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A Microsimulation Study of Bus Priority with Pre-Signaling

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Abstract

The provision of transit priority has been shown to offer numerous societal benefits in urban areas, including alleviating congestion, improving air quality, reducing climate impacts, and saving energy. Furthermore, bus priority has the potential to break the vicious cycle in which congestion reduces bus reliability and efficiency, causing individuals to switch to private cars and further exacerbating delays and congestion. 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. Although pre-signals are already in use in some urban areas, and various studies have been conducted to improve their functionality through the use of adaptive control algorithms that respond to changing traffic demand, the optimal distance between the pre-signal and main intersection has not been thoroughly investigated along corridors, as previous studies have primarily focused on isolated intersections. The current study seeks to address this gap by developing an algorithm for determining the optimal pre-signal distance from the main signal in real networks, while also taking into account user safety. The study aims to achieve two primary goals: reducing delays experienced by public transit users and improving the intersection's discharge rate for private vehicles when the bus priority network is in use.

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 proposed by Colombaroni and Fusco et al. (2020), including the use of bus priority systems. These systems aim to give buses priority over other vehicles at

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signalized intersections, reducing the delay experienced by buses and improving their speed and reliability Kumara et al. (2006). Two 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, which ends the bus lane before the main signal. However, does not apply any control to private vehicles at this point and private vehicles (e.g., cars) and buses freely merge (Fig. 1b). A promising approach to implement bus priority by reducing the penalties for private transport is through the use of pre-signaling, which can identify approaching buses and give them priority by stopping other vehicles before the main intersection, allowing buses to pass through without delay, To maximize the capacity of the intersection, the main signal allows all lanes to be utilized by cars as soon as the bus obtains the first position in the queue (Fig. 1c).

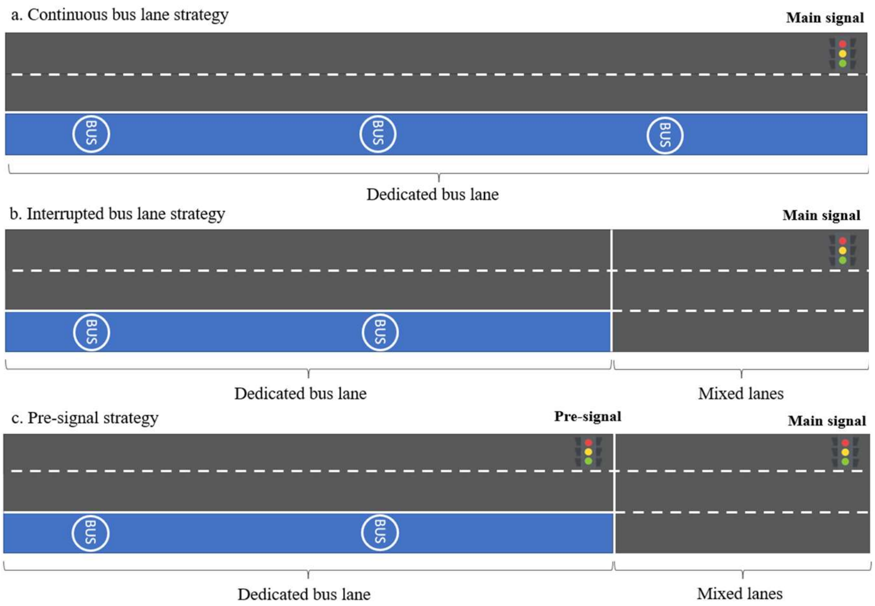

Fig 1. Layout of three strategies upstream of the intersection (a) Continuous bus lane strategy, (b) Interrupted bus lane strategy, (c) Pre-signal

The use of pre-signaling as part of a bus priority system has been shown to significantly reduce the delay experienced by buses at signalized intersections Wang et al. (2019b), making them more reliable and attractive to commuters. However, experts are grappling with negative consequences that arise from pre-signaling, with the most prominent and challenging issue being the increase in the discharge rate of private transport and the extension of queues upstream of the main signal. This leads to congestion and waste of the green phase of the main signal for private transport, ultimately resulting in further delays. The purpose of this research is to determine the optimal distance of the pre-signal with respect to the main signal in order to enhance the adaptive control for pre-signal tailored to real time private and public transportation demand considering the real scenario constraints both in network as well as demand.

1.1 Literature review

The implementation of bus priority systems has become increasingly popular in urban transportation planning as a means to improve bus service reliability and speed. The term "bus pre-signal" refers to traffic signals implemented behind intersections Peak et al. (2006). Wu and Hounsell et al. (1998) proposed the use of signals to prioritize buses, and categorized the methods as (1) pre-signals with uncontrolled buses, (2) pre-signals with controlling both buses and cars and (3) giving the red signal to private vehicles during arriving buses to pre-signal and then giving the red signal to the bus lane. However, using pre-signals upstream of urban intersections leads 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. Xuan et al. (2011) suggested the use of mid-block pre-signals to store traffic flow efficiently between pre-signals and main intersections. He et al. (2016) proposed an adaptive algorithm to control pre-signals in real-time based on demand for private and public transportation, leading to the stimulation of buses' use and reduction of person delay. Xuan et al. (2011) suggested using a tandem design to increase the intersections' flow capacity. Kejun et al. (2008) studied prioritizing buses at a single intersection using a pre-signal and passive priority. Guler and Menendez et al. (2014) estimated delays of cars and buses in pre-signalized intersections analytically using queuing theory, concluding that pre-signal systems minimize delay more than dedicated bus lanes. They presented practical instructions for implementing pre-signals upstream of intersections to improve transit services and private transportation systems simultaneously. provide even greater flexibility and efficiency in bus priority systems. Virtual bus lanes are another innovative approach to improving bus service Pollak et al. (2003). Implementation of these measures should be carefully planned and evaluated using microsimulation tools to ensure optimal performance, especially in light of advancements in technology and new approaches to bus priority systems.

1.2 Objective and Motivation

Guler and Menendez et al. (2015) presented a formulation for calculating the distance between pre-signals and main signals, and He et al. (2016) developed an adaptive control based on it, these previous studies have been addressed for an isolated intersection assuming no more than one bus arrival for each single cycle. This problem can be 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 crucial for virtual or dynamic bus lanes and virtual pre-signals since it affects the trajectory of buses and number of cars that can be accommodated. The position of virtual pre-signals can be dynamically adjusted based on current traffic conditions and the progression of buses. It is worth noting that the optimal positioning of pre-signals is vital not only for public transport but also to improve the discharge rate of private vehicles at the main intersection. This paper introduces a method and formulation for such computations.

1.3 Study area

The study area corresponds to via "Prenestina" an important artery in east part of Rome, Italy. The corridor is consist of the total 21 signalized intersection. The simulated study area corresponds to a stretch of 5 intersections , starting from intersection (1) "Centro Servizio" to intersection (5) "Tor De' Schiavi" as it is shown in Fig. 2a. The length of the artery is 1432 meters starting from the intersection (1) to intersection (5), made up of carriageways of 2 and 3 lanes and served with exclusive tram lane. Via Prenestina was chosen due to its importance and severe traffic congestion during the peak hour.

Fig 2. Study area Via Prenestina (a) Sketch of 5 intersections, (b) Microsimulation with dedicated bus lane and pre-signal

2. Operation of the pre-signal

The presignal system triggers a signal that turns red for private vehicles, allowing buses to pass through the intersection smoothly and without delays, while private vehicles must stop at the pre-signal. Initial signal settings for pre-signal is set to green for all three lanes (during the warm up time). As the bus is detected upstream of the pre-signal , the command is sent to the pre-signal and the operation is described in the Fig. 3. Note that the loop detector should be far enough such that the pre-signal could operate in due time for changing the settings in a way that bus movement does not interrupt.

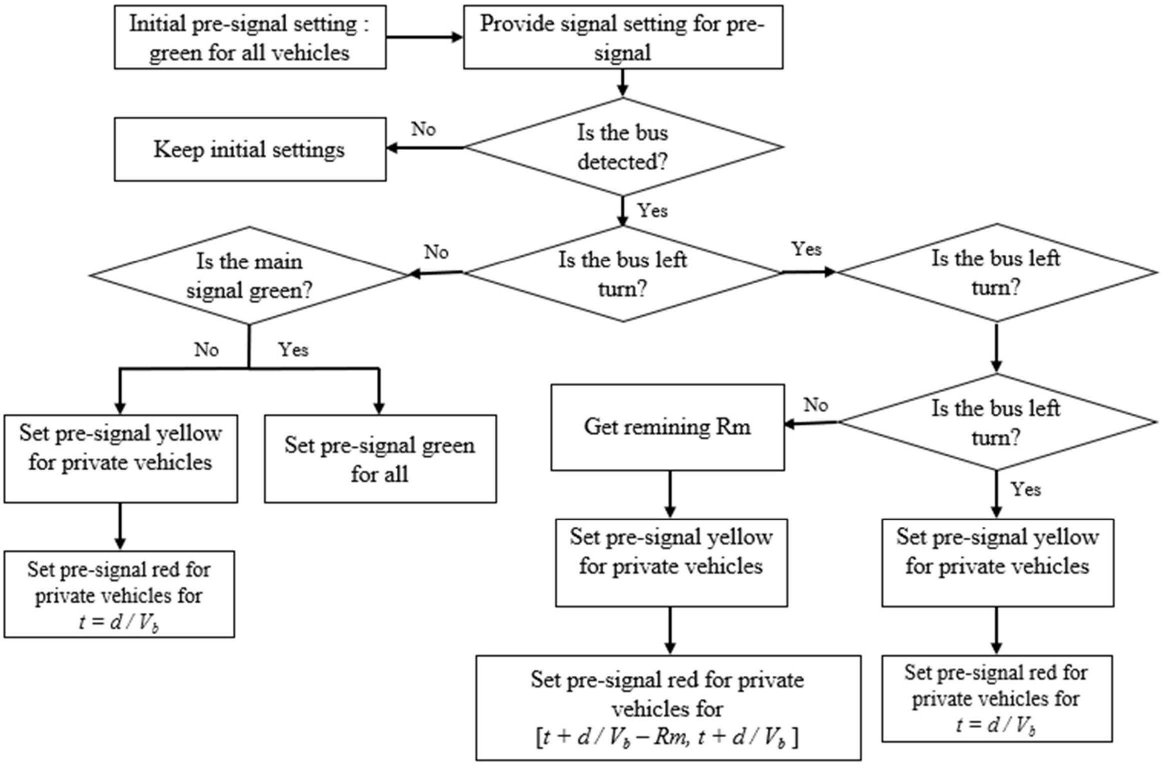

Fig 3. Flow chart for the operation of the pre-signal

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.

3. Methodology

The pre-signal system triggers a signal that turns red for private vehicles, allowing buses to pass through the intersection smoothly and without delays, while private vehicles must stop at the pre-signal. To assess the efficiency of the system and explore the impact of different variables affecting its performance in a realistic case, a microsimulation approach was utilized to determine the optimal location of the pre-signal considering different factors**,** such as traffic speed, intersection capacity. An additional crucial element to consider is the clearance time required for left-turning buses, as their movement is no longer linear, and the curvature of their maneuver must be taken into account. Above all, minimizing the objective function in the case of presence of multiple buses approaching the intersection while the main intersection is in the red phase. In this study, we have simulated different scenarios of a network with different flow and saturation rates in a micro simulator to have a more comprehensive formulation.

3.1. Distance Calculation

For the reader's convenience, a list with the notation used in this article is summarized in Table 2.
In this paper the distance $\boldsymbol{d}$ refers to the distance between pre-signal and the main signal. If the pre-signal is located far from the main signal, it may cause safety problem for the users due to the fact that it may not provide sufficient warning to drivers to adjust to adjust their speed and prepare to stop. This can lead to a higher incidence of red-light violations and accidents. On the other hand, if the pre-signal is positioned too close to the intersection, it may not provide enough space for buses to queue up and make their way through the intersection, which could result in delays and congestion. Additionally , the distance $\boldsymbol{d}$ must provide enough space to saturate the main signal when it is in green phase. In fact the pre-signal should not cause an additional delay to private vehicles during cycles where no bus is approaching and ensure that the last vehicle from the pre-signal must pass the main signal during the same cycle. Having said these limitations , the boundaries were defined as following : the minimum acceptable distance is given by :

$$\begin{cases} d = Clearance\ time\ * V_{max} \\ Clearance\ time = \frac{Bus\ length+art\quad width}{V_{max}} + Safety\ Factor \end{cases} \tag{2}$$

However, as mentioned before this doesn't consider the extra delay to cars or safe braking of the platoon in case of facing red at the main signal. So in the reality the distance would be higher than what is resulted from the formulation above. We have considered the maximum acceptable distance given by Guler and Menendez et al. (2015):

$$d = \frac{G\mu}{K_{jam}} \tag{3}$$

List of notation	
M	Main signal
P	Pre-signal
O	Loop detector
G	Effective green time duration of the main signal [s]
d	Distance MP
μ	Capacity of a single lane [veh/s]
K_{jam}	Jam density of a single lane [veh/m]
R_m	Red time duration of the main signal
V_b	Bus velocity

Table 1 . List of notations

3.2. Objective function formulation

The pre-signal is located at the distance $\boldsymbol{d}$ from the main signal. The objective function corresponds to sum of multiple terms in the most delayed scenarios (worst case scenario) where the red at the main signal is about to end and the first bus arrives at the pre-signal (t_0), at this point the pre-signal is still red, indicating that cars should stop and allow the bus to approached to the advanced area, then the second bus arrives with the time gap t_{gap} ($t_2 < \delta\ t_1$) after the first bus, t_1 is equal to d/V_b in this case, 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. After positioning of the buses at the beginning of the queue at the main signal, the pre-signal can turn green to allow private vehicles to reach the stop line. However in this case some considerations need to be taken into account. The clearance time (t_c) which corresponds to the clearance time of the car queue should be added to the extension of the red duration of pre-signal to have the bus advanced area free of cars when the bus arrives. Such an extension should be partially superimposed to the red at the beginning of main signal's green. To avoid any possible interference in case of queue overflow the worst case assumes these two times are simply added. Optimization of this objective function will respect to the elements mentioned, find the optimal ***d*** where not only the bus delays are minimized but also the additional delay both for second buses and the queue of vehicles is considered see Fig. 4.

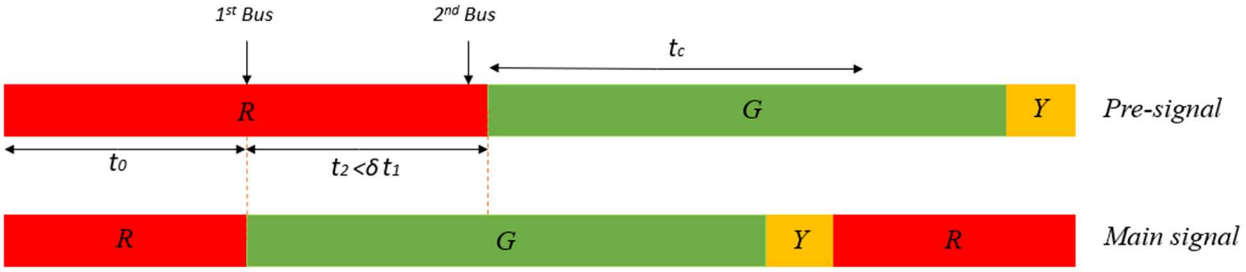

Fig 4. Bus arrivals with respect to the pre-signal and the main signal cycle

41 out of 72 total simulations scenarios were selected to find the optimal placement of the pre-signal. The objective function is as follows:

$$minimize\ T = \left[\frac{d}{V_{max}}\right] + \left((n-1) * t_{gap}\right) + \left(\frac{L}{flow_{rate}}\right) \quad (1)$$

Term	Formulation	Definition
Travel Time	$\left[\frac{d}{V_{max}}\right]$	The travel time from the pre-signal to the main signal
Time gap	$\left((n-1) * t_{gap}\right)$	The time gap between the buses, where $(n-1)$ is the number of buses ahead of the current bus and t_{gap} is the minimum allowed time gap between buses
Additional delay (Clearance time)	$\left(\frac{L}{flow_{rate}}\right)$	Represents the time spent waiting in the queue behind the main signal, where L is the length of the queue and $flow_{rate}$ is the saturation flow rate of the main signal

Table 2. Objective Function

3.3. Distance Optimization

In order to determine the optimal distance, an empirical approach was employed. A simulation of the corresponding network was conducted, considering the defined demand. Starting from an initial distance of 58 meters from the main signal, the value of T was evaluated for 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 optimal distance was determined to be 108 meters from the main signal. It is important to note that distances exceeding 118 meters were deemed unacceptable based on formula 3.These findings highlight the importance of balancing safety considerations, efficient traffic flow, 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.

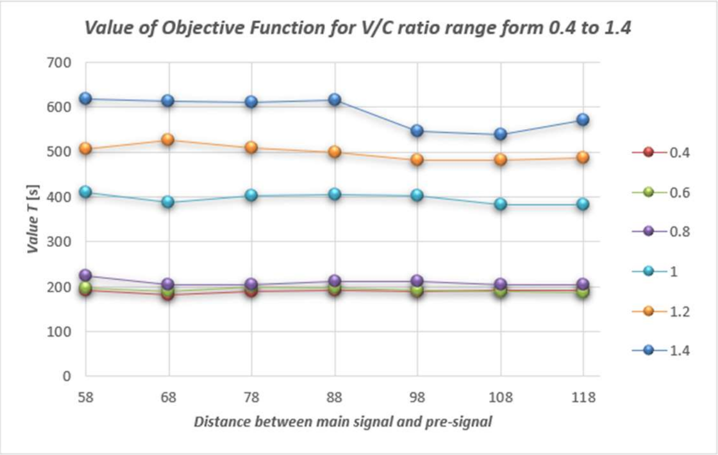

Fig 5. Value T for V/C ratio range 0.4 to 1.4

It can be clearly seen in the 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 minimum value T corresponds to higher d , being 108 meters the minimum value. Since the network normally deals with a range of volume during the day , we opt the 108 meters as our desired distance.

4. Boundary condition and effectiveness of each strategy

Examining the delays experienced by cars and buses individually, Fig. 6 illustrates that, as expected, the continuous bus lane strategy leads to significantly greater car delays compared to the other two strategies, although it consistently produces the smallest average delay for buses. 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.

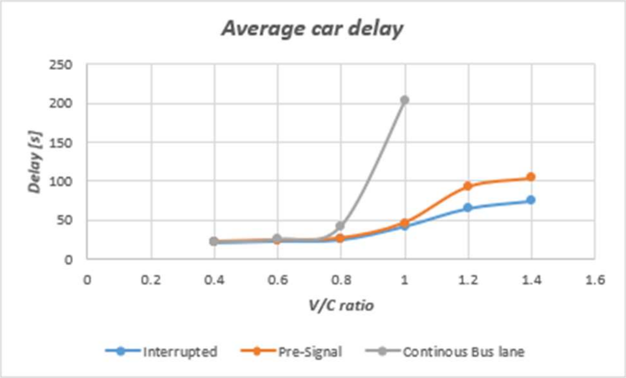

Fig 6. Average Car delay for range of V/C ratio from 0.4 to 1.4

4.1 Sensitivity to bus frequency

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 will shift 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 2 minutes, 4 minutes, and 6 minutes, respectively.

Within our study, the main artery is served by two types of buses: equally divided between those making through movements and those making left turns.

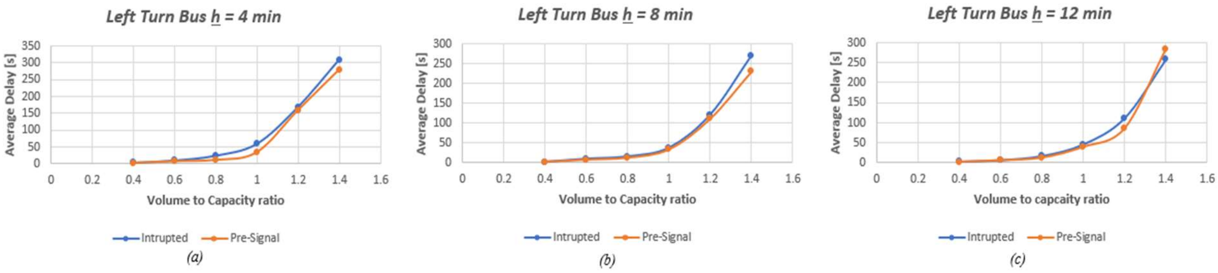

Fig 7. Average left turn bus delay vs V/C ratio. a) headway = 4 min, b) headway = 8 min, c) headway = 12 min

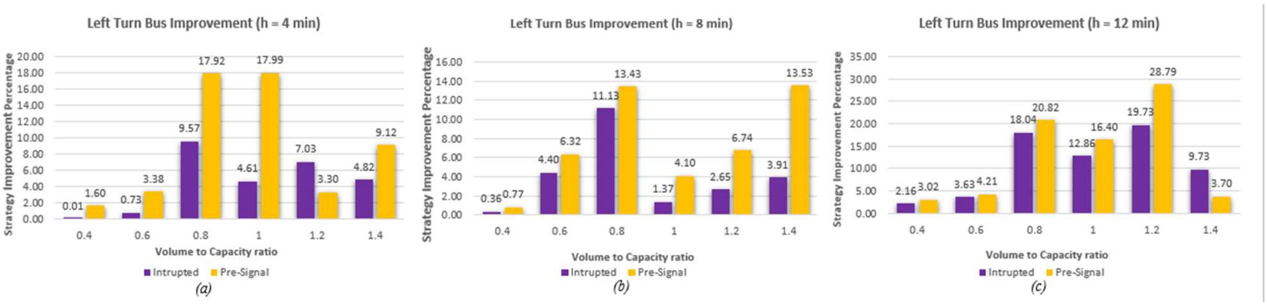

Fig 8. Delay improvement of left turn buses vs V/C ratio. a) headway = 4 min, b) headway = 8 min, c) headway = 12 min

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.

5. 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 formula 3, 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.

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