Advanced Techniques for Transit Priority at Roundabouts Utilizing Signal Metering

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Received: 29 December 2024 | Revised: 10 February 2025 | Accepted: 14 February 2025

DOI: https://doi.org/10.48084/etasr.9863

ABSTRACT

Transit priority strategies frequently focus on conventional Transit Signal Priority (TSP) at intersections, overlooking the distinct operational characteristics of roundabouts, including signalized, metered, and yield-based control methods. This study introduces a new approach, Transit Metering Signal Priority (TMSP), which uses metering signals to provide Public Transport Vehicles (PTVs) preference at roundabouts. A distinguishing feature of TMSP is its compatibility with the existing yield or metering control strategies employed by roundabouts, allowing them to maintain these methods without the full signalization of all approaches for priority allocation to PTVs the latter involves. The efficacy of the proposed TMSP model is assessed through numerical experiments, with yield control (no priority) serving as the baseline. Comparisons are drawn between conventional TSP and TMSP scenarios under varying congestion levels. The findings suggest that the proposed TMSP logic can lead to a reduction in bus delays by 2 sec to 16.6 sec, with minimal impact on general traffic, while also decreasing travel time variability by up to 19 sec (standard deviation). In comparison to TSP, TMSP exhibits clear advantages for public transportation by reducing delays and providing more stable travel times, while minimizing disruptions to the general traffic flow. The implementation of the TMSP method enhances the performance and reliability of public transport services, contributing to the development of more resilient and sustainable urban mobility systems.

Keywords-public transport; roundabout metering; smart mobility; transit metering signal priority; transit signal priority

I. INTRODUCTION

Public transportation plays a crucial role in achieving sustainable mobility and reducing traffic congestion in urban areas. A fundamental aspect of advancing sustainable mobility solutions is encouraging a shift from private vehicles to public transport. However, users make self-advantageous travel mode choices, selecting options that maximize their utility within their abilities and needs. Some of the key determinants influencing mode choice include travel time and reliability [1-7]. Transit services operating in mixed-traffic environments face challenges in competing with private vehicles due to the additional time spent serving passengers at stops, including dwelling, drop-off, and pick-up times. Consequently, transit priority along mixed-traffic routes is essential for PTVs to compete with private vehicles, particularly in terms of travel time and reliability. A prominent priority strategy is TSP, which involves the control of signalized intersections to give priority to PTVs. Signalized intersections are known as bottlenecks in urban traffic, so the expeditious movement of PTVs at these locations is imperative to enhance public transportation services and their competitiveness with private vehicles. Transit priority applications are categorized as space-based, time-based, or combined approaches. The space-based approach entails the implementation of exclusive bus lanes, a strategy that has yielded positive outcomes but is often constrained by geometric and capacity limitations [8-10]. Conversely, the time-based approach, exemplified by TSP, prioritizes PTVs at signalized intersections by adjusting signal timing to minimize delays. A comprehensive review of the extant literature reveals that numerous studies have explored and evaluated TSP methods for conventional intersections (i.e., crossroads) [11-15]. Existing TSP methods can be classified into two categories: passive and active. Passive TSP adjusts signal timing based on historical data but does not detect PTVs in real time [16, 17]. In contrast, active TSP detects PTVs and provides priority either unconditionally (absolute priority) or conditionally based on predefined criteria. Conditional priority has been shown to balance transit benefits while minimizing disruptions to general traffic [18-20]. A multitude of studies have evaluated TSP strategies based on factors, such as bus delay reduction, general traffic impact, corridor throughput, and Total System-wide Passenger Travel (TSPT) time [21-25].

Advanced TSP strategies do not differentiate between intersections and roundabouts, not considering that although a roundabout is a type of intersection, its operational and geometric characteristics differ significantly. Unlike conventional intersections, roundabouts can be safely operated with yield rules at all traffic volume levels due to their unique geometric characteristics. The distinct geometric design elements of roundabouts, such as the central and splitter islands, contribute to a reduction in conflict points, decreased entry speeds, and less severe potential accidents [26–29]. Conversely, previous studies have indicated that the conversion of signalized intersections to roundabouts can lead to a substantial reduction in traffic delays [30–33]. Additionally, it was emphasized that roundabouts, particularly non-signalized ones, exhibit a more significant reduction in delays when compared to their signalized alternatives. This enhancement is ascribed to their continuous flow configuration, which minimizes the necessity for vehicles to come to a complete stop. However, while roundabouts generally result in reduced delays and enhanced traffic flow, these advantages tend to wane as traffic volumes escalate considerably [34]. Nonetheless, signalizing a roundabout is recommended only under exceptional circumstances, particularly in instances involving high traffic volumes or imbalanced flow conditions [35-38]. Consequently, a hybrid approach, integrating signalized (or metered) control during periods of peak traffic and reverting to traffic rules during other times, may be a viable solution in certain situations. Traditional TSP strategies effectively manage the flow of PTVs at intersections; however, their efficacy becomes questionable when applied to roundabouts. This is due to the fact that fully signalizing all roundabout legs is necessary to implement conventional TSP for PTVs, which may not offer the same benefits as in signalized intersections. Therefore, this study aims to enhance TSP control strategies to improve public transport service at roundabouts while preserving their inherent advantages and operational characteristics. TMSP creates controlled entry gaps for PTVs, improving their travel times while minimizing delays for general traffic. The effectiveness of TMSP is evaluated through microsimulation experiments under various congestion levels. As roundabouts are increasingly adopted worldwide, further research into roundabouts and their integration into all aspects of urban transportation systems is essential. This study seeks to address this need by evaluating the effectiveness of a novel transit priority control strategy, TMSP, which employs metering signals to prioritize PTVs without fully signalizing the roundabout.

II. METHODS

This study proposes TMSP, a new roundabout transit priority technique that uses metering signals to provide better traffic flow of the PTVs, by creating gaps in the circulating stream [40]. However, in the case of TMSP, the metering objective also includes reducing the travel time of PTVs through the roundabout. Figure 1 shows the model structure, which proposes a system that integrates TMSP, a novel transit priority strategy, with existing TSP strategies, such as green extension and early green. The core of the proposed system consists of three key components: priority rules, priority strategy, and parameter constraints.

A. Priority Rules

It has been observed that TSP and TMSP are not equivalent to emergency vehicle pre-emption [41]. Consequently, not all calls from PTVs to the control center are converted to actual immediate priority, and some calls are denied based on the existing rules. The rules for signal priority are determined by the objectives of the transit urgency system and the available operational technology for signal control. In the proposed framework, priority requests for PTVs were evaluated in two rule layers before implementation.

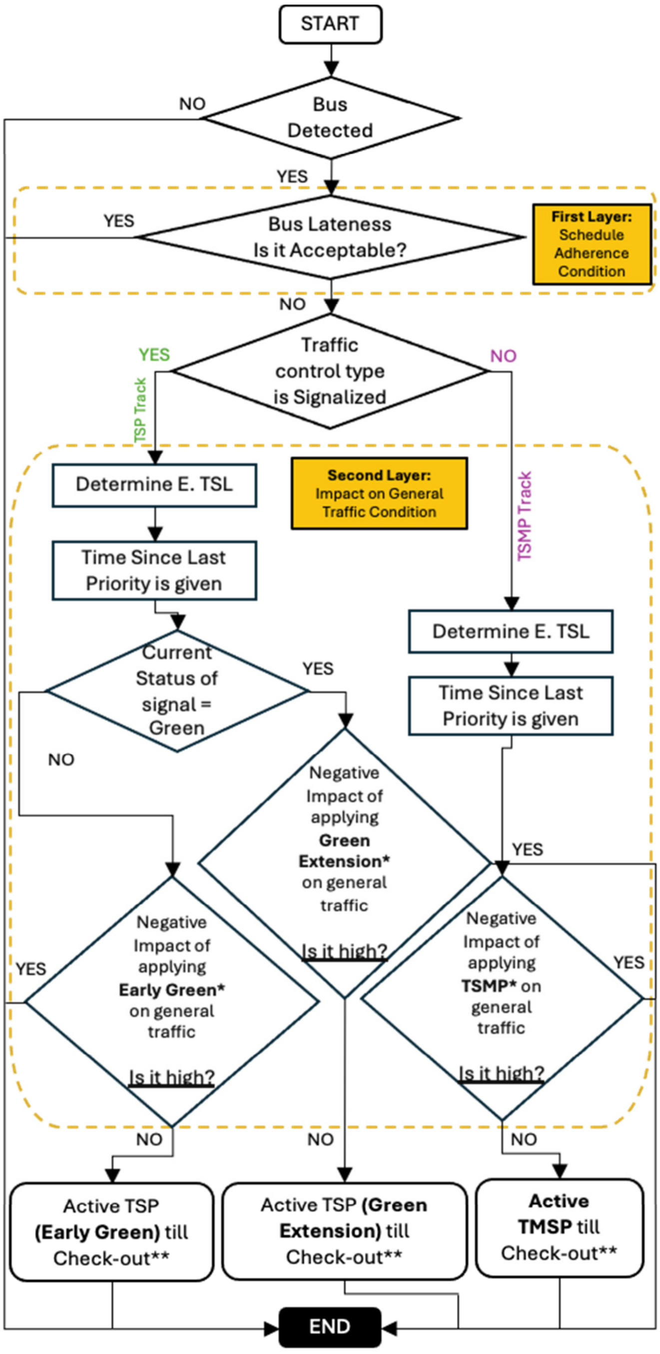

Fig. 1. Model structure.

The initial layer is the conditional priority criterion, which ensures that a call is rejected if it does not fulfill control conditions that are typically based on actual schedule adherence. Conditional active priority is a schedule comparison, and thus, a priority request for a PTV is granted only if the PTV's delay from the scheduled arrival time to intersection is higher than the time condition set to the signal priority. The second evaluation layer considers the impact of transit-priority treatments on non-transit and pedestrian traffic. For instance, if a call for TSP or TMSP significantly worsens the overall traffic congestion, it will be delayed. This layer relies on three components: the time required for PTV to reach the stop line, the level of congestion at the roundabout, and the available priority strategies. The operator's judgment in evaluating the conditions is crucial, and the implementation of all conditional layers is not obligatory.

B. Priority Strategies

The proposed system integrates TMSP with existing TSP strategies to ensure efficient service provision throughout the day, as seen in Figure 1. When roundabout entrances are fully signalized, conventional TSP strategies can be implemented using the available TSP control options. Various TSP strategies have been developed and implemented globally, including green extension, red truncation, phase rotation, and phase insertion. Green extension and red truncation are the most commonly used TSP applications in several countries. While green extension assists a limited number of PTVs, red truncation yields greater benefits [14]. However, red truncation's effectiveness is inferior to that of green extension for PTVs. Consequently, the integration of multiple TSP strategies at a single intersection has emerged as a prevalent approach to enhance the benefits of TSP. Moreover, the implementation of the TMSP strategy is contingent upon the roundabout's operation based on yield rules or metering strategies. In the case of active TMSP, roundabout approaches (entrances) operate in either controlled or metered mode. Once a transit priority request is accepted, the signals on the conflicting approaches transition to metering mode, while the transit approach shifts to controlled mode. In a controlled approach, the signal for the transit approach remains deactivated (blank) until the PTVs pass the checkout detector or the priority period reaches its maximum. During this period, drivers are obligated to adhere to yield regulations at the roundabout, decelerate before reaching the yield line, and wait for a safe opportunity to enter. In contrast, the metering approach (non-transit approach) functions as a standard roundabout metering signal, cycling between blank and red, with the light completely turning off (blank) briefly before turning red again. Drivers must adhere to the yield rules when the traffic signal is blank; once the signal turns red, entering the roundabout is strictly prohibited. It is important to note that the stop line for the metering signal must be positioned at least 3 meters ahead of the yield line [40]. The metering of all conflicting approaches to the PTV's approach results in fewer intersections and larger gaps, allowing the PTV (and vehicles in its approach) to travel through the roundabout more efficiently and smoothly. This configuration facilitates expedited service for the PTV without entirely obstructing the entry of opposing movements, leveraging the distinct geometric design of roundabouts.

C. Parameter Constraints

The design of an effective metering system requires the specification of essential parameters, including the metering cycle, blank interval, and length of the priority period. These parameters must be carefully calibrated within operational constraints to achieve a balance between prioritizing PTVs and maintaining acceptable service levels for general traffic. Once these constraints are met, adjustments can be made, provided that the maximum queue length is not exceeded.

1) Blank Interval

The blank interval must take into account the minimum time required for a vehicle to cross the stop line toward the yield line. This can be expressed as:

$$C - r \geq l_s + d_s \tag{1}$$

where C is the total metering cycle length, r is the red interval duration, l_s is the start-up loss time, and d_s is the discharge time for a vehicle. The red time ratio, defined as the proportion of each metering cycle assigned to the red interval, constitutes a significant component in the management of traffic circulation patterns at roundabouts. Increasing the red time ratio results in a reduction in entry for conflicting traffic, thereby enabling unobstructed passage for prioritized PTVs with minimal delays. However, it is important to note that a higher red time ratio concurrently leads to a decrease in the service time for the conflicting traffic phase. This aspect necessitates meticulous management to avert instances of excessive queueing.

2) Length of Priority Period

The length of the priority period, designated as p_p, must not be shorter than the Estimated Time to Stop Line (ETSL) for PTVs. When a priority strategy is anticipated to fully benefit PTVs, it should be no shorter than the estimated travel time from detection to the stop line [42, 43].

$$p_p \geq \gamma \cdot ETSL \tag{2}$$

where γ is a variability factor that accounts for fluctuations in travel time. The estimation of ETSL involves several key variables. First, the Bus Position (BP) data, obtained through high-frequency GPS, provide real-time updates on the PTV's location. The queue length at the stop line (Q_L) can be estimated using various approaches, including the shockwave theory [44], historical cycle data [45, 46], multi-camera systems [47], and connected vehicle data, which offer near real-time information [48-49]. This study used camera detection to effectively monitor queue length. Finally, the vehicle discharge rate (D_r) at the stop line is critical for calculating queue clearance times, and this rate can be measured continuously deploying modern detection technology to track vehicle flow and occupancy. Together, these variables enable a precise calculation of ETSL:

$$ETSL_i = Max\left\{\frac{\mathrm{D}_{St} - Q_L}{V_{PT}}, \frac{Q_L \cdot D_r}{S}\right\} \tag{3}$$

where D_{St} is the distance from the yield/stop line, Q_L is the estimated queue length, V_{PT} is the estimated velocity of the

PTV, and S is the distance between the identical locations of two consecutive vehicles in a queue.

3) Queue Length Management

In certain cases, the queue length must be closely monitored in proximity to roundabouts to prevent upstream traffic movement. The queue length is influenced by the metering cycle, the blank interval, the length of the priority period (P_p), and the discharge rate at the entrances. Equation (4) provides a constraint that can be integrated into the parameter setting of the metering approach:

$$\left[\frac{v}{3600\,n}\cdot Int\left(\frac{p_p}{C}\right)\cdot r\right]-\left[Int\left(\frac{p_p}{C}\right)\cdot Dv_g\right]\leq Q_L max \qquad (4)$$

where v is the volume of approaching vehicles per hour, n is the number of lanes, C is the cycle length, r is the red interval length, Dv_g is the expected number of vehicles discharging in each cycle, $Q_L max$ is the maximum allowable queue (vehicles per lane), and *Int* is an integer function that rounds the value to the nearest highest integer.

III. EXPERIMENTAL SETTINGS

A number of studies have employed microsimulation models to evaluate the efficiency of transit priority [50-53], a methodology that is also appropriate for the present study. The proposed methodology was evaluated in VISSIM, a microscopic traffic simulation environment [54], and modeled on a 15-kilometer-long network, as depicted Figure 2. The models included three roundabouts and signalized intersections. The implementation of the strategies was conducted at the intersection of Omar Bin Al-Khattab Road and King Abdullah Street in Medina, KSA (study site).

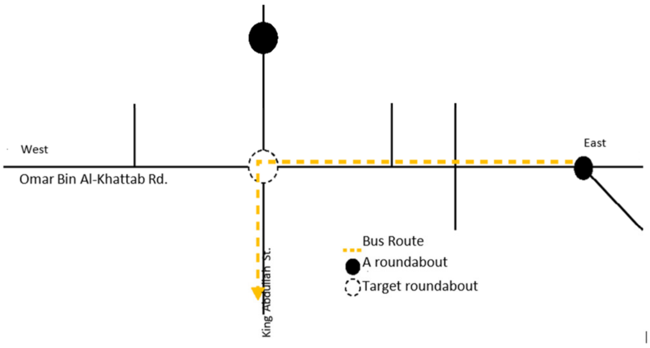

Fig. 2. Layout of the study site (Medina, Saudi Arabia).

The ratio of the turn movement profile was obtained from a field study, and the volumes were modified (increased and decreased) to generate various scenarios. Intersection Capacity Utilization (ICU) was employed to denote the level of congestion [55]. To assess the model's performance under adverse circumstances, six distinct ICU ratio scenarios (0.65, 0.75, 0.85, 0.90, 0.95, and 1) were created for each case, with three control strategies (TSP, TMSP, and yield) having beenintegrated into the experiment. The base case scenario involves a yielding control strategy, where the roundabout is unsignalized. Conversely, a consistent demand level was employed for the bus route to minimize the bias between the compared scenarios. The regularity of the scheduled headway for buses was 10 sec, with a frequency of six buses per hour. The bus routes made left turns at the roundabout, as seen in Figure 2, and a green extension of 15 sec was permitted for TSP. The TMSP cycle length was set to 15 sec, with 12 sec of red light for an ICU lower than 0.9. For an ICU of 0.9 and above, the cycles were set to 8 sec, with 5 sec of red light and Pmax was set to 20 sec. Each scenario was simulated twenty times, and the results were reported for the 60-min simulation that followed a 10-min warm-up for each run. Signal control was modeled using the program logic of the VAP signal controller. In addition, the integrated COM interface of VISSIM with Python programs was employed to assess the performance of the models. In the experiment several parameters were selected from regional research to calibrate driver behavior in the model [56], rather than conducting field measurements because this is not within the scope of the current study.

IV. RESULTS AND DISCUSSION

The data used for the evaluation included bus delay, general traffic delay, and bus travel time variability under each combination of ICU and control strategies. As illustrated in Figure 3, the change in vehicle delays for general traffic and buses is compared between TSP and TMSP with yield control across various scenarios. With respect to the general delay, the relationship is inversely positive with increased levels of congestion. TMSP has been shown to result in a decrease in bus delays compared to the baseline cases by 2.0 sec, 2.2 sec, 6.6 sec, 8.7 sec, and 12.5 sec at ICU levels of 0.65, 0.75, 0.85, 0.90, and 0.95, respectively. Concurrently, the average increase in delay for general traffic remained minimal, falling below 3 sec. However, under the condition that the ICU reaches 1.0, indicating a saturated intersection, metering exerts a modest influence on general traffic, with a marginal 6-sec increase, while bus delays undergo a substantial reduction of 17 sec. The efficacy of bus prioritization becomes more evident under conditions of intensifying congestion [57]. While TSP is widely anticipated to curtail bus delays under diverse conditions [58], this study finds that such reductions occur only under specific conditions. TSP reduces bus delays only when the ICU level is 0.9 or higher, with benefits increasing as the ICU level rises, resulting in a maximum decrease of 6 sec at an ICU of 1. In terms of its impact on general traffic, delays increase by 10 sec to 13 sec when ICU levels range from 0.65 to 0.9. As the ICU approaches 0.95, delays rise to 31 sec, reaching a peak of 73 sec at an ICU of 1. These findings indicate that while TSP can enhance bus transit times at higher ICU levels, it does not uniformly accelerate bus traffic and may potentially exacerbate general traffic delays.

The effectiveness of TSP can be attributed to the conversion of roundabout entrances into signalized configurations, a prerequisite for TSP implementation. Previous studies indicate that signalizing roundabouts generally increases traffic delays, deviating from the expected efficiency of the original yield-controlled configuration. Consequently, decision-makers must consider the trade-offs involved in implementing TSP, as although TSP may improve bus traffic, the advantages of maintaining a non-signalized roundabout often outweigh the benefits of TSP. In contrast, the maximum increase in general traffic delay with TMSP was 6 sec at ICU of 1, resulting in a 17-sec reduction in bus delay.

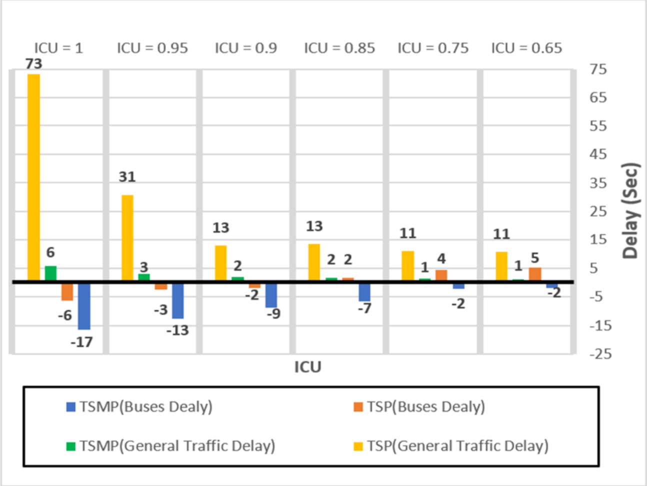

Fig. 3. Change in vehicle delays for general traffic and buses: comparison of TSP and TMSP versus yield control under multiple scenarios.

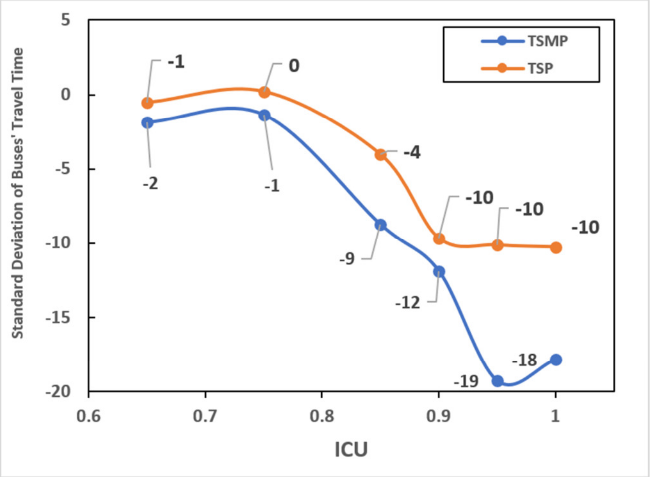

Fig. 4. Change in the standard deviation of the travel time for buses passing through the targeted roundabout, compared to the yield control case.

In all cases, the impact on general traffic was greater with TSP than with TMSP. In addition to travel time delays, service reliability is critical for transit operators and users [59-61]. Reliability exerts a negative influence on the mode choices of travelers and has financial consequences for transit agencies. Figure 4 provides an evaluation of travel time variability by showing the Standard Deviation of Travel Time (SDTT) of the bus, through the roundabout in comparison with the base case. Authors in [62, 63] reported that TSP reduces bus running time variability, and this experiment corroborates that finding. Meanwhile, the results indicate that TMSP reduced the travel time variability for the bus through the roundabout area in all cases, even more than TSP. A consistent pattern of reduced travel time variability emerged across all evaluated priority scenarios, hence highlighting the robustness of these strategies for enhancing transportation efficiency. The TMSP strategy exhibited a substantial decrease in SDTT, with reductions ranging from modest values of 1.9 and 1.4 at lower ICU levels of 0.65 and 0.75 to more substantial declines of 19.2 and 17.8 at ICU levels of 0.95 and 1, respectively.

In summary, the results indicate that the difference in average delays between the conventional TSP strategy and the proposed TMSP is significant across various congestion levels (ICU), favoring the TMSP for public transport and general traffic. Furthermore, the TMSP improves the reliability of public transport's travel time, highlighting its adaptability and effectiveness under both mild and severe congestion scenarios. The consistent performance of the TMSP strategy suggests that urban planners and traffic authorities should consider adopting such a strategy to optimize bus travel times in areas near roundabouts.

V. CONCLUSIONS

The present study proposes a methodology for the prioritization of Public Transport Vehicles (PTVs) passing through a roundabout. This methodology uses a novel framework that integrates Transit Signal Priority (TSP) with a new method called Transit Metering Signal Priority (TMSP). The TMSP is designed to meter a roundabout entrance to prioritize PTV movements. This study deployed a signal-metering strategy for the prioritization of PTVs at roundabouts and the efficacy of the proposed control framework was assessed through a microsimulation environment in VISSIM, using a roundabout model based on a real-world scenario in Medina, KSA. The experiment compared two traffic signal control strategies: Transit Signal Priority (TSP) and TMSP. These strategies were evaluated against the conventional yield-control approach through a sensitivity analysis covering seven distinct levels of traffic congestion. As congestion levels increased, the difference between the TSP and TMSP strategies became more evident. The impact of the TMSP strategy remained stable and positive for buses across varying congestion levels, without causing substantial delays for general traffic. Furthermore, TMSP led to a reduction in running time variability for buses navigating roundabouts, suggesting a potential enhancement in bus service reliability. According to the findings of this case study, the TMSP strategy resulted in a reduction of up to 17 sec in bus delays per roundabout. In contrast, the TSP strategy exhibited improvements only at higher congestion levels (ICU ≥ 0.9) and was less effective under moderate conditions. TMSP exhibited a maximum impact on regular traffic of 6 sec, significantly less than the 73 sec increased by TSP. Additionally, TMSP reduced the running time standard deviation by up to 19 sec, while TSP demonstrated smaller improvements and greater variability in effectiveness across congestion levels. In conclusion, the proposed method offers distinct advantages over TSP for public transportation vehicles, as it reduces delays and travel time variability while exerting the minimal negative impact on general traffic. Additionally, the proposed TMSP framework is adaptable to both centralized and decentralized control, making it a flexible solution for various urban traffic conditions. Future research should further examine this approach, considering different transportation facilities and scenarios.

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