shared bus lanes would increase the capacity of the roadway as compared to fully dedicated bus lanes. This work also tested the use of shared bus lanes on a case study using means of simulation, and showed that dynamically shared lanes can decrease bus delays without inflicting large car delays as compared to the two modes operating completely mixed on roadways. Chiabaut et al. (2012) theoretically analyzed the capacity of BLIPs while also taking into account capacity drops that might arise due to the merging and acceleration of lane-changing vehicles at the first signalized intersection of an arterial where BLIPs are implemented. The authors concluded that this activation effect can be negated if the signalized arterial on which BLIPs are implemented is long enough (i.e., consists of 6 or more intersections). Beyond this length, travel time benefits to buses can be expected with the implementation of BLIPs. Other works have used cellular automaton models to compare different bus operating strategies (IBLs, dedicated bus lanes, mixed use lanes) in terms of flows and velocities of buses and cars (Zhu, 2010), and also to determine suitable traffic conditions for which IBLs could be implemented (Qiu et al., 2014).

The use of pre-signals (i.e., an additional signal upstream of the main signal) has been proposed by Wu and Hounsell (1998) to increase the discharge flow from isolated signalized intersections while still providing bus priority. When there are multiple lanes approaching the intersection, and one is dedicated for bus-use only, the idea is to discontinue this bus lane some distance upstream of the intersection. A pre-signal is used at this location to provide bus priority. The pre-signal allows cars to use all lanes to discharge from the main signal, except when a bus arrives to this location. At that time, the pre-signal turns red for cars. This allows for buses to maneuver into the intersection without encountering conflicts from cars, and provides bus priority by moving them to the front of the intersection.

Wu and Hounsell (1998) suggests and evaluates three different control strategies for pre-signals. However, this work makes two restrictive assumptions which affect the modeling: (i) a constant arrival of buses to the intersection, which is a very coarse approximation when looking at a single cycle where typically at most one bus will arrive; and (ii) a fixed operation at the pre-signal not responsive to the arrival of a bus, which can impose unnecessary delays on buses. While these assumptions make the analysis simpler, most operational complications which arise with the use of pre-signals cannot be modeled (for example disruptions in the car flow, car queues which may not clear in a given cycle, etc.). Therefore, both of these assumptions are relaxed in this paper. First, this paper explicitly models the car and bus delays which arise with the arrival of individual buses to the pre-signal. This improves the model suggested by Wu and Hounsell (1998) since the car delays which are expected to occur when a bus arrives to the pre-signal are more accurately determined, and the bus operations are modeled more realistically. Note that the modeling approach used in this paper is also slightly restrictive since it can at most consider one bus per signal cycle. However, even with this restriction, relatively high bus flows can still be modeled (e.g., the flow would be 60 buses/h for a cycle length of a minute). Second, this paper allows the bus to always have priority at the pre-signal, regardless of when it arrives (even if this priority leads to a loss of the main signal capacity). This improves the model of Wu and Hounsell (1998) since bus delays can be further reduced.

Notice that no empirical evaluation of pre-signals have been found in the literature. This might be due to the fact that, to the best of the authors' knowledge, real-world implementations of pre-signals are very limited. They are used at several locations in London in a manner similar to that described in Wu and Hounsell (1998) and Transport for London (2005). One implementation of a pre-signal in Switzerland is found in Zurich, where a dedicated lane for buses and one lane for cars on an intersection approach merge into a single mixed-use lane at a signalized intersection. A pre-signal is located at the location of the merge to give priority to buses when approaching the main signal. In this paper, we present empirical data collected at this location. This allows us to empirically evaluate the operation of pre-signals, and more importantly verify the improved analytical models.

While pre-signals can increase the total number of vehicles discharging from the intersection (i.e., maximize capacity with respect to dedicated bus lanes) it is unclear whether this strategy would also minimize the system-wide person hours of delays. In Section 2 the operation of a pre-signal and the analytical modeling of delays at a pre-signal are described. The empirical data collected to validate the analytical model and a summary of the results are presented in Section 3. Once a complete understanding of delays encountered at pre-signals is obtained, domains on bus occupancies for which pre-signals can minimize the total person hour delay are determined in Section 4. A summary of results and future research directions are discussed in Section 5.

2. Operation and evaluation of pre-signals

A typical layout for a pre-signal can be seen in Fig. 1. The pre-signal is located upstream of the main signal at a distance such that when buses are not present the green time at the main signal can be fully utilized (i.e., it is possible to have enough queued cars to saturate the green phase). While multiple operating strategies for the pre-signal can exist, for the remainder