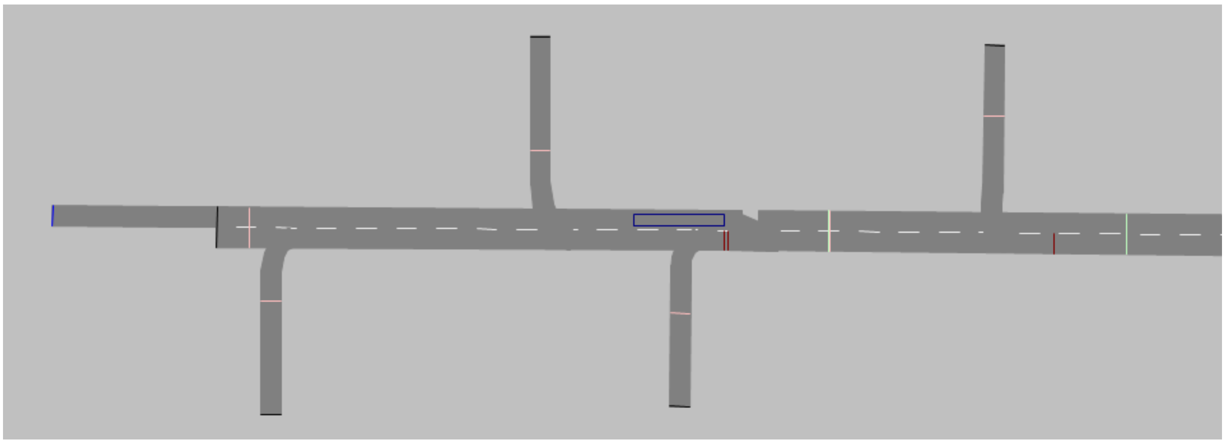

The effects of pre-signals at an isolated intersection: simulation results

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Abstract

A pre-signal is an additional signal upstream of the main signal which can be used to provide bus priority. Its primary purpose is to allow buses to jump the car queues at the intersection while cars can still use all lanes at the main signal to fully utilize the capacity of the intersection. In this way, bus delay at the intersection is reduced without causing extra stress to the overall traffic.

The effects of the pre-signals at an isolated intersection have been analytically studied and compared to empirical measurement. However, on the arterial and network level, it is very difficult to study the effects analytically and from our best knowledge there does not exist real work examples. Therefore a simulation model is needed.

The goal of this research is to validate the simulation approach by showing that at the isolated intersection level a VISSIM simulation model calibrated with the collected empirical data produces similar results. Therefore, it can be used to understand the mechanism behind the operation of pre-signals and can provide direct visual insights into its effects on traffic flow.

With the developed micro-simulation, the effects of the red time duration at the presence of buses could be examined. Recommendations could then be given regarding how long this red signal should be when implementing pre-signals.

Keywords

pre-signals – bus priority – bus operation

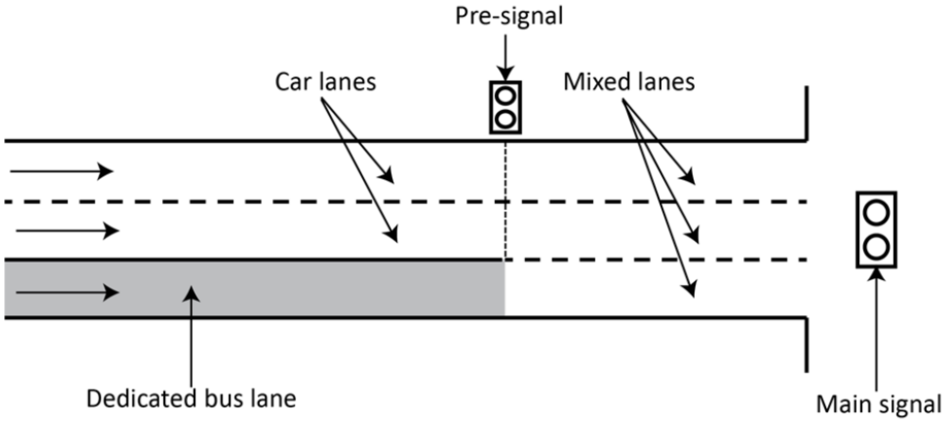
1. Introduction

In an urban setting, providing bus priority cuts down journey time of buses. Consequently, this encourages the public to use the public transport mode and reduces carbon emissions. Moreover, by providing bus priority more people are transported using the existing limited road space, which could reduce the overall system-wide person hours of delay when implemented correctly.

This kind of priority can be provided by dedicating a lane for bus use only. However, this might not always be feasible due to space restrictions or political feasibility. It might also not be the most efficient solution especially if bus flows are low, car demands are high or there are bottlenecks, for example at the traffic signals. Under such situations, alternative strategies must be proposed in order to provide bus priority.

This research will investigate one of such alternative strategies to provide bus priority. This strategy involves using an additional signal (hereafter referred to as pre-signal) upstream of the main signal at a road intersection, as illustrated in Figure 1. Its primary purpose is to allow buses to jump the car queues at the intersection while cars can still use all lanes before the main signal to fully utilize the capacity of the intersection. In this way, bus delays at the intersection are reduced without causing extra stress to the overall traffic.

Figure 1 Layout of a pre-signal



Guler and Menendez (2013b)

For this purpose, Guler and Menendez (2014a) have proposed and analytically investigated a specific operating strategy. In this strategy the pre-signal turns red in advance of a red main signal and also when a bus arrives to the pre-signal irrespective of the status of the main signal. The goal is to ensure any arriving bus to move in front of the car queue and discharge immediately when the main signal turns green. The pre-signal turns green in advance of the main signal when buses are not present such that cars do not experience additional delays, or after the buses have left the main signal when buses are present. An analytical model was built to examine the effects of this strategy. The analytical model was validated according to empirical data collected at an intersection on Langstrasse, Zurich, Switzerland.

The goal of this research is to examine the effects of this pre-signal on buses and cars by implementing this strategy in a micro-simulation using VISSIM. The micro-simulation is constructed according to the geometry of the site in Zurich where empirical data were collected. The research involves the following two aspects.

Firstly, while it is possible to theoretically analyze most effects of pre-signals at an isolated intersection with an analytical model, it is difficult to do so for the arterial case, let alone the network case. This is due to the complexity of the problem and the massive number of options for an implementation strategy. However, with the simulation method, the mechanism behind the operation of pre-signals can be better understood and visual insights on the effects of its operation on the traffic flow can be obtained. Therefore, this research validates the simulation approach by showing that a VISSIM simulation model calibrated with the collected empirical data produces similar results. This builds the foundation to justify using micro-simulation with VISSIM to examine the effects of pre-signals on the arterial and network level.

Secondly, while safety is the main consideration in the red-signal duration upon arrival of buses for the pre-signal on Langstrasse Zurich, the main metric of the theoretical analysis is the total system delay. This, however, was not fully understood in the analytical model. To complete the analysis, this research studies its effect by varying this red time duration in the micro-simulation in 1 second steps. The relationship between this red-signal duration and the total system delay is subsequently analyzed.

The remainder of the paper is organized as follows. In Section 2, existing literature on the operation of pre-signal is reviewed. In Section 3, the site and the simulation model are described. The collected empirical data and the input simulation data are summarized. In Section 4, the calibration and validation of the VISSIM simulation model are discussed. In this section, the results of the simulation model are presented, and a relationship between the additional red pre-signal duration for bus priority and the total system delay is drawn. Some concluding remarks are presented in Section 5.

2. Literature Review

The real-world implementation of pre-signals is under continued review. Our current best knowledge is that such implementation is rare. A similar idea is mentioned in the German Manual for Transit Priority (Merkblatt für Maßnahmen zur Beschleunigung des ÖPNV) and there are similar implementations in several locations in London (Wu and Hounsell, 1998). However, the only pre-signal which we know of with our prescribed operating strategy is on Langstrasse, Zurich, Switzerland. Although there is previous literature that examines the operating strategy and effects of pre-signals (e.g., Wu and Hounsell, 1998; Stein, 1961; Xuan et al., 2011), analytical and empirical analysis of the effects of our prescribed operating strategy is only recently presented in Guler and Menendez (2014a).

Empirical evaluation of bus and car delays at the pre-signal on Langstrasse Zurich was carried out in Guler and Menendez (2013a). It was observed that average car delays at the intersection increase when a bus is present and the discharge flow from the main intersection is reduced. However, the bus delay is also reduced and hence bus priority is provided and the more sustainable bus mode is promoted.

An analytical model was subsequently built in Guler and Menendez (2014a) to study the effects of pre-signals at under-saturated signalized intersections using queuing theory. The expected average bus delay and average private vehicle delay were calculated with the analytical model and the total system person delay was computed. It was concluded that pre-signal is the best strategy compared to mixed-use and dedicated bus lane under a wide and realistic range of bus occupancies (10-70 passengers) and car demands, in terms of minimizing total system delays.

The case where such a pre-signal is implemented at an over-saturated signalized intersection is also studied in Guler and Menendez (2014b). The analysis shows that pre-signals always result in lower total system delay compared to dedicated bus lanes at over saturated intersections. Moreover, pre-signals result in lower total system delay compared to mixed-use lanes if the peak demand is greater than 105% of the signal capacity and the non-peak demand is less than 85% of the signal capacity.

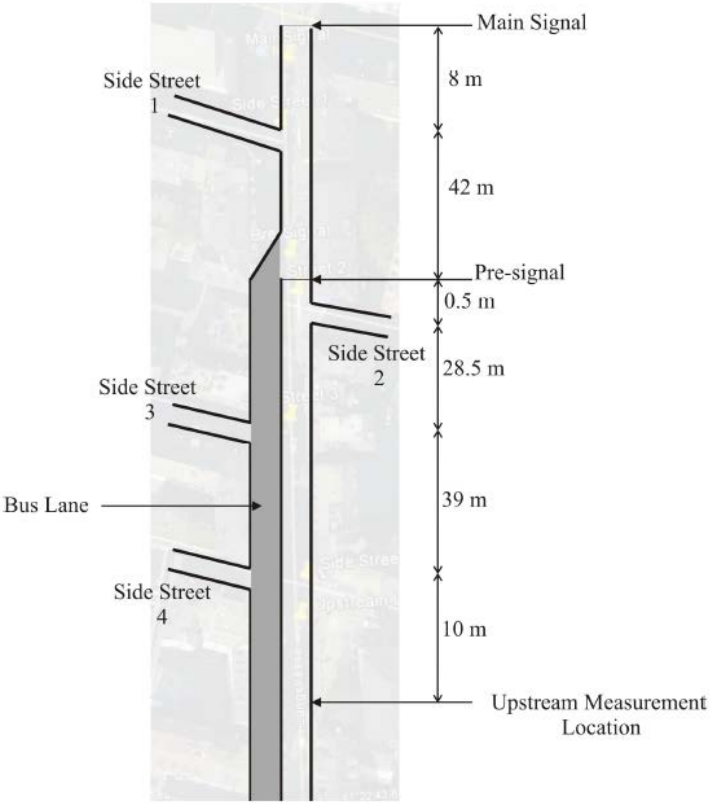
The guidelines for implementing pre-signals at signalized intersections were presented in Guler and Menendez (2013b). Qualitative assessment tools for the feasibility, design and implementation of pre-signals were presented. It was pointed out that in most scenarios pre-signals perform better than dedicated bus lanes and for a realistic range of bus occupancies pre-signals can provide the lowest system wide delays.

3. Description of the site and the VISSIM model

3.1 Description of the site and empirical data

One intersection on Langstrasse in Zurich has a pre-signal operation similar to the one prescribed in this paper. The layout of the streets is as in Figure 2. On this section of the road, traffic comes from both upstream of the main signal and from the 4 side streets. The road upstream of the pre-signal consists of one bus lane and one private vehicle lane. Between the main signal and the pre-signal, these two lanes merge into a single lane shared by both the buses and the private vehicles. There is a slight complication in this case as the bus lane on the main road is a special bi-directional bus lane. This, however, is not of concern to us as it does not affect the operation of the pre-signal or the traffic flow in the direction of interest.

Figure 2 Layout of the streets and data collection points on Langstrasse, Zurich



Guler and Menendez (2013a)

The signals at this intersection operate as follows. The pre-signal always turns red before the main signal so that the last vehicle passing the pre-signal can also pass the main signal as long as the intersection is not already blocked. The private vehicles then queue in front of the pre-signal so that an arriving bus can jump the queue and directly arrive at the main signal. The pre-signal turns green such that the first car in the queue arrives at the main signal just as it turns green as long as the road is not already blocked. Also, whenever there is a bus approaching the pre-signal, the pre-signal always turns red so that the bus could directly move to the main signal without being blocked by any cars, as long as there is not a vehicle coming from side street 1. This follows exactly the operating strategy proposed by Guler and Menendez. However, there is again a slight complication in this case as the signals are adaptive with an unknown algorithm and transit signal priority is implemented. Therefore, each cycle might have different cycle length, green-time and red-time.

Guler and Menendez (2013a) measured traffic flow and signal data at this site. Two data sets from them are applied in this research. Data set 1 was collected between 14:00-15:10 on the 14th of November 2013. Data set 2 was collected between 8:20-8:30 on the 25th of September 2012. In each set of data, the arrival/departure timing of all vehicles and the signal timing were recorded. From this data, the traffic flow rates into the intersection are calculated and summarized in Table 1. The bus arrives with a uniformly scheduled frequency. It is calculated based on data set 1 to be 8 buses/hour.

Table 1 Traffic flows from main road and side streets (vehicles/hour)

	main road	side street 1	side street 2	side street 3	side street 4
data set 1	288.1	28.9	10.6	29.7	13.6
data set 2	346.8	39.5	2.6	7.2	3.3

Guler and Menendez (2013a) observed that although the signals are adaptive, during the measurement period the cycle length and green times remained nearly constant. We have further observed from the recorded video that most drivers do not prepare to start the vehicle during red-amber[1] phase so in effect the red-amber phase acts as an extended red phase. Therefore it is consolidated into the red signal. In addition, the length of the red signal and

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[1] The red-amber phase is implemented in some countries in Europe before the green phase to alert the drivers of the start of the green phase so that the drivers prepare to start driving.

green signal for both the main signal and the pre-signal are the same. The average measurement of the of the signal lengths are summarized in Table 2.

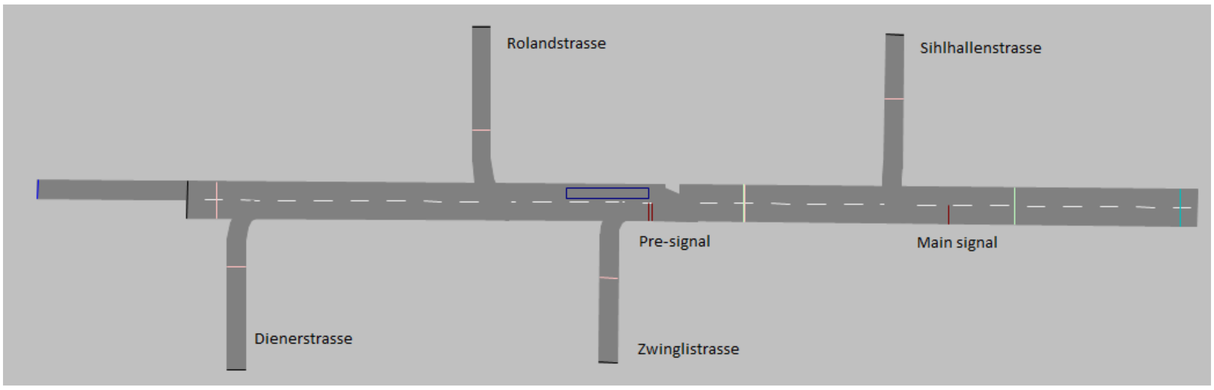
Table 2 Average signal length values (seconds)

Cycle length	Red signal	Green signal	Red pre-signal with bus arriving	Pre-signal advance time
52	30	25	12	7

3.2 Description of the simulation model

The simulation model was built in VISSIM according to the exact geometry specifications of the site as shown in Figure 3. Vehicles flow into the intersection from the main road and the 4 side streets according to the traffic flow rates in Table 1. Buses arrive from the bus lane and merge into the single mixed lane after the pre-signal. Note that the other lane adjacent to this single mixed lane is closed to all traffic flow in the simulation and has no effect on the outcome.

Figure 3 Layout of the simulation model



The pre-signal is constructed with two separate signals which together have the same effect as the implemented pre-signal. One signal is a normal signal which is 7 seconds in advance of the main signal. The other signal is a bus actuated signal which turns red for 12 seconds whenever a bus is detected before the pre-signal. These two signals are placed closely together in the simulation layout and hence act in effect as a single signal to the incoming vehicles. The signal timings for both the pre-signal and the main signal are according to signal data in Table 2.

It is observed in the recorded video that there are various types of trucks, lorries and other large vehicles in the traffic flow. Overall they make up a significant percentage of traffic but the exact composition was not measured during the data collection. It is also complicated and unnecessary to represent the various types of larger vehicles with different vehicle types in the simulation. Therefore, a single larger vehicle percentage factor is used to aggregately account for the effects due to the presence of all types of larger vehicles. This is one of the parameters used to calibrate the simulation model.

The desired speed (i.e. free-flow speed) and the acceleration of the vehicles are two other parameters used to calibrate the simulation model. In the analytical model, the free-flow speed before the pre-signal is assumed to be 45km/h and after the pre-signal 30km/h. In the video it is observed that vehicles generally drive slowly irrespective of the state of the traffic so an overall desired speed of 30km/h is used in the simulation. Moreover, it is observed that all vehicles start and accelerate slowly in this urban road so a low desired acceleration profile is used.

In VISSIM, the delay at the signals cannot be directly measured. Therefore, the travel time of all vehicles from all road and streets are measured instead. Travel time is measured between 6 sections, from the main road upstream to the pre-signal, from the side streets 2-4 to the pre-signal, from side street 1 to the main signal, and from the pre-signal to the main signal.

4. Results and discussion

4.1 Model calibration and validation

This model is calibrated with data set 1 and validated with data set 2. The main benchmark against which the model is calibrated and validated is the average vehicle delays calculated with the two measured data sets. There are two parts of the delay, one part due to the pre-signal (delay PS) and the other part due to the main signal (delay MS). The measured average delays are summarized in Table 3.

Table 3 Measured average delays (seconds)

	Cycles	Average delay PS	Average delay MS	Total delay
Data set 1	bus not present	35.0	6.3	41.2
	bus present	36.2	6.4	42.6
Data set 2	bus not present	16.8	5.9	22.7
	bus present	8.2	6.4	14.6

Each simulation run is 3700 seconds long which is a bit more than 1 hour and about 71 cycles. There is a bus coming every 450 seconds so during this period a total of 9 buses would pass through the intersection in 9 cycles. The number of vehicles and average travel times are measured between 6 sections as in the model description, from which the total travel time could then be calculated. One representation of the result from one simulation run is shown in Table 4 to clarify the explanation. Note that the total number of vehicles that have passed through the main road upstream and side streets 2-4 do not equal to the total number of vehicles that have passed through the main signal from the pre-signal. This is because there are residual vehicles that have not finished their journeys yet by the end of the simulation. We assume these vehicles will finish their journey with the average travel time calculated from the other vehicles. In this way, the average travel time of vehicles from upstream to the pre-signal and from the pre-signal to the main signal could be separately calculated[2].

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[2] Note that the sum of the average travel time from the two sections is not equal to the average total travel time because there are vehicles joining from side street 1 which is not taken into the average before the pre-signal. The sum of two averages is not equal to the average of two sums when sample size are different.

Table 4 One simulation run result

Measurement	Vehicle Count	Average travel time (s)	Total travel time (s)
Upstream to PS	302	30.5	9209.2
Side street 4 to PS	21	41.9	880.5
Side street 3 to PS	27	42.1	1137.5
Side street 2 to PS	15	19.1	286.7
PS to MS	363	6.2	2265.9
Side street 1 to MS	28	38.1	1065.8

One disadvantage of this simulation approach is that the final result is the aggregate average travel time involving both cycles in which a bus is present, and cycles in which there is no bus. It is very difficult to trace the raw data in VISSIM to separate these two types of cycles. One solution is to run simulations without any buses to get the average travel time in cycles in which there is no bus. The opposite, however, is not true. Running the simulation with a bus coming in every cycle will lead to accumulated delays due to the high frequency of buses which does not happen in reality where the bus frequency is about 8 bus/hour. If we want to calculate the delay in cycles where a bus is present, a more accurate approach to get the average travel time during cycles with buses present is to reversely calculate the travel time from the following relationship: total mixed-cycles travel time is the sum of the total no-bus cycles travel time plus the total with-bus cycles travel time. The average travel time for the mixed-cycles and the no-bus cycles are already calculated, so the average travel time for the with-bus cycles could be deducted. However, note that this is not calculated in this research because the average vehicle travel time for both the mixed-cycles case and the without-bus case have a large variance. The calculated result from the above relationship would be unreliable.

Eventually, our concern is the delay. Therefore, we also have simulation runs in which there are no signals in operation. This corresponds to the free-flow case. The difference between the average travel time with the signal and the average travel time without the signal is the average delay. The average delay could be separately calculated for the average delay before the pre-signal, the average delay before the main signal, and the total average delay. Note again that the sum of the two delays from the pre-signal and from the main signal is not equal to the average total delay calculated in this way. Again, this is because there are vehicles joining from side street 1 which are not taken into the average before the pre-signal.

The average delay values in data set 1 for cycles when a bus is not present were used to calibrate the simulation model with the speed, acceleration and large vehicle ratio. The calibration result is summarized and compared to the measured values in Table 5.

Table 5 Calibration results

	Average delay PS	Average delay MS	Total delay
Measured value	35.0	6.3	41.2
Simulation result	33.5	7.6	40.5

With this calibrated model, data set 2 is then tested to validate the model. The simulation was run with 10 different random seeds for each of the three cases: simulation with 8 bus/hour (normal mixed cycles), simulation without buses and simulation without traffic signals. The statistical results are summarized in Table 6.

Table 6 Data set 2 simulation results

Normal mixed cycles	Up to pre-signal	Pre-signal to main signal	Total
Average travel time	30.4	11.9	40.2
Standard deviation	5.2	0.8	5.3

Without buses	Up to pre-signal	Pre-signal to main signal	Total
Average travel time	28.3	11.0	38.6
Standard deviation	4.1	0.8	4.1

Without signals	Up to pre-signal	Pre-signal to main signal	Total
Average travel time	10.3	5.7	15.4
Standard deviation	0.1	0.1	0.2

From the results, firstly we notice that the variance of travel times across different runs with different random seeds is large for normal mixed cycles. Secondly, most of the travel time variance happens in the section before the pre-signal. Thirdly, the presence of the buses increases this variance. This big variance is expected since it corresponds to the variance in the arrival of traffic, which could vary significantly depending on when the data is recorded. Two main sources of variation are identified. First, variation arises due to vehicles arriving from the side streets at random times. These vehicles need to wait before merging into the main road. The number of vehicles from the side streets and the traffic situation when these vehicles arrive at the main road both cause variation in the travel time. This is especially true for data set 2 where the traffic flow from the side streets is low. Second, variation arises due to the different times at which the pre-signal is actuated by arriving buses. The traffic situation when the bus actuates the pre-signal determines how many vehicles will be stopped at the pre-signal. The variation reflects the various different traffic conditions which the pre-signal could be operating under. Therefore, the measured data sets and each run of the simulation only represent one of the many possible scenarios. In the long run, it is expected that the analytical values presented in Guler and Menendez (2014a) will be reached. Moreover, it is also observed that the average travel time increases at the presence of buses. This agrees with the empirical observation in Guler and Menendez (2013a).

As mentioned previously, the calculated value for the average delay when bus is present will be unreliable due to the large variance of the results above. Therefore, only the average delay values when bus is not present are thereafter calculated by taking the average of the difference between the average travel time without buses and the average travel time without signals in each simulation. They are summarized and compared to the measured value in Table 7 to validate the simulation model.

Table 7 Comparison of delay values from data set 2

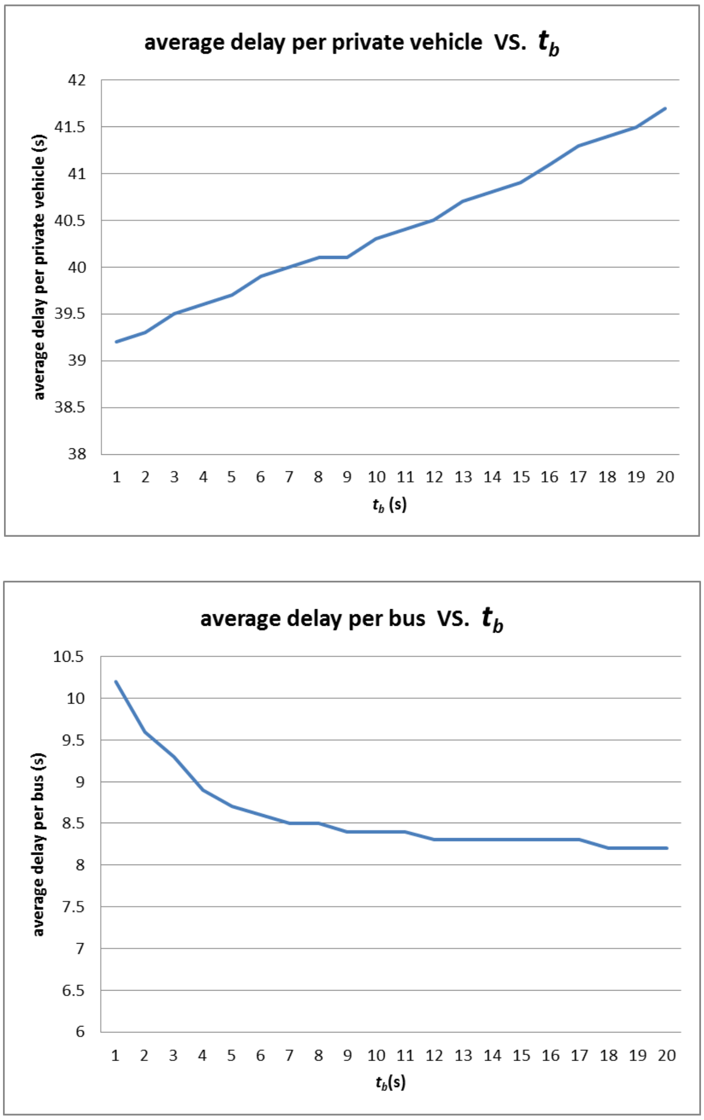
	Average delay PS	Average delay MS	Total delay
Measured value	16.8	5.9	22.7
Simulation result	18.0	5.3	23.2
Standard deviation	4.0	0.8	4.1

From Table 7 we see that the measured values all fall within the range of the simulation results. Moreover, from Tables 6 and 7, we observe that the results of the simulation agree with the general pattern of the results from the empirical measurement. Therefore, the simulation model is validated and we believe the micro-simulation with VISSIM correctly models the mechanism behind the operation of pre-signals. However, although the simulation model is a good tool to provide direct visual insights into the operation of the pre-signal, it should be used with caution when generating exact numerical results due to the large variance involved. The range of variation should always be tested first and the cause of the variation understood before we can make sense of the numerical results. The simulation should either be run over a long enough period of time or run multiple rounds with different random seeds to average over many possible traffic situations.

4.2 Red time duration at the presence of buses (t_b)

When a bus arrives at the pre-signal, regardless of the phase, the pre-signal turns red for cars for a certain duration, t_b. The goal is to analyze how the change in t_b affects the vehicle delay, the bus delay and hence the total system delay. For this purpose, t_b is varied between 1-20 seconds in 1 second increments using the values for data set 1. The average delay values are calculated for each t_b value. The results are plotted in Figure 4.

Figure 4 Relationship between t_b and average delays



From Figure 4 we see that the average bus delay decreases approximately exponentially while the average vehicle delay increases approximately linearly. Obviously, a longer red signal duration provides more priority to the buses. However, as the red signal duration gets longer, the incremental decrease in bus delays gets smaller, while the incremental increase in car delays is still substantial. Due to this trade-off there exists a point where the total system delay is minimized.

To provide insights into the value of t_b that minimizes system delays, we present here an analysis of the system-wide delays based on data set 1 where the total number of vehicles is approximately 400 and there are 9 buses going through the intersection during the 70 mins time period. This represents a typical under-saturated scenario. Under this scenario, the total system delay will be a function of the bus occupancy. Table 8 presents the identification of the range of optimal t_b for the system assuming private vehicle occupancy is 1.

Table 8 Total system delay with bus occupancy and t_b

Red signal (s)	occupancy	20			occupancy	40			occupancy	60			occupancy	80			occupancy	100	
	Total bus passenger delay (s)	Total car passenger delay (s)	Total system delay (s)		Total bus passenger delay (s)	Total car passenger delay (s)	Total system delay (s)		Total bus passenger delay (s)	Total car passenger delay (s)	Total system delay (s)		Total bus passenger delay (s)	Total car passenger delay (s)	Total system delay (s)		Total bus passenger delay (s)	Total car passenger delay (s)	Total system delay (s)
1	1836	15680	17516		3672	15680	19352		5508	15680	21188		7344	15680	23024		9180	15680	24860
2	1728	15720	17448		3456	15720	19176		5184	15720	20904		6912	15720	22632		8640	15720	24360
3	1674	15800	17474		3348	15800	19148		5022	15800	20822		6696	15800	22496		8370	15800	24170
4	1602	15840	17442		3204	15840	19044		4806	15840	20646		6408	15840	22248		8010	15840	23850
5	1566	15880	17446		3132	15880	19012		4698	15880	20578		6264	15880	22144		7830	15880	23710
6	1548	15960	17508		3096	15960	19056		4644	15960	20604		6192	15960	22152		7740	15960	23700
7	1530	16000	17530		3060	16000	19060		4590	16000	20590		6120	16000	22120		7650	16000	23650
8	1530	16040	17570		3060	16040	19100		4590	16040	20630		6120	16040	22160		7650	16040	23690
9	1512	16040	17552		3024	16040	19064		4536	16040	20576		6048	16040	22088		7560	16040	23600
10	1512	16120	17632		3024	16120	19144		4536	16120	20656		6048	16120	22168		7560	16120	23680
11	1512	16160	17672		3024	16160	19184		4536	16160	20696		6048	16160	22208		7560	16160	23720
12	1494	16200	17694		2988	16200	19188		4482	16200	20682		5976	16200	22176		7470	16200	23670
13	1494	16280	17774		2988	16280	19268		4482	16280	20762		5976	16280	22256		7470	16280	23750
14	1494	16320	17814		2988	16320	19308		4482	16320	20802		5976	16320	22296		7470	16320	23790
15	1494	16360	17854		2988	16360	19348		4482	16360	20842		5976	16360	22336		7470	16360	23830
16	1494	16440	17934		2988	16440	19428		4482	16440	20922		5976	16440	22416		7470	16440	23910
17	1494	16520	18014		2988	16520	19508		4482	16520	21002		5976	16520	22496		7470	16520	23990
18	1476	16560	18036		2952	16560	19512		4428	16560	20988		5904	16560	22464		7380	16560	23940
19	1476	16600	18076		2952	16600	19552		4428	16600	21028		5904	16600	22504		7380	16600	23980
20	1476	16680	18156		2952	16680	19632		4428	16680	21108		5904	16680	22584		7380	16680	24060

From the table we notice that for each bus occupancy level, there exists a range of t_b (marked in black border) that minimizes the total system delay. This is a stable minimal point where the total system delay is not sensitive to the changes in red time duration within this range. Also, the range of optimal t_b increases with increasing bus occupancy. This is as expected since the priority provided to buses becomes more valuable as the number of passengers on the bus increases. Since the bus occupancy is rarely over 100 (especially in the city of Zurich), we recommend that this red time duration normally should not exceed 10 seconds. In the case of Langstrasse in Zurich, as long as safety criterion is guaranteed, we believe the red signal duration should be lowered from the current level (12s).

5. Conclusion

This paper presented a micro-simulation model with VISSIM to model the operation of the pre-signal on Langstrasse Zurich. The simulation model was calibrated and validated with two data sets from measurement on two days. It was shown that the model correctly simulates the operation of pre-signals and provides direct visual insights into the traffic situation. In particular, it was observed that the traffic situation and corresponding results varies significantly, so further empirical measurements and simulation studies should cover a wide enough range of situations.

With the developed micro-simulation, the effect of the red time duration at the pre-signal due to the presence of buses (t_b) was examined. It was observed that with increasing t_b the average bus delay decreases approximately exponentially while the average vehicle delay increases approximately linearly. The range of t_b that results in minimal total system delay was identified for a demand rate of approximately 400 veh/hour, which increases with increasing bus occupancy. It was concluded that t_b should not exceed 10s in general when implementing pre-signals.

The greater significance of this simulation tool lies in the study of the effects of pre-signals in the arterial and network cases. The simulation method will be used to study how the multiple parameters involved can affect both cars and buses in an urban network. The ultimate goal is to identify the optimal operating strategy for pre-signals at the network level.

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