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Two-way Cooperative Priority Control of Bus Transit with Stop Capacity Constraint

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Abstract: Signal priority control and speed guidance are effective ways to reduce the delay of buses at intersections. Previous work generally focused on the optimization strategy at the intersection area, without simultaneously considering the influence on adjacent downstream bus stops. This probably leads to the size of the passed bus platoon exceeding the capacity of berths and queuing, which in turn causes additional delay to the overall bus travel time. Focusing on this problem, this paper proposes a two-way cooperative control strategy that constrains the size of the upstream platoon. Besides this, to avoid bus bunching, no more than two buses from the same route can be admitted in the same platoon. Based on these principles, we modeled how to make buses pass without stopping by simultaneously considering the signal control and speed guidance. Finally, the effectiveness was validated by simulation in Verkehr in Städten Simulation (VISSIM , German for "Traffic in cities – simulation"), a microscopic traffic simulator. The results show that compared to the existing methods, which only use signal control, the cooperative strategy reduces the total delay at the intersection and the downstream stop. It alleviates the queuing phenomenon at the downstream bus stop greatly, and the bus arrivals tend to be more uniform, which helps improve the reliability and sustainability of bus services.

Keywords: transit priority control; two-way cooperative control; speed guidance; stop capacity constraint; bus bunching

1. Introduction

Research on transit priority control began in the 1960s and has been developing and improving continuously. At present, there are two kinds of transit priority control strategies at signalized intersections: (I) signal control—the signal phase responds to bus priority request; (II) speed control—buses actively adapt to signal phase, which is mainly realized by optimizing the speed guidance. Compared with the signal control approach, speed control is a control strategy that has less impact on passengers and is easier to accept [1]. It can also reduce stops, fuel consumption, and emissions [2,3].

The first strategy is referred to as transit signal priority (TSP). The active effects of TSP have been evaluated by many studies, which can improve transit reliability and mobility [4,5]. For example, some scholars proposed a signal control model to minimize the overall delay at the near-saturated intersection [6]. Lian et al. [7] proposed an improved transit signal priority strategy for real-world signal controllers that considers the number of bus arrivals. Shaaban and Ghanim [8] investigated the impact of implementing a TSP treatment along a major arterial. With the development of infrastructure communication technology, there have been a bunch of studies about TSP under the connected vehicle environment [9,10]. In those studies, the commonly used signal control strategy of

TSP is the phase extension, such as extending the green light and cutting off the red light early. However, the strategy of phase extension is not always efficient due to the uncertainty of vehicle arrivals, and the effect of the TSP gradually decreases as traffic flow increases [11]. The optimization effects of TSP are therefore limited. Speed control is expected to solve these problems. Combining speed control with signal control, the accuracy of the estimation of vehicle arrivals can be increased, and hence better optimization is supposed to be achieved through cooperative controls.

At present, speed control is mainly used for bus service reliability control. Based on real-time headway information, Daganzo and Pilachowski [12,13] proposed a scheme that dynamically determines bus holding times at a route's control points and adjusts bus cruising speed in real-time. To deal with bus bunching, He et al. [14] presented a strategy that adaptively determines the actual holding time and adjusts the bus cruising speed when a bus arrives at a bus stop. Zhang and Lo [15] analyzed the two-way-looking self-equalizing control method; both deterministic and stochastic running time scenarios were considered. Ampountolas et al. [16] proposed practical linear and nonlinear control laws to regulate space headways and speeds, which would limit bus bunching. The coordinated strategy for multiple bus lines is also a method to alleviate bus bunching [17]. It can be found that speed control is used to mitigate bus bunching in some research [18], but it is seldom used in cooperation with signal control. Some studies have introduced speed guidance into transit priority. For example, Teng and Jin [19] developed a bus operation control system to dynamically adjust bus speed. Liang and Wei [20] proposed a method including speed guidance and signal priority control, to enhance bus punctuality and maximize the average passenger revenue of bus transit and other road users. Wu et al. [21] presented a bus operation control strategy to minimize the total cost through the integrated optimization of bus speed and holding time. However, the capacity of the downstream bus stop has not been considered in these studies. When speed guidance is implemented to achieve transit priority, buses attend to be bunched together. This is represented as the compression of headways and vehicles passing through the intersection in a platoon. Takashi Nagatani [22] found that dividing the traffic cluster depends highly on the signal control. Even with the benefits of transit priority at intersections, the problem of queues at downstream stops would cause additional delays. Additionally, the current studies on bus stops mainly focus on passenger flow analysis and the influence of capacity on the adjacent lane [23,24]. Therefore, given the whole system, the size of the platoon should be constrained by the downstream stop capacity while applying transit priority control.

This paper proposes a two-way cooperative control strategy to regulate buses in the bus lane. It adopts signal control and speed guidance simultaneously to achieve transit priority in the intersection. Considering both the downstream stop capacity and bus bunching prevention, two admission rules are suggested when the platoon is emerging. We adopt four strategies to control the platoon, concerning the relationship between the arrival time window and the green phase. To optimize the regulation effect, the delay of buses and general vehicles are calculated to constrain the strategies. Besides this, the effectiveness of the cooperative strategy and the significance of the stop capacity constraint are demonstrated by the secondary development of VISSIM.

The remainder of this paper is organized as follows: Section 2 presents the two-way cooperative control model, including the general intersection descriptions, platoon admission rules, control strategies, and optimization models; Section 3 illustrates the simulation results and numerical analysis; Section 4 offers the conclusions of this study.

2. Methodology

2.1. General Intersection Description

Without loss of generality, we chose a typical urban intersection in the town center as the modeling object, where an arterial and a secondary road intersect. There is a bus stop in the downstream of the arterial road and the third lane from the center-line is the bus lane (shown in Figure 1). The priority of the buses that go straight on the arterial road was studied. Besides this, the

signal phase was set as the classic four-phase with a fixed period. There were no additional signal control or speed control measures.

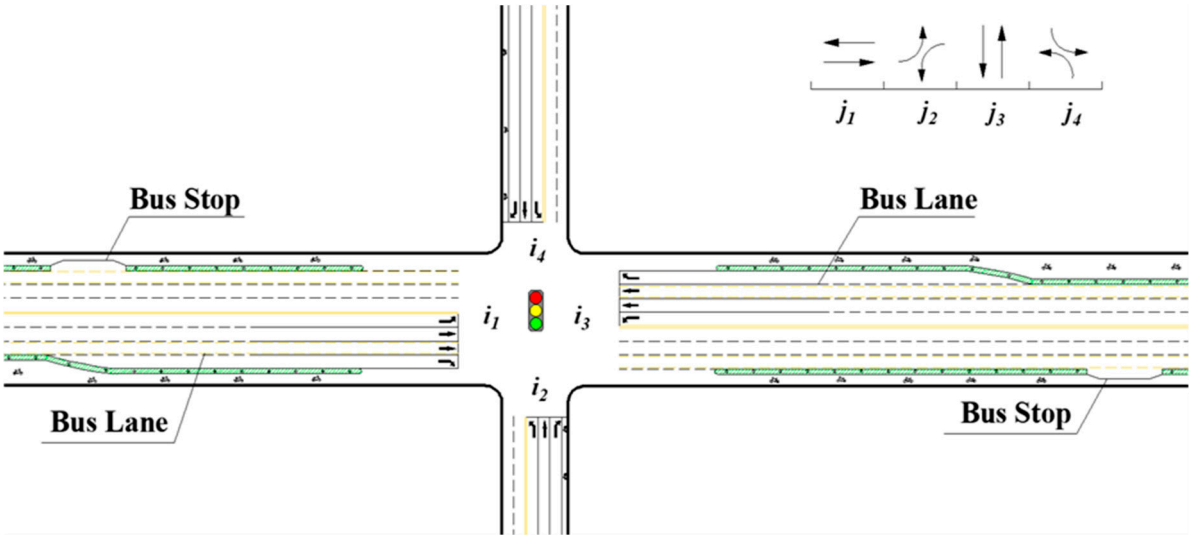


Figure 1. The general description of the studied intersection.

According to Figure 1, the priority phase is phase j_1. The buses on the intersection entrances i_1 and i_3 are regulated. To simplify the model, the model was formulated based on the following assumptions:

- The buses are connected vehicles under internet of vehicles (IOV) technology, whose arrivals pattern follows a Poisson distribution, while the general vehicles are controlled under current traffic;
- The buses travel at the recommended speed on the bus lane without overtaking, lane changing, acceleration, and deceleration;
- The traffic volumes of left-turn vehicles and vehicles on the secondary road are relatively small, and the passenger load is 40 per bus.

2.2. Platoon Admission Rules

Whether buses can be admitted into a platoon should be judged by the following two rules: bunching prevention and capacity constraint.

Bunching prevention forbids two buses from the same route to go into the same platoon. Otherwise, it may cause bus bunching. For example, there is no more than one No.112 bus in a platoon. N_k is the number of buses belonging to line k. When there is more than one bus belonging to Route 112 in a platoon ($N_k = 1$), the next No.112 bus will be incorporated into the next platoon and the platoon will be separated by speed control and signal control.

As for the capacity constraint, the size of a platoon should be satisfied with the capacity constraint of the downstream bus stop. For each direction of traffic, the bus stop is perceived outside the area of the analyzed intersection. Otherwise, it may result in an overflow of stopping buses and delay at the bus stop. So, when a bus enters the control zone of the intersection, if the size of the current platoon is smaller than the bus stop capacity, this means the bus stop can accommodate the current platoon. Therefore, these buses can be served at the bus stop. In cases that the size of the current platoon is equal to the bus stop capacity, the next coming bus would be guided into the next platoon.

2.3. Control Strategies

When buses enter the control zone of the intersection, there are four states: passing through by accelerating, passing freely without speed adjustment, passing through by decelerating, and suffering a stop inevitably (shown in Figure 2).

The first state, passing through by accelerating, means that when vehicles are in the position defined by the maximum speed (the blue line) and the general speed (the green line), the vehicle can pass through the intersection by accelerating. The second state, passing freely without speed adjustment, means that when vehicles are in the position defined by the general speed (the two green lines), the vehicle can pass the intersection freely without speed adjustment. Thirdly, when vehicles are in the position defined by the general speed (the green line) and the minimum speed (the red line), they can pass through the intersection by decelerating. Finally, when vehicles are between the red line and the stop line, the vehicle would inevitably encounter the red lights and have to stop. The symbol X_d in Figure 2 means the control zone of the intersection. Buses with a distance more than X_d from the stop line would be controlled in the next cycle.

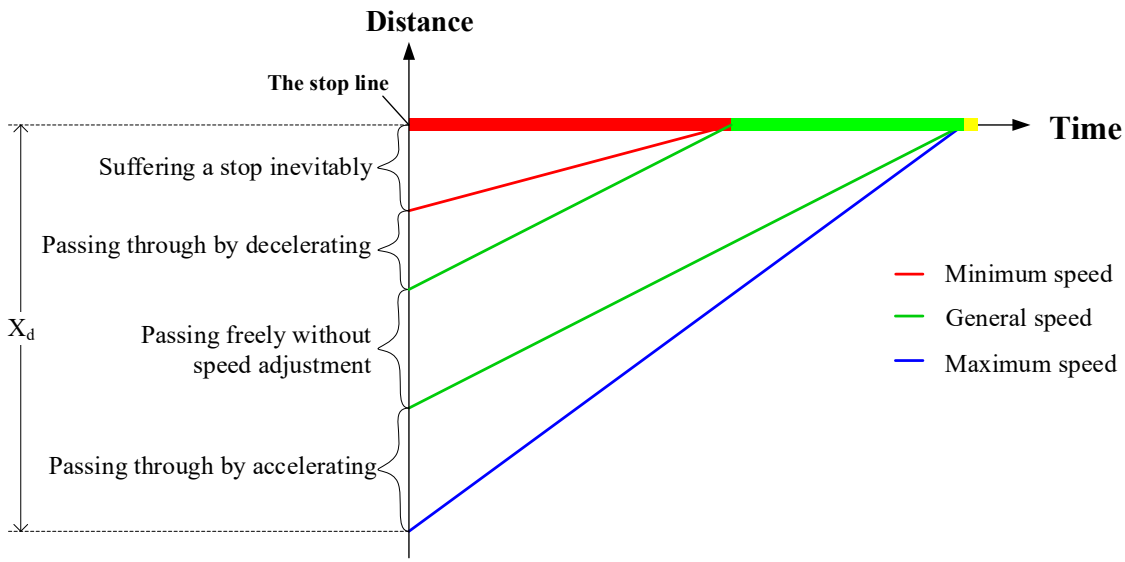


Figure 2. Illustration of vehicles accessibility.

As shown in Figure 2, a time window is formed between the time when the bus arrives with the maximum speed and the minimum speed, which is referred to as the arrival time-window in this paper. If there is an overlap between the arrival time-window and the green phase, it means that by proper speed guidance, the bus can pass through the intersection without stopping. On the contrary, if there is no overlap, it means that signal control is also needed. In this study, extending the green light and cutting off the red light early were adopted for signal control. Therefore, for each incoming bus, the model regulated it by judging the relationship between the arrival time-window and the green phase, as shown in Equations (1) and (2):

$$\left[T_0 + \frac{d_{n,k}}{V_{\max}}, T_0 + \frac{d_{n,k}}{V_{\min}}\right] \cap \left[T_{j,s}(G), T_{j,e}(G)\right] \neq \varnothing \tag{1}$$

In Equation (1), T_0 is the detection time, $d_{n,k}$ is the distance between the bus and the stop line, V_{max} and V_{min} are the permitted maximum and minimum speed of buses, respectively. $T_{j,s}$ and $T_{j,e}$ are the green light start time and end time of the priority phase, respectively, and their difference is the length of the green light phase. When Equation (1) is satisfied, it means that there is an overlap between the arrival time-window of preceding buses in the platoon and the green phase. Otherwise, there is no overlap.

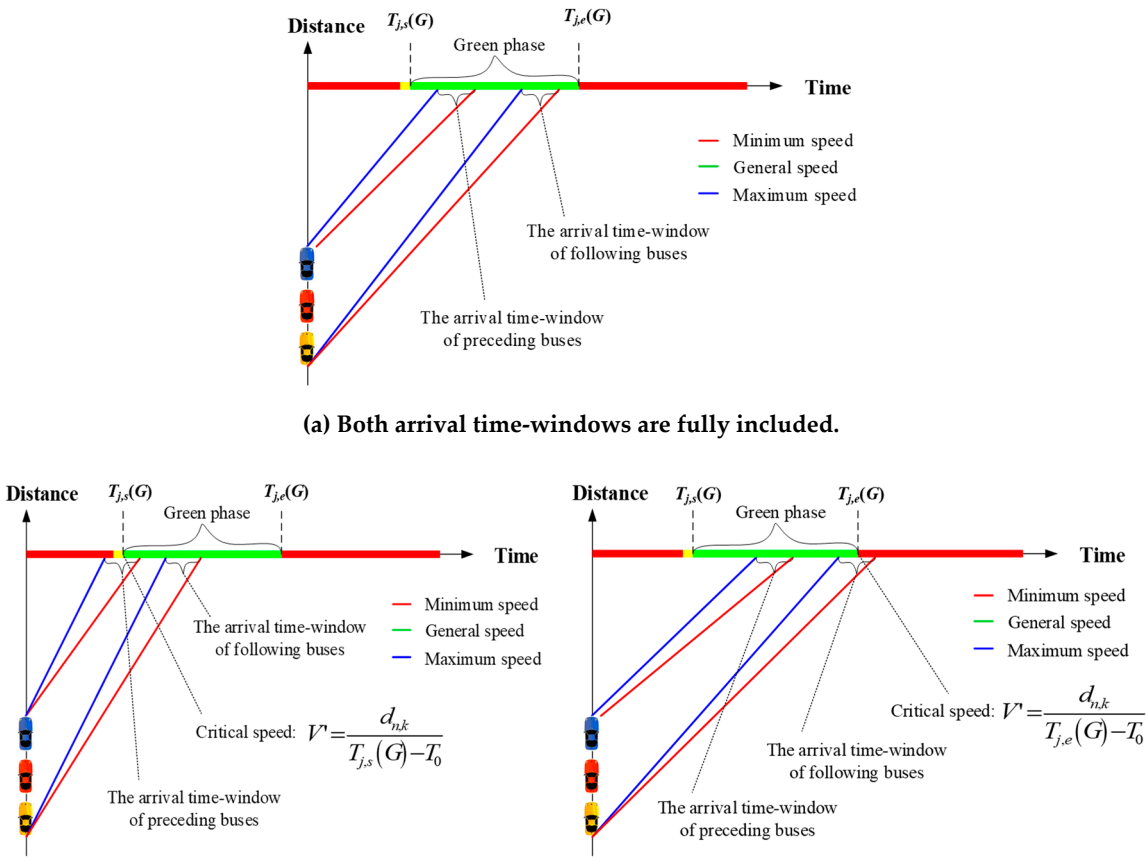
$$\left[T_0+\frac{d_{n,k}}{V_{\max}}+(N_m-1)\times\Delta\mathrm{h},T_0+\frac{d_{n,k}}{V_{\min}}+(N_m-1)\times\Delta\mathrm{h}\right]\cap\left[T_{j,s}(G),T_{j,e}(G)\right]\neq\varnothing \quad (2)$$

In Equation (2), N_m is the number of buses in the platoon and Δh is the saturation headway. When Equation (2) is satisfied, it means that there is an overlap between the arrival time-window of the following buses in the platoon and the green phase. Otherwise, there is no overlap. Therefore, based on the relationship between arrival time-window and green phase determined in Equations (1) and (2), control strategies can be divided into the following four types. They are adopted depending on whether Equation (1) or Equation (2) is satisfied.

Strategy I: Only speed guidance

This is adopted when both Equation (1) and Equation (2) are satisfied. Under this case, both the arrival time-window of the preceding buses and the following buses have an overlap with the green phase, and the platoon can pass through the intersection with the speed guidance alone. There are three situations (shown in Figure 3).

When both arrival time-windows are fully included in the green phase (shown in Figure 3 (a)), buses can pass through the intersection without signal control strategies. In other cases, when the arrival time-window of the preceding buses or the following buses is not fully covered by the green phase (shown in Figure 3(b) and Figure 3(c)), the speed guidance strategy needs to be implemented. The bus speed is controlled between the critical speed and the maximum speed or minimum speed to pass the intersection. The critical speed is the speed at which the bus can just pass the intersection, as shown in Figure 3(b) and (c).



(a) Both arrival time-windows are fully included.

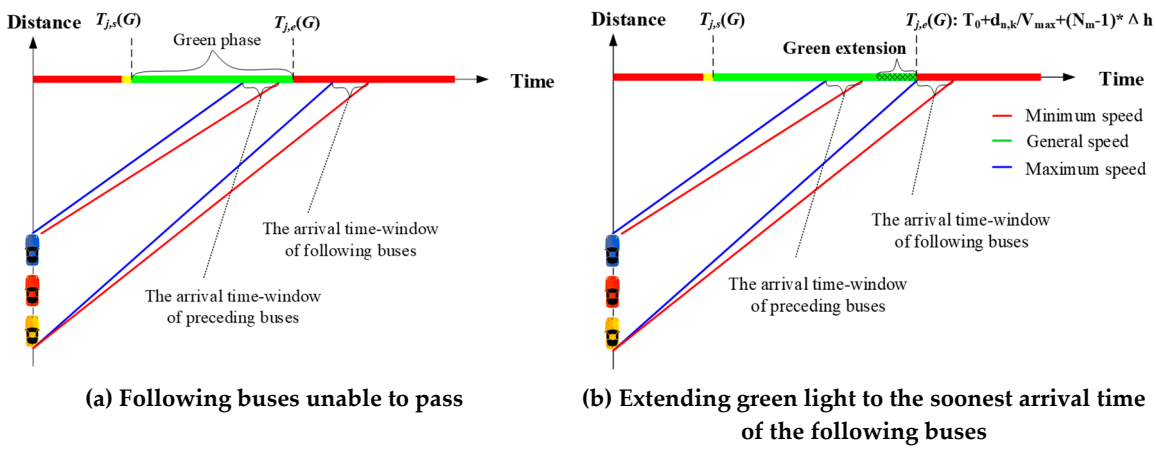
(b) Arrival time-window of preceding buses is not fully included

(c) Arrival time-window of following buses is not fully included

Figure 3. No-stop pass by speed guidance strategy.

Strategy II: Both extending green light and speed guidance are needed

This is adopted when only Equation (1) is satisfied. In this case, there is only one overlap between the arrival time-window of the preceding buses and the green phase (shown in Figure 4(a)). The preceding buses can pass the intersection by speed guidance alone, while the following buses need to take advantage of both the signal control strategy and speed guidance strategy to pass the intersection. For the following buses, the green phase is extended to the soonest arrival time of the following buses, and the speed should be adjusted to the maximum speed. The strategy is illustrated in Figure 4(b).

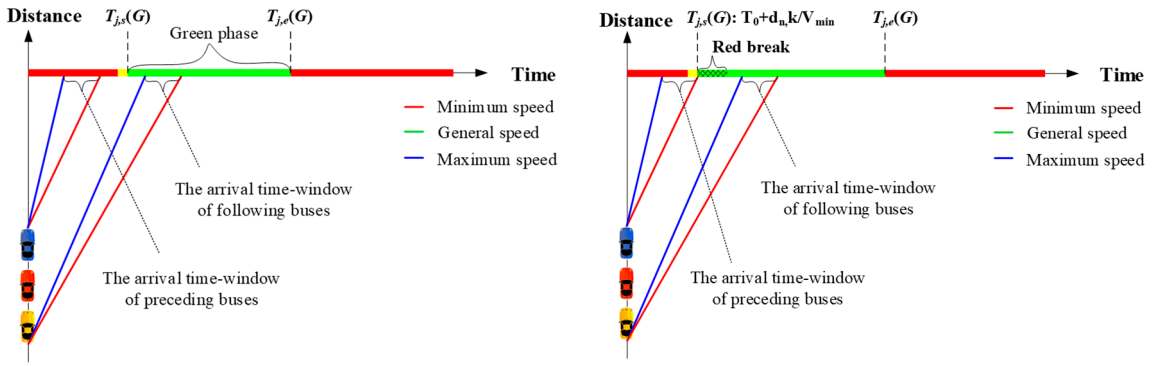


(a) Following buses unable to pass **(b) Extending green light to the soonest arrival time of the following buses**

Figure 4. Illustration of strategy II.

Strategy III: Both cutting off red light and speed guidance are needed

This is adopted when only Equation (2) is satisfied. Vice versa, similar to strategy II, if there is only one overlap between the arrival time-window of the following buses and the green phase (shown in Figure 5(a)). The following buses can pass the intersection by speed guidance alone, while the preceding buses have to call for both the signal control strategy and speed guidance strategy. Therefore, the red light time has to be cut off to the time when the preceding buses arrive with the slowest speed, and the speed has to be adjusted to the minimum value. The strategy is illustrated in Figure 5(b).



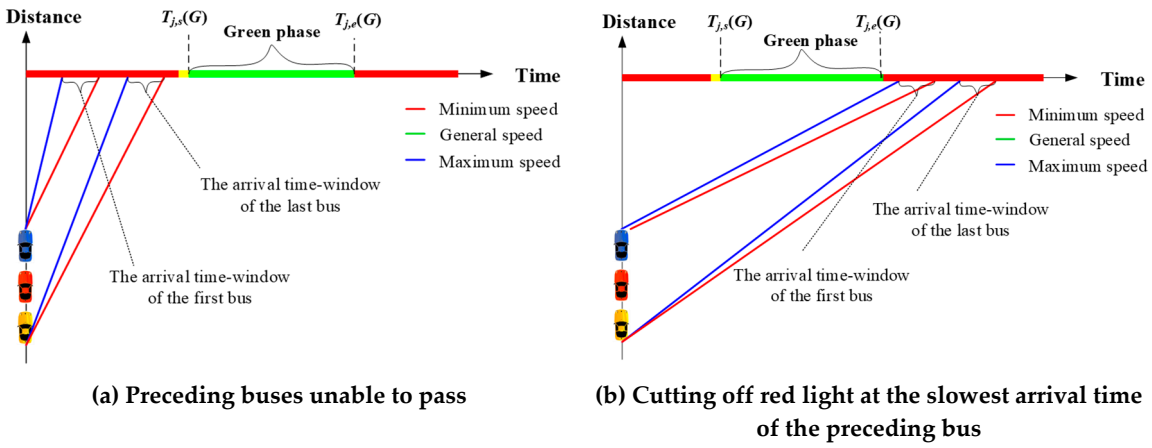
(a) Preceding buses unable to pass **(b) Cutting off red light at the slowest arrival time of the preceding bus**

Figure 5. Illustration of strategy III.

Strategy IV: Controlled as strategy II or strategy III

This is adopted when neither Equation (1) nor Equation (2) are satisfied. In the last strategy, there is no overlap between the arrival time-window of all the buses and the green phase. There are two cases. If the platoon arrives before the green phase, as shown in Figure 6(a), the control strategy is the same as strategy III, which is to break the green phase at the slowest arrival time of the

preceding buses and the speed should be minimized. In the other case, that the platoon arrives after the green phase, as shown in Figure 6(b), the buses should be controlled as in strategy II, i.e., to extend the green phase to the soonest arrival time of the following buses and the speed is adjusted to the maximum value.



(a) Preceding buses unable to pass **(b) Cutting off red light at the slowest arrival time of the preceding bus**

Figure 6. Illustration of strategy IV.

2.4. Optimization Models

The objective of this optimization model is to minimize the total delay at the single intersection within one period, including both the general vehicle delay and the bus delay. In the meantime, priority is given to the buses on arterial roads, and the general vehicles on the secondary roads do not have to sacrifice too much to pass the intersection.

2.4.1. Delay Calculation

(1) The delay of buses

This model focuses on the priority of the buses that go straight on the arterial road. The left-turn vehicles on the arterial road and the vehicles on the secondary road are negligible, so delaying them will not change much. Therefore, the bus delay on other phases can be ignored and only the delay of buses that go straight on the arterial road is calculated, as formulated in Equation (3).

$$D(B)=\lambda\times[(N_{i_1}+N_{i_3}-\sum N_m)\times r_{j_1}] \tag{3}$$

In Equation (3), $D(B)$ is the bus delay in one cycle, λ is the bus equivalent ratio based on passenger volume, which is set at 40 according to the empirical value in this model. N_{i1} and N_{i3} are the numbers of the buses going straight on entrances i_1 and i_3 respectively, which have entered into the control zone of the intersection. $\sum N_m$ is the total number of buses that pass through the intersection in one cycle, including buses on entrances i_1 and entrance i_3. r_{j1} is the red-light duration of phase j_1.

(2) The delay of general vehicles

The arrival rate of the general vehicles was assumed to be a constant value in this study, so the delay of the general vehicles could be calculated as in the equilibrium phase delay formula based on the steady-state theory, and it is formulated as in Equation (4).

$$\begin{aligned}D(V)=&[\frac{q_{i_1,j_1}s_{j_1}}{2(s_{j_1}-q_{i_1,j_1})}+\frac{q_{i_3,j_1}s_{j_1}}{2(s_{j_1}-q_{i_3,j_1})}]r_{j_1}^2+[\frac{q_{i_1,j_2}s_{j_2}}{2(s_{j_2}-q_{i_1,j_2})}+\frac{q_{i_3,j_2}s_{j_2}}{2(s_{j_2}-q_{i_3,j_2})}]r_{j_2}^2\\&+[\frac{q_{i_4,j_3}s_{j_3}}{2(s_{j_3}-q_{i_4,j_3})}+\frac{q_{i_2,j_3}s_{j_3}}{2(s_{j_3}-q_{i_2,j_3})}]r_{j_3}^2+[\frac{q_{i_4,j_4}s_{j_4}}{2(s_{j_4}-q_{i_4,j_4})}+\frac{q_{i_2,j_4}s_{j_4}}{2(s_{j_4}-q_{i_2,j_4})}]r_{j_4}^2\end{aligned} \tag{4}$$

In Equation (4), $D(V)$ is the delay of the general vehicles in one cycle, $s_{j1,\,j2,\,j3,\,j4}$ are the saturation flows of each phase. $r_{j1,\,j2,\,j3,\,j4}$ are the red light duration of each phase, and $q_{i,\,j}$ is the average arrival rate

of the passing vehicles that go straight on the entrance i in the phase j. When the signal phase has to be changed, extending the green light or cutting off the red light early, the green time of each phase needs to be reallocated. Therefore, based on the fixed signal timing plan, the adjusting time of phase j_1 (Δr_{j1}) is allocated to other phases according to the green split result. The increased red-light time in other phases (Δr_{j1}, Δr_{j2} andΔr_{j3}) can be calculated as Equation (5).

$$\Delta r_{j_2} = \frac{g_{j_2}}{g}\Delta r_{j_1}, \Delta r_{j_3} = \frac{g_{j_3}}{g}\Delta r_{j_1}, \Delta r_{j_4} = \frac{g_{j_4}}{g}\Delta r_{j_1} \tag{5}$$

In Equation (5), g is the total green light duration in a cycle, g_{j2}, g_{j3}, g_{j4} are the green light duration of phase j_1, j_2, and j_3, respectively. More specifically, μ_1, μ_2, μ_3, and μ_4 are formulated as in Equation (6). D is the total delay at the intersection within one period, that is, $D = D(V) + D(B)$. Therefore, with regulation, the value of D can be calculated as in Equation (7).

$$\begin{cases} \mu_1 = \dfrac{q_{i_1,j_1}s_{j_1}}{2(s_{j_1} - q_{i_1,j_1})} + \dfrac{q_{i_3,j_1}s_{j_1}}{2(s_{j_1} - q_{i_3,j_1})} \\ \mu_2 = \dfrac{q_{i_1,j_2}s_{j_2}}{2(s_{j_2} - q_{i_1,j_2})} + \dfrac{q_{i_3,j_2}s_{j_2}}{2(s_{j_2} - q_{i_3,j_2})} \\ \mu_3 = \dfrac{q_{i_4,j_3}s_{j_3}}{2(s_{j_3} - q_{i_4,j_3})} + \dfrac{q_{i_2,j_3}s_{j_3}}{2(s_{j_3} - q_{i_2,j_3})} \\ \mu_4 = \dfrac{q_{i_4,j_4}s_{j_4}}{2(s_{j_4} - q_{i_4,j_4})} + \dfrac{q_{i_2,j_4}s_{j_4}}{2(s_{j_4} - q_{i_2,j_4})} \end{cases} \tag{6}$$

$$\begin{aligned} D = & \mu_1(r_{j_1} - \Delta r_{j_1})^2 + \mu_2(r_{j_2} + \frac{g_{j_2}}{g}\Delta r_{j_1})^2 + \mu_3(r_{j_3} + \frac{g_{j_3}}{g}\Delta r_{j_1})^2 \\ & + \mu_4(r_{j_4} + \frac{g_{j_4}}{g}\Delta r_{j_1})^2 + \lambda \times [(N_{i_1} + N_{i_3} - \sum N_m) \times r_{j_1}] \end{aligned} \tag{7}$$

2.4.2. Strategical Constraints

In order to give priority to the buses on the arterial road, the green light time of the priority phase is extended. This would result in a rapid increase in the general vehicle delay and the bus delay in other phases, so it is necessary to limit the extension of phase j_1. There are two constraints for the strategy, as follows:

(1) Bus system priority constraint

Because the green time of priority phase is extended for platoon passing, the total delay of the buses in other phases also increases. Considering the bus system priority principle, the total delay of all buses should be reduced. This means that the decrease in the bus delay in the priority phase should be greater than the increase in the bus delay in other phases, as shown in Equation (8).

$$D(B) - D_0(B) \geq N_{j_2} \times \Delta r_{j_2} + N_{j_3} \times \Delta r_{j_3} + N_{j_4} \times \Delta r_{j_4} \tag{8}$$

In Equation (8), $D_0(B)$ is the total bus delay with regulation, $D(B)$ is the total bus delay without regulation, and N_{j2}, N_{j3}, and N_{j4} are the numbers of the buses that stopped and waited for the green phase. If Equation (8) is satisfied, the total delay of all buses decreases after the regulation. Otherwise, the total delay increases, which means the strategy is invalid.

(2) Strategic effectiveness constraint

The green time increment of the buses may lead to an excessive increase in the general vehicle delay, which makes the total delay at the intersection increase. Therefore, to ensure that the control

strategy is effective, the total delay at the intersection with regulation should be smaller than that without regulation, as shown in Equation (9):

$$D < D_0 \tag{9}$$

where D_0 is the total delay at the intersection within one period without regulation. If Equation (9) is satisfied, the total delay will decrease with the regulation, which indicates the strategy is effective. We should adopt the strategy under the situation that both the constraints are satisfied, and the speed and green phases are controlled according to the calculation. Otherwise, we will not control the platoon, and let the buses decelerate smoothly to stop until reaching the stop line.

To sum up, considering the admission rules to regulate the platoon, this model adopts four strategies, which depend on the relationship between the arrival time-window and the green phase to guide the platoon. Regulatory logic is shown in Figure 7.

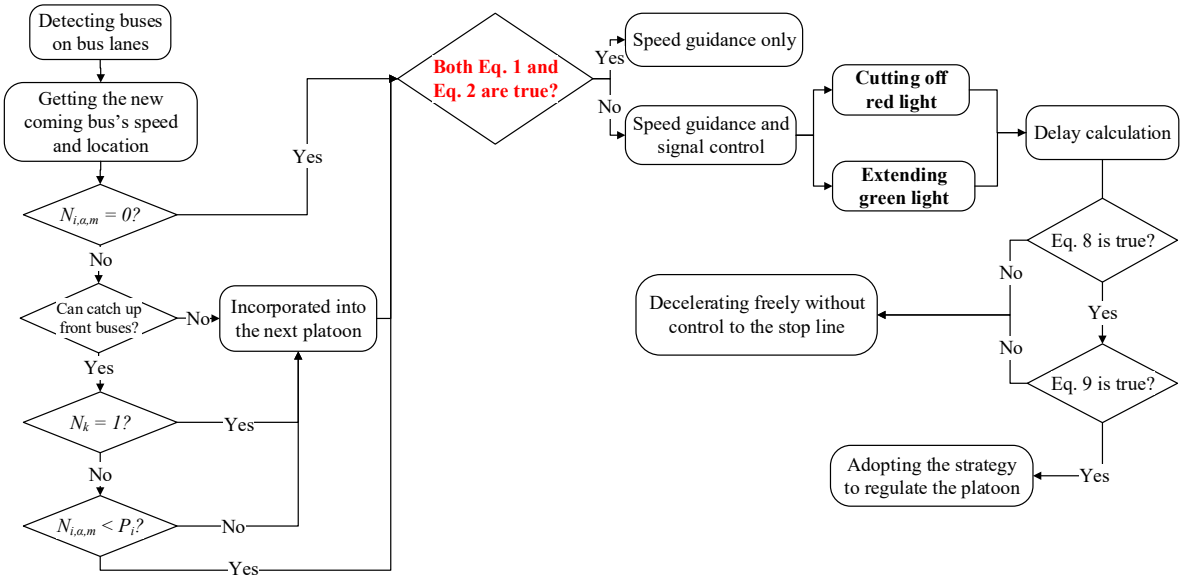


Figure 7. Model regulatory logic.

3. Numerical Analysis

In this section, we report the simulation results and provide the analysis. Based on the survey data at the intersection of Youyi Road and Tieji Road in Wuhan, Hubei province, this model was simulated and verified in VISSIM. The COM, secondary development interface of VISSIM, was introduced to build the model. The control strategies were applied through the COM interface. In order to cut down the random deviation of simulation and ensure the validity and reliability of the results, the simulation time was set as 3600 s with 10 different random seeds. We calculated the average results as the evaluation criterion.

Comparing the results with and without the two-way cooperative control strategy (shown in Table 1), the travel time was lowered by 16.45% and the delay was lowered by 25.18%. This proves the effectiveness of the control strategy. In particular, the average queue length decreased by as large as 37.66%, which shows that the proposed strategy had an obvious effect for relieving the queuing in the intersection. To further investigate the influence of the stop capacity constraint for regulation, we compared the intersection with and without the admission rules. The simulation results are presented in Table 2.

Table 1. Simulation results compared with the intersection without regulation.

Simulation Results	Without Control	With Control	Optimization
Travel time (s)	81.54	68.13	16.45%
Delay (s)	29.23	21.87	25.18%
Parking time (s)	18.90	13.09	30.74%
Stop frequency (times)	0.64	0.45	30.33%
Average queue length (m)	21.95	13.68	37.66%
Maximum queue length (m)	123.43	108.60	12.02%

Table 2. Comparison of the results with and without the stop capacity constraint.

Simulation Results	Intersection Entrance i_1			Intersection Entrance i_3		
	With	Without	Change	With	Without	Change
Travel time (s)	67.10	68.13	1.54%	82.80	83.09	0.35%
Delay (s)	20.05	21.87	9.08%	15.60	16.39	5.06%
Stopping time (s)	11.28	13.09	16.01%	8.20	8.85	7.93%
Stop frequency (times)	0.43	0.45	4.19%	0.27	0.31	12.96%
Average queue length (m)	12.67	13.68	8.03%	4.81	4.90	1.80%
Maximum queue length (m)	101.47	108.60	7.02%	52.50	52.63	0.24%

Table 2 illustrates the influence of the stop capacity constraint. The results show that with the constraint of the size of a platoon, simulation results increased by 1% - 16%. This indicates that operation efficiency at the intersection decreased. This is because of the limited bus stop capacity. The size of the platoon was constrained, so the passing rate diminished. However, it can be found that according to the results in Table 2, the increase was very small. For example, the travel time of entrance i_1 increased by 1.54% and the delay of entrance i_3 increased by 5.06%. This suggests that even though the stop capacity constraint restricts the number of buses passing through, the reduction in operational efficiency is relatively small. To explore the influence of the platoon admission rules on the whole system, we evaluated the effectiveness of the intersection and the downstream bus stop. The simulation results are presented in Table 3.

Table 3. Comparison of the whole system's effectiveness with and without stop capacity constraint.

Simulation Seeds	Travel time with/without the stop capacity constraint		
	With(s)	Without(s)	Reduction(s)
13	160.2	157.3	2.9
22	159.6	157.8	1.8
35	157.5	156.8	0.7
47	154.8	154.7	0.1
50	155.7	154.2	1.5
60	156.6	156.1	0.5
70	157.2	155.7	1.5
86	158.8	157.3	1.5
97	157.7	156.5	1.2
100	158.2	154.9	3.3
Average reduction			1.5

As shown in Table 3, with ten different simulation seeds, the travel time of the whole system reduced by 1.5 s on average. This indicates that the buses took less time from entering the control zone of the intersection to leaving the bus stop. The reduction in travel time is shown in Figure 8. It can be regarded as a normal distribution. Although the travel time of the whole system was not optimized too much, the mean value of the distribution was obviously greater than zero. This means that the travel time decreased and the results are promising.

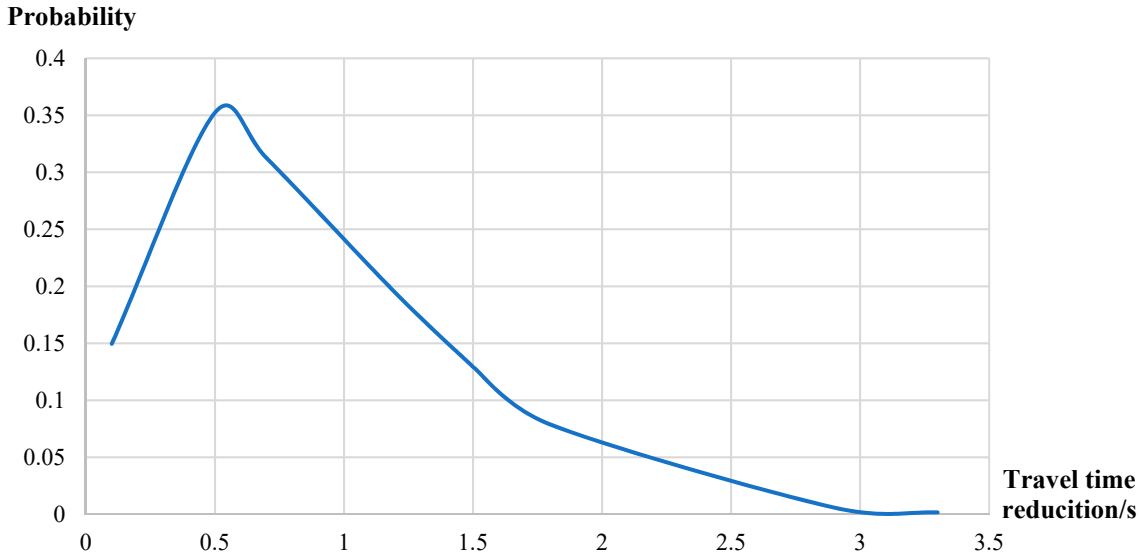


Figure 8. The probability distribution of travel time reduction.

Analyzing the results in Table 3, it can be seen that simply considering the optimal intersection effectiveness without the downstream stop capacity cannot obtain the optimal system. As the number of buses in a platoon is constrained, the effectiveness of the intersection is reduced because fewer buses can pass the intersection. However, the queue at the bus stop is alleviated and the delay at the bus stop decreases. As a whole, the reduction of the delay at the bus stop is more than the increase of the delay at the intersection. For the whole system, the effectiveness is better. Thus, we can draw the conclusion that considering the stop capacity constraint, our regulation can improve the whole system's effectiveness. In addition, to evaluate the bunching prevention constraint, the time difference between the arrivals of the buses of the same route was analyzed.

The study collected the arrival time data of three bus routes. The values of the mean and standard deviation of the arrival time were calculated (shown in Table 4). The results show that with bunching prevention, the arrival time increased. The spacing of buses belonging to the same routes was enlarged, which indicates that the bus bunching can be alleviated. On the contrary, the standard deviation decreased after implementing this bunching prevention rule. This demonstrates that the arrival times became more concentrated and the fluctuations reduced. The buses belonging to the same route tended to arrive regularly, which shows an improvement in the reliability of bus services.

Table 4. Arrival times with and without bunching prevention.

Route		Arrival Time with/without Bunching Prevention		
		Before	After	Variation
Route 1	Mean(s)	608.23	662.76	+54.53
	Standard deviation(s)	81.24	70.98	−10.26
Route 2	Mean(s)	659.05	696.78	+37.73
	Standard deviation(s)	82.07	80.58	−1.49
Route 3	Mean(s)	851.97	915.32	+63.35

Standard deviation(s)	90.72	88.32	−2.40

4. Conclusions

This paper proposed a two-way cooperative control strategy that considers the downstream bus stop capacity for guiding the platoon. We could generate the following conclusions according to the numerical analysis.

First, simply considering the control effect in the intersection is insufficient. Although the downstream stop capacity constraint impairs the effectiveness of the intersection, the delay at the stop can be significantly lessened. On the whole, the system efficiency is optimized. The introduction of the stop capacity constraint is of significance. Second, this strategy can limit bus bunching and the buses tend to travel with an even headway. The reliability and sustainability of bus services were improved. Third, this strategy can help to achieve transit priority while the capacity of the downstream stop is guaranteed. The total delay of the intersection and downstream stop was reduced and this study will be useful for controlling the traffic by signals and speed guidance.

The priority control of bus transit is a complex issue that requires comprehensive consideration of roads, signal phases, social vehicles, and other factors. In this paper, a two-way cooperative priority control model based on the platoon admission rules was proposed. There were some limitations, which can be improved in future research. For example, the studied intersection in this paper was a single intersection without consideration of the relationship with adjacent intersections. So, the vehicles in VISSIM did not arrive in clusters as they do on the road. In future studies, a model with multi-intersection control can be taken into account. In addition, the feasibility of this model for other intersections of various traffic flows should be analyzed.

On the other hand, the control effect of the model is closely related to bus traffic; therefore, a comprehensive assessment is needed. The proposed approach in this paper regulates the platoon first and then guides it by the signal control strategy and speed guidance strategy. Future studies can combine the platoon organization and control strategies simultaneously to optimize the control effect.

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