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

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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 more complicated and less operable, which are mainly applicable to intersection groups with symmetrical entrance release mode. Based on engineering practice, a new method of bidirectional progression green wave coordination control is presented by designing particular overlapping phases on the basis of NEMA dual-ring phasing configuration. According to 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 improves the bandwidth of bidirectional green wave band effectively, but also reduces the average delay and the average number of stops on the main road.

1.Introduction

With the development of society and economy, modern means of transport in the city are increasing day by day, and the traffic pressure of the urban main roads also increases. 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 operations 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 travelling along the entire arterial so as to provide the maximum green wave bandwidth, reduce the delay and number of stops, and keep the traffic moving on the main road smoothly. 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 graphical method, algebraic method, Purdy, MAXBAND and MULTIBAND [5,6]. 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 order of left-turn phases to maximize the inbound and outbound bandwidths along an arterial. A fundamental limitation of MAXBAND is that they do not take the actual traffic volume and flow capacity of each link into consideration. This may cause that some segments may have excessive green times, while others may have inadequate green times that result in the frequent interruption of vehicle platoons. 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. So Gartner et al.[9] constructed the MULTIBAND model which designed an individually weighted bandwidth for each directional road section, considering the traffic volumes and flow capacities. Extensive research has been constantly provided based on the MAXBAND and MULTIBAND models[10–12] Messer et al.[13,14] proposed green wave bandwidth optimization algorithm including 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 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 artery. Hu et al.[16] established a fuzzy system to adjust time parameters and traffic signal phase to realize corridor control based on fuzzy control theory. Tang et al.[17] 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.[18] constructed an optimization model of the offset for artery based on traffic wave theory. a phase sequence adjustment method for improving the bandwidth of green band in bidirectional green wave control is proposed by Zhang[19], and a process-oriented and high-efficiency graphical method for symmetrical bidirectional corridor progression is proposed by Lu et al.[20].

In addition, considering the geometric characteristics of different plane intersections, traffic flow characteristics and the difference of selected signals phase, the green wave coordinated control methods above is not suitable for the specific intersections with complex asymmetric traffic flow. Lu et al.[21] presented a new algebraic method of bidirectional green wave coordinated control under asymmetric traffic conditions by making use of velocity transformation and phase combination method. Lu and Cheng [22]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. In this study, based on the characteristics of asymmetric entrance release mode, we designed a unique overlapping phase by using NEMA[23] 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 improves the scientific rationality and adaptation range of the model, better utilizes available green times in each progression direction and demonstrates 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, which helps to compare the coordinated optimization effect of the two methods, and 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 get the green wave bandwidth as large as possible and obtain the best coordination effect [24]. 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 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 are 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 of traffic volume a and saturation b can be expressed as follows:

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

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.

2.2.1 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) as follows, the best coordination effect can be achieved:

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

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:

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

2.2.2 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 uncoordinated phase should not exceed the threshold x_p (Generally x_p is equal to 0.9). The effective green time of 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 non-coordinated phase; c_m is the common cycle length; q_n is the flow rate of the critical lane with uncoordinated phase; S_n is the saturation flow of the critical lane with coordinated phase; x_p is the threshold of the degree of saturation with uncoordinated phase; y_n is the flow ratio of the critical lane with 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 uncoordinated phase; I_n is the interval green time of uncoordinated phase; l_n is the loss time of uncoordinated phase.

The effective green time and the display green time of non-coordinated phase can be figured out by Equation (4) and Equation (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).

2.2.3 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).

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

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

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

Here Δt is dissipation time of queuing vehicles at downstream intersection (s).

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

Where: m is the number of queuing vehicles at downstream intersection (veh); S is saturation flow rate of queuing traffic at 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 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 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 upstream intersection;

q_i is the flow rate of phase i at upstream intersection (pcu /s);

r is the red interval of coordinated phase (s);

n is the number of entrance lanes of coordinated phase.

In summary, according to the parameters calculated above, 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.

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 less 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 are chosen for two-way green wave coordinated design. The traffic volume data of each intersection are based on the traffic flow surveyed on the morning of October 13, 2020 (7:30-8:30). For ease of expression, codes of each coordinated control intersection on Ziwu Road are assigned A, B, C, D and E from north to south. 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	

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 Ziwu Road coordinated control system are calculated by algebraic method as follows.

Step1. Determine the initial common cycle length C_m=120s. 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=11.1m/s(40km/h).

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 $VC_m/2$=760m, the best system coordination efficiency can be obtained. The displacement difference between D~C and ideal signal is the largest （210m）， that is, the displacement between ideal signal and D is 210, and the distance between ideal signal and A is 0, which is the first ideal signal. Then, each ideal signal is listed among the actual signals every 760m intervals, as shown in Figure 1.

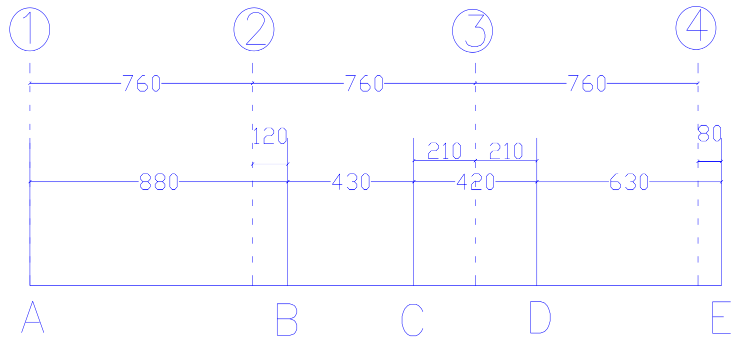


FIGURE 1: Relative position between ideal signal and actual signal (size units: m)

Step4. Make the continuous through band. The ideal signals in Figure 1 are listed successively below the nearest actual signals (row 2 of Table 2), and then the positions of each signal (A~E) at the left or right of ideal signal are filled 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.

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

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

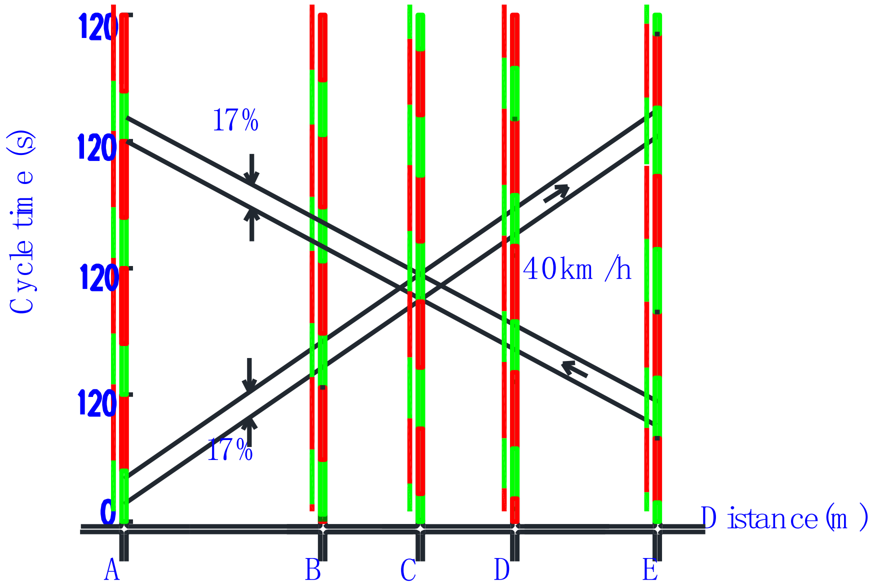
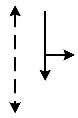
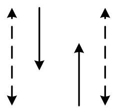
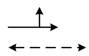
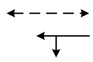
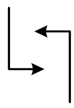


FIGURE 2: Bidirectional green wave design result under symmetric release mode

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: Calculation result of signal timing design at the intersection of Ziwu Road and Caiyun Road

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

Note: The solid arrows in the Table 3 represent motor vehicles' movement and the dotted arrows in both directions represent pedestrians' movement.

Secondly, determine common cycle length. In the green wave design of Ziwu Road, the design speed is set as 40km/h (11m/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: $\frac{880\times2}{11\times2}\approx80$ （s）;

The ideal cycle time of intersection B to C is: : $\frac{430\times2}{11}\approx78$ （s）;

The ideal cycle time of intersection C to D is: $\frac{420\times2}{11}\approx76$ （s）;

The ideal cycle time of intersection D to E is: $\frac{630\times2}{11}\approx115$ （s）.

According to the trial calculation, the ideal cycle time of the intersections under green wave coordinated control is about 100s. At the same time, combined with the traffic volume data of all intersections, the optimal cycle time of each intersection is about 125s calculated by using signal timing strategy of isolated intersection control. Therefore, 120s is selected as common cycle length of all the 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 uncoordinated phase is calculated by Equation (4) as follows.

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

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

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

The effective green time of 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 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 graphical method, and the final bidirectional green wave coordinated control schemes of ziwu road are shown in Table 4~ Table 8.

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

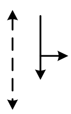
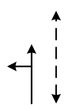
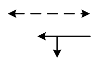
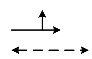
(A)	Phase 1	Phase 2	Phase 3	Phase 4
Intersection of Ziwu Road and Changxing road				
Green time (s)	31	27	25	25

TABLE 5: Signal timing optimization plan at intersection of Ziwu Road and Jingjiang Road

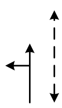
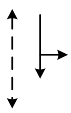
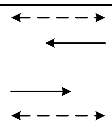
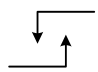
(C)	Phase 1	Phase 2	Phase 3	Phase 4
Intersection of Ziwu Road and Jingjiang Road				
Green time (s)	27	31	30	20

TABLE 6: Signal timing optimization plan at intersection of Ziwu Road and Yunyu Road

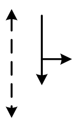
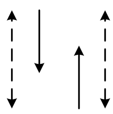
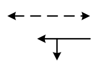
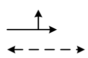
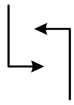
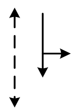
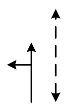
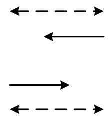
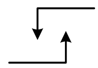
(D)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Intersection of Ziwu Road and Yunyu Road					
Green time (s)	17	25	23	23	17

TABLE 7: Signal timing optimization plan at intersection of Ziwu Road and Wenbi Road

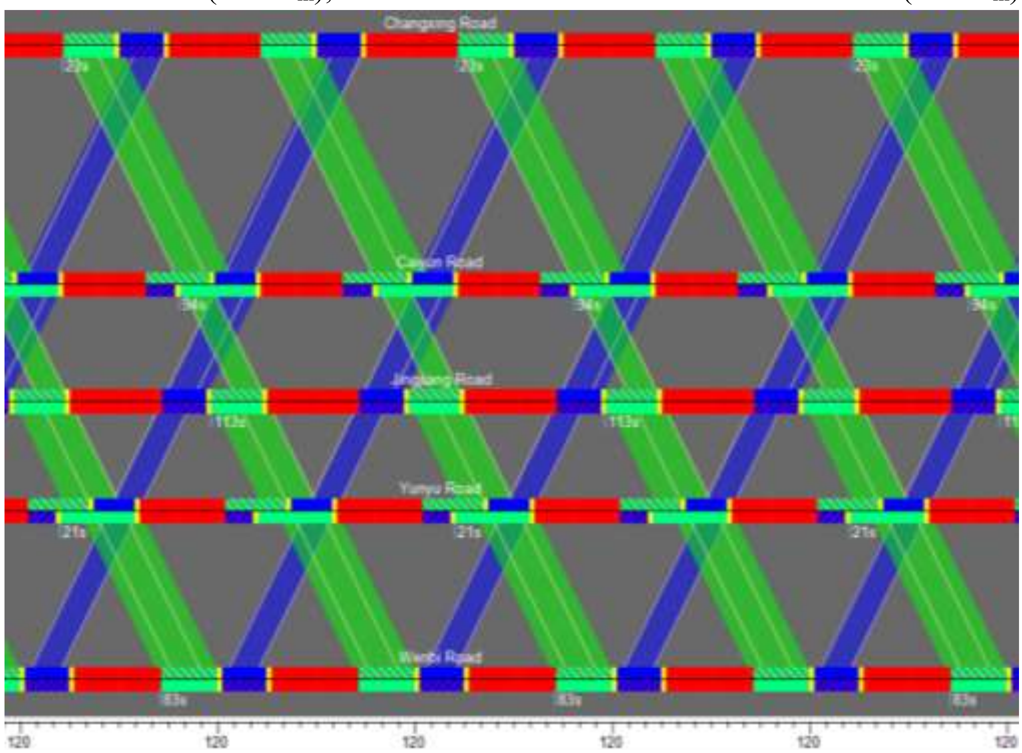
(E)	Phase 1	Phase 2	Phase 3	Phase 4
Intersection of Ziwu Road and Wenbi Road				
Green time (s)	34	27	27	20

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

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 Table 3~Table 7 and offsets in Table 8, the coordination control result of bidirectional progression green wave can be obtained, as shown in Figure 3. 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 seconds (18%C_m), and the maximum bandwidth is 37 seconds (31%C_m).



The green time of left-turn phase on Ziwu Road (s)

The green time of straight phase on Ziwu Road (s)

Note: Green band means driving from north to south, and blue band means from south to north.

FIGURE 3: Design of bidirectional progression green wave under asymmetric release mode

3.3. Discussion

The effects of 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 and average number of stops on arterial road were collected with an interval of 3.6ks and a simulation time of 5h, namely 18000 simulation steps. The comparison results were shown in Table 9.

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)	
	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
7.2	42.6	34.8	44.8	35.2	1.7	1.1	1.8	1.2
10.8	41.4	34.7	45.6	36.0	1.6	1.0	1.9	1.4
14.4	40.6	31.4	48.2	37.1	1.5	1.0	1.7	1.3
18.0	43.1	34.9	47.3	36.9.	1.8	1.2	1.8	1.2
average value	41.9	33.7	46.3	36.4	1.6	1.0	1.8	1.3

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

It can be seen that the bandwidth of green wave band obtained by coordinated control scheme under asymmetric release on Ziwu Road was 10%-85% higher than that of symmetric release scheme, the average delay of inbound vehicles decreased from 41.9s to 33.7s, and the average number of stops reduced from 1.6 to 1.0. The average delay of outbound vehicles decreased from 46.3s to 36.4s, 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 and the average number of stops greatly, and improved the traffic efficiency.

4. Conclusion

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 crusing speed and residual queues into full consideration when revising the optimal offset. It also selects the optimal signal timing parameters for coordinated control, and realizes the maximization of green wave bandwidth. The above method is beneficial to engineering application and has achieved good results in the application of Ziwu Road intersections group, which minimizes delay and number of stops, mitigates traffic emissions, and reduces the probabilities for rear-end collisions, thus decreasing the occurrence of traffic accidents to the greatest extent and obtaining good social and economic benefits. However, with the increase of traffic flow at intersections, it is necessary to readjust and optimize signal timing, phase sequence and offset at intersections to ensure the feasibility of green wave. Once the traffic flow reaches saturation state, maybe we will seek for more applicable methods and models related to intelligent transportation systems to improve the traffic operation efficiency, which will be the focus of future research.

Author contributions

C.W. has the whole research object; J.L.N. verified, explained and discussed the main body of the research.

Competing interests

The authors declare no competing interests.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Additional information

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