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Method of Bidirectional Green Wave Coordinated Control for Arterials under Asymmetric Release Mode

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Abstract: The existing coordinated control methods of green wave are complicated, difficult to operate and mainly applicable to intersection groups with symmetrical arriving upstream flows. Based on engineering practice, a new method of bidirectional progression green wave coordination control was presented by designing particular overlapping phases on the basis of NEMA dual-ring phasing configuration. Applying the characteristics of asymmetric release mode and the requirements of green wave coordinated control, the overall optimization designs of phase sequence combination and offset were carried out, and the influences of cruising speed and residual queues at red light on offset were considered, and then the classical bidirectional green wave graphic method was optimized. Based on the investigation data of the intersections group of Ziwu Road in Qujing City, bidirectional green wave designs were conducted under both symmetric and asymmetric release mode. The results show that the latter approach not only improved the bandwidth of bidirectional green wave band effectively, but also reduced the average delay and the average number of stops on the main road.

Keywords: traffic engineering; bidirectional green wave; asymmetric release mode; overlapping phase; offset; coordinated control

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1. Introduction

With social and economic development, modern means of transport in the city are increasing day by day, and the traffic pressure on urban main roads is also increasing. Intersections are the road network nodes that frequently cause traffic disruption, severe delays, and accidents in a city [1]. Therefore, coordinated control has always been an effective way to improve traffic safety and operational efficiency at intersections [2,3]. Closely spaced traffic signals along an arterial are typically coordinated with a common cycle length and appropriate offsets such that a platoon of vehicles can meet green light as much as possible when traveling along the entire arterial so as to provide the maximum green wave bandwidth, reduce delay and the number of stops, and keep the traffic moving smoothly on the main road. This approach is termed green wave coordinated control for arterials [4].

There are many common methods of green wave coordinated control for arterials, such as the graphical method [4], algebraic method [5], MAXBAND [6] and MULTIBAND [6]. Many researchers have devoted themselves to this study. Little [7] proposed a bandwidth maximization model based on mixed-integer linear programming. Later, Little et al. [8] developed the MAXBAND model which optimized cycle time, offsets, speeds, and the order of left-turn phases to maximize the inbound and outbound bandwidths along an arterial. To ensure that the signal coordination plan can suitably match the actual traffic demand, it is insufficient to use only the average ratio of inbound and outbound traffic volumes in the signal optimization model. Therefore, Gartner et al. [9] constructed the MULTIBAND model, which designed an individually weighted bandwidth for each directional road section, taking into account traffic volumes and flow capacities. Extensive research has been consistently provided based on the MAXBAND and MULTIBAND models [10–12]. Messer et al. [13,14] proposed a green wave bandwidth- optimization algorithm including a left-turn phase on the basis of previous studies, which is widely used in PASSER II, MAXBAND and other bandwidth optimization software.

In recent years, some other studies have been presented. Given the abundance of the literature in this area, it is challenging to provide an exhaustive review. Selected studies closely related to our research topic are briefly summarized below. Wong [15] constructed the coordination timing control strategy of arterial street based on the minimum delay to realize the overall optimization of an artery. Macioszek et al. [16] proposed a model that allowed for the estimation of the maximum queue size at the signal-controlled intersection approach. Hu et al. [17] established a fuzzy system to adjust time parameters and traffic signal phase to realize corridor control based on fuzzy control theory. Tang et al. [18] proposed the MULTIBAND coordinated control model, which improved the bandwidth of the green wave band by eliminating the central symmetry constraint of the green wave band and increasing the position constraint. Qu et al. [19] constructed an optimization model of the offset for an artery based on traffic wave theory. A phase sequence adjustment method for improving the bandwidth of green band in bidirectional green wave control was proposed by Zhang [20], and a process-oriented and high-efficiency graphical method for symmetrical bidirectional corridor progression was proposed by Lu et al. [21]. Moreover, signal retiming and optimization processes have been improved in innovative ways based on advances in data-driven and traffic simulation tools [22–24].

In addition, considering the geometric characteristics of different plane intersections, traffic flow characteristics and the difference in selected phase signals, the green wave coordinated control methods above are not suitable for specific intersections with complex asymmetric traffic flow. Lu et al. [25] presented a new algebraic method of bidirectional green wave coordinated control under asymmetric traffic conditions by making use of velocity transformation and the phase combination method. Li et al. [26] proposed a coordination control optimization method based on an asymmetrical multiband model with phase optimization. Lu and Cheng [27] used the time-space diagram to find the bottleneck intersection, and then optimized the graphic method of bidirectional green wave coordinated control under the asymmetric phase sequence mode. Asymmetric release modes mainly include separate release phasing for each entrance, leading-left-turn phasing, lagging-left-turn phasing and lead–lag phasing. In this study, based on the characteristics of asymmetric entrance release mode, we designed a unique overlapping phase by using NEMA [28] dual-ring phasing configuration, and proposed a new bidirectional progression green wave scheme of coordinated control for arterials in combination with the actual traffic flow condition. The effectiveness and practicability of the scheme were verified by its application on Ziwu Road in Qujing City. The proposed method improved the scientific rationality and adaptation range of the model, better utilized available green times in each progression direction, and demonstrated superior performance. The remainder of the article is organized as follows: Section 2 introduces the design processes of the bidirectional green wave coordinated control method under symmetric and asymmetric signal mode, respectively. Section 3 presents a case study that helps to compare the coordinated optimization effect of the two methods, and to verify the effectiveness and practicability of the proposed method. Concluding remarks are provided in the last section.

2. Materials and Methods

2.1. Design Process under Symmetric Release Mode

The bidirectional green wave design under symmetric entrance release mode usually uses algebraic method to determine the best common cycle length and offset by seeking the ideal intersection spacing that matches the actual intersection spacing best, so as to make the corridor control system produce a green wave bandwidth as large as possible and obtain the best coordination effect [29]. The calculation steps are as follows:

Step1. Determine the initial common cycle length C_m.

Step2. Determine the value range of the ideal intersection spacing S_i, namely $[VC_m/2-\Delta S_i, VC_m/2+\Delta S_i]$, where V is the speed of the green wave band and ΔS_i is the floating range of ideal intersection spacing.

Step3. Determine the most appropriate location of the ideal signal to ensure that the optimal ideal intersection spacing matches the actual intersection spacing.

Step4. Make the continuous through band.

Step5. Determine each signal offset according to the intersection position relative to the ideal intersection.

Step6. Calculate the bidirectional green wave bandwidth B_w.

2.2. Design Method under Asymmetric Release Mode

Asymmetric release modes mainly include separate release phasing for each entrance, leading-left-turn phasing, lagging-left-turn phasing and lead–lag phasing. In green wave design, they can flexibly adjust the signal timing plan to maximize green wave bandwidth, which is suitable for intersections of asymmetric traffic flow. Asymmetric traffic flow refers to the traffic flow that has a large difference in the opposite traffic flow direction at the same phase and meets the given conditions. Taking the north–south through traffic flow at the intersection as an example, it is assumed that the through traffic volume of south entrance is q_{st}, the through traffic volume of north entrance is q_{nt}, and $q_{st} > q_{nt}$. The relative difference in traffic volume a and saturation b can be expressed as follows:

$$a = \frac{|q_{st} - q_{nt}|}{\max(q_{st}, q_{nt})},\ b = \frac{\max(q_{st}, q_{nt})}{S} \tag{1}$$

where: S is the sum of saturation flow of all through lanes at the entrance corresponding to $\max(q_{st}, q_{nt})$. If $0.5 < a < 1$ and $0.2 < b < 0.9$, q_{st}, q_{nt} can be called asymmetric traffic flows.

The main parameters of bidirectional green wave design under asymmetric release mode are common cycle length, split and offset. The determination methods of the three key parameters are described below.

(1) Common cycle length

In the corridor traffic signal coordination control system, the cycle time of each traffic signal is unified in order to make the traffic signals at each intersection coordinated. The timing plan of traffic signal control at the isolated intersection mostly adopts the F·Webster—B·Cobb theory and the method proposed by them (referred to as the F-B method).

The cycle time of each intersection can be obtained through the F-B method as an initial reference value. The design method of green wave coordinated control takes the maximum signal cycle time of coordinated intersections as the common cycle length generally, without considering the relationship between the common cycle length and the effect of green wave coordinated control. In this study on bidirectional green wave design under asymmetric release mode, the determination of the common cycle length not only considers the actual traffic demand of each intersection, but also calculates the optimal cycle time suitable for bidirectional green wave coordination control according to the distance between intersections. Then, the common cycle length suitable for coordinated control is determined by comprehensive comparison.

When the intersection spacing meets Equation (2) [30] as follows, the best coordination effect can be achieved:

$$s = \frac{vC}{2} \cdot n \tag{2}$$

where: s is the distance between two adjacent intersections (m); v is the speed of a platoon of vehicles (m/s); C is cycle time (s); n is a non-negative integer.

According to Equation (2), the equation of the ideal cycle time that can achieve the best green wave coordination effect can be inversely deduced as follows:

$$C = \frac{2s}{n \cdot v} \tag{3}$$

(2) Split

In order to ensure the effect of green wave coordination control, the remaining green time is allocated to the coordinated phase on the basis of ensuring that the degree of saturation with the uncoordinated phase should not exceed the threshold x_p (generally, x_p is equal to 0.9). The effective green time of the non-coordinated phase can be calculated as follows:

$$g_{ne} = \frac{c_m q_n}{S_n x_p} = \frac{c_m y_n}{x_p} \tag{4}$$

where: g_{ne} is the effective green time of the non-coordinated phase; c_m is the common cycle length; q_n is the flow rate of the critical lane with the uncoordinated phase; S_n is the saturation flow of the critical lane with the coordinated phase; x_p is the threshold of the degree of saturation with the uncoordinated phase; y_n is the flow ratio of the critical lane with the uncoordinated phase.

Furthermore, through the relationship between the effective green time and the display green time, the display green time of the uncoordinated phase can be determined as follows:

$$g_n = g_{ne} - I_n + l_n \tag{5}$$

where: g_n is the display green time of the uncoordinated phase; I_n is the interval green time of the uncoordinated phase; l_n is the loss time of the uncoordinated phase.

The effective green time and the display green time of the non-coordinated phase can be figured out by Equations (4) and (5). After determining the green time of all the non-coordinated phases, the effective green time of the coordinated phase g_e can be determined as follows:

$$g_e = C - L - \sum g_{ne} \tag{6}$$

Then, the display green time of coordinated phase can be determined by Equation (5).

(3) Offset

The processes of determining the offset of green wave coordinated design under asymmetric release mode are as follows:

Step1. The offset of unidirectional coordinated green wave in the two coordination directions is calculated, respectively. The ideal offset of unidirectional coordination control is determined by Equation (7).

$${O_f}^i = \mathrm{mod}\left(\frac{L/v}{C}\right) \tag{7}$$

where: ${O_f}^i$ is the ideal offset (s); L is the distance between the upstream- and downstream-adjacent intersections (m); v is the speed of a platoon of vehicles (m/s).

Step2. Considering the influence of queuing vehicles, the optimal theoretical offset is modified then.

Due to the merging of right-turn movement and left-turn movement of conflicting phases at the upstream intersection, some vehicles will have queued up before the traffic of coordinated phase arrives at this intersection. Therefore, Equation (7) should be modified to make the downstream intersection light green in advance to ensure that the queued vehicles have dissipated completely when the traffic of the coordinated phase reaches the downstream intersection. The calculation equation of the modified offset is as follows:

$${O_f}^i = \mathrm{mod}\left(\frac{L/v}{C}\right) - \Delta t \tag{8}$$

where: Δt is the dissipation time of queuing vehicles at the downstream intersection (s)

$$\Delta t = \frac{3600 \cdot m}{S} \tag{9}$$

where: m is the number of queuing vehicles at the downstream intersection (veh); S is the saturation flow rate of queuing traffic at the downstream intersection (veh/h).

There are two methods to determine the value of m. One is to count the number of vehicles queuing directly during the red interval of the coordinated phase at the intersection and then determine the value of m according to the actual traffic survey results. The other is to determine the number of queuing vehicles during the red time of the coordinated phase according to the flow of the relevant phase at the upstream intersection and the red interval of the coordinated phase. The specific calculation equation is as follows:

$$m = \frac{\sum n_i q_i r}{n} \tag{10}$$

where: n_i is the number of entrance lanes of phase i at the upstream intersection; q_i is the flow rate of phase i at the upstream intersection (pcu/s); r is the red interval of the coordinated phase (s); n is the number of entrance lanes of the coordinated phase.

In summary, according to the parameters calculated above, the graphic method is used to draw the diagram of bidirectional progression green wave coordination control by fine-tuning the space-time map repeatedly to find the maximum bandwidth in TranSync-D software [31].

3. Case Study

3.1. Basic Traffic Data

In the case study, we selected Ziwu Road (Qujing, China) as the method validation site. Ziwu Road, which runs north–south and has 6 two-way lanes with large traffic flow, is an important urban arterial road in Qilin District. The traffic flow of the intersecting road is significantly lower than that of the main road. In addition, the space between intersections along Ziwu Road is relatively close, which meets the ideal conditions of green wave design. Therefore, five adjacent intersections of Ziwu Road were chosen for two-way green wave coordinated design. The traffic volume data of each intersection were based on the traffic flow surveyed on the morning of 13 October 2020 (7:30–8:30). For ease of expression, codes of each coordinated control intersection on Ziwu Road were assigned A, B, C, D and E from north to south, as shown in Figure 1. Basic data of each intersection are shown in Table 1.

Table 1. Basic data of each intersection on Ziwu Road.

Name of Intersection	Changxing Road	Caiyun Road	Jingjiang Road	Yunyu Road	Wenbi Road
Type	cross	cross	cross	cross	cross
Code	A	B	C	D	E
Spacing (m)	880	430	420	630	

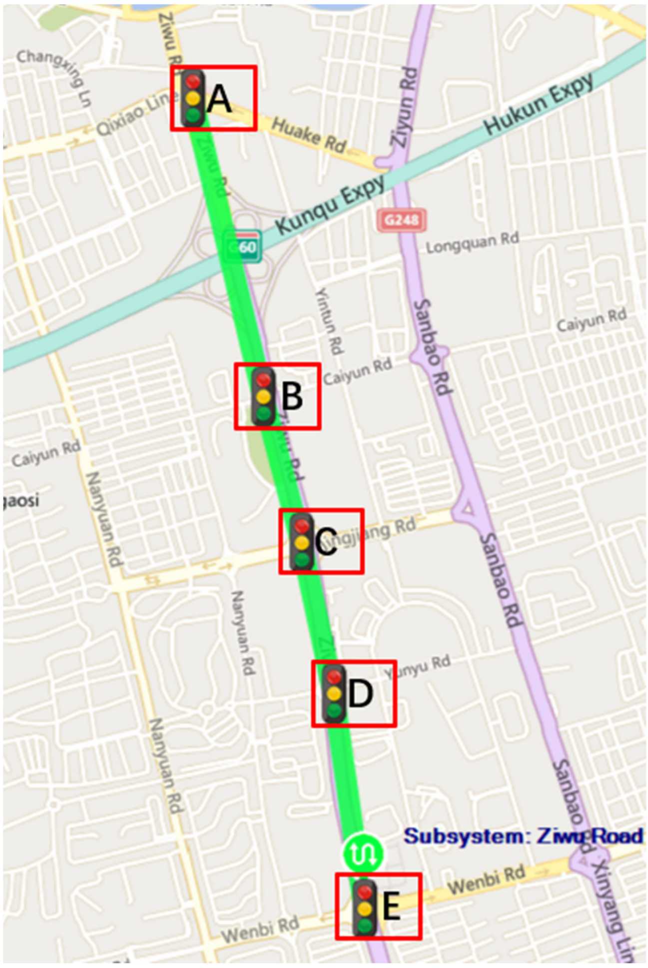


Figure 1. Distribution map of coordinated intersections of Ziwu Road. A: intersection of Ziwu Road and Changxing Road, B: intersection of Ziwu Road and Caiyun Road, C: intersection of Ziwu Road and Jingjiang Road, D: intersection of Ziwu Road and Yunyu Road, E: intersection of Ziwu Road and Wenbi Road.

3.2. Calculation Results and Analysis

3.2.1. Green Wave Design under Symmetric Release Mode

Under symmetric release condition, the offsets between adjacent signals of the Ziwu Road coordinated control system were calculated by algebraic method as follows.

Step1. Determine the initial common cycle length C_m = 120 s. The split of arterial road calculated by signal timing at each intersection is listed in row 4 of Table 2, and the corridor progression design speed of the system is temporarily set as V = 11.1 m/s (40 km/h).

Table 2. Calculated results of signal offsets.

Intersections	A	B	C	D	E
Ideal signal no.	①	②	③	③	④
Signal position	doublication	right	left	right	right
Split λ (%)	40	43	48	40	42
Loss (%)	0	15	27	27	11
Effective split (%)	40	28	21	13	31
Green offset (%)	80	28.5	76	80	29

Step2. Determine the value range of the ideal intersection spacing S_i [56, 76].

Step3. Determine the most appropriate location of the ideal signal. According to the calculation result, when $VC_m/2 = 760$ m, the best system coordination efficiency can be obtained. The displacement difference between D~C and ideal signal is the largest (210 m); that is, the displacement between the ideal signal and D is 210, and the distance between the ideal signal and A is 0, which is the first ideal signal. Then, each ideal signal is listed among the actual signals every 760 m interval, as shown in Figure 2.

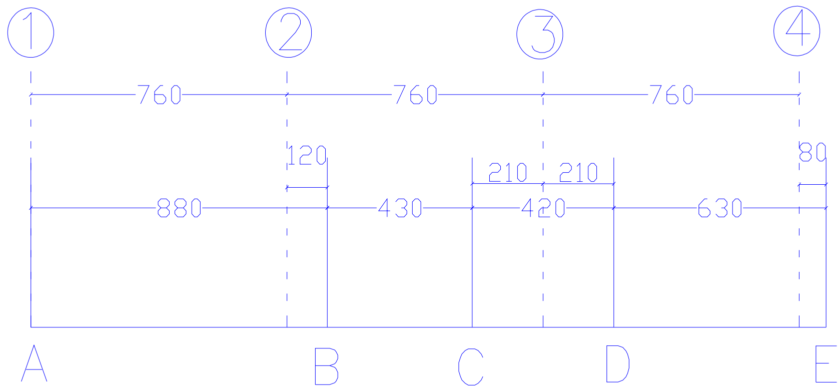


Figure 2. Relative position between ideal signal and actual signal (size units: m). A~E represent the five adjacent intersections on Ziwu Road. Numbers ①~④ represent the ideal signals.

Step4. Make the continuous through band. The ideal signals in Figure 2 are listed successively below the nearest actual signals (row 2 of Table 2), and the positions of each signal (A~E) at the left or right of the ideal signal are given in row 3 of Table 2.

Step5. According to the position of each intersection relative to the ideal intersection, the offsets are calculated, and the results are shown in Table 2.

It can be seen from Table 2 that the bandwidth of the continuous through band is 17%, which is the average value of the effective split at intersection C (21%) and that at intersection D (13%). The above calculation results can be expressed by a time-space diagram shown in Figure 3, with the horizontal axis representing distance between adjacent intersections on Ziwu Road and the vertical axis representing cycle time. Figure 3 shows the bidirectional green wave design result under symmetric release mode.

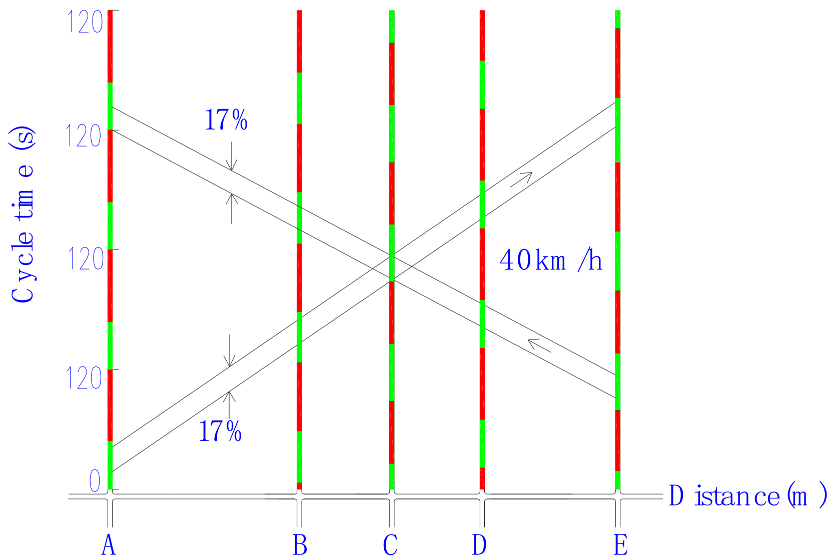
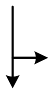
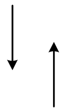
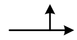
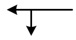
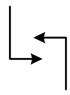


Figure 3. Bidirectional green wave design result under symmetric release mode. A~E represent the five adjacent intersections on Ziwu Road. The green bar indicates the green time of the coordinated phase. The red bar indicates the red time of the coordinated phase.

3.2.2. Green Wave Design under Asymmetrical Release Mode

Firstly, according to the requirements of green wave coordination control and actual traffic volume data, the phase sequence of each coordinated intersection is optimized. Taking the intersection of Ziwu Road and Caiyun Road as an example, a particular overlapping phase is designed by using NEMA dual-ring phasing configuration, as shown in Table 3.

Table 3. Signal timing optimization plan at intersection of Ziwu Road and Caiyun Road.

	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
(B) Intersection of Ziwu Road and Caiyun Road					
Green time (s)	18	25	22	22	18

Note: The solid arrows in Table 3 represent motor vehicles' movement.

Secondly, determine common cycle length. In the green wave design of Ziwu Road, the design speed is set as 40 km/h (11 m/s), and the distance between intersections is shown in Table 1. The ideal cycle time between intersections can be calculated according to Equation (3) as follows: The ideal cycle time of intersection A to B is 80 (s); the ideal cycle time of intersection B to C is 78 (s); the ideal cycle time of intersection C to D is 76 (s); the ideal cycle time of intersection D to E is 115 (s).

According to the trial calculation, the ideal cycle time of the intersections under green wave coordinated control is about 100 s. At the same time, combined with the traffic volume data of all intersections, the optimal cycle time of each intersection is about 125 s, as calculated by using the signal timing strategy of isolated intersection control. Therefore, 120 s is selected as the common cycle length of all five intersections comprehensively.

Thirdly, calculate the display green time of the coordinated phase. Taking the intersection of Ziwu Road and Caiyun Road as an example, the effective green time of the uncoordinated phase is calculated by Equation (4) as follows.

$$g_{3e} = \frac{c_m q_3}{S_3 x_p} = \frac{c_m y_3}{x_p} = \frac{120 \times 0.162}{0.9} = 22(\text{s})$$

$$g_{4e} = \frac{c_m q_4}{S_4 x_p} = \frac{c_m y_4}{x_p} = \frac{120 \times 0.162}{0.9} = 22(\text{s})$$

$$g_{5e} = \frac{c_m q_5}{S_5 x_p} = \frac{c_m y_5}{x_p} = \frac{120 \times 0.132}{0.9} = 18(\text{s})$$

The effective green time of the coordinated phase is determined by Equation (6).

$$g_e = C - L - \sum g_{ne} = 120 - 3 \times 5 - 62 = 43(s)$$

Then, the display green time of the coordinated phase and uncoordinated phases at the intersection of Ziwu Road and Caiyun Road can be calculated from Equation (5), as shown in Table 3.

Finally, considering the influence of driving speed and queuing vehicles, the theoretical optimal offsets are modified and adjusted by using the graphical method in TranSync-D software, and the final bidirectional green wave coordinated control schemes of Ziwu Road are shown in Tables 4–8.

Table 4. Signal timing optimization plan at intersection of Ziwu Road and Changxing Road under asymmetric release mode.

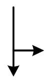
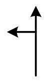
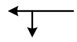
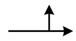
(A) Intersection of Ziwu Road and Changxing Road	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**
				
Green time(s)	31	27	25	25

Table 5. Signal timing optimization plan at intersection of Ziwu Road and Jingjiang Road.

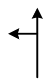
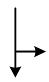
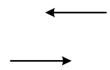
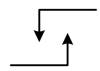
(C) Intersection of Ziwu Road and Jingjiang Road	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**
				
Green time (s)	27	31	30	20

Table 6. Signal timing optimization plan at intersection of Ziwu Road and Yunyu Road.

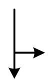
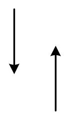
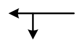
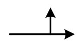
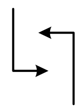
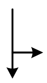
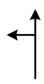
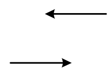
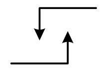
(D) Intersection of Ziwu Road and Yunyu Road	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
					
Green time (s)	17	25	23	23	17

Table 7. Signal timing optimization plan at intersection of Ziwu Road and Wenbi Road.

(E) Intersection of Ziwu Road and Wenbi Road	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**
				
Green time (s)	34	27	27	20

Note: common cycle time C_m = 120 s, yellow time A = 3 s.

Table 8. Calculation result of offset for each intersection on Ziwu Road.

Intersection Code	**A**	**B**	**C**	**D**	**E**
Reference coordinated phase	Phase 1	Phase 1	Phase 2	Phase 1	Phase 1
Absolute Offset (s)	23	94	113	21	83

By applying the signal timing plans in Tables 3–7 and offsets in Table 8, the coordination control result of bidirectional progression green wave can be obtained, as shown in Figure 4. The time (horizontal) axis is displayed based on the cycle time of the timing plan, 120 s, and the vertical axis represents the distances between the five signalized intersections. The minimum bandwidth of bidirectional green wave through band is 22 s (18%C_m), and the maximum bandwidth is 37 s (31%C_m).

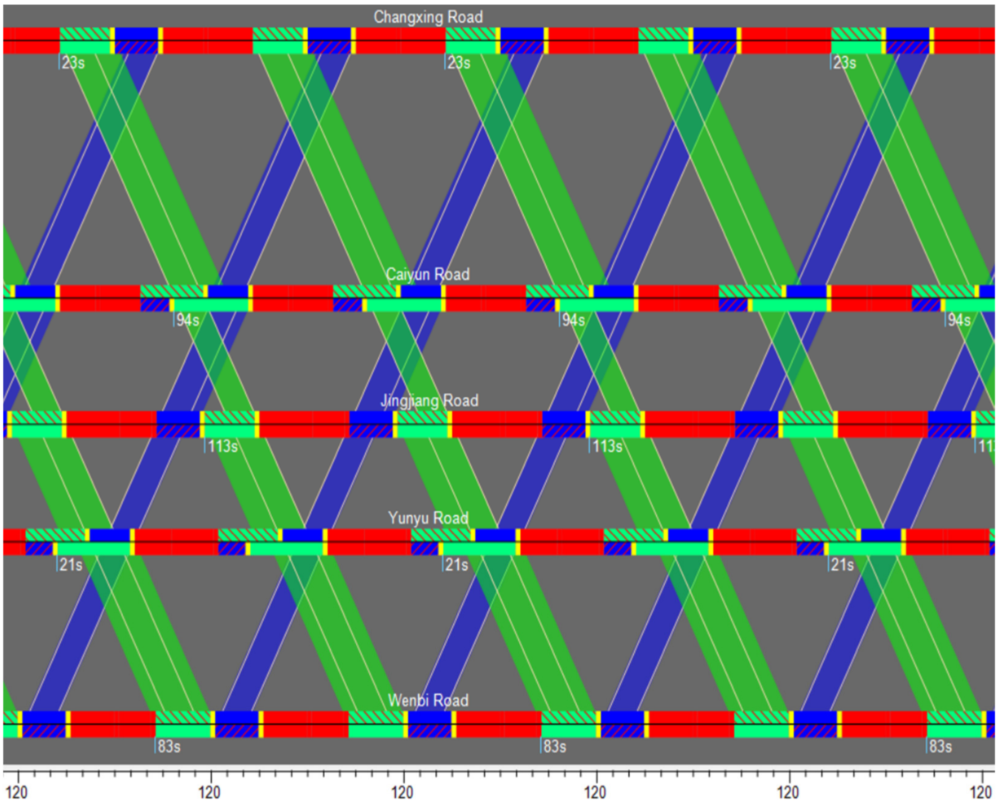


Figure 4. Design of bidirectional progression green wave under asymmetric release mode. the green time of left-turn phase on Ziwu Road (s); the green time of straight phase on Ziwu Road (s). Note: the yellow bar indicates the yellow time; the red bar indicates the red time of the coordinated phase; green band means driving from north to south, and blue band means from south to north.

3.3. Discussion

The effects of the two green wave design schemes above were simulated by VISSIM software. Two groups of travel time detectors were set at the entrance of the first intersection and the exit of the last intersection in the inbound and outbound directions, and simulation tests were conducted on the green wave control plans of symmetrical release and asymmetric release at five intersections of Ziwu Road, respectively. The average delay, average travel time and average number of stops on the arterial road were collected with an interval of 3.6 ks and a simulation time of 5 h, namely 18,000 simulation steps. The comparison results are shown in Table 9.

It can be seen that the bandwidth of the green wave band obtained by the coordinated control scheme under asymmetric release on Ziwu Road was 10–85% higher than that obtained with the symmetric release scheme, the average delay and travel time of inbound vehicles decreased from 41.9 s and 313.3 s to 33.7 s and 279.3 s, respectively, and the average number of stops reduced from 1.6 to 1.0. The average delay and travel time of outbound vehicles decreased from 46.3 s and 329.9 s to 36.4 s and 294.8 s, respectively, and the average number of stops reduced from 1.8 to 1.3. The proposed scheme coordinated the arterial road intersections group effectively, reduced the average delay, average travel time and the average number of stops greatly and improved traffic efficiency.

Table 9. Comparison of effects between two bidirectional green wave control plans.

Time (ks)	Inbound (A–F) Average Delay (s/veh)		Outbound (F–A) Average Delay (s/veh)		Inbound (A–F) Average Number of Stops (stops/veh)		Outbound (F–A) Average Number of Stops (stops/veh)		Inbound (A–F) Average Travel Time (s)		Outbound (F–A) Average Travel Time (s)	
	Plan 1	Plan 2	Plan 1	Plan 2	Plan 1	Plan 2	Plan 1	Plan 2	Plan 1	Plan 2	Plan 1	Plan 2
3.6	41.8	32.7	45.7	36.6	1.5	0.9	2.0	1.5	312.0	276.9	330.9	296.8
7.2	42.6	34.8	44.8	35.2	1.7	1.1	1.8	1.2	314.8	281.0	328.0	292.4
10.8	41.4	34.7	45.6	36.0	1.6	1.0	1.9	1.4	312.6	279.9	329.8	295.2
14.4	40.6	31.4	48.2	37.1	1.5	1.0	1.7	1.3	310.8	276.6	330.4	295.3
18.0	43.1	34.9	47.3	36.9.	1.8	1.2	1.8	1.2	316.3	282.1	330.5	294.1
average value	41.9	33.7	46.3	36.4	1.6	1.0	1.8	1.3	313.3	279.3	329.9	294.8

Note: plan 1 represents the bidirectional green wave scheme under symmetric release mode, while Plan 2 represents the bidirectional green wave scheme under asymmetric release mode.

4. Conclusions

To sum up, compared with the traditional green wave implementation method under symmetric release mode, the bidirectional progression green wave implementation method proposed by the author is suitable for arterial intersections group that adopt asymmetric release mode due to asymmetric geometric conditions or unbalanced traffic flow. The proposed method takes advantage of the particular design of overlapping phase so as to optimize the signal phase sequence combination, and takes the influence of cruising speed and residual queues into full consideration when revising the optimal offset. It also selects the optimal signal timing parameters for coordinated control, and increases the possibility of obtaining a larger green wave bandwidth. The above method is beneficial for engineering applications and achieved good results in the application of the Ziwu Road intersections group, which minimized delay and the number of stops, mitigated traffic emissions and reduced the probability of rear-end collisions, thus decreasing the occurrence of traffic accidents to the greatest extent and obtaining good social and economic benefits. The simulation software VISSIM verified the feasibility and applicability of the proposed method. From the perspective of coordinated control, the optimization effects for average travel time, average delay and average number of stops are remarkable. The results show that the proposed method has a better optimization effect on the bidirectional green wave bandwidth and various evaluation indexes. With the increase in traffic flow at intersections, traffic managers can consider green wave coordinated control for arterials and the appropriate expansion of urban roads to improve the operational efficiency of urban traffic. Once the traffic flow reaches the saturation state, maybe we will seek more applicable methods and models related to intelligent transportation systems to improve traffic operation efficiency, which will be the focus of future research.

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