Final Report

Assessing the Feasibility of Deploying Transit Signal Priority with Connected Vehicle Technology

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Date
October 2025

Prepared for the Safety and Mobility Advancements Regional Transportation and Economics Research (SMARTER) Center, Morgan State University, CBEIS 327, 1700 E. Coldspring Lane, Baltimore, MD 21251

ACKNOWLEDGMENT

This research was supported by the Safety and Mobility Advancements Regional Transportation and Economics Research (SMARTER) Center at Morgan State University and the University Transportation Center(s) Program of the U.S. Department of Transportation.

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, under grant number 69A3552348303 from the U.S. Department of Transportation's University Transportation Centers Program. The U.S. Government assumes no liability for the contents or use thereof. A version of this report was presented and published at the 10th International Conference on Vehicle Technology and Intelligent Transportation Systems 2024 in Angers, France.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Assessing Feasibility of Deploying Transit Signal Priority with Connected Vehicle Technology

5. Report Date

6. Performing Organization Code

7. Author(s) *Include ORCID #*
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8. Performing Organization Report No.

9. Performing Organization Name and Address
University of Virginia, Morgan State University

10. Work Unit No.

11. Contract or Grant No.
69A3552348303

12. Sponsoring Agency Name and Address
US Department of Transportation
Office of the Secretary-Research
UTC Program, RDT-30
1200 New Jersey Ave., SE
Washington, DC 20590

13. Type of Report and Period Covered
Final,

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
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17. Key Words:
Transit Signal Priority, Connected Vehicles, Bus Priority

18. Distribution Statement

19. Security Classif. (of this report) :	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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1 INTRODUCTION

Transit Signal Priority (TSP) is a technology that enables changes in traffic signal cycles to prioritize the movements of various transit modes (Garrow and Machemehl 1999). TSP has been used as a traffic control strategy in U.S. cities since the 1970s to maintain public transit reliability amid growing congestion in metropolitan areas. During this time, developments in TSP have largely focused on improving transit efficiency at signalized intersections (Imran et al. 2021; Lin et al. 2015). Two of the most widely adopted approaches are Green Extension (GE) or Early Green (EG) and Green Time Reallocation (GR), both of which modify signal timing to facilitate the movement of transit vehicles such as buses or trams.

Green extension or early green is one of the earliest and simplest forms of TSP, designed to prolong the current green phase when a transit vehicle is detected approaching the intersection. When a priority request is made near the beginning or end of a green interval, the controller extends the green duration or starts the green phase early for a predefined maximum time to allow the transit vehicle to pass safely through the intersection without stopping (Ahn and Rakha 2006; Xu et al. 2016; Seredynski and Khadraoui 2014). This strategy is advantageous due to its ease of implementation, minimal disruption to other approaches, and relatively low computational requirements. Despite these enhancements, GE remains constrained by its reactive nature and inability to reallocate green time from other phases dynamically, which limits its effectiveness in congested or highly variable traffic environments.

Green Time Reallocation extends beyond simple green prolongation by redistributing green time from other signal phases to grant priority to the approaching transit vehicle (Hu et al. 2014). This can be achieved by shortening non-priority phases or adjusting the start and end times of green intervals within a signal cycle. Different GR approaches have been proposed to address different objectives, which have historically included reducing bus travel time, minimizing person delay, or balancing the impacts on cross-street traffic. For instance, several studies (Kim and Rilett 2005; Han et al. 2014; Anderson and Daganzo 2020; Wu et al. 2023) introduced advanced TSP control methods that incorporate multiple objective functions and account for dynamic traffic conditions. These models often utilize predictive techniques, including bus arrival time estimation and adaptive signal timing adjustments, to provide more responsive and efficient priority control. Another significant area of research focuses on managing conflicting priority requests, which is a critical challenge in real-world TSP implementation. When multiple transit vehicles simultaneously request priority at an intersection, decision-making mechanisms are required to resolve conflicts without causing excessive disruption to general traffic flow. Studies such as (He et al. 2014; Xu et al. 2016; Ye and Xu 2017) proposed multi-criteria decision frameworks and multi-agent control schemes to determine which vehicle should be granted priority based on factors like estimated delay reduction, service schedule adherence, and overall system benefit.

The widespread adoption of connected vehicle (CV) technology enables more comprehensive TSP algorithm development by making real-time information readily available and easily shared between systems (Li et al. 2019). Early studies (Yang and Fan 2023) integrating CV technology into TSP focused on improving detection and communication reliability. Compared to conventional detection, CV-enabled systems significantly reduce latency in priority activation and improve prediction accuracy for bus arrivals at stop bars. With advancements in vehicular and infrastructure technology, researchers now have access to detailed traffic data at both microscopic and network-wide levels. This integration of hardware, software, and data has enabled the development and implementation of more dynamic TSP algorithms and systems, allowing for real-time adaptability and enhanced traffic management. Subsequent research explored predictive TSP algorithms leveraging connected data (Yang et al. 2019; Zeng et al. 2021; Cvijovic et al. 2022; Kim et al. 2024).

Despite these advancements, existing TSP research still faces several limitations. First, most studies primarily emphasize bus arrival prediction between stops without fully leveraging accurate arrival estimations at intersections, which are crucial for making precise priority decisions. While prior work has demonstrated the potential of CAV applications in optimizing TSP, it does not fully explore how intersection-level prediction accuracy could enhance the reallocation of green time and minimize disruption to other traffic. Second, many CV-based TSP algorithms lack adaptive mechanisms that can dynamically respond to real-time traffic states and varying market penetration rates. Static or rule-based green time reallocation methods cannot optimally balance transit priority with overall traffic efficiency, especially under mixed traffic conditions with partial connectivity. Furthermore, few studies have considered strategies to mitigate the negative impact of granting priority, such as compensating other approaches after a TSP request, which is essential for maintaining fairness and minimizing total person delay.

To address these gaps, this paper proposes a dynamic green time reallocation strategy enhanced with an optional compensation mechanism. Leveraging connected bus arrival estimation and CV data, the proposed method dynamically adjusts green time allocations and provides targeted compensation to non-prioritized approaches. This approach improves TSP success rates, reduces bus delays, and minimizes system-wide person delays. The contributions of this paper are summarized:

1. Developed an adaptive TSP control method that dynamically reallocates green time in real time based on CV data for queue length estimation and connected bus arrival time estimation.
2. Introduced a novel compensation strategy that reallocates green time to previously deprived approaches after granting TSP priority, ensuring fairness and minimizing negative impacts on cross-street traffic.
3. Leveraged CV information to enhance the accuracy and efficiency of TSP decisions and demonstrated significant improvements in the bus delay and total person delay over no connectivity.

The remainder of this paper is organized as follows. METHODOLOGY details the proposed methodology, outlining the system architecture, connected bus arrival prediction model, and the design of the dynamic green time reallocation algorithm with an optional compensation mechanism. EXPERIMENTAL SETUP describes the experimental setup and simulation framework used to evaluate the proposed approach. RESULTS AND ANALYSIS presents the results and analysis, comparing the performance of the proposed method with conventional TSP strategies with and without connected vehicles. CONCLUSION AND FUTURE WORK concludes the paper and highlights directions for future research.

2 METHODOLOGY

2.1 System Overview

The proposed TSP framework operates within a CV-enabled traffic control environment, where real-time vehicle-to-infrastructure (V2I) communication facilitates adaptive signal priority for buses. In this system, the bus is equipped with an onboard unit capable of continuously transmitting its position, speed, and trajectory information to a roadside unit (RSU) located at the intersection. The RSU aggregates this data and relays it to the traffic signal controller, enabling precise detection of approaching buses and prediction of their arrival times at the stop bar.

Upon receiving a TSP request, the controller dynamically evaluates current traffic conditions, including queue length and the cycle status. Unlike traditional methods that rely on fixed priority rules, this system employs an arrival time estimator combined with a Dynamic Green Time Reallocation algorithm to determine the optimal timing adjustment. This real-time adaptation allows for more efficient allocation of green time, minimizing disruption to non-priority traffic.

Additionally, an optional compensation mechanism is integrated to maintain system-level fairness. After granting priority to a bus, the controller reallocates compensated green time to previously delayed approaches in subsequent cycles. This feature is particularly important in high-frequency transit corridors or intersections with multiple conflicting priority requests, as it ensures that improvements in bus performance do not come at the expense of excessive delay for other road users.

2.2 Queue Length and Bus Arrival Time Estimation

The methodology incorporates real-time queue length calculation and bus arrival time estimation to enhance TSP decision-making. With full connectivity, the queue lengths are dynamically estimated using vehicle trajectory data obtained from the RSU. For each simulation frame, the algorithm identifies vehicles positioned within the detection zone of an intersection and calculates the number of vehicles queued per lane. The queue length estimation accounts for both vehicle kinematics and current signal timing to more accurately capture the dynamic formation and dissipation of queues. A vehicle is classified as queued if it is approaching during a red or yellow signal, indicating imminent stopping. The queue length is calculated:

$$Q_{\text{lane}}(t) = \sum_{i=1}^{N} I_{\text{queue}}\left(\left(S_{\text{signal}}(t) \in \{\text{Red, Yellow}\}\right) \wedge \left(d_i(t) \leq d_{\text{approach}}\right)\right)$$

Where N is the number of preceding vehicles satisfying the condition (I_{queue}), $S_{\text{signal}}(t)$ is the signal state for the lane, d_{approach} is a larger approach distance for forming queues during red or yellow phases, and $d_i(t)$ is the current position of the vehicle i. This formulation ensures that vehicles delayed due to signal timing are included in the queue length calculation, allowing the controller to better estimate the true end-of-queue position.

The bus arrival time estimation predicts the expected time of arrival (ETA) of a transit vehicle at the stop bar. In a CV-enabled environment, bus arrival time estimation can be significantly improved by leveraging real-time information from preceding vehicles.

Traditional estimation methods rely solely on the bus's instantaneous speed, acceleration, and remaining distance to the stop bar, which can lead to underestimation of delays caused by slow-moving or queued vehicles ahead. To address this, we introduce an adjusted bus speed ($v_{\text{adj}}(t)$) that accounts for the collective dynamics of all connected preceding vehicles within the same lane. The adjusted speed is defined as:

$$v_{\text{adj}}(t) = \min\left(v_{\text{bus}}(t), \frac{1}{M}\sum_{j=1}^{M} v_j(t)\right)$$

where $v_{\text{bus}}(t)$ is the bus's own speed, $v_j(t)$ is the instantaneous speed of the j^{th} preceding vehicle, and M is the number of preceding vehicles communicating via V2V or V2I technology. This formulation ensures that the predicted speed does not exceed the average speed of the traffic queue ahead of the bus. To calculate the bus's effective distance to the end of the queue, we adjusted the raw distance to the stop bar by accounting for the queued vehicles ahead:

$$d_{\text{bus}}(t) = d_{\text{stopbar}}(t) - Q_{\text{lane}}(t) \cdot \left(d_{\text{stop}} + L_{\text{veh}}\right)$$

where $d_{\text{stopbar}}(t)$ is the distance from the bus to the stop bar, d_{stop} is the typical stopping headway between queued vehicles, and L_{veh} is the average vehicle length. Using the adjusted speed and the bus distance to the end of the queue, the ETA is calculated as:

$$\text{ETA}_{\text{bus}}(t) = \frac{d_{\text{bus}}(t)}{v_{\text{adj}}(t)} = \frac{d_{\text{stopbar}}(t) - Q_{\text{lane}}(t)\left(d_{\text{stop}} + L_{\text{veh}}\right)}{v_{\text{adj}}(t)}$$

By combining $Q_{\text{lane}}(t)$ and $\text{ETA}_{\text{bus}}(t)$, the dynamic green time reallocation algorithm determines the optimal timing adjustments to minimize bus delay while avoiding excessive disruption to other traffic streams. This queue length information provides critical input for traffic state assessment, enabling the controller to balance priority decisions and minimize disruption to non-transit traffic.

2.3 Dynamic Green Time Reallocation

Traditional TSP approaches, such as green extension or static green time reallocation, predefine fixed durations of priority without considering real-time traffic conditions or the varying arrival times of buses. This limitation can lead to inefficiencies, including excessive green extensions and increased delays for non-prioritized traffic. To overcome these issues, we propose a dynamic green time reallocation strategy that adaptively redistributes green time based on CV information and continuously updated bus arrival predictions.

The dynamic reallocation mechanism operates in two steps:

- Priority Triggering: A TSP request is initiated when the predicted bus arrival time $\text{ETA}_{\text{bus}}(t)$ falls within a decision window before the start or end of the current signal phase. Unlike static approaches, this method uses high-resolution CV data to dynamically assess when priority is beneficial and feasible.
- Real-Time Green Time Adjustment: Upon granting priority, the algorithm

reallocates green time by adjusting the phase durations of the traffic signal. The amount of reallocated green time is computed dynamically as:

$$\Delta \mathrm{G(t)} = \min\Big(\mathrm{G_{max}} - \mathrm{G_{current}(t)},\ \max\big(0,\ \mathrm{ETA_{bus}(t)} + \mathrm{Q_{lane}(t)} \cdot \mathrm{h_{veh}} - \mathrm{R_{current}(t)}\big)\Big)$$

where $G_{\max}$ is the maximum green time for the phase, $G_{\text{current}}(t)$, is the currently allocated green time, $\text{ETA}_{\text{bus}}(t)$ is the predicted bus arrival time, $Q_{\text{lane}}(t)$ is the number of queued vehicles, h_{veh} is the average discharge headway, and $R_{\text{current}}(t)$ is the remaining green time in the cycle.

This formulation ensures that the controller only provides the necessary additional green time to allow the bus and queued vehicles to clear the intersection while maintaining overall cycle stability. Considering the potential impacts on non-prioritized approaches, the controller determines whether to compensate these approaches in subsequent signal cycles using the *Optional Compensation* mechanism. The synergy of dynamic reallocation and compensation ensures that transit priority is provided efficiently while minimizing negative effects on general traffic flow and maintaining fairness across all intersection approaches.

2.4 Optional Compensation Mechanism

While dynamic green time reallocation improves bus priority effectiveness, reallocating green time to transit phases can reduce available green time for non-priority approaches. To mitigate long-term negative impacts and maintain fairness, we introduce an *Optional Compensation* mechanism.

When TSP grants additional green time to favor a bus, other approaches may experience increased queue lengths. The optional compensation mechanism dynamically compensates these approaches in subsequent cycles by allocating additional green time proportionally to their queue lengths. This mechanism prevents persistent disadvantages for non-prioritized traffic streams while maintaining overall signal efficiency. The compensation value for the non-prioritized approach is determined as:

$$G_{\text{compensation}}^{(k)}(t+1) = \min\big(Q_k(t) \cdot h_{\text{veh}},\ \Delta G(t)\big)$$

where $Q_k(t)$ is the queue length of the non-prioritized approach, $G_{\text{compensation}}^{(k)}(t+1)$ is the additional green time allocated to approach k in the next cycle, and $\Delta G(t)$ is the green time borrowed during the priority operation. This formulation ensures that non-prioritized approaches with longer queues receive proportionally larger compensation, balancing the signal timing in subsequent cycles. If no significant queues are detected, the mechanism does not trigger, avoiding unnecessary green time adjustments.

Algorithm 1 summarizes the proposed Dynamic TSP with the Optional Compensation strategy. The algorithm operates in a frame-by-frame manner, first estimating the queue length for each lane by identifying vehicles that are stopped or expected to stop based on signal states and approach distances. It then predicts the bus arrival time by adjusting the bus's instantaneous speed with the average speed of connected preceding vehicles and accounting for the queue length ahead of the bus. A TSP request is triggered when the ETA falls within a predefined decision window. Upon granting priority, the algorithm dynamically reallocates green time based on real-time traffic conditions, ensuring that only the necessary additional green is provided to allow the bus and queued vehicles to clear the intersection. To maintain fairness, an Optional Compensation mechanism compensates non-prioritized approaches in the next signal cycle proportionally to their queue lengths. This integrated approach allows the controller to efficiently prioritize transit vehicles while minimizing disruption to general traffic and maintaining overall intersection performance.

3 EXPERIMENTAL SETUP

This section describes the experimental framework developed to evaluate the proposed dynamic green reallocation strategy with optional compensation. The setup integrates a high-fidelity traffic simulation environment with real-world trajectory data to replicate urban intersection operations. The experimental design includes details of the simulation environment, the dataset used for simulation, scenario configurations such as traffic demand and full CV scenarios, and the baseline strategies used for comparison. The goal of this setup is to provide a realistic and controlled platform for quantifying the performance of different TSP approaches in terms of bus delay, person delay, and overall traffic efficiency.

3.1 Simulation Environments and Data

The proposed TSP strategy and other TSP strategies, including no TSP, were evaluated using a custom simulation environment developed in Python. Vehicle dynamics, including acceleration, deceleration, and queue formation, were modeled based on the high-resolution trajectory data combined with an intelligent driver model (Treiber et al. 2000) The simulation was repeated for 30 runs, with each run featuring a randomly deployed bus in the southbound approach. Vehicle arrivals were generated either using a Poisson distribution (for stochastic demand scenarios) or based on actual traffic flow data (from the NGSIM dataset). By randomly assigning the bus and simulating under varying traffic arrival conditions, the resulting bus arrival times and queue lengths exhibit natural variability. This approach allows the evaluation of TSP strategies under a wide range of operational scenarios, capturing the randomness of real-world bus operations and intersection dynamics. The framework also integrates CV communication, enabling real-time V2I interactions for dynamic green time reallocation and optional compensation implementation.

The simulation was developed using the Next-Generation Simulation (NGSIM) dataset provided by the Federal Highway Administration (U.S. Department Of Transportation Federal Highway Administration 2017). Specifically, we utilized the Peachtree Street dataset collected in Atlanta, Georgia, which contains detailed vehicle trajectory data sampled at 0.1-second intervals. Data were gathered over two days, and for this study, we focused on the period between 4:00 pm and 4:15 pm, as it exhibited higher traffic volumes compared to the midday dataset (12:45 pm–1:00 pm). To maintain a microscopic analysis suitable for testing TSP strategies, the simulated network focused on the southernmost intersection and the two adjacent roadway segments. This section was selected because it met key criteria: higher traffic counts, a signalized intersection, and the absence of additional side streets that could complicate the traffic flow analysis.

Algorithm 1 Dynamic TSP with Compensation Payback

Inputs: Vehicle trajectories from RSU, signal state $S_{\text{signal}}(t)$, bus speed $v_{\text{bus}}(t)$, distance $d_{\text{stopbar}}(t)$
Parameters: $d_{\text{approach}}, v_{\text{queue}}, d_{\text{stop}}, L_{\text{veh}}, G_{\max}, h_{\text{veh}}$
Initialize $Q_{\text{lane}}(t) \leftarrow 0$, $\text{ETA}_{\text{bus}}(t) \leftarrow \infty$, $\mathit{Compensation}[k] \leftarrow 0$ for each non-priority approach k
for each simulation frame t **do**
  Queue Length Estimation:
  $Q_{\text{lane}}(t) \leftarrow 0$
  for each vehicle i in lane **do**
    if $(S_{\text{signal}}(t) \in \{\text{Red, Yellow}\} \wedge d_i(t) \leq d_{\text{approach}})$ **or** $(v_i(t) \leq v_{\text{queue}})$ **then**
      Mark vehicle as queued
      $Q_{\text{lane}}(t) \leftarrow Q_{\text{lane}}(t) + 1$
    end if
  end for
  Bus Arrival Time Estimation:
  Collect speeds of all M preceding connected vehicles
  $v_{\text{adj}}(t) \leftarrow \min(v_{\text{bus}}(t), \frac{1}{M}\sum_{j=1}^{M} v_j(t))$
  $d_{\text{bus}}(t) \leftarrow d_{\text{stopbar}}(t) - Q_{\text{lane}}(t)\left(d_{\text{stop}} + L_{\text{veh}}\right)$
  $\text{ETA}_{\text{bus}}(t) \leftarrow \frac{d_{\text{bus}}(t)}{v_{\text{adj}}(t)}$
  Priority Triggering:
  if $\text{ETA}_{\text{bus}}(t) \leq$ decision window **and** bus is approaching **then**
    Trigger TSP request
    Dynamic Green Time Reallocation:
    $\Delta G(t) \leftarrow \min(G_{\max} - G_{\text{current}}(t),$
      $\max(0, \text{ETA}_{\text{bus}}(t) + Q_{\text{lane}}(t)h_{\text{veh}} - R_{\text{current}}(t)))$
    Extend green for bus approach by $\Delta G(t)$
    $\mathit{Borrowed\_Green} \leftarrow \Delta G(t)$
    Optional Compensation Mechanism:
    for each non-priority approach k **do**
      $\mathit{Compensation}[k] \leftarrow \min(Q_k(t)h_{\text{veh}}, \mathit{Borrowed\_Green})$
    end for
  end if
  Compensation in Next Cycle:
  for each approach k **do**
    if $\mathit{Compensation}[k] > 0$ **then**
      Add $\mathit{Compensation}[k]$ to next cycle green time for approach k
      $\mathit{Compensation}[k] \leftarrow 0$
    end if
  end for
end for
Output: Adjusted signal timings, queue lengths, and bus delays

The modeled road segment spans 200 meters from the northbound to the southbound approaches and 120 meters from eastbound to westbound approaches of the intersection, as shown in Figure 1. The distance from the southbound entry point to the intersection stop bar measures 120 meters, providing a reasonable approach length to effectively activate and evaluate TSP strategies when the bus comes. In contrast, the distance from the northbound, eastbound, and westbound entry to the stop bar is 40 meters, which is long enough to have vehicles enter and queue for vehicle and total person delay evaluation. From the selected 15-minute dataset, we extracted a 10-minute segment that contained the highest overall vehicle counts to ensure robust evaluation of the proposed TSP strategies. With a signal cycle length of 100 seconds, a 10-minute (600s) simulation covers exactly six full signal cycles, which is sufficient to observe priority requests and dynamic responses of the signal controller without extending computational requirements unnecessarily.

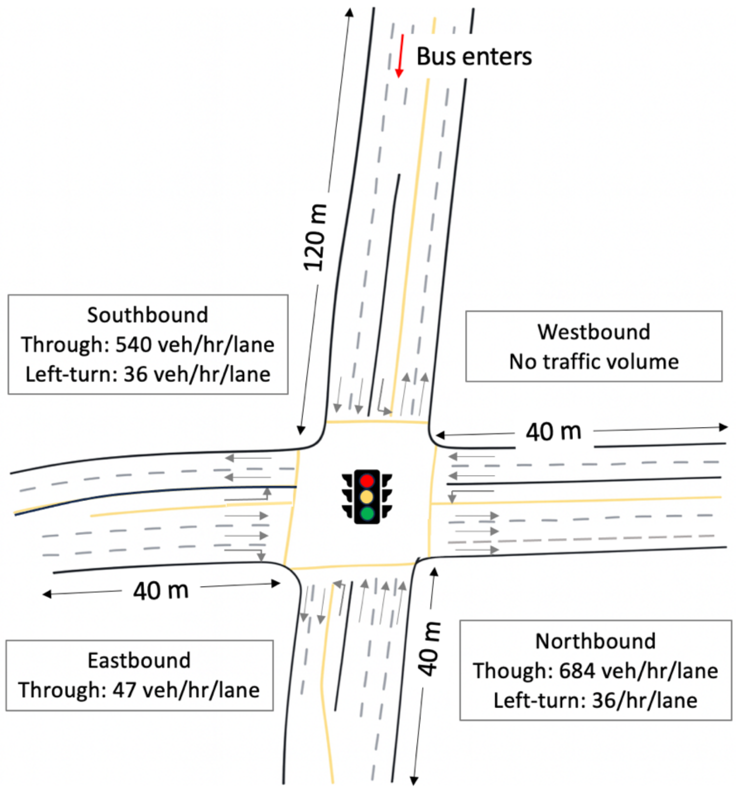

Figure 1: Traffic volumes at the intersection from the NGSIM dataset

Figure 1 shows the traffic volume for each movement at the study intersection based on peak 10-minute data from the NGSIM dataset. The traffic volume is expressed in hourly traffic volume (vehicles/hour/lane). The northbound approach carries the highest demand. The southbound approach shows slightly lower demand. The eastbound approach experiences minimal through traffic, while left-turn traffic is negligible. No westbound movements were observed in the selected dataset. Given this directional imbalance and the variability of real-world arrivals, we first evaluate the proposed TSP strategies under randomized traffic arrivals generated using a Poisson process. Specifically, arrival rates based on traffic volume data are calculated to model stochastic vehicle arrivals. This approach provides a controlled environment to assess TSP performance under typical, probabilistic traffic patterns without being affected by specific vehicle platoons or anomalies present in the dataset. Subsequently, we evaluate the strategies using the actual NGSIM traffic flow to validate the findings. Comparing results from both the randomized

Poisson arrival model and the actual traffic flow allows for a more comprehensive understanding of the proposed TSP strategy's effectiveness and robustness.

3.2 TSP Configurations for Comparisons

To evaluate the effectiveness of the proposed dynamic Green Time Reallocation with Optional Compensation strategy, several baseline methods were implemented for comparison. These include conventional Fixed-Time Control (No TSP), Green Extension or Early Green, and Static Green Time Reallocation with Mandatory Compensation.

No TSP (Fixed-Time Control)

In this scenario, the intersection operates under standard fixed-time signal control with no priority treatment for transit vehicles. Signal phases are pre-timed and remain unchanged regardless of bus presence or schedule adherence. As a result, buses experience the same delay as regular vehicles when encountering a red signal. This case serves as the reference scenario to quantify the benefits of introducing any TSP strategy.

Green Extension or Early Green (GE/EG)

The Green Extension or Early Green (GE/EG) strategy is implemented as a reactive transit signal priority method that provides limited, on-demand adjustments to the signal timing when a bus is detected approaching the intersection. Specifically, when a connected bus enters the detection zone, the controller dynamically evaluates the current signal state. If the bus is detected during an active green phase and is predicted to reach the stop bar near or just after the scheduled end of the green phase based on Section 2.2, the controller extends the green time by up to 5 or 7 seconds to allow the bus to clear the intersection without stopping. Conversely, if the bus is detected during a red phase, the controller can expedite the start of the bus's green phase by shortening the conflicting movement's green time, provided safety constraints and minimum green times are maintained. This adjustment is limited to a single intervention per cycle, with no compensation or reallocation of lost green time in subsequent cycles.

Static Green Time Reallocation with Mandatory Compensation (SGR-MC)

The Static Green Time Reallocation with Mandatory Compensation (SGR-MC) strategy provides transit signal priority by reallocating green time within the current signal cycle to favor a detected bus. When a bus enters the detection zone and is predicted to arrive during or shortly after the active green phase based on Section 2.2, the controller shifts green time from one non-priority phase to the bus's phase. Unlike GE/EG, this method adjusts phase splits rather than merely extending or advancing green. The reallocation is predefined and capped at a maximum of 5–7 seconds to limit disruption to other approaches. To maintain fairness and long-term signal stability, the mandatory compensation mechanism ensures that any green time borrowed from non-priority phases is restored in the subsequent cycle. This compensation allocation is applied deterministically, regardless of queue length or traffic state, making it "mandatory."

Additionally, static green time reallocation with optional compensation (SGR-MC), dynamic green time reallocation with mandatory compensation (DGR-MC) strategies were simulated and evaluated to enable a comprehensive performance comparison. Furthermore, to assess the impact of vehicle connectivity on TSP effectiveness, two scenarios were considered: a no-connectivity baseline and a full-connectivity environment. In the no-connectivity case, the queue length $Q_{\text{lane}}(t)$, and bus arrival time prediction $\text{ETA}_{\text{bus}}(t)$, were estimated using historical average data. In contrast, the full-connectivity scenario utilized real-time information from connected vehicles to dynamically update queue length estimates and bus arrival predictions, enabling more responsive and accurate priority control.

3.3 Simulation Environments and Data

To evaluate the effectiveness of the proposed TSP strategy, four key performance metrics were utilized. Average bus delay measures the additional time a bus experiences compared to free-flow travel, directly reflecting the primary goal of TSP. It is computed as:

$$D_{\text{bus}} = \frac{1}{N_{\text{bus}}} \sum_{i=1}^{N_{\text{bus}}} \left(T_i^{\text{actual}} - T_i^{\text{free}} \right)$$

where N_{bus} denotes the total number of buses, T_i^{actual} is the actual travel time of bus i, and T_i^{free} is the free-flow travel time without any signal delay or congestion.

The total person delay captures the cumulative delay for all occupants in both buses and passenger cars, ensuring that improvements for transit do not disproportionately increase delays for general traffic. It is formulated as:

$$D_{\text{total}} = \sum_{i=1}^{N_{\text{veh}}} \left(T_i^{\text{actual}} - T_i^{\text{free}} \right) \cdot \text{Occ}_{\text{veh}} + \sum_{j=1}^{N_{\text{bus}}} \left(T_j^{\text{actual}} - T_j^{\text{free}} \right) \cdot \text{Occ}_{\text{bus}}$$

where N_{veh} and $N_{\text{bus}}$are the numbers of regular vehicles and buses, respectively, and Occ_{veh} and Occ_{bus} represent their corresponding average occupancy levels (1.1 persons/vehicle for regular vehicles and 20 persons/bus). Vehicle delay by approach provides directional insights into how each strategy affects different intersection movements, highlighting potential imbalances caused by green time reallocation.

TSP Granted represents the total number of instances where the signal controller issued a priority adjustment in response to an approaching bus request. Bus Pass denotes the number of buses that successfully traversed the intersection without stopping. Finally, the TSP success rate quantifies the proportion of priority requests that are successfully executed such that the bus can traverse the intersection without stopping. A TSP attempt is considered unsuccessful in two cases: (i) when a priority request is granted but the bus is still required to stop due to insufficient timing adjustments, or (ii) when a priority request is granted unnecessarily even though the bus would have cleared the intersection without additional green time. This metric, therefore, reflects both the effectiveness and the efficiency of the priority strategy in accurately identifying and serving genuine priority needs. These metrics offer a comprehensive assessment of operational performance and fairness under both synthetic and real-world traffic conditions.

4 RESULTS AND ANALYSIS

This section presents the performance evaluation of the proposed TSP strategy compared with existing TSP strategies and No TSP (fixed-time), such as Green Extension or Early Green (GE/EG), Static Green Time Reallocation with Mandatory Compensation and Optional Compensation (SGR-MC and SGR-OC), and Dynamic Green Time Reallocation with Mandatory Compensation (DGR-MC). The analysis was conducted under two distinct traffic conditions: randomized vehicle arrivals and actual traffic flow in no connectivity and full connectivity scenarios. Performance was assessed using multiple metrics: average bus delay, total person delay, vehicle delay by approach, and TSP success rate. These metrics collectively measure not only the improvement in transit operations but also the overall impact on intersection efficiency and fairness across different traffic movements.

4.1 Results under Random Arrivals

Table 1 summarizes all the performances of different TSP strategies. The TSP success rate and bus delay are first evaluated, as the OP strategy only affects total person delay and vehicle delay in this study. Figure 2 compares the TSP success rate and average bus delay for different signal priority strategies under randomly generated vehicle arrivals modeled as Poisson processes. The No TSP scenarios do not use TSP, resulting in a success rate of zero and the highest bus delay, indicating significant delays when no priority is applied. The GE/EG method provided only minor improvements, with success rates near zero and limited bus delay reduction. In contrast, SGR achieved moderate gains, increasing the TSP success rate to approximately 50–67% and reducing bus delay by around 8 seconds when connectivity was available.

The DGR strategy demonstrated the most substantial improvement, achieving the highest success rate (65% without connectivity, 80% with connectivity) and the lowest bus delay (12.6 s without connectivity, 10.4 s with connectivity). These results highlight that connected vehicle information significantly enhances TSP effectiveness by enabling more accurate bus arrival predictions and better signal timing adjustments. Overall, DGR consistently outperformed all baseline methods, demonstrating its robustness and adaptability under stochastic traffic arrivals.

Table 1 summarizes the total person delay and vehicle delay by movements for different TSP strategies under random arrivals, comparing performance between no connectivity and full connectivity scenarios. The results indicate that connectivity provides measurable improvements in both system-level and approach-specific delays. For total person delay, all strategies show slight reductions when connectivity is introduced. The largest improvement is observed in DGR-OM, decreasing from 10,345 s without connectivity to 9,825 s with connectivity, representing a 5% improvement. Similarly, SGR-OM achieves a notable reduction from 10,560 s to 10,294 s.

TABLE 1 Performance Comparison of Different TSP Strategies under Random Arrivals

Metric	No TSP	GE/EG	SGR-MC	SGR-OC	DGR-MC	DGR-OC
No Connectivity						
TSP Success Rate (%)	0	0	50		65	
Bus Delay	28.2	27.9	27.3		12.6	
Bus Pass	11/30	11/30	14/30	14/30	24/30	24/30
TSP Granted	-	2/30	4/30	4/30	20/30	20/30
Vehicle Delay Eastbound (s)	16.4	16.4	16.1	16.4	15.2	16.1
Vehicle Delay Northbound (s)	31.8	31.7	32.0	31.6	33.5	31.9
Vehicle Delay Westbound (s)	17.7	17.9	17.5	17.7	16.6	17.7
Vehicle Delay Southbound (s)	29.3	29.3	29.5	29.25	31.7	29.6
Total Person Delay (s)	10623.7	10600.0	10669.3	10560.0	10884.3	10344.5
Full Connectivity						
TSP Success Rate (%)	0	25	67		89	
Bus Delay	28.3	25.9	20.4		10.4	
Bus Pass	11/30	12/30	19/30	19/30	27/30	27/30
TSP Granted	-	4/30	12/30	12/30	20/30	20/30
Vehicle Delay Eastbound (s)	16.4	16.8	15.8	16.6	15.1	16.6
Vehicle Delay Northbound (s)	31.8	32.0	32.4	31.2	32.5	30.2
Vehicle Delay Westbound (s)	17.8	17.3	17.3	17.9	16.7	17.9
Vehicle Delay Southbound (s)	29.4	29.4	29.6	28.9	30.2	28.1
Total Person Delay (s)	10623.7	10581.0	10583.3	10294.1	10462.0	9825.2

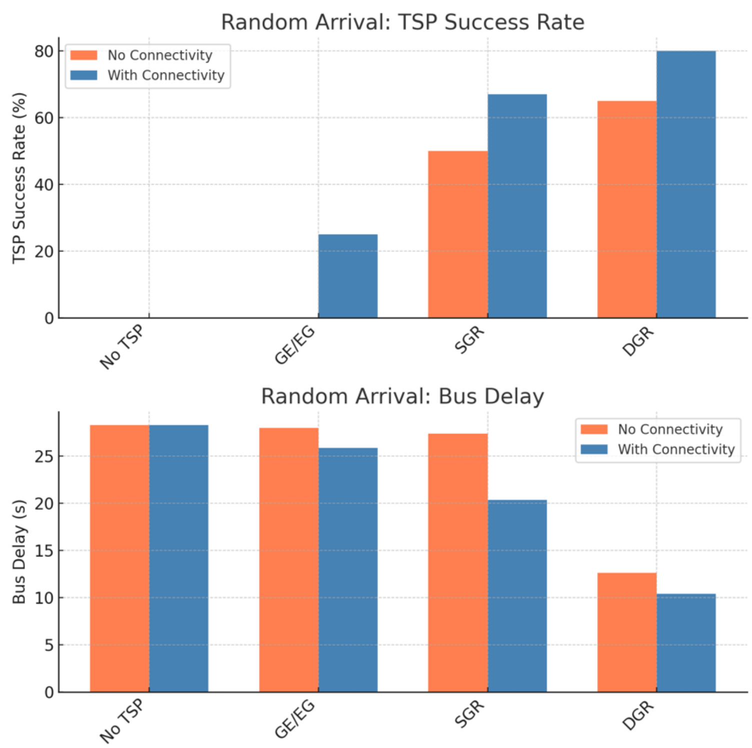

Figure 2: Comparison of TSP Success Rate and Bus Delay Under Random Vehicle Arrivals

In terms of vehicle delay, northbound and southbound approaches consistently experience higher delays due to the dominant traffic flow. However, strategies incorporating connectivity, particularly DGR-OM, significantly reduce delays for these approaches. Eastbound and westbound delays remain relatively low across all methods, with minor fluctuations. Overall, the table shows that dynamic green time reallocation, especially with optional compensation, achieves the greatest improvements in both person-level and vehicle-level delays. These findings reinforce the advantage of leveraging connected vehicle information to enhance TSP effectiveness, leading to better intersection efficiency while balancing delays across all approaches.

4.2 Results under Actual Traffic Data Flow

Table 2 summarizes the performance of all TSP strategies. Figure 3 presents the performance of all TSP strategies using actual traffic flow data from the NGSIM Peachtree Street dataset. Similar to the random arrival scenario, the No TSP baseline produced the highest bus delays. The GE/EG method offered limited improvement without connectivity, while connectivity increased its success rate to 67% with a slight reduction in bus delay to 20.3 s. The SGR approach achieved moderate improvements, with success rates rising from 42% under no connectivity to 78% with connectivity, and bus delays decreasing from 19.2 s to 15.3 s. However, the DGR strategy again outperformed all other methods, achieving the highest success rates and the lowest bus delays. These results confirm the findings from the random arrival scenario, demonstrating that Dynamic Green Time Reallocation, particularly when supported by connected vehicle data, provides superior responsiveness to transit vehicles and reduces intersection delays more effectively than static or reactive TSP methods. The presence of connectivity significantly enhances overall TSP effectiveness, leading to improved traffic signal coordination and reduced delays for public transit.

Table 2 summarizes the results of bus operations, total person delay, vehicle delay, and TSP performance for different strategies under actual traffic flow conditions. The No TSP scenario resulted in the highest bus delay. The GE/EG method showed limited impact without connectivity, whereas full connectivity improved its success rate from 0% to 67%, reducing bus delay to 20.31 s. SGR demonstrated a stronger ability to process bus priority requests, with success rates increasing from 42% without connectivity to 78% with connectivity. Correspondingly, bus delays were reduced from 19.18 s to 15.26 s. The DGR consistently outperformed other methods, achieving the highest success rate.

An interesting observation from Table 2 is that, under the DGR strategy, the no-connectivity scenario occasionally produces slightly lower bus delays compared to full connectivity. This counterintuitive outcome arises from the over-granting of TSP requests when CV information is unavailable, which ultimately leads to higher total person delays with mandatory compensation. In the absence of precise, real-time bus arrival predictions, the DGR controller relies on historical average traffic volumes to estimate queue lengths. Due to occasional extreme queuing conditions in the dataset, these averages tend to be inflated, causing the system to overestimate queues and issue more or longer green time reallocations than necessary. For instance, the no-connectivity case granted 24 TSP requests with a 38% success rate, compared to 10 grants with an 80% success rate under full connectivity. This limitation is less pronounced in random arrival scenarios, where arrivals follow a Poisson distribution, resulting in average queue lengths that are more representative of real-time

TABLE 2 Performance Comparison of Different TSP Strategies under Actual Traffic Flow

Metric	No TSP	GE/EG	SGR-MC	SGR-OC	DGR-MC	DGR-OC
No Connectivity						
TSP Success Rate (%)	-	0	42		38	
Bus Delay	20.9	20.6	19.2		13.5	
Bus Pass	17/30	17/30	23/30	23/30	26/30	26/30
TSP Granted	-	5/30	12/30	12/30	24/30	24/30
Vehicle Delay Eastbound (s)	4.2	4.4	4.3	4.4	4.4	4.8
Vehicle Delay Northbound (s)	32.4	32.8	32.4	32.0	32.0	31.1
Vehicle Delay Westbound (s)	-	-	-	-	-	-
Vehicle Delay Southbound (s)	20.8	21.1	20.8	20.4	21.5	20.3
Total Person Delay (s)	7210.5	7293.4	7167.1	7078.7	7112.2	6850.6
Full Connectivity						
TSP Success Rate (%)	-	67	78		80	
Bus Delay	20.9	20.3	15.3		14.9	
Bus Pass	17/30	19/30	24/30	24/30	25/30	25/30
TSP Granted	-	3/30	9/30	9/30	10/30	10/30
Vehicle Delay Eastbound (s)	4.2	4.2	4.1	4.3	4.0	4.3
Vehicle Delay Northbound (s)	32.4	32.4	32.4	32.1	32.1	32.0
Vehicle Delay Westbound (s)	-	-	-	-	-	-
Vehicle Delay Southbound (s)	20.8	20.7	20.7	20.4	20.6	20.3
Total Person Delay (s)	7210.5	7173.2	7061.5	7003.6	7035.7	6978.6

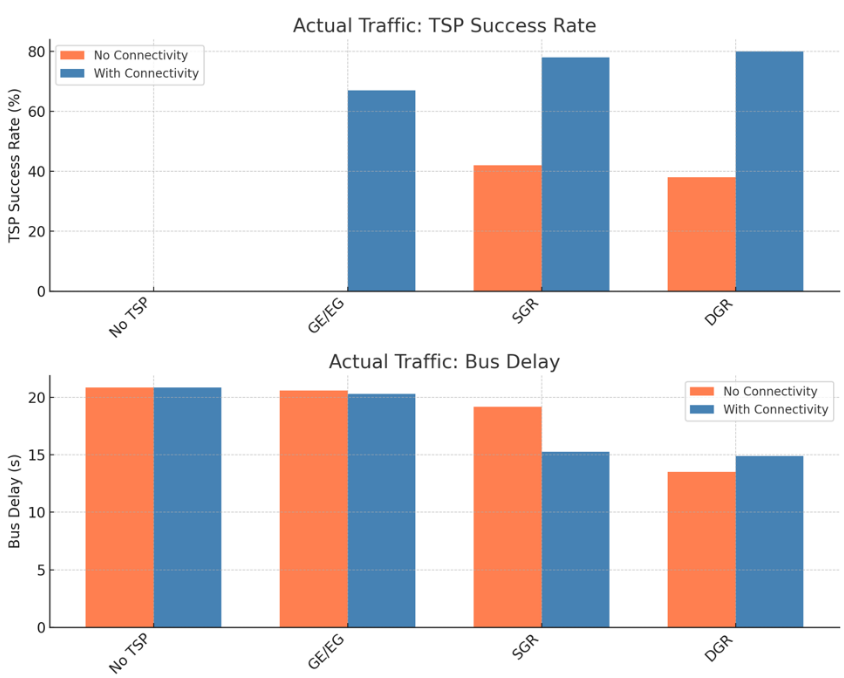

Figure 3: Comparison of TSP Success Rate and Bus Delay Under Actual Traffic Flow Conditions

traffic states. These findings highlight the risk of relying solely on historical traffic averages without connectivity. When non-prioritized approaches experience higher traffic demand (i.e., the East–West direction), the excessive green time allocation can result in unnecessary priority activations and a substantial increase in overall person delays.

As shown in Table 1, this over-allocation of green time causes the highest total person delay under DGR-MC. In contrast, the DGR with optional compensation configuration achieves the lowest total person delay, primarily because North-South traffic volumes are substantially higher than East-West volumes. By not fully compensating non-prioritized approaches in subsequent cycles, DGR-OC retains more green time for the high-demand North-South direction, improving overall intersection efficiency and reducing system-wide person delays more effectively.

5 CONCLUSIONS AND FUTURE WORK

This study proposed and evaluated a dynamic green time reallocation strategy with an optional compensation mechanism to enhance TSP performance at signalized intersections. The approach adaptively reallocates green time based on bus arrival time prediction, queue length, and signal timing constraints, while the optional compensation mechanism dynamically compensates non-priority phases in subsequent cycles to maintain fairness. Performance was compared against baseline methods, including fixed-time control (No TSP), green extension or early green (GE/EG), and static green time reallocation (SGR) under both random arrivals and actual traffic flow conditions. Simulation results demonstrated that DGR with Optional Compensation consistently outperforms all baseline methods, achieving the highest TSP success rates and the lowest bus delays while maintaining balanced total person delays. The integration of CV information further enhanced performance by enabling more accurate bus arrival predictions and targeted priority activations, improving efficiency and fairness.

Future work will extend this research in several directions. First, the proposed TSP framework could be extended to handle multiple buses, addressing potential conflicts between concurrent priority requests and optimizing signal control to balance bus service reliability and overall intersection efficiency. Second, the impact of varying market penetration rates of CV on the effectiveness of the proposed TSP strategy should be investigated, assessing its scalability and adaptability under different levels of connectivity in mixed traffic environments. Third, integration with multi-intersection signal coordination and transit corridors could be explored to assess system-level benefits. Additionally, advanced machine learning-based arrival prediction models could be incorporated to further improve TSP decision-making accuracy. Finally, the interaction of TSP strategies with other traffic management policies, such as adaptive signal control, could be studied to design more comprehensive and balanced urban mobility solutions.

REFERENCES

Ahn, Kyoungho, and H. Rakha. 2006. "System-Wide Impacts of Green Extension Transit Signal Priority." *2006 IEEE Intelligent Transportation Systems Conference*, 91–96. https://doi.org/10.1109/ITSC.2006.1706724.

Anderson, Paul, and Carlos F. Daganzo. 2020. "Effect of Transit Signal Priority on Bus Service Reliability." *Transportation Research Part B: Methodological* 132: 2–14. https://doi.org/10.1016/j.trb.2019.01.016.

Cvijovic, Zorica, Milan Zlatkovic, Aleksandar Stevanovic, and Yu Song. 2022. "Conditional Transit Signal Priority for Connected Transit Vehicles." *Transportation Research Record* 2676 (2): 490–503. https://doi.org/10.1177/03611981211044459.

Garrow, Michael, and Randy Machemehl. 1999. "Development and Evaluation of Transit Signal Priority Strategies." *Journal of Public Transportation* 2 (2): 65–90. https://doi.org/10.5038/2375-0901.2.2.4.

Han, Xu, Pengfei Li, Rajib Sikder, Zhijun (Tony) Qiu, and Amy Kim. 2014. "Development and Evaluation of Adaptive Transit Signal Priority Control with Updated Transit Delay Model." *Transportation Research Record* 2438 (1): 45–54. https://doi.org/10.3141/2438-05.

He, Qing, K. Larry Head, and Jun Ding. 2014. "Multi-Modal Traffic Signal Control with Priority, Signal Actuation and Coordination." *Transportation Research Part C: Emerging Technologies* 46: 65–82. https://doi.org/10.1016/j.trc.2014.05.001.

Hu, Jia, Byungkyu (Brian) Park, and A. Emily Parkany. 2014. "Transit Signal Priority with Connected Vehicle Technology." *Transportation Research Record* 2418 (1): 20–29. https://doi.org/10.3141/2418-03.

Imran, Nazia Tazin, Anagha Girijan, and Lelitha Devi Vanajakshi. 2021. "A Review on Bus Signal Priority Systems." *Transportation in Developing Economies* 8 (1): 2. https://doi.org/10.1007/s40890-021-00138-z.

Kim, Minji, Yohee Han, and Youngchan Kim. 2024. "Coordinated Transit Signal Priority and Vehicle Guidance for Automated Buses." *IEEE Access* 12: 117143–53. https://doi.org/10.1109/ACCESS.2024.3419901.

Kim, Wonho, and L. R. Rilett. 2005. "Improved Transit Signal Priority System for Networks with Nearside Bus Stops." *Transportation Research Record* 1925 (1): 205–14. https://doi.org/10.1177/0361198105192500121.

Li, Yansong, Qian Luo, Jiajia Liu, Hongzhi Guo, and Nei Kato. 2019. "TSP Security in Intelligent and Connected Vehicles: Challenges and Solutions." *IEEE Wireless Communications* 26 (3): 125–31. https://doi.org/10.1109/MWC.2019.1800289.

Lin, Y., X. Yang, N. Zou, and M. Franz. 2015. "Transit Signal Priority Control at Signalized

Intersections: A Comprehensive Review." *Transportation Letters* 7 (3): 168–80. https://doi.org/10.1179/1942787514Y.0000000044.

Seredynski, Marcin, and Djamel Khadraoui. 2014. "Complementing Transit Signal Priority with Speed and Dwell Time Extension Advisories." *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 1009–14. https://doi.org/10.1109/ITSC.2014.6957820.

Treiber, Martin, Ansgar Hennecke, and Dirk Helbing. 2000. "Congested Traffic States in Empirical Observations and Microscopic Simulations." *Physical Review E* 62 (2): 1805–24. https://doi.org/10.1103/PhysRevE.62.1805.

U.S. Department Of Transportation Federal Highway Administration. 2017. "Next Generation Simulation (NGSIM) Vehicle Trajectories and Supporting Data." Not Available. https://doi.org/10.21949/1504477.

Wu, Bing, Haishan Wang, Yanli Wang, Ben Zhai, and Hang Yang. 2023. "Transit Signal Priority Method Based on Speed Guidance and Coordination Among Consecutive Intersections." *Transportation Research Record* 2677 (5): 1226–40. https://doi.org/10.1177/03611981221141430.

Xu, Mingtao, Zhirui Ye, Huaqiang Sun, and Wei Wang. 2016. "Optimization Model for Transit Signal Priority Under Conflicting Priority Requests." *Transportation Research Record* 2539 (1): 140–48. https://doi.org/10.3141/2539-16.

Yang, Kaidi, Monica Menendez, and S. Ilgin Guler. 2019. "Implementing Transit Signal Priority in a Connected Vehicle Environment with and without Bus Stops." *Transportmetrica B: Transport Dynamics* 7 (1): 423–45. https://doi.org/10.1080/21680566.2018.1434019.

Yang, Tianjia, and Wei (David) Fan. 2023. "Evaluation of Transit Signal Priority at Signalized Intersections under Connected Vehicle Environment." *Transportation Planning and Technology* 46 (2): 145–59. https://doi.org/10.1080/03081060.2023.2176308.

Ye, Zhirui, and Mingtao Xu. 2017. "Decision Model for Resolving Conflicting Transit Signal Priority Requests." *IEEE Transactions on Intelligent Transportation Systems* 18 (1): 59–68. https://doi.org/10.1109/TITS.2016.2556000.

Zeng, Xiaosi, Yunlong Zhang, Jian Jiao, and Kai Yin. 2021. "Route-Based Transit Signal Priority Using Connected Vehicle Technology to Promote Bus Schedule Adherence." *IEEE Transactions on Intelligent Transportation Systems* 22 (2): 1174–84. https://doi.org/10.1109/TITS.2020.2963839.