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A microsimulation study of bus priority system with pre-signaling

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Abstract

The provision of transit priority has been shown to improve the performance of public transport, which is more efficient consumer of energy and space than private transport. On the other hand, the implementation of transit priority may also have disadvantages and penalize the general traffic. Thus, the design of the transit priority needs to balance these two opposing effects. This research aims to implement a bus priority system that utilizes a dedicated bus lane terminated upstream of the intersection, along with an additional signal, known as a pre-signal, at this location. A wide literature exists with studies of adaptive control pre-signals that are primarily focused on isolated intersections and concern simple traffic schemes. The current study investigates the performances of pre-signals in more realistic contexts through microsimulation and focuses specifically on two issues: the position of the pre-signal with respect to the main signal and the application domain of pre-signal strategies compared to the standard layouts of bus lanes, either continuous or interrupted.

Keywords: Bus priority system; pre-signal; delay reduction

1. Introduction

The increasing demand for public transportation and the growing number of private vehicles on the roads have resulted in significant traffic congestion in many urban areas. In the usual case of shared lanes for buses and private vehicles, this congestion can lead to significant delays for bus services, making them less reliable and less attractive to users. As a result, a further demand shift may occur from public to private transport, exacerbating the problem of traffic congestion. To tackle this problem, several solutions have been implemented and dealt with in the technical (KFH Group, 2013) and scientific literature (see, among others: Ibarra-Rojas, 2015; Dadashzadeh & Ergun, 2018; Bhattacharyya et al. 2020), including the use of bus priority systems. These systems aim to give buses priority over other vehicles at signalized intersections, reducing the delay experienced by buses and improving their speed and reliability along urban road corridors (Colombaroni et al., 2020).

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The use of signals to prioritize buses was firstly proposed by Wu and Hounsell et al. (1998), who categorized the methods as (1) pre-signals with uncontrolled buses, (2) pre-signals with controlling both buses and cars and (3) a mixed method consisting in giving the red signal to private vehicles during arriving buses to pre-signal and then giving the red signal to the bus lane. However, not well-designed pre-signals may lead to a decrease in discharge rate and waste of green time. Kumara and Hounsell et al. (2006) proposed queue relocation and bus priority as priority methods to avoid wasting the main intersections' green time. Kejun et al. (2008) studied prioritizing buses at a single intersection using a pre-signal and passive priority. Xuan et al. (2011) suggested the use of mid-block pre-signals to store traffic flow efficiently between pre-signals and main intersections. Xuan et al. (2011) suggested using a tandem design to increase the intersections' flow capacity. Guler and Menendez et al. (2014) introduced an analytical model to estimate the delays of cars and buses in pre-signalized intersections using queuing theory, concluding that pre-signal systems minimize delay more than dedicated bus lanes. Guler and Menendez et al. (2015) presented practical instructions for implementing pre-signals upstream of intersections to improve transit services and private transportation systems simultaneously and introduced a formulation for calculating the distance between pre-signals and main signals. He et al. (2016) developed an adaptive control based on it. Recently, Wang et al. (2023) extended the idea of pre-signal to a mixed traffic stream for human-driven and connected automated vehicles and presented a reasonable pre-signal timing scheme and position of pre-stop line. Their approach generalizes the concept of virtual bus lanes (Pollak et al., 2003) which is promising for future applications with connected vehicles. The literature review has shown that the pre-signal system has been object of a significant research effort with both analytical and simulation-based applications. However, all these previous studies have been addressed for isolated intersections and assumed no more than one bus arrival for each single cycle. In this paper, this problem is generalized to a corridor with multiple intersections and considering various scenarios, such as different lane occupancy levels, randomization of traffic, geometry of the intersection, and arrival of multiple buses from different lanes at the pre-signal simultaneously or with a negligible time gap. Computing the optimal distance between pre-signals and main signals is an important design factor (Guler and Menendez, 2015) since it affects both the trajectory of buses and the number of cars that can be accommodated in the bus advanced area and becomes crucial in the perspective of virtual or dynamic bus lane applications. In this future scenario, the position of virtual pre-signals can be dynamically adjusted based on current traffic conditions and the progression of buses. The purpose of this research is to investigate through simulation the optimal distance of the pre-signal with respect to the main signal in terms of average delays for cars and bus passengers with adaptive control, considering the real scenario constraints both in network as well as demand and to identify the application domain of pre-signals with respect to the traditional bus lane strategies for different bus line directions and traffic volumes.

2. Problem Description

2.1. Bus lane layouts

Standard approaches of bus priority along corridors are a continuous bus lane strategy, which extends the dedicated bus lane all the way to the signalized intersections (Fig. 1a) reducing the discharge rate of private transport, and the interrupted bus lane strategy (Fig. 1b), which ends the bus lane before the main signal. However, it does not apply any control to private vehicles (e.g., cars). To prevent buses being delayed in queue with private vehicles and avoid reducing capacity, a pre-signaling system was introduced (Fig. 1c), which can identify approaching buses and give them priority by stopping other vehicles out of a bus advanced area set before the main intersection, allowing buses to pass through, and obtaining the first position in the queue. Then, the pre-signal shifts to green and allows private vehicles approaching the intersection using all the lanes at the approach. The whole road capacity at the approach will be ensured provided that the pre-signal and the main signal are well synchronized and well-spaced to prevents queue spillback. The waiting time of the bus is minimized as it is the first in the queue and is potentially nil if a bus priority control is implemented at the main signal.

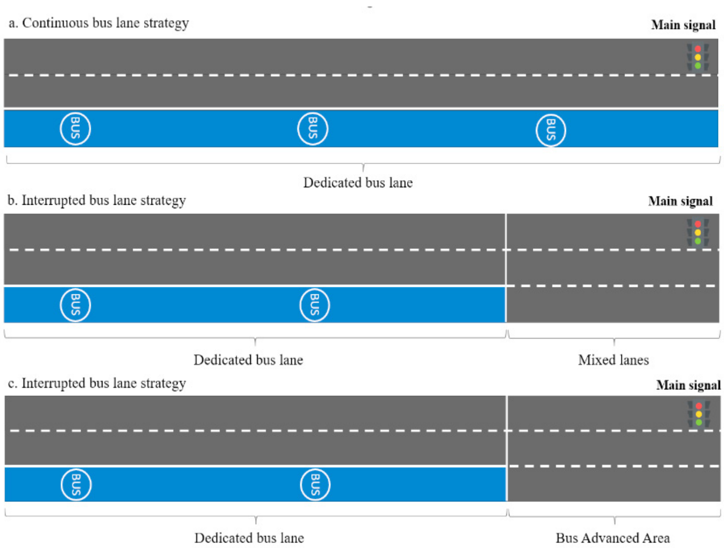

Fig 1. Layout of three strategies upstream of the intersection (a) Continuous bus lane strategy, (b) Interrupted bus lane strategy, (c) Pre-signal

2.2. Pre-signal operations

Pre-signal operations are described in Fig. 2. As the bus is detected upstream of the pre-signal, the command is sent to the pre-signal. Note that the bus detector should be far enough to allow changing the pre-signal settings in a way that the bus movement does not interrupt. In the case of arrival of two buses with the t_{gap} before changing the phase after the detection of the first bus, the red phase for private vehicles will be extended equal to the time gap. When the main signal is showing a green light, regular through-moving buses can continue without any interruptions. However, if a left-turning bus is detected, even during the green phase of the main signal, the pre-signal immediately switches to green exclusively for left-turning buses. This helps left-turning buses safely enter the intersection but also means that private vehicles need to stop at the pre-signal to prevent any possible conflicts with the left-turning buses.

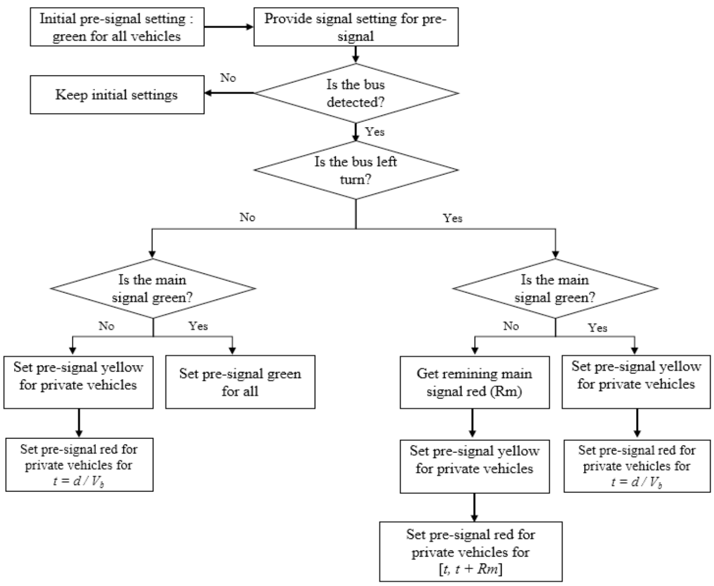

Fig 2. Flow chart for the operation of the pre-signal

The pre-signal control algorithm is specifically designed to handle more intricate situations, particularly when the main signal at the intersection comprises more than two phases and there exists a temporal discrepancy between the green phases for through movement and left-turning traffic. For instance, in our simulated intersection, the traffic signal incorporates three phases, with the left-turn phase activating 14 seconds subsequent to the through movement phase. Consequently, it is critical to incorporate the remaining red duration for left-turning traffic (Rm) into the stopping time for private vehicles at the pre-signal to mitigate potential conflicts between private vehicles and left-turning buses during their manoeuvring.

2.3. Analysis of suitable pre-signal location

The positioning of the pre-signal at a distance denoted as "d" from the main signal holds critical significance. This choice of distance is pivotal because it can greatly affect the overall efficiency of the intersection. If the pre-signal is placed too far from the main signal, it results in an extended time for vehicles to cover the distance to reach the main signal. During this period, the pre-signal must remain in the red state, causing potential delays. Conversely, if the pre-signal is positioned too close to the intersection, it may inadequately accommodate the queuing requirements of buses and, more broadly, fail to allocate sufficient space for private vehicles to fully utilize the green phase of the main signal. It is essential that the placement of the pre-signal does not introduce unnecessary delays for private vehicles during cycles when no buses are approaching. Additionally, it must ensure that the last vehicle from the pre-signal crosses the main signal within the same cycle. To address these considerations comprehensively, specific boundaries have been defined as follows:

$$d \geq Clearance\ time * V_{max}; \quad Clearance\ time = \frac{Bus\ length + artery\ width}{V_{max}} + Safety\ Factor \tag{1}$$

The maximum distance can be determined, as suggested by Guler and Menendez et al. (2015), by ensuring that the size of the bus advanced area is capable of accommodating the number of vehicles that can be served within the duration of the effective green phase (G) of the main signal. where μ and K_{jam} are the capacity of each lane and the jam density of a single lane, respectively.

$$d \leq \frac{G\mu}{K_{jam}} \tag{2}$$

The conditions facilitating buses to traverse the bus advanced area at the desired speed, while also ensuring that other vehicles can cross it within the allotted time to be served during the green phase of the main signal, become progressively complex when the frequency of the bus line is sufficiently high, potentially resulting in the arrival of more than one bus during a single signal cycle. Limiting the analysis to the case of two buses, the worst condition, depicted in Fig.3, occurs when the first bus arrives as the red of the main signal is about to end and the second bus arrives with a time gap t_{gap} ($t_2 < \delta\ t_1$) after the first bus, where t_1 is equal to d/V_b. The red at the pre-signal for the private cars will be extended to ensure that the second bus arrives at the main signal without interfering with cars. Once the buses are positioned at the front of the queue at the main intersection, the pre-signal can switch to green, allowing private vehicles to approach the stop line. However, several considerations come into play. The time required to clear the queue of private cars must be factored in and added to the extension of the red signal duration at the pre-signal. This extension should partially overlap with the initial green phase at the main signal. To prevent any potential interference in the event of a queue overflow, the worst-case scenario assumes that these two time intervals are simply added to the time it takes for the buses to traverse the bus advanced area. Consequently, the total time "T" required to enable the buses to pass through the intersection without any delays adheres to the following condition.

$$T = \left[\frac{d}{V_{max}}\right] + \left((n-1) * t_{gap}\right) + \left(\frac{k_{jam}L}{s}\right) \tag{3}$$

where q is the traffic flow, n is the number of buses, and L is the length of the car queue and s is the saturation flow.

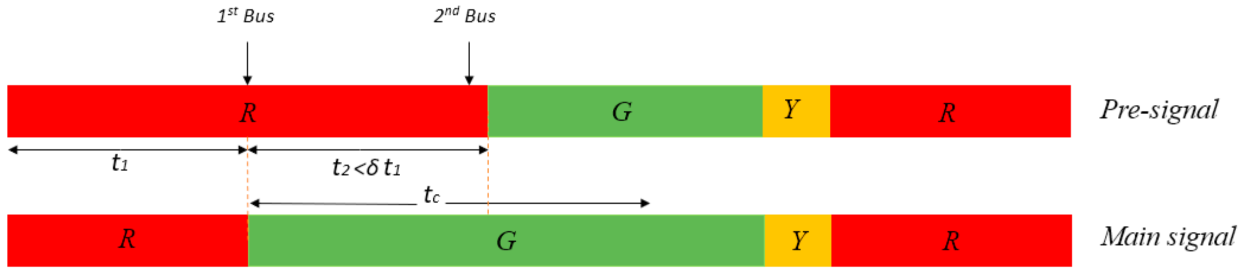

Fig 3. Bus arrivals with respect to the pre-signal and the main signal cycle

3. Numerical Experiments

3.1. Methodological Approach

To assess the efficiency of the system and explore the impact of different variables affecting its performance in a realistic case, a microsimulation approach is utilized to investigate the effect of the location of the pre-signal considering different factors, such as traffic volumes, intersection layout, bus frequencies and manoeuvres. An additional significant element to consider is the clearance time required for left-turning buses, as the curvature of their manoeuvre must be taken into account. Above all, a relevant case to investigate is the presence of multiple buses approaching the intersection while the main intersection is in the red phase.

In this study, we have simulated many different scenarios of a network with different traffic flow and several various bus lines to have a more comprehensive analysis. Specifically, 41 out of 72 total simulations scenarios were selected to investigate the most convenient placement of the pre-signal.

3.2. Study area

The study area corresponds to via "Prenestina", an important artery in the East part of Rome, Italy, chosen due to its importance and severe traffic congestion during the peak hour. The whole corridor includes 21 signalized intersections and 3 main transit lines, while the simulated study area corresponds to a 1432m long stretch of 5 intersections, made up of carriageways of 2 and 3 lanes and served with exclusive tram lane, starting from intersection (1) "Centro Servizio" to intersection (5) "Tor De' Schiavi", as it is shown in Fig. 4a. The simulations were carried out by using a model developed in SUMO that was accurately calibrated with traffic counts collected at almost all the intersections along the corridor.

Fig 4. Study area Via Prenestina: (a) Sketch of 5 intersections, (b) Microsimulation with dedicated bus lane and pre-signal.

3.3. Empirical investigation on the most suitable pre-signal location

In order to investigate the effect of the distance on the average delays of cars and bus passengers and identify reasonable ranges of the optimal distance for different values of the external factors, an empirical approach was employed. A simulation of the corresponding network was conducted, considering the demand as given. Starting from an initial distance of 58 meters from the main signal, the metric T was evaluated for volume/capacity (V/C) ratios ranging from 0.4 to 1.4. The distance was then incremented by 10 meters in each iteration, and the corresponding value of T was obtained. Based on the results displayed in the chart below, the lowest values of T are obtained for a distance of 108 meters from the main signal for every value of the V/C ratio. It can be clearly seen also in Fig. 5 that in relatively low V/C ratios the placement of pre-signal has minimal effect on the Value T; however, as the V/C ratio increases longer distance *d* becomes convenient. Distances exceeding 118 meters are deemed unacceptable based on equation (2) as they would leave more space than it can be exploited to serve car traffic demand during the green. These findings highlight the importance of balancing safety considerations, efficient traffic flow and characteristics of a network. The combination of empirical simulation and the consideration of both minimum and maximum acceptable distances provides valuable insights for optimizing pre-signal placement in transportation systems. In the specific case under investigation, since the network normally deals with a range of high volume during the day, the value of 108 meters is suggested as the desired distance.

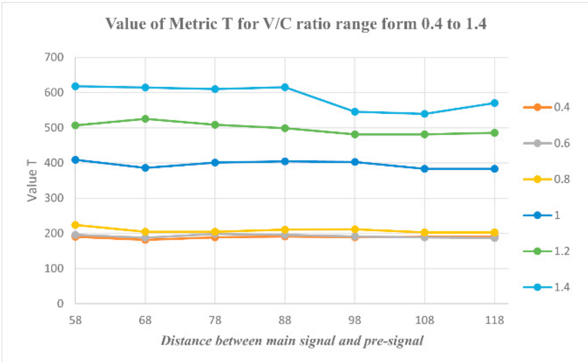

Fig 5. Value T for V/C ratio range 0.4 to 1.4

3.4. Boundary conditions and comparison of different bus priority strategies

After having estimated the best value for the distance between pre-signal and main signal, the present section investigates the application domain of the pre-signal system with respect to the standard bus lanes layouts: continuous or interrupted. Since such different layouts privileges either car traffic or transit, we are now examining the delays experienced by cars and buses individually for each control strategy. Results are illustrated in Fig. 6 for different V/C ratios. As expected, the continuous bus lane strategy consistently produces the smallest average delay for buses and leads to significantly greater car delays compared to the other two strategies. In contrast, the interrupted bus lane strategy consistently yields the lowest average delay for private vehicles. Nevertheless, the graph reveals a steep rise in delay for continuous bus lane beyond a V/C ratio of 0.8, rendering this strategy unsuitable for the network, except in cases of exceptionally high bus frequency and occupancy.

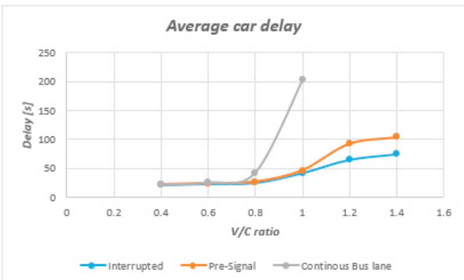

Fig 6. Average Car delay for range of V/C ratio from 0.4 to 1.4

Based on our previous discussion, it becomes clear that the continuous bus lane strategy isn't suitable for general cases due to the increased delays of private vehicles. As a result, we shifted our focus towards analyzing the interrupted bus lane strategy and the pre-signal strategy. We conducted tests on these two strategies, considering three different bus frequencies with headways of 4 minutes, 8 minutes, and 12 minutes, respectively, two lines of buses, with equal frequency, one making through movements and the other making left turns.

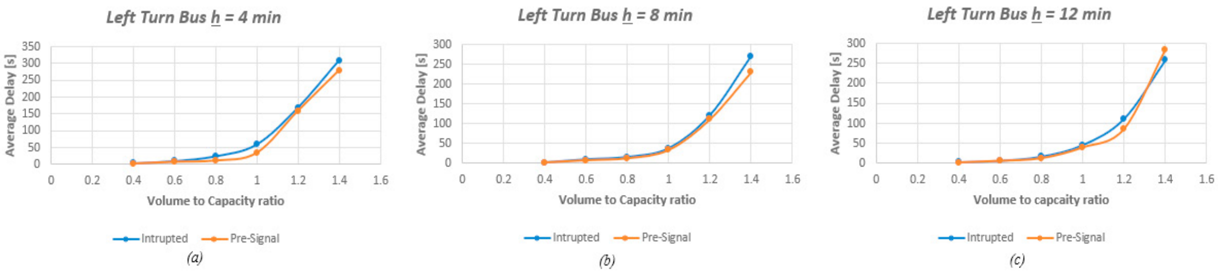

Fig 7. Average left turn bus delay vs V/C ratio. a) headway = 4 min, b) headway = 8 min, c) headway = 12 min

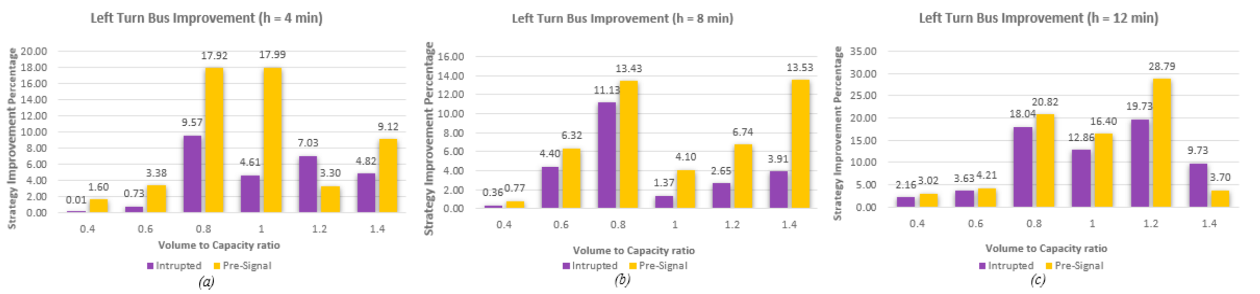

Fig 8. Delay improvement of left turn buses vs V/C ratio. a) headway = 4 min, b) headway = 8 min, c) headway = 12 min

It can be observed that the pre-signal strategy consistently outperforms other strategies in the case of left-turning buses, as it minimizes the interaction between cars and buses. In Figure 8a, where the headway is 4 minutes, the V/C ratio reaches its peak at 0.8 and 1, with improvements of 17.92% and 17.99% respectively. In Figure 8b, with an 8-minute headway, the V/C ratio also peaks at 0.8, but there is a slight reduction in the V/C ratio at 1. Finally, in Figure 8c, with a 12-minute headway, the majority of improvements are observed for V/C ratios greater than 0.8. However, it should be noted that to establish a definitive pattern and formulate concrete recommendations, a larger number of cases with varying bus frequencies should be tested. This will provide a more comprehensive understanding of the effectiveness of the pre-signal strategy.

4. Conclusion

In conclusion, this research focused on determining the optimal placement of pre-signals in a bus priority system, with a particular emphasis on a real network of Via Prenestina in the eastern part of Rome. Through extensive testing and simulations conducted on a sketch of 5 intersections, the study successfully evaluated the strategies in a realistic network configuration, taking into account the challenges that arise in such complex environments. The findings revealed that the optimal distance between the pre-signal and the main signal in the real network differs from the theoretical distance calculated using formula2, which suggests a desired distance of 118 meters. However, the empirical method employed in this study identified the optimal distance as 108 meters. This difference of 10 meters which is calculated based on the worst case scenario as mentioned holds significant importance in urban areas where space is limited, as highlighted in the abstract. Furthermore, the results indicated that in scenarios with lower V/C (volume-to-capacity) ratios, the pre-signal can be positioned closer to the main signal while still ensuring the safety and comfort of passengers during braking. This finding offers valuable insights for urban planners and transportation authorities in optimizing the placement of pre-signals based on varying traffic conditions. Additionally, the research highlighted the effectiveness of employing pre-signals specifically for left-turning buses, as this strategy proved to be the most suitable in terms of minimizing delays for buses. This finding underscores the potential benefits of incorporating pre-signals into bus priority systems to enhance overall traffic flow and improve the commuting experience for all road users. In summary, this study provides valuable empirical evidence and insights into the optimal placement of pre-signals in real network configurations, highlighting the importance of considering practical constraints and traffic dynamics when designing bus priority systems. The findings contribute to the ongoing efforts in urban transportation planning and offer potential solutions to alleviate traffic congestion and improve efficiency in bus operations. Lastly, We recognize and acknowledge the limitations associated with the implementation of pre-signals in our study. Firstly, it's important to note that these systems may not be universally applicable, particularly in cases where intersections are situated relatively close to each other. This spatial constraint could impact the feasibility and effectiveness of pre-signals. Secondly, our research findings have shown that the continuous dedicated bus lane strategy proves to be optimal for enhancing bus system performance. However, it's noteworthy that this advantageous impact on bus systems is accompanied by a significant adverse effect on private vehicles. This trade-off is a critical consideration in the practical application of such strategies. In light of these limitations and considering the need for a balanced and sustainable solution, our forthcoming endeavors will be directed towards resolving this issue. Specifically, we intend to explore the implementation of dynamic lane allocation for the bus system. This approach holds promise for mitigating the negative impact on private cars while still fostering the efficiency of the bus system.

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