Empirical Evaluation of Bus and Car Delays at Pre-signals

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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. This strategy allows the bus to skip the car queues and minimizes the delay experienced due to the signal. However, especially when bus flows are low, this strategy can waste valuable green time at signals and impose additional delays to cars. Overall, the total person hours of delay in the system (i.e., buses and cars) can increase due to excessive delays experienced by car users even when bus passengers enjoy reduced travel times.

To this end, the use of pre-signals, which is an additional signal upstream of the main signal, has been proposed to utilize the full capacity of the main signal while still providing bus priority. When there are multiple lanes (2 or more) 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 to stop cars 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.

While pre-signals have been proposed, to the authors' knowledge the realized benefits to buses, and dis-benefits to cars that arise from this strategy have not been quantified. Therefore, the goal of this research is to collect data to empirically quantify the delays encountered by cars and buses with the use of pre-signals. By doing so, a better understanding of the changes in car and bus operations due to interactions between these modes, and the effects of strategies to mitigate these effects can be obtained.

Keywords

pre-signals, bus priority, bus operations

1 Introduction

In urban environments, where buses and cars operate in mixed fashion, bus delays can be exacerbated at signalized intersections due to the interactions with cars. When it is not possible to fully dedicate a lane for bus-use only due to limited road space, this problem can be deemed unsolvable. However, bus delays at signalized intersections can still be reduced without taking a lane fully away from cars, especially when bus flows are low.

To this end, this research will investigate the use of additional signals to provide priority to buses at signalized intersections. The ideas involve using a pre-signal upstream of the main signal to allow buses to jump the car queues. That way, cars can still use all lanes at the main intersection to fully utilize the capacity of the signal when buses are not present.

In the case when there are multiple lanes (2 or more) approaching the intersection in the direction of interest, and one is dedicated for bus-use only, the idea is to discontinue this bus lane some distance upstream of the intersection and use a pre-signal to stop cars at this location to provide bus priority (see Figure 1). 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. In other words, the pre-signal in this case intermittently changes the allocation of one lane.

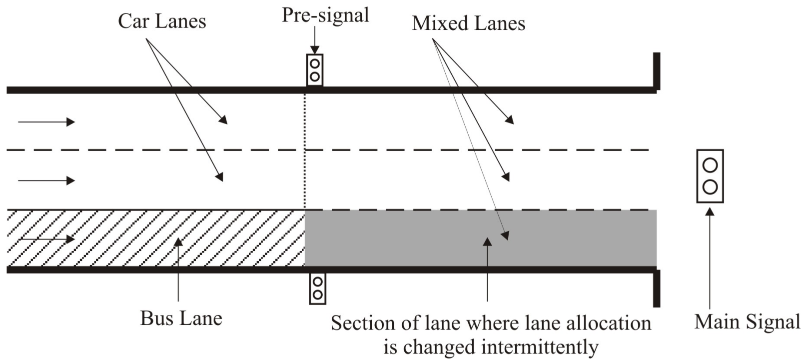

Figure 1: Layout of a pre-signal

This paper empirically analyzes the delays encountered at pre-signals used to dynamically provide bus priority at signalized intersections. In Section 2 existing literature on dynamically allowing buses to share a lane with cars will be discussed. Section 3 will describe the location of the pre-signal and the data collected at this site. The results of the data collection and the bus and car delays encountered at the pre-signal location will be discussed in Section 4. Section 5 will present some concluding remarks.

2 Literature Review

Traffic operation in urban environments is often limited by the amount of road space available. The use of public transportation, specifically buses, can help use this space more efficiently since buses carry more people using less road space. Lately, a few research works have looked at the proper allocation of space across different transportation modes (e.g. Gonzales, 2011, Daganzo *et al.,* 2012). Still, there is often not enough space to provide dedicated road infrastructure for each mode individually. Hence, to increase the attractiveness of buses and induce modal shifts, often times it is necessary to improve their operation through less permanent bus priority strategies.

Treatments that provide bus priority are typically less expensive than investing in other public transport infrastructure (e.g., building rail systems). The goal of these strategies is typically to allow buses to jump car queues in order to reduce bus delays and increase the reliability of bus systems. Murray and Wu (2003) showed that such improvements can significantly increase the perceived quality and attractiveness of bus service.

In urban areas, to provide faster and more reliable bus service, priority to buses is often given by dedicating an existing mixed-use lane for bus-use only. However when urban space is built out and there is not enough space to put an extra lane for buses, this is typically done by converting an existing mixed-use lane for bus-use only. When bus flows are low, this conversion can significantly reduce discharge flows from bottlenecks. These reduced discharge flows can increase delays to cars and cause car queues to grow and spill back to other intersections. However, by allowing cars to share the space between buses only at bottlenecks the system can be improved without harming buses.

To do so, dynamically allowing cars to share a bus lane have previously been investigated. On signalized arterials the use of intermittent bus lanes 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. However cars already presiding in the restricted portion of a lane may remain in their lane. 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 leave to vacate their present lane when the restriction is activated. Field experiments conducted in Lisbon, Portugal showed that intermittent bus lanes can increase bus speeds by 15 to 25 % as compared against buses and cars traveling mixed in traffic (Viegas *et al.,* 2007). 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. In a similar idea proposed by Eichler and Daganzo (2006) cars are required to leave their lane before an approaching bus. In this theoretical study the authors found that the application of BLIPs reduces the interaction between buses and cars which can significantly reduce delays to buses. More recent work has explored the domains of application of shared bus lanes (Guler and Cassidy, 2012). By using traffic flow theory tools this work theoretically 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 simulated case study, and showed that they 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 merging and acceleration of lane-changing vehicles at the first signalized intersection of an arterial where BLIPs are implemented. The authors conclude that this activation effect can be negated if the signalized arterial on which BLIPs are implemented is long enough (6 or more intersections). Beyond this length, travel time benefits to buses will be observed with the implementation of BLIPs.

To increase the discharge flow from isolated signalized intersections the use of pre-signals has been proposed by Wu and Hounsell (1998). This paper suggests and theoretically evaluates delays for three different control strategies for pre-signals. However, (i) a constant arrival of buses to the intersection is assumed, which is a very coarse approximation when looking at a single cycle where typically at most one bus will arrive; and (ii) the operation of the pre-signal is assumed constant regardless of the bus arrival time, which can impose unnecessary delays on buses.

Other uses of pre-signals also exist in the literature. Stein (1961) analyzed the use of pre-signals to reduce the time lost at signalized intersections due to the bounded acceleration of vehicles. That work shows that if there are only cars in a traffic stream, approximately 4 seconds of additional green time can be gained at intersections with the use of this type of pre-signals. More recent work has explored the use of pre-signals to increase intersection capacity by resolving these and other types of vehicular conflicts that would otherwise occur at the signalized intersection downstream (Xuan *et al.,* 2011).

Another proposed treatment, termed queue jumper lanes, allows buses to use right turn bays at signalized intersections to bypass car queues. Nowlin and Fitzpatrick (1997) used simulation to predict that, when combined with signal priority for buses, queue jumper lanes can be effective in increasing bus speeds by a range between 5 and 15 km/hr. Zhou and Gan (2005) also evaluated different signal priority options, bus stop locations, and car congestion levels using simulation, and found that queue jumper lanes alone were not as effective in increasing bus speeds as if signal priority was also provided.

To the best of the authors' knowledge, real-world implementations of pre-signals are limited. They are used at several locations in London in a manner similar to that described in Wu and Hounsell (1998) (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 the intersection approach merge into a single mixed use lane at the signalized intersection. A pre-signal is located at the location of the merge to give priority to buses when approaching the main signal.

3 Description of site and data collected

To better understand the operation of pre-signals and their effects on car and bus delays empirical data from an existing pre-signal in Zurich, Switzerland was collected with the aid of video cameras (Figure 2). This location is unique since along a portion of Langstrasse a single lane is used by buses traveling in both directions. When approaching Langstrasse near Militarstrasse, the bi-directional bus lane changes to become a single direction bus lane. Hence buses traveling on a dedicated bi-directional bus lane merge with cars traveling in the same direction on to a single mixed-use lane to pass through a signalized intersection. A pre-signal is located at the location of the merge to give priority to buses when approaching the main signal. Car departure times from the seven locations shown in Figure 2 (main signal, side street 1, pre-signal, side street 2, side street 3, side street 4, and upstream measurement location) was collected during the morning peak period (7:30 am to 8:30 am) on the 25th of September 2012 (Tuesday).

The pre-signal is operated at this site as follows. While the main signal is red, cars at the pre-signal also receive a red light and are queued upstream of the pre-signal. This ensures that an arriving bus can move to the stop line at the main signal and discharge immediately when the main signal turns green. Queued cars at the pre-signal receive a green signal such that the first car in queue arrives to the main signal just as it is turning green. Regardless of the main signal's phase, an arriving bus triggers the pre-signal to turn red for cars giving the bus priority to move to the main signal without encountering conflicting maneuvers from cars.

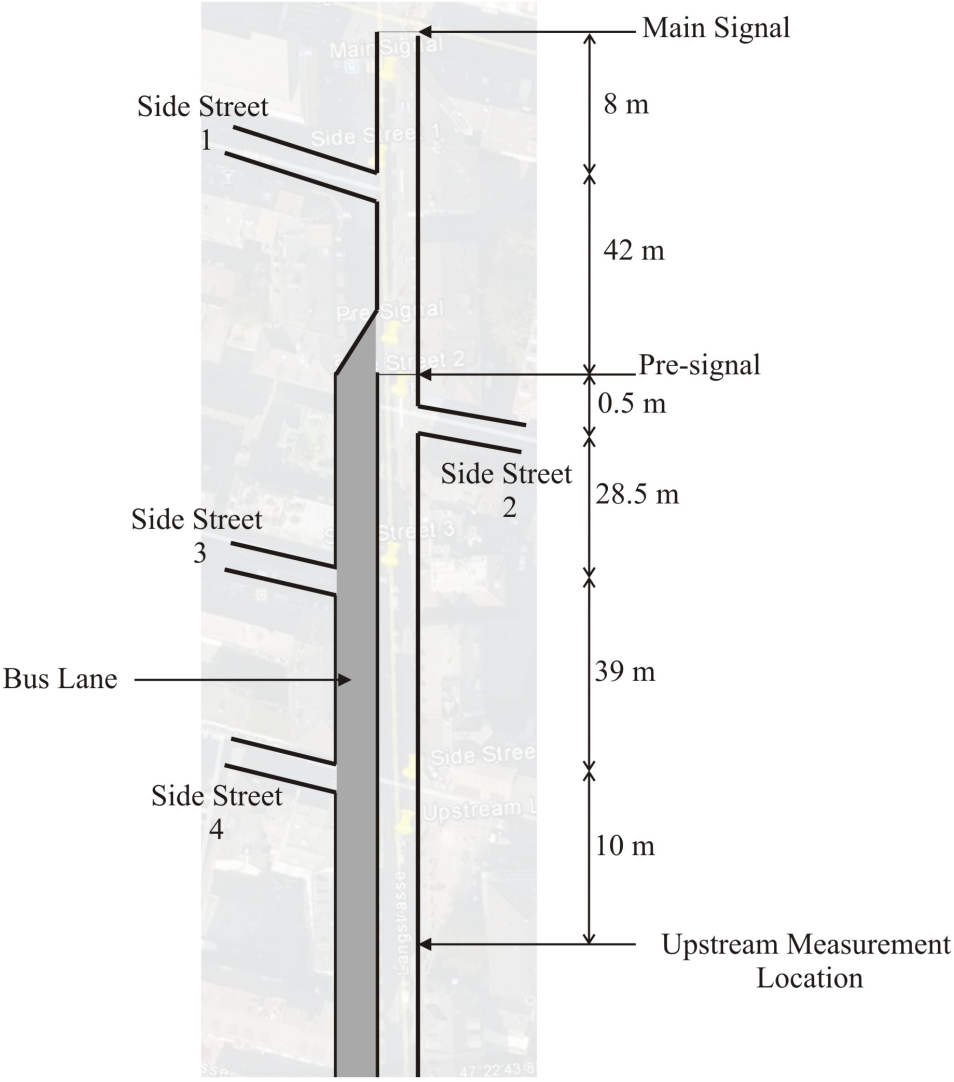

Figure 2: Location of the pre-signal and data collection points on Langstrasse, Zurich, Switzerland

4 Results

From the measured departure times, transformed cumulative curves of car arrivals to the upstream location, the pre-signal and the main signal were constructed. To do so, the counts at each location were shifted by the free flow travel time to the main signal, and a background flow of 300 veh/hour was subtracted for improved resolution (Cassidy and Windover, 1995). The resulting cumulative curves can be seen in Figure 3. Shifted counts from the side streets were also added to the upstream and pre-signal counts when necessary.

Using the cumulative curves, the delay encountered by cars upstream of the pre-signal and

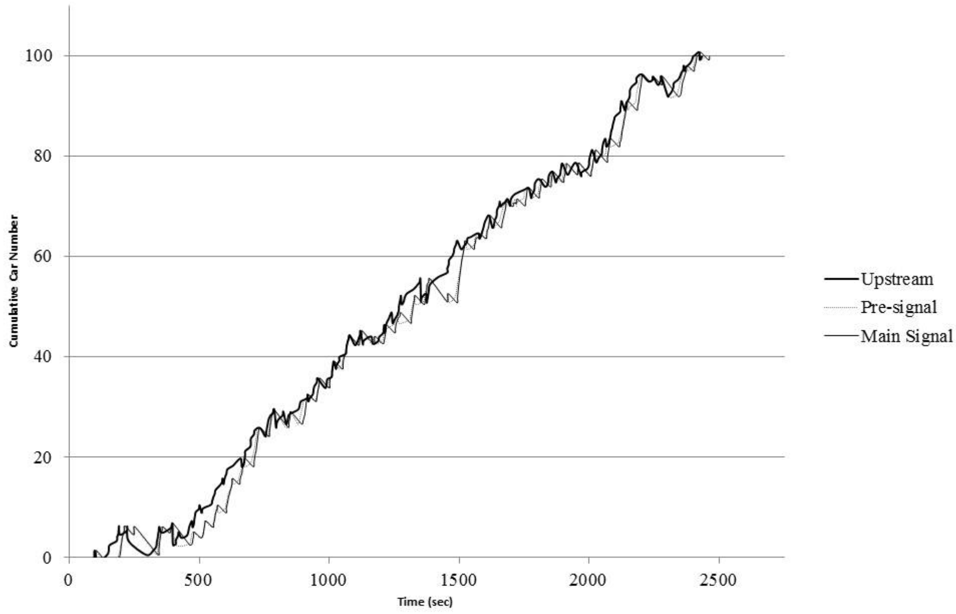

Figure 3: Transformed cumulative curve of empirical data at the upstream location, the pre-signal and the main signal.

between the pre-signal and main signal (and hence the total delay) was calculated for each cycle. For each observed cycle, the cycle length, red time, car delay upstream of the pre-signal, car delay between the pre-signal and main signal, and the total delay can be found in Table 1. This table also shows the discharge rate of cars (veh/hour) during each cycle and whether or not a bus was present at the pre-signal during that cycle. During the data collection period most cycles were under-saturated, however due to fluctuations in demand, on several occasions, a queue persisted for a couple of cycles. The cycle numbers marked with stars represent the cycles during which the queue at the main signal did not completely dissipate.

Table 1: For each observed cycle: Cycle and red times, car delays upstream of the pre-signal (PS), between the pre-signal (PS) and main signal (MS) and total, the discharge rate and presence of a bus.

Cycle #	Cycle time (sec)	Red Time (sec)	Car delay upstream of PS (sec)	Car delay between PS & MS (sec)	Total car delay (sec)	Discharge rate (veh/hour)	Bus present (Y/N)
1	47	23	0.5	5.0	5.6	300	N
2*	52	29	73.7	31.0	104.7	1252	N

3*	43	23	61.7	12.5	74.2	540	Y
4*	65	27	426.4	81.1	507.5	1137	N
5	49	29	104.5	5.5	110.0	540	N
6	49	29	68.3	1.5	69.8	180	N
7	47	23	104.4	34.1	138.5	1200	N
8	48	23	45.2	5.5	50.7	576	N
9*	71	51	227.6	84.5	312.2	1080	Y
10*	44	23	351.5	15.5	367.1	1029	N
11*	48	26	512.7	17.0	529.7	1145	N
12*	56	26	550.7	58.0	608.8	1200	N
13*	47	23	329.0	60.5	389.6	1200	N
14*	61	29	205.8	105.1	310.9	1238	N
15	51	29	54.1	12.5	66.7	1309	N
16	68	48	179.3	17.0	196.3	1080	Y
17	64	31	215.9	104.5	320.5	982	N
18	54	27	113.9	14.0	127.9	933	N
19	51	23	32.0	12.5	44.6	1029	N
20	55	24	55.0	23.0	78.1	1161	N
21	57	31	26.7	15.5	42.2	692	N
22	43	23	83.5	15.5	99.0	720	Y
23	46	25	48.0	63.5	111.5	1029	N
24*	56	22	139.7	123.0	262.7	741	N
25*	52	29	392.1	71.0	463.1	1252	N
26*	55	29	431.4	48.0	479.4	1108	N
27*	71	51	280.6	7.0	87.6	720	Y
28*	67	29	1058.7	72.6	1131.2	1516	N
29*	48	27	134.7	57.1	191.8	1029	N
30	51	26	102.9	20.0	122.9	1008	N
31	55	31	119.8	115.6	235.4	1350	Y
32	43	23	96.2	76.0	172.3	720	N
33	50	25	134.4	96.5	231.0	864	N
34	50	29	81.6	60.0	141.6	1200	Y
35	49	24	19.4	42.1	61.5	720	N
36	50	23	91.7	39.5	131.2	800	N
37	49	29	93.7	9.5	103.2	720	N
38	63	29	152.8	17.5	170.3	847	N
39*	49	28	72.3	124.6	196.8	1200	N

40*	67	28	385.8	90.5	476.3	1200	N
41*	58	29	192.5	141.6	334.1	1241	N
42	43	23	0.0	8.5	6.7	540	N
43	45	25	21.4	3.5	24.9	540	N
44	79	41	134.0	134.5	268.5	947	N
45	53	25	83.9	63.6	147.5	1029	Y

A summary of the car delays over all the cycles can be found in Table 2. These aggregated results are as expected. The first observation is that car delay encountered upstream of the pre-signal is significantly greater than car delay encountered between the pre-signal and the main signal. In fact, in an ideal situation, one would expect to observe no delays between the pre-signal and the main signal since the pre-signal and main signal timings are perfectly coordinated. However cars turning on to the main street from side street 1 (Figure 2) lead to additional delays at the main signal. Also note that, car delays observed upstream of the pre-signal are significantly higher during cycles which buses are present as compared to cycles during which buses are not present. This also follows intuition since with the presence of a bus, cars experience longer red times at the pre-signal to give priority to the bus. The presence of a bus during a cycle also increases the car delay observed between the pre-signal and the main signal. This increase is observed due to the large amount of space a bus occupies on the roadway. Since more space is used, less number of vehicles can discharge from the main signal. Evidence for reduced discharge flows can also be seen in the disaggregate data of Table 1. To isolate the capacity only cycles which are over-saturated were considered (since during under-saturated cycles the discharge rate would also depend on the arrival rate). In this case a statistically significant difference in the discharge flows when buses are present,780 veh/hour, compared against when buses are not present, 1166 veh/hour, can be observed (at a 95 % confidence level). However note that only three observations of bus being present in an over saturated cycle exists.

Table 2: Measured average total car delay per cycle (sec).

Total car delay per cycle (sec)	Number of Cycles	Upstream of Pre-signal	Between Pre-signal and Main Signal	Total
Bus not present	22	78	34	112
Bus present	5	110	54	164

The measured delay for buses can be found in Table 3. In this table, the delay for each bus and the percentage of green time wasted during the cycle for which the bus was present are depicted. Note that the duration of green time wasted indicates the duration during which cars would have normally discharged from the main signal but could not because of a red pre-signal. This value is important to understand how the presence of a bus can affect the operation of cars. Comparing this value to the discharge rate for each of these cycles from Table 1 it is interesting to observe that the cycles during which green time is wasted are not necessarily the ones with the lowest discharge rates. This shows that low discharge rates can be observed even if the pre-signal does not starve the main signal of flow. The bus delays observed are much smaller during cycles which green time is wasted, perhaps indicating that these buses arrived during the green time of the main signal and were able to pass the main signal without encountering any delays. Regardless, the observed bus delays (average delay per bus is 10.9 sec) are much smaller than the average car delay (the average delay per car during cycles which a bus is not present is 19.4 and during cycles which a bus is present is 28.3 sec), indicating that the priority provided at the pre-signal does in fact reduce bus delays. The difference between the delay per bus and delay per car for cycles during which a bus exists is also statistically significant at a 95% confidence level. However, it is also known that transit signal priority exists at the main signal which also helps reduce bus delays. Unfortunately during this evaluation it was not possible to separate the reduction in delay due to transit signal priority from that due to the use of the pre-signal.

Table 3: Bus delays (sec), and the green time at the main signal and wasted green time (sec) for the associated cycle.

Bus #	Delay (sec)	Percentage of wasted green time (%)
1	6	0
2	16	0
3	28	0
4	6	0
5	0	30
6	18	0
7	1	36
8	12	0

5 Conclusions

This paper empirically analyzed bus and car delays observed when a pre-signal is used to provide priority to buses at a signalized intersections. Data was collected in Zurich, Switzerland where a current implementation of a pre-signal exists. The results give insights on how the presence of a pre-signal can affect interactions between cars and buses, and the additional delays imposed on cars due to the presence of a bus. It was observed that average car delays at the intersection increase when a bus is present. It was also observed that the presence of a bus reduces the discharge flow from the main intersection. Bus delays were found to be significantly lower than average car delays implying that pre-signals can provide a good level of priority to buses at signalized intersections. While the effects of existing transit signal priority on reducing bus delays could not be isolated for this study, the authors expect that even without transit signal priority pre-signals would reduce bus delays. The intuition for this is that a pre-signal allows buses to move in front of car queues which otherwise could not be cleared with the use of transit signal priority.

The benefits of implementing pre-signals is not only limited to improving bus operations. If done properly, pre-signals could also reduce delays and increase reliability of buses to help promote the more sustainable bus mode. Induced demand for the bus mode and some mode shift from cars to buses could be expected then in the long term. Overall, as more users shift to the greener mode, the transportation system of the city could move toward becoming more environmentally sustainable.

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