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RESEARCH ARTICLE

Dynamic Bus Scheduling Method Based on Mixed Control Strategy With Signal Timing Adjustment and Bus Holding

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ABSTRACT Passengers traveling on urban bus rapid transit tend to arrive randomly. They are more concerned about whether the buses can arrive at stops at the scheduled time intervals. However, influenced by the dwell time at stops, the traveling speed on the road section, and the signal status of intersections, the travel time of the bus between two stops becomes unstable, which in turn changes the headway of the bus fleet. In this paper, we propose a dynamic scheduling method for a bus fleet based on a mixed control strategy, which is composed of multi-cycle signal timing adjustment and bus holding. The dynamic scheduling model is formulated with objectives of minimizing the deviation degree of headways between stops and the increased degree of average vehicle delay at intersections. Then, the genetic algorithm is applied to derive the scheduling scheme for the bus fleet between adjacent stops on a rolling basis. Finally, simulation indicates that the dynamic scheduling method can improve the stability of bus headways effectively, while not having a great impact on intersection vehicle delay.

INDEX TERMS Dynamic bus scheduling, headway, bus holding, signal timing adjustment, delay.

I. INTRODUCTION

Bus rapid transit (BRT) system has dedicated lane which effectively mitigates interference from private vehicles and ensures consistent operational stability. The service level of BRT is comparable to that of rail transit, yet it is more cost-effective, making it the preferred urban transit choice for many cities [1], [2]. On high-frequency BRT routes, passengers typically do not rely on timetables, opting instead for random arrivals. And they are more concerned about whether buses arrive at stops within scheduled time intervals. Factors such as dwell time at the stop, travel speed on the road section, and signal status at intersections lead to variations in bus travel time between stops [3] [4] [5] [6]. These variances cause fluctuations in the headway of the bus fleet, and the cumulative effect can even cause bus bunching.

With the Global Positioning System, Vehicle-to-Infrastructure communication, adaptive signal control, and other technologies widely used in the traffic system, the capture of real-time data on bus operation is enabled. Using these data, we can more accurately predict the bus location, optimize the bus departure time and dwell time at stops, and adjust traffic signal parameters along the BRT route, so as to bolster the operational stability [7], [8]. The prevalent dynamic bus scheduling methods include:

a) Bus holding: it recommends buses to hold at stops for a period of time after passengers boarding.
b) Skip-stop: it allows buses to skip certain stops during operation and continue running without pausing.
c) Shuttle bus schedule: it limits bus operation between selected stops, typically those with higher passenger volumes.
d) Signal timing adjustment: it regulates bus movement by modulating signal timings at intersections, including

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prolonging green time, curtailing red time, and adding extra signal phases.

Although the skip-stop method can somewhat abbreviate travel times, it may inadvertently lengthen the passenger waiting time at skipped stops, thus affecting the equity and fairness of the transit service. Shuttle bus schedule method is better suited for complex traffic conditions on urban roads and may necessitate an expanded fleet size to meet varying demands across different road sections. In contrast, bus holding and signal timing adjustment methods align better with the operational characteristics and needs of urban BRT routes, facilitating dynamic control of bus headways [9], [10], [11].

Regarding the bus holding methods, Asgharzadeh and Shafahi [12] presented a mathematical model that minimized passenger waiting time to obtain the optimal holding time. Seman et al. [13] implemented the integrated bus holding strategy in decision variables. They applied the desired bus headway provisions for multiple BRT lines sharing a corridor. Gkiotsalitis and Cats [14] considered the detrimental effects of bus holding on travel times of on-board passengers and developed a nonlinear optimization programming with constraints. Liang et al. [15] obtained the movement of buses by means of the headway-based holding strategy, so as to minimize the cost for bus company and cost for passengers. Considering the scheduled charging times and adding it to the objective function, Gkiotsalitis [16] expanded the traditional bus holding models which are headway-based for the electric one. Olvera-Toscano et al. [17] proposed a model with a linear objective function and quadratic constraints and developed a beam-search heuristic to determine the bus dwell times. The bus holding method is particularly suited to scenarios where buses operate at higher speeds and reach stops ahead of schedule, rather than in cases of delay [18].

Regarding the signal timing adjustment methods, most existing research focuses on the control algorithms for Transit Signal Priority, often prioritizing buses over the entire traffic traveler at intersections. Lin [19] presented a transit signal priority model for headway-based bus operations. They determined the optimal green extension time based on transit priority requests from multiple routes. Chow and Li [20] developed strategies for regulating bus headway by adjusting signal timing schemes to improve bus service regularity. Truong et al. [21] introduced an advanced transit signal priority method that considered the bus headway levels, traffic congestion levels, and dwell-time distributions. Long et al. [22] established an optimal signal control model for multi-route buses, to minimize deviation between the expected and actual bus headway. Seman et al. [23] proposed a control method that integrates bus headway adjustment and bus prioritization at intersections for real-time operation. Considering the need to balance bus headways, Zhai et al. [24] found signal cycle and green duration for bus priority using an optimization model. Liang et al. developed robust bus priority methods for demand-responsive transport without exclusive bus lanes [25] and with exclusive bus lane [26]. Ji et al. proposed cooperative optimization methods of signal timing adjustment with tram prioritization [27], tram timetabling [28], and adjusting bidirectional scheduled tram trajectories [29].

In studies concerning the coordination of signal timing adjustment and bus holding methods, Koehler et al. [30] introduced it for minimizing total passenger delay. Liang et al. [31] developed an integrated bus holding and robust signal prioritization method that considered stochastic bus speeds and the number of vehicles queuing under mixed traffic.

In general, current research predominantly employs the bus holding method and signal timing adjustment method separately to control bus operation. The independent bus holding method can readily result in extended bus headway and bus bunching. While the independent signal timing adjustment method may significantly exacerbate delay for other vehicles sharing the intersection. The collaborative optimization of dwell time at stops and signal timing adjustment scheme can help to balance the limitation of both. There are few studies on synergies between the two, and they only adjust the signal timing for a single cycle within one intersection.

In this paper, we propose a dynamic scheduling framework that integrates multi-cycle signal timing adjustment and bus holding methods. It can make the headways between buses when departing from bus stops closer to the expected headway (departure interval). Using real-time data on bus routes, the bus arrival time at intersections is predicted and multi-cycle signal timings are adjusted in advance. The small adjustment amplitude of each cycle facilitates a more harmonious balance among traffic travelers, thereby reducing negative impacts on the intersection signals. Furthermore, as complementary to multi-cycle signal timing adjustments, the bus holding method is introduced and the dwell time at stops is optimized.

II. METHOD

A. PROBLEM DESCRIPTION

The BRT route consists of M bus stops. Buses regularly depart from the initial stop at interval H_1. As depicted in Figure 1, L_m denotes the distance between adjacent stops, labeled m and $m+1$. The bus operates at an average speed v_0. There are $N(m)$ signalized intersections, sequentially numbered from 1 to $N(m)$. The distance from intersection n ($1 \leq n \leq N(m)$) to stop m is denoted by L_m^n. We introduce C_m^n as the initial signal cycle and g_m^n as the green time for buses of intersection n between stop m and $m+1$.

Integrated with parameters of signal intersections, current information detection technologies are capable of acquiring real-time data on the location and speed of buses. If the headways of successive buses equal the expected interval, it indicates that the buses are operating on schedule. Otherwise, the multi-cycle signal timing adjustment and bus holding methods are required to control them. Specifically, using the departure time from stops as the decision points, predictions can be made regarding its departure time from subsequent stops. The information can then be utilized to adjust the signal timing at intersections and determine dwell time at next stop.

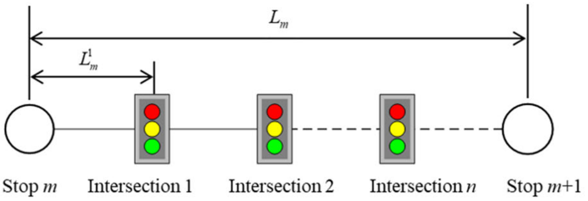


FIGURE 1. Signalized intersections distribution between stops.

B. OPERATIONAL STATES EXPRESSION

The following discussion is based on the bus i-1 and its succeeding bus i. When bus i is about to leave stop m, the status of bus i-1 can be categorized into two distinct scenarios:

Scenario 1: Bus i-1 has already departed from stop $m+1$.

Scenario 2: Bus i-1 has not yet departed from stop $m+1$.

Due to the dynamic fluctuation of the headways between consecutive buses, establishing a reference point is crucial for analysis. In this study, the departure time from the stop serves as the reference point. In Scenario 1, the control objective for bus i is to maintain a departure interval from stop $m+1$ that is equal to the scheduled interval H_1. In Scenario 2, when bus i leaves from stop m and bus i-1 has not yet left stop $m+1$, it becomes necessary to first predict the time when bus i-1 leaves from stop $m+1$ and subsequently adjust the time when bus i leaves from stop $m+1$, so as to ensure that their headway matches the expected interval H_1.

Let $d_{i,m}$ represent the actual time when bus i left from stop m. The expected time when bus i arrives at downstream intersections is determined by Eq. (1).

$$\tilde{t}^n_{i,m} = \begin{cases} d_{i,m} + L^1_m/v_0 & \text{if } n = 1 \\ \tilde{d}^{n-1}_{i,m} + \left(L^n_m - L^{n-1}_m\right)/v_0 & \text{if } n > 1 \end{cases} \tag{1}$$

where $\tilde{t}^n_{i,m}$ represents the expected time when bus i arrives at intersection n between stop m and stop $m+1$; $\tilde{d}^{n-1}_{i,m}$ denotes the expected time when bus i leaves from intersection n-1 between stop m and $m+1$.

In Scenario 1, the signal serves bus i from the next cycle after it leaves stop m until it departs from the intersection. The adjustment may span one or multiple cycles. To simplify the calculation, we assume that the green time for each cycle after adjustment is set to the same value. The expected number of signal cycles which are adjusted for bus i at intersection n between stop m and $m+1$ ($\tilde{B}^n_{i,m}$) and the expected time passed since the beginning of the last green time for bus i upon its reach at intersection n ($\tilde{P}^n_{i,m}$) are given by the following expressions:

$$\tilde{B}^n_{i,m} = \left\lceil \left(P^n_{i,m} + \left(\tilde{t}^n_{i,m} - d_{i,m} - C^n_m\right)\right)/\tilde{C}^n_{i,m} \right\rceil \tag{2}$$

$$\tilde{P}^n_{i,m} = \left[\tilde{t}^n_{i,m} - \left(C^n_m - P^n_{i,m}\right) - d_{i,m}\right] \bmod \tilde{C}^n_{i,m} \tag{3}$$

where $P^n_{i,m}$ represents the time passed since the last green time began at intersection n when bus i departed from stop m; $\tilde{C}^n_{i,m}$ is the expected signal cycle after intersection n being adjusted for bus i; the symbol $\lceil\rceil$ denotes the upward rounding operator; the mod represents the remainder operator.

In Scenario 2, bus i leaves stop m before the preceding bus leaves the next stop $m+1$. Consequently, intersection n may be unable to adjust the signal green time for bus i immediately. It has to wait for bus i-1 to leave from intersection n and to serve bus i from the next cycle until bus i departs from intersection n. The calculation of $\tilde{B}^n_{i,m}$ and $\tilde{P}^n_{i,m}$ are given as Eqs. (4) and (5).

$$\tilde{B}^n_{i,m} = \left\lceil \left(\tilde{t}^n_{i,m} - \tilde{d}^n_{i-1,m} - C^n_m + \tilde{P}^n_{i-1,m}\right)/\tilde{C}^n_{i,m} \right\rceil \tag{4}$$

$$\tilde{P}^n_{i,m} = \left[\tilde{t}^n_{i,m} - \tilde{d}^n_{i-1,m} - \left(\tilde{C}^n_{i-1,m} - \tilde{P}^n_{i-1,m}\right)\right] \bmod \tilde{C}^n_{i,m} \tag{5}$$

where $\tilde{d}^n_{i-1,m}$ refers to the expected time when bus i-1 departs from intersection n; $\tilde{P}^n_{i-1,m}$ represents the expected time passed since the last green time started at intersection n when bus i-1 departed from stop m; $\tilde{C}^n_{i-1,m}$ is the expected signal cycle after intersection n being adjusted for bus i-1.

Taking signalized intersection n as an example, the process of signal timing adjustment is illustrated in Figure 2 below.

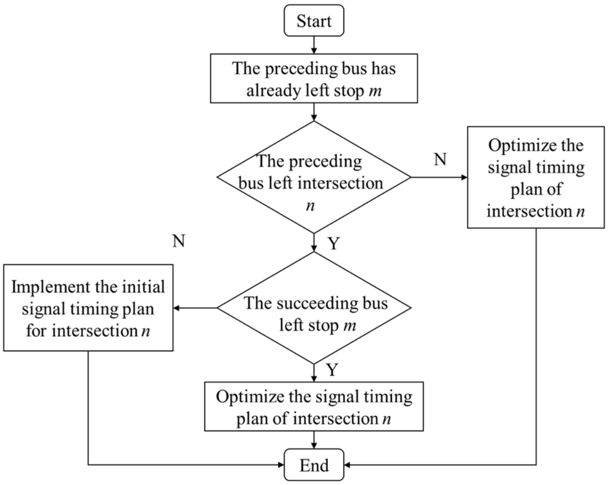


FIGURE 2. Signal timing adjustment for signalized intersection.

Upon arrival at intersection n, bus i is permitted to pass directly if the current signal state is green. Otherwise, it must wait to pass through the next green signal. The expected waiting time $\tilde{T}^n_{i,m}$ for bus i at intersection n can be obtained:

$$\tilde{T}^n_{i,m} = \begin{cases} 0 & \text{if } 0 \le \tilde{P}^n_{i,m} \le \tilde{g}^n_{i,m} \\ \tilde{C}^n_{i,m} - \tilde{P}^n_{i,m} & \text{if } \tilde{g}^n_{i,m} < \tilde{P}^n_{i,m} < \tilde{C}^n_{i,m} \end{cases} \tag{6}$$

where $\tilde{g}^n_{i,m}$ represents the green time after intersection n being adjusted for bus i.

We calculate $\tilde{d}^n_{i,m}$ and $\tilde{t}_{i,m+1}$ according to Eq. (7) and Eq. (8), respectively. The $\tilde{d}^n_{i,m}$ is denoted as the expected time when bus i leaves from intersection n. The $\tilde{t}_{i,m+1}$ is referred as the expected time when bus i arrives at stop $m+1$.

$$\tilde{d}^n_{i,m} = \tilde{t}^n_{i,m} + \tilde{T}^n_{i,m} \tag{7}$$

$$\tilde{t}_{i,m+1} = d_{i,m} + (L_m/v_0) + \sum_{n=1}^{N(m)} \tilde{T}^n_{i,m} \tag{8}$$

Let $\tilde{T}^{\beta}_{i,m+1}$ represent the time when bus i dwells at stop $m+1$. The expected time when bus i leaves from stop $m+1$ $\tilde{d}_{i,m+1}$ is computed by Eq. (9).

$$\tilde{d}_{i,m+1} = \frac{L_m}{v_0} + \tilde{d}_{i,m} + \sum_{n=1}^{N(m)} \tilde{T}^n_{i,m} + \tilde{T}^{\alpha}_{i,m+1} + \tilde{T}^{\beta}_{i,m+1} \tag{9}$$

C. MODEL FORMULATION

To control the deviation between the actual headways and the expected departure interval, we set minimizing the deviation degree of headways between stops $Z^1_{i,m+1}$ as one of the optimization objectives. The specific calculation method is shown in Eq. (10). When bus i leaves stop m, the preceding bus i-1 has already left the next stop $m+1$, let the expected time ($\tilde{d}_{i-1,m+1}$) equal the actual one ($d_{i-1,m+1}$).

$$\min\ Z^1_{i,m+1} = \left(|\tilde{d}_{i,m+1} - \tilde{d}_{i-1,m+1} - H_1|/H_1\right)^2 \tag{10}$$

We suppose that the initial signal timing scheme is the optimal, which reduces the average vehicle delay within the current intersection. Changes in the green time for bus phase may result in an increase in average vehicle delay in other phases. To prevent excessive adjustments from increasing delay, we also set minimizing the increased degree of average vehicle delay at intersections $Z^2_{i,m+1}$ as one of the optimization objectives. The specific calculation formula is as follows:

$$Z^2_{i,m+1} = \sum_{n=1}^{N(m)} \left(\frac{\tilde{D}^n_m - D^n_m}{D^n_m}\right)^2 \tag{11}$$

$$D^n_m = \frac{1}{\sum_{a=1}^{A(n)} v^n_{m,a}} \cdot \sum_{a=1}^{A(n)} D^n_{m,a} \cdot q^n_{m,a} \tag{12}$$

$$\tilde{D}^n_m = \frac{1}{\sum_{a=1}^{A(n)} v^n_{m,a}} \cdot \sum_{a=1}^{A(n)} \tilde{D}^n_{m,a} \cdot q^n_{m,a} \tag{13}$$

where D^n_m and $\tilde{D}^n_m$ represent the average vehicle delay at intersection n between stop m and $m+1$, before and after adjustment; $D^n_{m,a}$ and $\tilde{D}^n_{m,a}$ denote the average vehicle delay of phase a at intersection n, before and after adjustment [32], [33]; $q^n_{m,a}$ is the hourly traffic volume of phase a within intersection n; $A(n)$ refers to the phase number of intersection n, with phase number being a.

Let φ_1 represent the weight coefficient for the deviation degree of headways between stops, and φ_2 represent the weight coefficient for the increased degree of average vehicle delay at intersections. The weight coefficients can be adjusted according to actual conditions and the requirements of managers. The optimization objective function for dynamic bus scheduling is as follows:

TABLE 1. **Distribution of stop and intersection locations and passenger arrival rates at stops.**

Stop NO.	Stop location (m)	Intersection number	Distance from stop 1 (m)	Arrival rate (pax/h)
1	0	1, 2	400, 1100	108
2	1400	3	1900	100
3	2100	4, 5	2600, 3200	98
4	3700	6, 7, 8	3900, 4500, 5000	94
5	5300	9	5800	95
6	6400	10, 11	6400, 6700	110
7	7700	12, 13	7300, 8100	96
8	9000	--	--	97

$$Z_{i,m+1} = \varphi_1 \cdot Z^1_{i,m+1} + \varphi_2 \cdot Z^2_{i,m+1} \tag{14}$$

Changing the phase sequence would make it difficult for travelers to adapt in a short time, leading to potential traffic chaos [34]. Thus, we do not change the phase sequence but only the specific cycles and green times in the optimization process within reasonable limits. We make the upper and lower limits on the cycles and green times by introducing adjustment coefficients ω_1 and ω_2, as shown in Eqs. (15) and (16).

$$\omega_1 \cdot g^n_m \le \tilde{g}^n_{i,m} \le \omega_2 \cdot g^n_m \tag{15}$$

$$\omega_1 \cdot C^n_m \le \tilde{C}^n_{i,m} \le \omega_2 \cdot C^n_m \tag{16}$$

Additionally, prolonged dwell times at stops would increase the travel time of buses and also cause anxiety among the passengers on board. Therefore, it is necessary to limit the dwell time at stops, as indicated by Eq. (17). Here, ΔT_0 represents the maximum dwell time of buses at stops.

$$\tilde{T}^2_{i,m+1} \le \Delta T_0 \tag{17}$$

D. SOLUTION ALGORITHM

The Genetic Algorithm (GA) is a randomized search method that is derived from the evolutionary principles of biology. Solutions to the model are encoded into chromosomes, with each chromosome representing an individual. A collection of these individuals forms a population. Each individual is evaluated based on the objective function and assigned a fitness value accordingly. Based on this fitness value, individuals are selected for reproduction, crossover, and mutation. A new population inherits the advantageous traits of the previous generation and may also produce some individuals who are superior to the previous generation. This process evolves towards better solutions through continuous iterations until convergence criteria are met or a set number of iterations is completed. The genetic algorithm parameters can be conveniently set using MATLAB's GA tool. The results of the preceding bus serve as the baseline for the succeeding bus.

TABLE 2. **Initial timing and traffic flow at intersections.**

Intersection		Green time of Phases (s)				Critical traffic flow of Phases (pcu/h)			
NO.	Cycle (s)	1	2	3	4	1	2	3	4
1	53	17	30	/	/	900	1600	/	/
2	68	32	30	/	/	1400	1300	/	/
3	79	24	11	35	/	900	400	1300	/
4	85	23	12	26	12	800	400	900	400
5	59	18	35	/	/	850	1700	/	/
6	53	28	19	/	/	1500	1000	/	/
7	76	31	8	28	/	1200	300	1100	/
8	59	33	20	/	/	1600	950	/	/
9	63	21	36	/	/	950	1650	/	/
10	66	26	31	/	/	1150	1500	/	/
11	68	26	12	21	/	1100	500	900	/
12	63	26	31	/	/	1200	1450	/	/
13	60	21	33	/	/	1000	1600	/	/

TABLE 3. **Departure times of bus 1 from stops.**

Stop location	1	2	3	4	5	6	7	8
Departure time (s)	0	188	280	485	710	842	1014	1202

Repeating this process allows for the acquisition of dynamic bus scheduling plans for the bus fleet.

III. SIMULATION

A. DATA PREPARATION

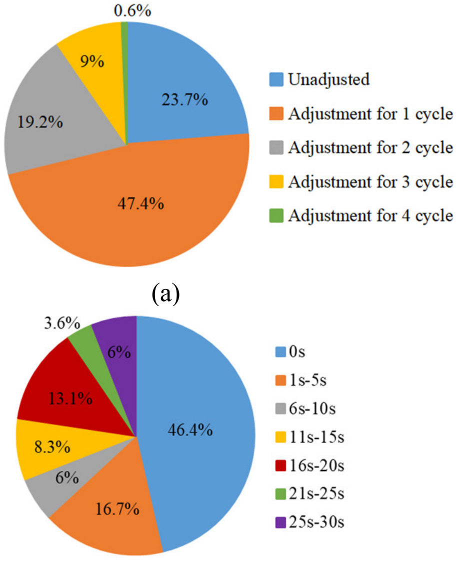
The BRT route has 8 stops and 13 signalized intersections. The distribution and distances of stops and intersections are shown in Table 1. The departure interval for the buses is 6 minutes, with 13 buses serving the route. Buses travel at an average speed of 10 m/s on dedicated lanes. Passengers arrive uniformly at stops, the boarding speed is 1.5 seconds per person, and other delays at stops are 7 seconds. The saturation flow rate at all intersections is set at 1550 pcu/h. The traffic flow on critical lanes at intersections and the initial signal timing are listed in Table 2. Buses passing through the intersection are all controlled by Phase 1.

B. DYNAMIC SCHEDULING PLAN

We set the simulation duration to 5500 seconds. Let $\varphi_1 = 2$, $\varphi_2 = 1, \omega_1 = 0.8, \omega_2 = 1.2$, and $\Delta T_d = 30$s. The time when bus 1 leaves stop 1 is set as zero. The time of bus 1 leaving from each stop obtained by simulation is shown in Table 3.

The subsequent 12 buses operate according to the dynamic bus scheduling method proposed in this paper. Each simulation decision starts when a bus departs from one stop and ends when it departs from the next stop. The scheduling plan is detailed in Tables 4 to 10, including the number of adjustment cycles, signal cycles, green times at intersections, and dwell times at stops.

The changes in signal timing at intersections are relatively minor, and the number of adjustment cycles varies within a certain range. The proportion of different number of adjustment cycles at intersections are shown in Figure 3(a).



(a)

(b)

FIGURE 3. **(a) Proportion of different number of adjustment cycles at intersections; (b) Proportion of different dwell times at stops.**

Since the decision point for the simulation begins when the bus leaves from the previous stop, the farther an intersection is from the previous stop, the more adjustment cycles it typically has. As most intersections are close to the previous stops, the optimized plans mainly involve 1 or 2 adjustment cycles and fewer involve 3 or 4 cycles. Meanwhile, there are quite a few cases where adjustments are not made. Possible reasons for this include: i) the intersection is too close to the upstream stop, and the current cycle (initial plan) still requires time to complete, preventing enough time for switching signal timing; ii) changing the signal timings within the permissible range does not affect bus operations (e.g., the light remains red before and after adjustments); iii) the initial and optimized signal timings are the same.

The proportion of different dwell times at stops is shown in Figure 3(b). When the predicted departure time from the next stop results in a headway that is long compared to the preceding bus, the optimized plan may choose to only adjust

TABLE 4. Scheduling plan for the bus fleet leaving from the stop 1 to stop 2.

Bus NO.	Cycle of intersection 1 (s)	Green time (s)	Number of adjustment cycles	Cycle of intersection 2 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 2 (s)
2	53	17	1	70	33	2	2
3	55	18	1	68	32	2	26
4	53	17	1	64	30	2	4
5	53	17	0	72	34	1	12
6	53	17	0	68	32	2	13
7	48	15	1	60	28	3	7
8	53	17	1	62	29	2	0
9	53	17	1	64	30	2	4
10	55	18	0	68	32	1	8
11	55	18	1	68	32	2	4
12	53	17	1	60	28	2	0
13	53	17	1	60	28	2	4

TABLE 5. Scheduling plan for the bus fleet leaving from the stop 2 to stop 3.

Bus NO.	Cycle of intersection 3 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 3 (s)
2	66	20	1	0
3	79	24	0	18
4	67	20	1	0
5	79	24	0	20
6	67	20	1	0
7	79	24	0	20
8	67	20	1	0
9	79	24	0	20
10	67	20	1	0
11	79	24	0	20
12	67	20	1	0
13	79	24	0	20

TABLE 6. Scheduling plan for the bus fleet leaving from the stop 3 to stop 4.

Bus NO.	Cycle of intersection 4 (s)	Green time (s)	Number of adjustment cycles	Cycle of intersection 5 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 4 (s)
2	71	19	1	51	15	3	0
3	79	21	1	63	19	3	0
4	87	24	0	53	16	2	0
5	91	25	0	59	18	2	29
6	71	19	1	59	18	3	0
7	97	27	1	53	16	4	30
8	91	25	0	53	16	2	0
9	91	25	0	59	18	2	30
10	71	19	1	59	18	3	0
11	79	21	1	56	17	3	0
12	85	23	1	62	19	2	4
13	93	26	0	62	19	2	16

the signal timing or adjust both the signal timing and dwell time. Conversely, if the predicted headway is short, the optimized plan may choose to extend the dwell time at the stop or adjust both the signal timing and dwell time. According to the results, about half of the buses choose to dwell at stops. In most cases, the dwell time is not lengthy, with dwell times longer than 20 seconds accounting for only 9.6%.

C. COMPARATIVE ANALYSIS

1) COMPARISON OF BUS HEADWAYS

Based on the dynamic scheduling plan mentioned above, the discrepancy between bus headways and departure intervals is reduced. To better illustrate the extent of this improvement, we compare the headways under the optimized plan with those under the initial plan. Figure 4 shows the times of buses leaving from stops under both the initial and optimized plans, where the solid line represents the operational status of buses under the initial plan, and the dashed line represents that under the optimized plan. It can be observed that the intervals between the dashed lines are more uniform than those of the solid lines, indicating that the overall headways deviation between buses is smaller under the optimized plan.

Under the initial plan, the average headway between buses is 358.5 seconds with a variance of 1335.4. While under the

TABLE 7. Scheduling plan for the bus fleet leaving from the stop 4 to stop 5.

Bus NO.	Cycle of intersection 6 (s)	Green time (s)	Number of adjustment cycles	Cycle of intersection 7 (s)	Green time (s)	Number of adjustment cycles	Cycle of intersection 8 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 5 (s)
2	58	31	1	66	26	1	60	34	3	0
3	56	30	0	76	31	1	59	33	2	11
4	50	26	0	78	32	1	64	36	2	0
5	48	25	0	76	31	1	56	31	3	0
6	56	30	0	76	31	1	59	33	3	0
7	56	30	0	85	35	1	57	32	3	22
8	56	30	1	78	32	1	60	34	2	20
9	53	28	0	78	32	2	62	35	3	23
10	53	28	1	76	31	1	64	36	2	5
11	56	30	0	68	27	1	56	31	3	0
12	58	31	0	66	26	1	67	38	3	0
13	51	27	0	83	34	1	60	34	2	30

TABLE 8. Scheduling plan for the bus fleet leaving from the stop 5 to stop 6.

Bus NO.	Cycle of intersection 9 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 6 (s)
2	63	21	0	0
3	52	17	1	0
4	63	21	1	11
5	63	21	0	5
6	63	21	0	0
7	52	17	1	0
8	63	21	1	9
9	63	21	0	5
10	55	18	1	0
11	63	21	1	13
12	73	25	1	0
13	63	21	1	0

TABLE 9. Scheduling plan for the bus fleet leaving from the stop 6 to stop 7.

Bus NO.	Cycle of intersection 10 (s)	Green time (s)	Number of adjustment cycles	Cycle of intersection 11 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 7 (s)
2	59	23	0	64	24	2	6
3	57	22	1	57	21	1	0
4	59	23	0	67	25	1	0
5	59	23	1	74	29	1	12
6	59	23	0	59	22	1	0
7	57	22	1	68	26	1	2
8	59	23	0	76	29	1	14
9	59	23	1	59	22	1	0
10	59	23	0	71	27	1	0
11	59	23	0	73	28	1	21
12	57	22	0	59	22	1	0
13	57	22	1	68	26	1	2

optimized plan, the average headway is 363.4 seconds, with a variance of 53.7. The average headways between buses are similar and around 360 seconds. However, the variance in headways is significantly smaller in the optimized plan compared to the initial one. This demonstrates that the dynamic bus scheduling method proposed in this paper can effectively reduce deviations in bus headways at stops, thereby enhancing the stability of bus operations.

In addition, the average headway deviation under the initial plan from stop 2 to stop 8 is 31.43 seconds, with the largest deviation occurring at stop 8 (53.08 seconds) and the smallest at stop 2 (17.42 seconds). The deviations from the departure interval are increased with the bus running. While the average headway deviation under the optimized plan from stop 2 to stop 8 is reduced to 4.26 seconds, an 86.44% decrease. The largest deviation under the optimized plan occurred at stop 4 (8.33 seconds), and the smallest at stop 2 (0.33 seconds). The deviations from the departure interval are not increased with the bus running. This indicates that the dynamic bus scheduling method proposed in this paper can significantly

TABLE 10. Scheduling plan for the bus fleet leaving from the stop 7 to stop 8.

Bus NO.	Cycle of intersection 12 (s)	Green time (s)	Number of adjustment cycles	Cycle of intersection 13 (s)	Green time (s)	Number of adjustment cycles	Dwell time at stop 8 (s)
2	63	26	1	58	20	3	1
3	55	22	1	60	21	2	0
4	65	27	1	60	21	1	3
5	65	27	0	60	21	1	3
6	63	26	0	60	21	2	0
7	54	22	1	60	21	2	0
8	70	29	1	58	20	2	18
9	63	26	1	65	23	1	8
10	63	26	0	63	22	2	0
11	59	24	1	50	17	2	0
12	63	26	1	60	21	2	16
13	63	26	1	60	21	2	16

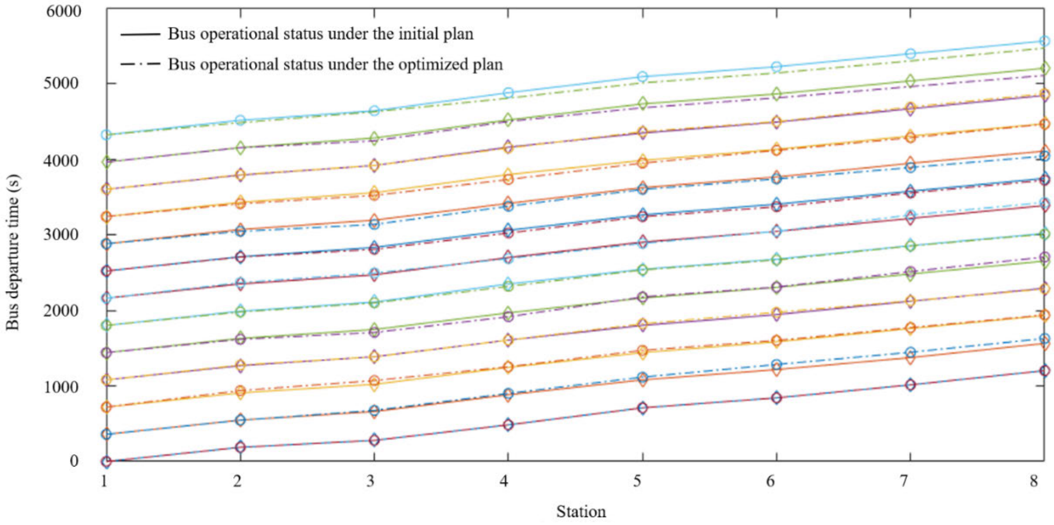


FIGURE 4. Comparison of bus operational status between the initial and optimized plan.

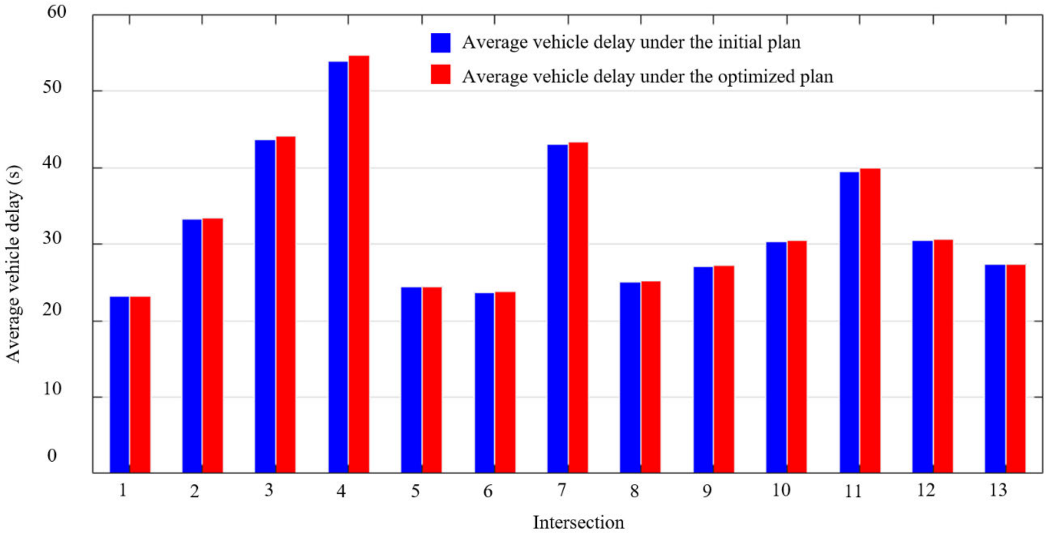


FIGURE 5. Comparison of average vehicle delay at intersections between the initial and optimized plans.

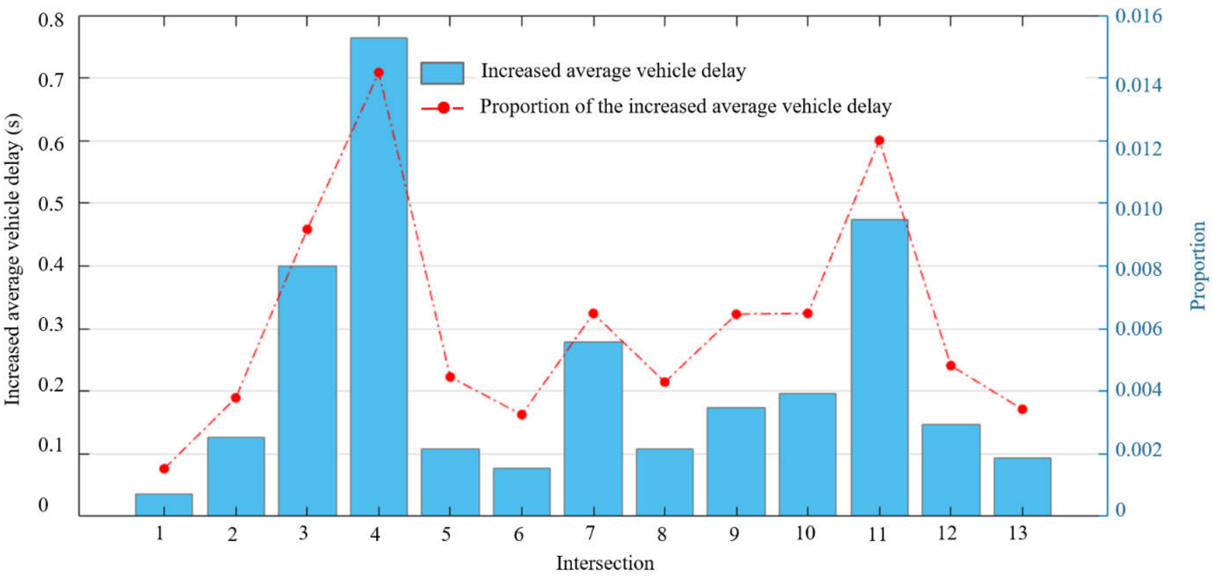


FIGURE 6. **Increased average vehicle delay under the optimized plan.**

avoid bus bunching and ensure uniform waiting times for passengers.

2) COMPARISON OF AVERAGE VEHICLE DELAY AT INTERSECTIONS

The optimized plan reduces the deviation of bus headways when departing from stops compared to the preceding bus. However, it would increase the delay for other traffic travelers at intersections. A comparison of average vehicle delay at intersections under the optimized and initial plan is shown in Figure 5. The average vehicle delay is increased but slightly under the optimized plan compared to the initial plan. To further analyze, the increase in average vehicle delay under optimized plan is illustrated in Figure 6.

The figure features a line graph showing the proportion of increased average vehicle delay and a bar graph representing the increase in average vehicle delay. After bus scheduling, the increase in average vehicle delay is 0.23 seconds, with a growth of 0.62%. It can be considered that the method of adjusting signal timing over multiple cycles has a minor impact on average vehicle delay. The intersection with the highest increase in average vehicle delay is 4 which increased by 0.764 seconds, with a growth of 1.42%. The main reason for this is that intersection 4 is controlled by a four-phase signal, each phase having shorter green times and high saturation, making changes in signal timing relatively more impactful on vehicle delay. Overall, it can be concluded that the initial plan has serious deviations in bus headways, but by combining signal timing adjustment and bus holding methods, there is a significant improvement in bus headways.

IV. CONCLUSION

We propose a dynamic bus scheduling approach for rapid transit buses that integrates signal timing adjustments and bus holding. We first predict the operational status of the buses using real-time data. Then, appropriate strategies for bus holding and multi-cycle signal adjustments are chosen. To minimize the deviation degree of headways between stops and the increased degree of average vehicle delay at intersections, we construct a dynamic bus scheduling model. A genetic algorithm is applied to find the optimal scheme. Simulation results indicate that, compared to the initial plan, the optimized plan significantly reduces the average headway deviation at stops by 86.44% and increases the average vehicle delay at intersections by only 0.62%. This effectively enhances the stability of bus operations while minimizing negative impacts on other traffic travelers.

Nevertheless, our research has certain limitations. For instance, we assumed that all passengers are able to board buses and the speed of passenger boarding is consistent. In reality, passengers frequently cannot board due to overcrowding, and it also influences passenger boarding speed. In the future, we will incorporate more influence factors and provide a more thorough study of these issues.

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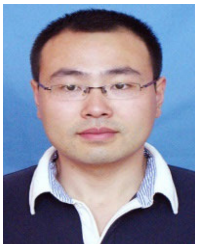

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