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Dynamic Right-of-Way Allocation on Bus Priority Lane Considering Traffic System Resilience

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Abstract: Bus priority is an effective way to improve traffic efficiency and sustainability. To achieve this, the Bus Priority Lane (BPL) is adopted to provide exclusive right-of-way for buses. However, the BPL is underutilization if the frequency of buses is low. To address this issue, many studies focus on improving the BPL's utilization efficiency by intermittently allowing general vehicles to access it. However, these studies still have some shortcomings: i) bus priority cannot be guaranteed if general vehicles run on the BPL; ii) the traffic system lacks resilience, especially when the traffic demand is unbalanced. This paper proposes a dynamic right-of-way allocation on the BPL considering traffic system resilience. On the one hand, it ensures absolute bus priority by controlling Connected Automated Vehicles (CAVs) to not interfere with buses. On the other hand, it can improve traffic system resilience by allocating right-of-way for CAVs with heavy turning-movement demand. To validate the effectiveness, the proposed control strategy is evaluated against the non-control baseline. Sensitivity analysis is conducted under seven unbalanced traffic demand levels, four congestion levels, and five CAV Penetration Rates. The results show that the proposed control strategy can ensure absolute bus priority and improve traffic efficiency and traffic system resilience.

Keywords: bus priority lane; dynamic right-of-way allocation; traffic system resilience

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1. Introduction

Congestion at signalized intersections poses significant challenges to urban transportation systems, and ensuring bus priority has emerged as a crucial strategy to mitigate congestion[1–3]. One commonly adopted approach is the implementation of a Bus Priority Lane (BPL), which provides exclusive right-of-way for buses, enabling them to bypass general traffic and improve traffic sustainability and efficiency[4,5].

However, an important concern arises when the utilization frequency of buses on the BPL is low, resulting in underutilization of this BPL. Such underutilization not only compromises the effectiveness of the transportation system in reducing congestion but also raises concerns about its overall efficiency and sustainability[6].

In response to this challenge, numerous studies have proposed strategies to improve the utilization efficiency of BPLs. Some of these studies focus on converting BPLs into intermittent BPLs[7–10]. Such intermittent BPLs allow general vehicles to access the BPL when the utilization frequency of buses is low. By opening up intermittent BPLs for general vehicles, these studies can improve lane occupancy and reduce vehicle delay on the general-purpose lanes[11]. With the advance of Automated Vehicle (AV) technology, AV is emerging to revolutionize the transportation system[12–17]. Unfortunately, it is still difficult for AVs at the current stage to cope with complex interactions with surrounding vehicles at the signalized intersection. Hence, other studies focus on providing exclusive right-of-way for AVs by converting BPLs into mixed-use AV/bus lanes[18,19]. Such mixed-use AV/bus lanes not only enhance AV safety but also improve the utilization efficiency of the BPL.

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Although these studies can improve the utilization efficiency of the BPL, they still have some shortcomings. Firstly, converting BPLs into intermittent BPLs raises concerns about ensuring bus priority, as the intermittent availability of the BPLs may lead to delays and reduced reliability for bus services[20–22]. This is because the transit buses would possibly be disturbed by general vehicles when approaching the signalized intersection. Secondly, the existing studies lack consideration of traffic system resilience[23,24]. Especially when the traffic demand is heavy and unbalanced, the traffic system cannot handle all vehicles and experiences collapse.

To overcome these shortcomings, an innovative control strategy is necessary to ensure bus priority while improving the resilience of the traffic system. This paper proposes a dynamic right-of-way allocation strategy on the bus priority lane, taking into account the concept of traffic system resilience. The proposed control strategy bears the following features:

- Improve traffic system efficiency at the signalized intersection.
- Enhance traffic system resilience under various traffic demand patterns.
- Guarantee absolute bus priority even when traffic is congested.

The remainder of this paper is structured as follows. Section "Problem Statement" describes scenarios and research problems. Section "Logic Structure of the control strategy" illustrates the logic of the proposed control strategy. Section "Mathematical Formulation" presents problem formulation and the associated solution. Section "Evaluation" shows the experiment design and associated results. Section "Conclusion" entails the conclusions from the experiments.

2. Problem statement

The research scenario is a signalized intersection in a mixed traffic environment. As illustrated in Figure 1, a control zone is divided into two sections: section I and section II. In the section I, there are three lanes. The topmost lane is a Bus Priority Lane (BPL). The other lanes are General Purpose Lanes (GPLs). Section II includes four lanes. One is the BPL and the other lanes are respectively for vehicles with left-turning movement, going-straight movements, and right-turning movement. All vehicles can be divided into general vehicles and buses. The general vehicles include Connected Automated Vehicles (CAVs) and Connected Human-driven Vehicles (CHVs). All vehicles enable communication with other vehicles and the roadside unit via Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) in real-time. All general vehicles only run on the GPLs when they come into the control zone. The BPL is designed to ensure absolute bus priority and is open to CAVs with heavy turning-movement demand.

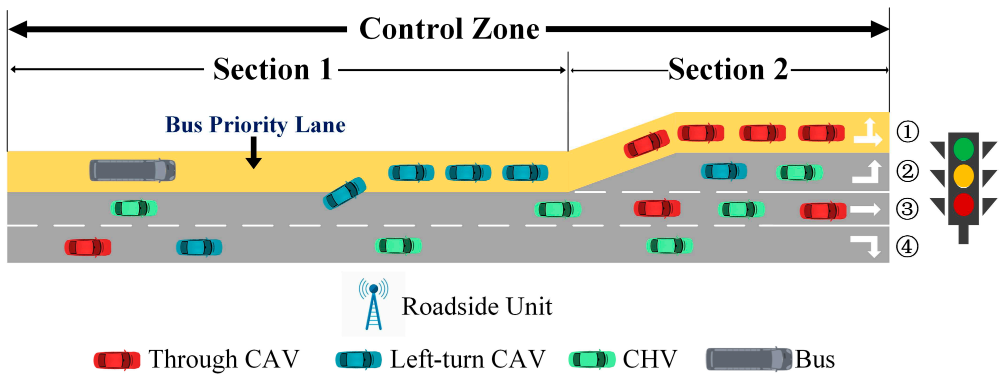

Figure 1. Illustration of research scenario.

3. Logic structure of the control strategy

In this section, the logic structure of the proposed control strategy has been illustrated in Figure 2. The proposed control strategy is designed to improve traffic system resilience when the traffic demand is heavy and unbalanced. The strategy can be divided into four components including traffic information collection, turning-movement demand level determination, dynamic right-of-way allocation of the BPL, and trajectory planning and implementation. In each time step, the control logic would be activated. Some detailed information about these four components has been described in the following sections.

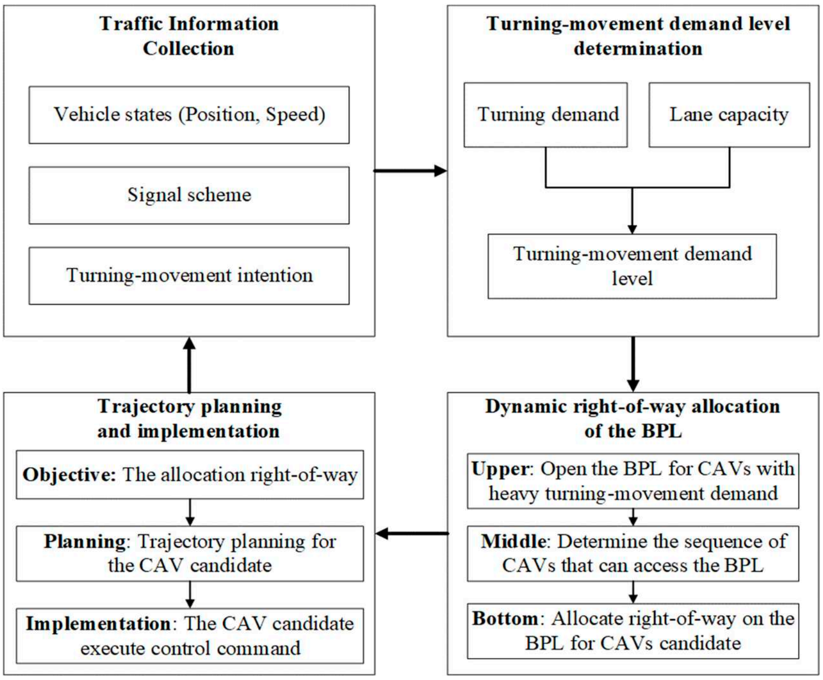

Figure 2. Logic structure of the control strategy.

3.1. Traffic Information Collection

The traffic information collection is the first component in the logic structure of the proposed control strategy. It is designed to collect traffic information about vehicle states, signal schemes, and turning-movement intentions. All the collected information would be the input of the next component (Turning-movement demand level determination).

3.2. Turning-movement Demand Level Determination

This section introduces the second component of the control logic. This component is a turning-movement demand level determination. It is designed to determine whether the current traffic demand is heavy and unbalanced. When the current signal scheme is fed to this component, this component would calculate the lane capacity for each turning movement. Compared with the current turning demand, this component would determine a demand level for each turning movement. Finally, the turning-movement demand level results would output to the next component.

3.3. Dynamic Right-of-Way Allocation of the BPL

This section introduces the third component of the control logic. This component is called the dynamic right-of-way allocation of the BPL. It is designed to determine whether and how to allocate the right-of-way of the BPL for CAVs. When the turning-movement demand level is high, this component is activated. Firstly, this component determines to open the BPL for turning-movement demand that is heavy and unbalanced. Next, this component would determine the sequence of CAV candidates that can access the BPL. Based on the determined sequence, this component would dynamically allocate the right-of-way of the BPL for CAV candidates. The information about the allocated right-of-way on the BPL would output to the next component.

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3.4. Trajectory Planning and Implementation

Trajectory planning and implementation is the fourth component of the control logic. According to the allocated right-of-way, this component would optimize the trajectory plan for CAV candidates to utilize the objective right-of-way on the BPL. Then, the component would convert the trajectory plan into a control command for CAV candidates to implement.

4. Mathematical formulation

4.1. Terminal Time Prediction

The optimized trajectory plan for CAVs accessing the Bus Priority Lane (BPL) consists of trajectory planning for vehicles at each time interval and determining the terminal time when vehicles reach the stop line. However, due to the uncertain behavior of CHVs in mixed traffic, the optimized trajectory plans for CAV candidates need to be updated at each time interval. Consequently, the prediction of the terminal time when vehicles reach the stop line must also be recalculated at each time interval. The calculation of the terminal time prediction is described below.

$$t_n^{f,d} = max\left(t_{n-1}^{f} + t_h, t_n^{f,e}\right) \qquad \forall n \in \boldsymbol{N} \tag{1}$$

$$t_n^{f,e} = t^0 + \frac{L - \dfrac{{v_{max}}^2 - {v_{t_n^0}}^2}{2a_{max}}}{v_{max}} + \frac{v_{max} - v_{t^0}^n}{a_{max}} \tag{2}$$

$$t_n^f = \begin{cases} t_n^{f,d} & \forall t_n^{f,d} \in \varphi_G \\ \left\lfloor \dfrac{t_n^{f,d}}{R+G} \right\rfloor * (R+G) + R & \forall t_n^{f,d} \in \varphi_G \end{cases} \tag{3}$$

where n is the vehicle index in the mixed traffic. N is the vehicle index set in the mixed traffic. $t_n^{f,d}$ is the initial time prediction of vehicle n arriving at the stop line. t_{n-1}^{f} is the initial time prediction of vehicle$n-1$ arriving at the stop line. $t_n^{f,e}$ is the earliest time vehicle n arrives at the stop line without considering the preceding vehicles and traffic signal. t^0 is the current time at each time interval for time prediction of the vehicle n arriving at the stop line. L, v_{max} and a_{max} respectively represent the length of the control zone the maximum speed and acceleration. $v_{t^0}^n$ is the speed of vehicle n at the current time. R and G are the duration of red light and green light. t_n^f is the terminal time of vehicle n arriving at the stop line.

4.2. CHV Trajectory Prediction

In the mixed traffic, CHVs can run on their own decisions. The implementation of CHVs' trajectory plans is influenced by factors such as the trajectory information of preceding vehicles and traffic signal information. Consequently, it becomes necessary to re-predict CHV trajectories at each time interval to accommodate the mixed traffic conditions. The Intelligent Driver Model (IDM) is a widely accepted model for predicting CHV trajectories. The predicted acceleration for CHVs can be mathematically formulated as follows.

$$a_t^{p,k} = a_{max}\left[1 - \left(\frac{v_t^k}{v_{max}}\right)^4 - \left(\frac{\Delta x_{pn,k}^d}{\Delta x_{pn,k}}\right)^2\right] \qquad \forall t \in \boldsymbol{T}, n \in \boldsymbol{N}, k \in \boldsymbol{N_k} \tag{4}$$

$$a_t^{l,k} = a_{max}\left[1 - \left(\frac{v_t^k}{v_{max}}\right)^4 - \left(\frac{\Delta x_k^{d*}}{L - x_t^k}\right)^2\right] \qquad \forall t \in \boldsymbol{T}, k \in \boldsymbol{N_k} \tag{5}$$

$$\Delta x_{n,k}^{d} = s_0 + max\left(v_t^k \cdot t_h + \frac{v_t^k \cdot \Delta v_t^{pn,k}}{2\sqrt{a_{max} \cdot \underline{a^d}}}, 0\right) \tag{6}$$

$$\Delta x_{n,k}^{d*} = s_0 + max\left(v_t^k \cdot t_h + \frac{{v_t^k}^2}{2\sqrt{a_{max} \cdot \underline{a^d}}}, 0\right) \tag{7}$$

$$t_R = \left\lfloor \frac{t_k^f}{R+G} \right\rfloor \cdot (R+G), \ \ \forall t_c^f \notin \omega_G, \forall k \in \boldsymbol{N_k} \tag{8}$$

$$a_t^k = \begin{cases} a^o & \forall t \notin [t^0, \infty] \cap [t_R, t_R + R] \\ a^l & \forall t \in [t^0, \infty] \cap [t_R, t_R + R] \end{cases} \tag{9}$$

where k is the vehicle index of CHVs. $\mathbf{N_k}$ is the vehicle index set of CHVs. v_t^k is the speed of vehicle k. x_t^k is the position of vehicle k. $\underline{a^d}$ is the desired deceleration of the vehicle. $\Delta v_t^{pn,k}$ is the speed difference between the vehicle k's preceding vehicle and the vehicle k. t_h is safe time headway. $\Delta x_{pn,k}^{d}$ is the desired minimum distance gap between the vehicle k's preceding vehicle and the vehicle k. $\Delta x_{pn,k}$ is the distance gap between the vehicle k's preceding vehicle and the vehicle k. Δx_k^{d*} is the desired minimum distance gap when there is no preceding vehicle. $a_t^{p,k}$ is the predicted acceleration of the vehicle k if there is a preceding vehicle. $a_t^{l,k}$ is the predicted acceleration of the vehicle k if there is no preceding vehicle. t_k^f denotes the terminal time of vehicle k arriving at the stop line. a_t^k is the terminal acceleration of vehicle k.

4.3. Turning-movement Demand Level Calculation

To calculate the turning-movement demand level, the model analyzes the spatiotemporal occupancy of traffic and considers the vehicles' turning-movement demand. To achieve this, we split the traffic flow as follows:

$$\Omega = \Omega_1 \cup \Omega_2 \cup \Omega_3 \tag{10}$$

where Ω represents the set of all vehicles on the continuous road, Ω_1 represents the set of all left-turn vehicles on the continuous road, Ω_2 represents the set of all through vehicles on the continuous road, and Ω_3 represents the set of all right-turn vehicles on the continuous road.

$$D(\Omega_i) = \frac{\left|\frac{\Omega_i}{\Omega_i^g}\right|}{r_i^g q_i^s} \tag{11}$$

where $D(\Omega_i)$ represents the demand intensity of the turning traffic flow, Ω_i^g represents the set of vehicles with turning i that can pass through the intersection in the most recent signal cycle, r_i^g represents the effective green signal ratio for the signal controlling the turning movement i, and q_i^s represents the saturation flow rate for the turning movement. Therefore, the turning movement with the highest demand intensity is:

$$i^* = \underset{i}{argmax} D(\Omega_i) \tag{12}$$

If $D(\Omega_{i^*}) = 0$, it means that all vehicles can pass through the intersection during the current green phase. Hence, the allocated right-of-ways on the BPL are not needed for any vehicles. Otherwise, the allocated right-of-ways are required to be provided for CAVs with heavy turning movement i^*.

4.4. Dynamic Allocation of the Right-of-way on the BPL

Right-of-way allocation is the spatial slice that is occupied by the vehicle at time t. The spatial slices for transit buses and CAVs are based on the current traffic conditions. Due to the different lengths of the transit bus and CAVs, the spatial slice determination should be divided into two kinds.

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$$s_t^c = \{x|x_t^c - l^c \le x \le x_t^c + l^c\} \ \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{13}$$

$$s_t^b = \{x|x_t^b - l^b \le x \le x_t^b + l^b\} \ \forall t \in \boldsymbol{T}, b \in \boldsymbol{N_b} \tag{14}$$

where s_t^c and s_t^b respectively denote spatial slices of the CAV (vehicle c) and spatial slices of the transit bus.

4.5. Trajectory Planning for CAVs

4.5.1. Cost Function

The cost function to be minimized consists of three terms, including travel time, fuel consumption, and the efficiency of vehicles passing the signalized intersection. It is formulated as:

$$J = \alpha \sum_c \tau^c + \beta \sum_c \sum_t |a_t^c| + \mu(|x_{tf}^c - L| + |v_{tf}^c - v_{max}|) \tag{15}$$

The first term in the cost function is about efficiency. c is the CAV index. The variable in this term is travel time τ^c of the vehicle c. The explanation of τ^c need to be defined as follows:

$$\tau^c = \sum_t \sum_m w_{m,t}^c \cdot \Delta t \qquad \forall c \in \boldsymbol{N_c} \tag{16}$$

$\mathbf{N_c}$ is the CAV index set of the mixed traffic. If the vehicle c is in the control zone, the binary decision variable $w_{m,t}^c$ must be updated at each time interval. $w_{m,t}^c$ is a binary decision variable to denote CAV c on the general-purpose lane or the BPL, Hence, the travel time can be illustrated as Constraint (16).

The second term illustrates the fuel consumption using the acceleration a_t^c. The last term describes that the vehicles should pass the intersection as fast as possible to improve traffic efficiency. x_{tf}^c and v_{tf}^c are respectively the position and speed of the vehicle c at the end of the time interval based on the terminal time prediction.

4.5.2. Constraints

1) Vehicle kinematic constraints

The movement of vehicles has to be subject to kinematic constraints as described below.

$$v_{min} \le v_t^c \le v_{max} \qquad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{17}$$

$$a_{min} \le a_t^c \le a_{max} \qquad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{18}$$

$$v_t^c = v_{t-1}^c + a_t^c \cdot \Delta_t \qquad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{19}$$

$$x_t^c = x_{t-1}^c + v_{t-1}^c \cdot \Delta t + \frac{1}{2} a_t^c \cdot \Delta t^2 \quad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{20}$$

where v_t^c is the instantaneous speed of vehicle c at time t, the speed of vehicle c must be limited within the minimum and maximum allowed values (v_{min},v_{max} respectively). Constraint (18) denotes that the acceleration and deceleration of vehicles must be in a feasible range. x_t^c is the position of vehicle c at time t. Constraints (19) and (20) depict the vehicle dynamics.

2) Vehicle conflict constraints

To keep safe, the trajectory planning for CAVs should avoid conflict with surrounding vehicles. The following constraints ensure that vehicle trajectories are conflict-free.

$$x_t^{pc} - x_t^c > s_0 + v_t^c \cdot t_h + 2 * l^c \qquad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{21}$$

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$$x_t^{pb} - x_t^b > s_0 + v_t^b \cdot t_h + 2 * l^b \quad \forall t \in \boldsymbol{T}, b \in \boldsymbol{B} \tag{22}$$

$$x_t^b - x_t^{fb} > s_0 + v_t^{fb} \cdot t_h + 2 * l^c \quad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c}, b \in \boldsymbol{B} \tag{23}$$

where b is the bus index, $\mathbf{B}$ is the bus index set. x_t^{pc} is the position of the vehicle c's preceding vehicle at time t. x_t^{pb} is the position of the bus b's preceding vehicle at time t. x_t^{fb} is the position of the bus b's following vehicle at time t. x_t^b and v_t^b respectively denote the position and speed of the bus b at time t. v_t^{fb} is the speed of the bus b's following vehicle at time t. l^c and l^b are the length of one CAV and the length of one bus.

3) Traffic signal constraints

The optimized vehicle trajectory plans must be subject to the signal phase and timing constraints. The following constraints are imposed:

$$t_{op}^s + \sum_t \sum_m w_{m,t}^c \cdot \Delta_t \geq t_{op}^e - G + (\xi^c - 1) \cdot M \quad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{25}$$

$$t_{op}^s + \sum_t \sum_m w_{m,t}^c \cdot \Delta_t \leq t_{op}^e + (1 - \xi^c) \cdot M \quad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{26}$$

$$x_{t_{op}^e}^c \geq L + (\xi^c - 1) \cdot M \quad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{27}$$

$$x_{t_{op}^e}^c \leq L + (1 - \xi^c) \cdot M \quad \forall t \in \boldsymbol{T}, c \in \boldsymbol{N_c} \tag{28}$$

where t_{op}^s, and t_{op}^e are respectively the start time of the optimization horizon and the end time of the optimization horizon. On the other side, another binary variable ξ^c has been introduced, and $\xi^c = 1$ if the vehicle c could get through the intersection during the given optimization horizon, otherwise 0. Constraints (24) and (25) ensure vehicles get through the intersection only during the given green time in the optimization horizon. Constraints (26) and (27) ensure vehicles are in the control zone if they cannot get through the signalized intersection in the current optimization horizon.

5. Evaluation

In this section, the proposed control strategy is evaluated through simulation experiments compared with the non-control baseline. The simulation experiments select throughput, delay, and fuel consumption as the measurements of effectiveness. The simulation experiments are conducted under five different congestion levels and five different CAV Penetration Rates. The goal is to fairly confirm the proposed control strategy can improve traffic system resilience while ensuring absolute bus priority.

5.1. Experiment Design

5.1.1. Testbed

The testbed in the simulation experiment has been illustrated in Figure 3. The testbed is a signalized intersection with a Bus Priority Lane (BPL). The control zone is composed of two sections: section 1 and section 2. The length of section 1 is 350 meters. The length of section 2 is 150 meters. Due to the lane channelization for different turning movements, section 2 contains four lanes. Besides, the roadside unit enabling V2I communication with vehicles is built. All vehicles enable communication via V2V. The simulation platform is based on PTV-VISSIM[25,26].

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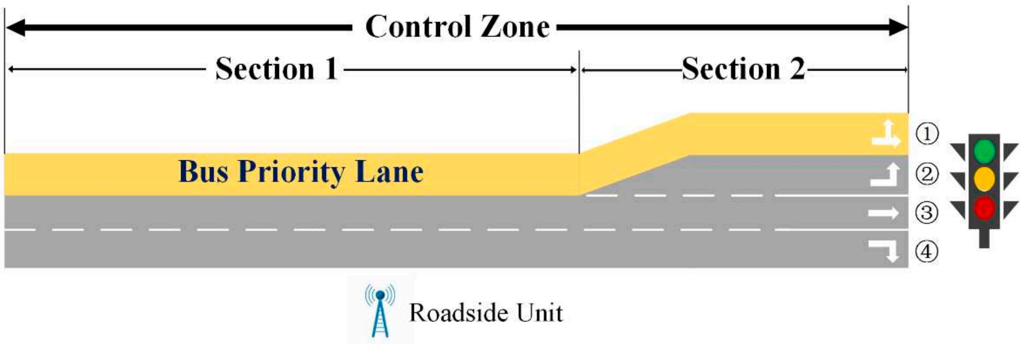

Figure 3. Testbed.

5.1.2. Scenario

Two scenarios considering absolute bus priority are tested:

- Non-control baseline: In this scenario, a dedicated bus lane is adopted to separate buses from general vehicles. All vehicles cannot be allowed to run with buses on the same lane. All general vehicles can only run on the General Purpose Lane (GPL).
- The proposed strategy: In this scenario, the BPL can be open to CAVs when the turning-movement demand is heavy and unbalanced. All CAVs utilize the allocated right-of-way of the BPL without interference with buses.

5.1.3. Measurements of Effectiveness

To validate the effectiveness of the proposed control strategy, three Measurements of Effectiveness (MOE) are selected, including throughput, delay, and traffic system resilience. The definition of the traffic system resilience can be described as follows:

$$Resilience = \frac{Delay_n - Delay_o}{Delay_n - Delay_s} \times 100\%$$

Where $Delay_n$ denotes the average vehicle delay in the non-control baseline scenario. $Delay_o$ represents the average vehicle delay in the proposed control strategy. $Delay_s$ denotes the average vehicle delay when the congestion level is 1.0 in the non-control baseline.

5.1.4. Sensitivity Analysis

To fairly confirm the validation of the proposed strategy, sensitivity analysis is conducted under seven different unbalanced demand levels, five different congestion levels (0.6, 0.8, 1.0, 1.2, and 1.4), and five different CAV penetration rates (10%, 20%, 30%, 40%, and 50%). Note that, the unbalanced demand level can be described as a different turning-movement demand proportion. For example, proportion 4:4:2 respectively denotes the left-turning demand proportion, go-straight demand proportion, and right-turning proportion. A higher unbalanced demand level means that the difference between the left-turning demand and go-straight demand is larger. Hence, the low unbalanced demand level includes proportions 3:5:2, 4:4:2, and 5:3:2. The high unbalanced demand level contains proportions 1:7:2, 2:6:2, 2:6:2, and 1:7:2.

5.2. Results

The simulation results are shown in this section. The results have validated that the proposed control strategy performs well against the non-control baseline under various turning-movement demand patterns, congestion levels, and CAV Penetration Rates (CPR). The benefit of the proposed control strategy can be observed in traffic efficiency improvement and traffic system resilience improvement. At the same time, the credibility of ensuring absolute bus priority has been confirmed.

5.2.1. Traffic Efficiency Improvement Validation

5.2.1.1 Throughput Comparison Results

Figure 4 shows the results of the throughput comparison between the non-control baseline and the proposed control strategy under the condition of low unbalanced demand levels (3:5:2, 4:4:2, and 5:3:2). Compared with the non-control baseline, the proposed control strategy has no obvious benefits when the congestion level is less than 1.0. The reason is that the traffic system can easily handle all vehicles when the traffic demand is low. When the congestion level is more than 1.0, it means that the traffic system is in the condition of oversaturated traffic demand. The proposed control strategy has more obvious benefits. This is because the proposed control strategy can improve intersection capacity by controlling CAVs to utilize the right-of-way on the BPL. With the increment of CPRs, the proposed control strategy performs better. The reason is that more CAVs can be controlled to improve traffic efficiency by utilizing the right-of-way on the BPL.

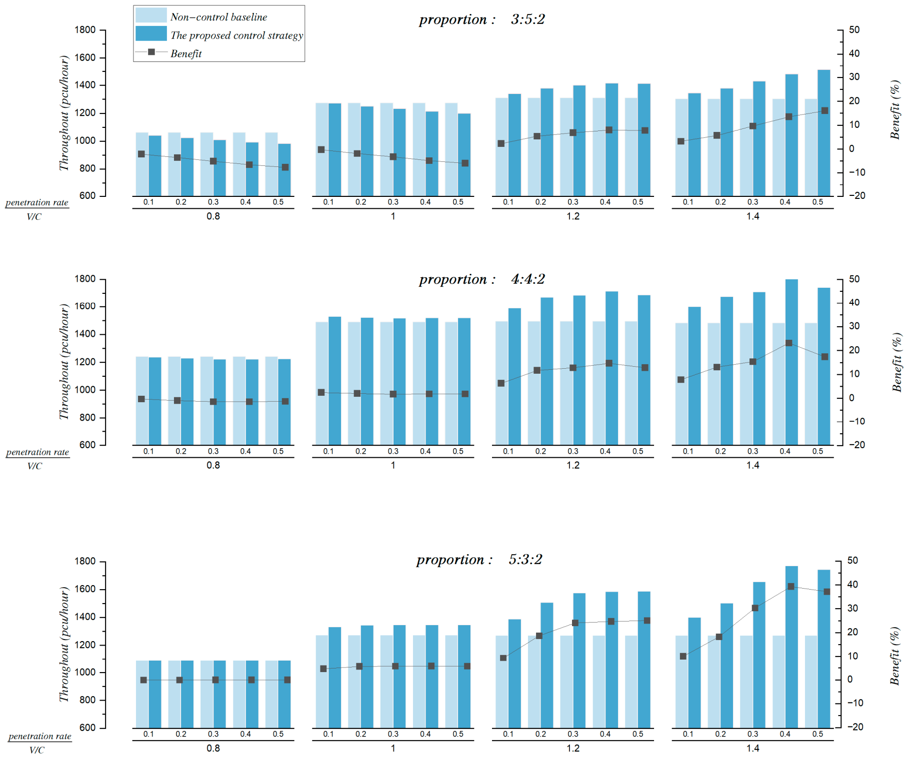

Figure 4. Throughput comparison results under low unbalanced traffic demand levels.

Figure 5 shows the results of the throughput comparison between the non-control baseline and the proposed control strategy under the condition of high unbalanced demand levels (1:7:2, 2:6:2, 6:2:2, and 7:1:2). The proposed strategy still performs well when the congestion level is more than 1.0. With the increment of congestion levels and CPRs, the greater benefits of throughput improvement can be observed. The reason is that the proposed control strategy can improve intersection capacity by allocating the unutilized right-of-way of the BPL for CAVs. To be noted, such allocation can improve the utilization efficiency of road resources. Hence, the proposed control strategy can achieve throughput improvement at the signalized intersection.

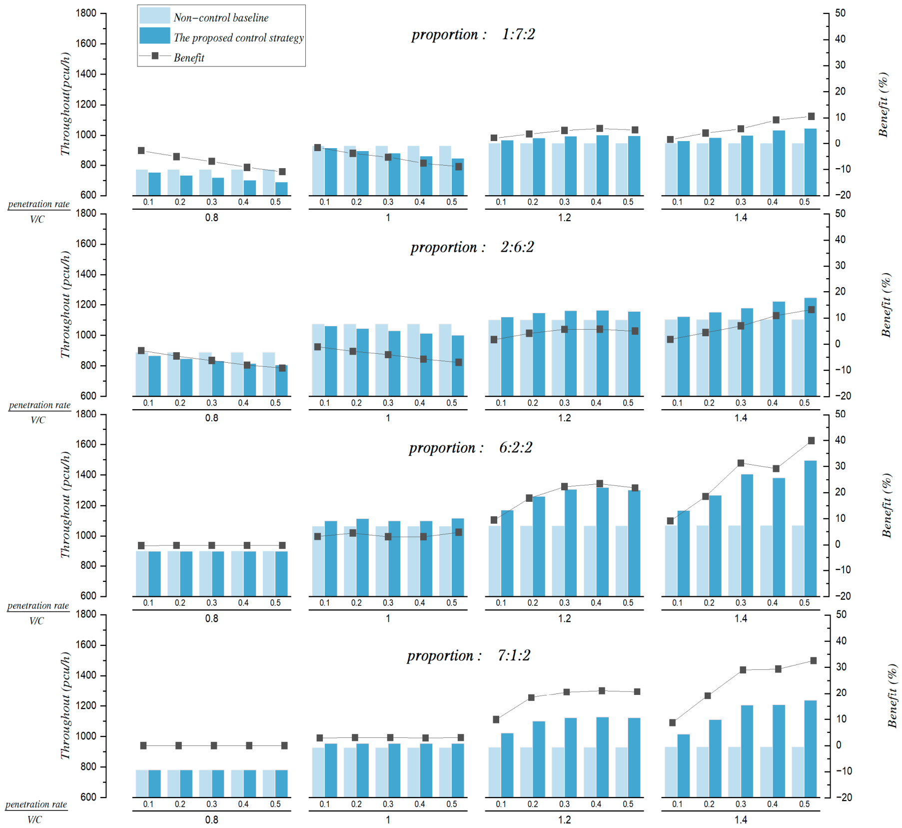

Figure 5. Throughput comparison results under high unbalanced traffic demand levels.

5.2.1.2 Delay Comparison Results

Figure 6 shows the results of the delay comparison between the non-control baseline and the proposed control strategy under the condition of low unbalanced demand levels (3:5:2, 4:4:2, and 5:3:2). Different from the throughput improvement, the proposed control strategy can effectively achieve delay reduction at any congestion levels. With the increment of congestion levels and CPRs, the benefits of delay reduction are more obvious.

The reason is that the proposed control strategy can allocate the right-of-way of the BPL for CAVs to avoid too long a queue on the GPL. When the congestion levels and CPRs are high, the proposed control strategy can reduce traffic delay by controlling more CAVs to utilize the allocated right-of-way on the BPL.

Figure 7 shows the results of the delay comparison between the non-control baseline and the proposed control strategy under the condition of high unbalanced demand levels (1:7:2, 2:6:2, 6:2:2, and 7:1:2). Compared with the low unbalanced demand levels, the proposed control strategy has more benefits of delay reduction. Under the condition of high unbalanced demand levels, heavy turning demand would easily exceed the lane capacity. Due to this, the proposed control strategy would balance traffic demand by controlling more CAVs to utilize the right-of-way of the BPL. Such control can greatly reduce vehicle delay by avoiding too long a queue on the GPL.

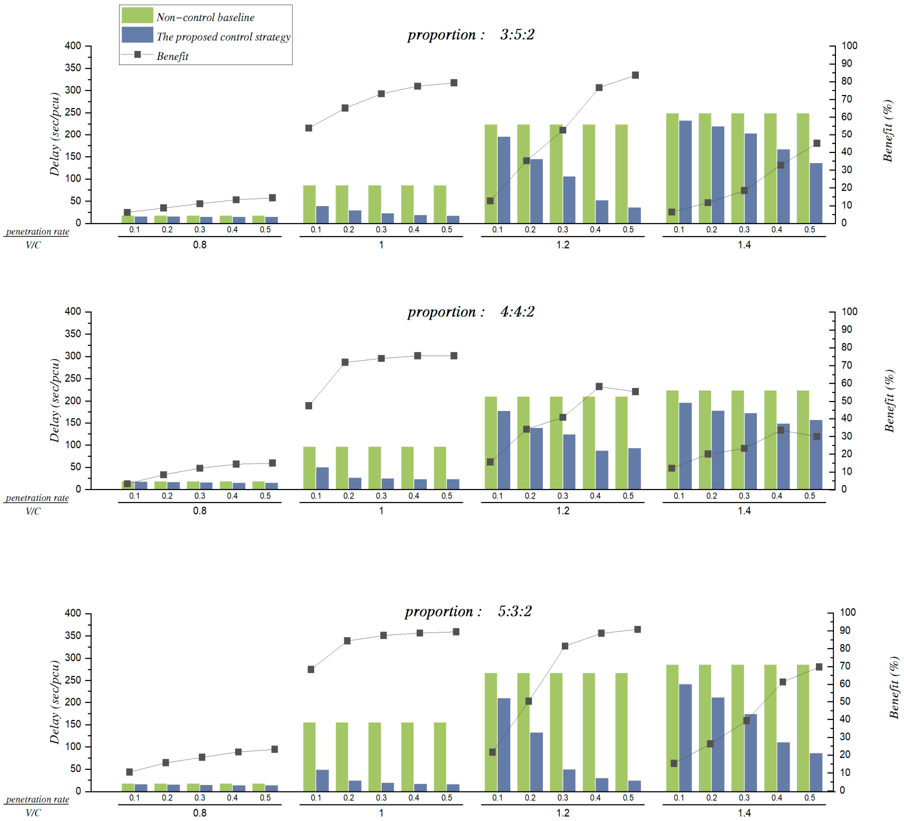

Figure 6. Delay comparison results under low unbalanced traffic demand levels.

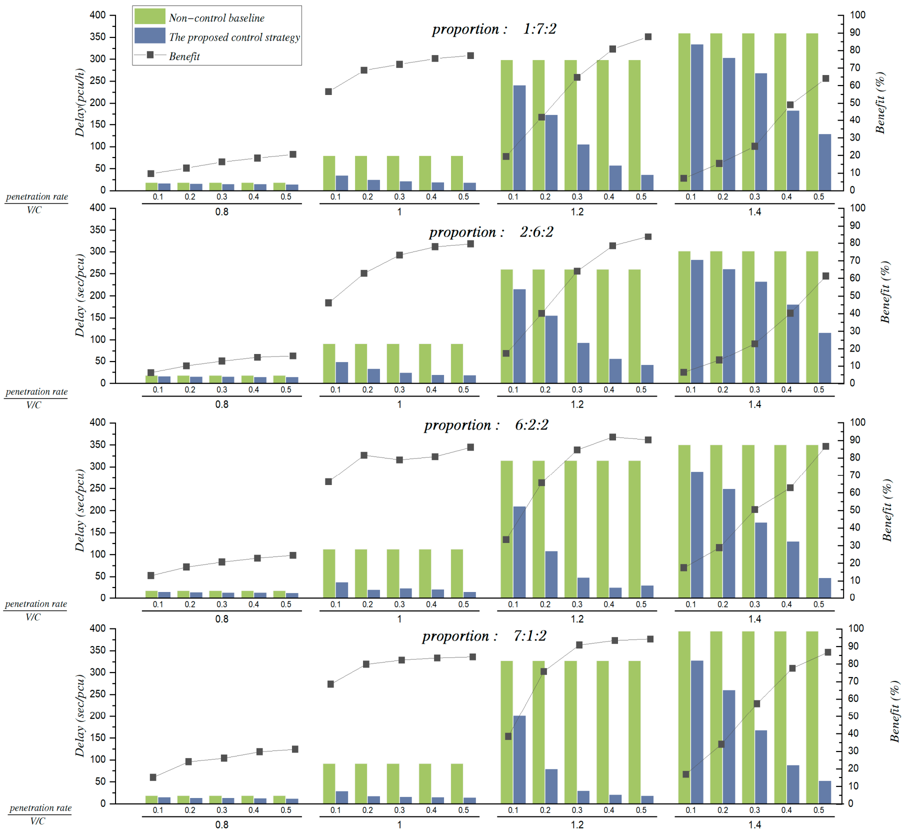

Figure 7. Delay comparison results under high unbalanced traffic demand levels.

5.2.2. Traffic System Resilience Improvement Validation

Figure 8 is the result of traffic system resilience comparison under various unbalanced demand levels. The proposed control strategy can improve traffic system resilience when the congestion level is 1.2 and 1.4. The reason for selecting high congestion levels is that the traffic system cannot easily experience system collapse without any control strategies. In Figure 8, the red dotted line denotes the resilience is 100%. To be specific, the proposed control strategy can effectively recover the traffic system from collapse to normal operation if the resilience is more than 1.0. Compared with the high unbalanced demand levels, the benefits of traffic system resilience improvement are more obvious under the conditions of low unbalanced demand levels. With the increment of CPRs, the proposed control strategy can perform better in traffic system resilience improvement.

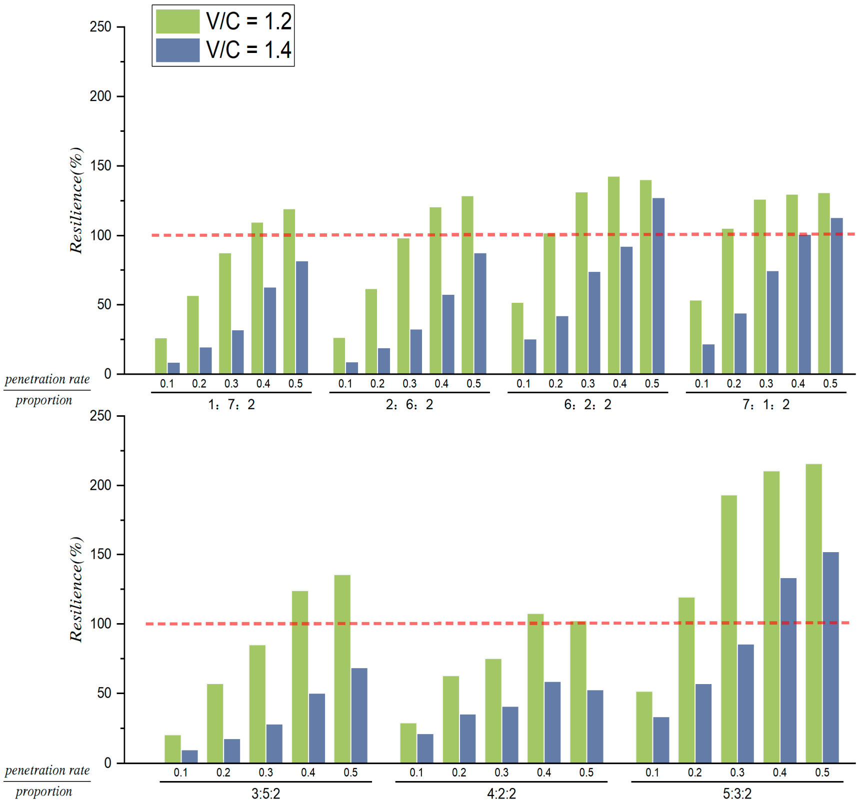

Figure 8. Traffic system resilience comparison results.

5.2.3. Bus Priority Validation

The proposed control strategy can improve traffic efficiency and traffic system resilience while ensuring bus priority. To validate the effectiveness of the capability of ensuring absolute bus priority, some experiments are conducted. As shown in Tables 1 and 2, the bus delay has been a MOE to evaluate the capability of ensuring absolute bus priority. The results demonstrate that the proposed control strategy can ensure that bus delay is less than 1 second under various congestion levels and unbalanced demand levels. Hence, the proposed control strategy has a credible capability of ensuring absolute bus priority.

Table 1. Bus delay under various congestion levels and unbalanced demand levels (CPR=0.3).

Penetration rate = 0.3

Delay in sec/pcu				
V/C \ Proportion	1:7:2	3:5:2	4:4:2	6:2:2
0.6	0	0	0	0
0.8	0	0	0	0.07
1.0	0	0	0	0.30
1.2	0	0	0.46	0.25
1.4	0	0	0.06	0.20

Table 2. Bus delay under various congestion levels and unbalanced demand levels (CPR=0.5).

Penetration rate = 0.5

Delay in sec/pcu				
V/C \ Proportion	1:7:2	3:5:2	4:4:2	6:2:2
0.6	0	0	0	0
0.8	0	0	0	0
1.0	0	0	0.33	0
1.2	0	0	0.57	0.60
1.4	0	0	0.04	0

6. Conclusion

This paper proposed a control strategy to improve traffic system resilience while ensuring absolute bus priority. The proposed control strategy can achieve traffic demand management by allocating the right-of-way for CAVs with heavy turning demand. To evaluate the proposed control strategy, simulation experiments have been conducted under the low unbalanced traffic demand levels and the high unbalanced traffic demand levels. Sensitivity analysis was performed for congestion levels and CPRs.

Compared with the non-control baseline, the effectiveness of the proposed control strategy is validated in terms of throughput, delay, and traffic system resilience. Some conclusions drawn from the results are as follows:

- Under various congestion levels, no obvious benefits of throughput improvement exist under the low congestion levels. The proposed control strategy has the benefit of throughput improvement when the congestion level is high (1.2 and 1.4). The throughput improvement benefits can be up to 10%-40%. Different from the throughput improvement, the proposed control strategy can obtain delay reduction benefits at any congestion levels.
- With the increment of the CPRs, the proposed control strategy can achieve more throughput improvement benefits and delay reduction benefits under high congestion levels. Especially when the congestion level is 1.4, the delay reduction benefits are more obvious.
- Compared with the non-control baseline, the proposed control strategy outperforms in traffic system resilience under high congestion levels. Especially when the left-turning demand proportion is high, the proposed control strategy can recover the traffic system to handle all vehicles even if the congestion level is 1.4.
- Absolute bus priority can be guaranteed under various congestion levels and CPRs. The bus delay is less than one second, which means that the bus priority is not interfered with general vehicles accessing the BPL.

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