Coordinated Control Method for Trams on Urban Arterial

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Abstract—To improve the operation efficiency of the trams on the arterial, a green-wave coordinated control scheduling method for trams at intersections is proposed. The influence of the tram on the green wave programming model is analyzed, and the calculation formula of the intersection distance in the programming model is amended. Tram priority signal control system is introduced, including the absolute priority and the relative priority. Combined with these two priority schemes, according to the type of intersection and the time when the tram arrives at the intersection, the tram priority control strategy is designed. Then the position of the tram detector is studied. According to the regularity of tram’s operation, the appropriate interval between the departure times of trams is proposed to prevent multiple trams arriving within the same traffic signal period. Finally, the microscopic traffic simulation software VISSIM is used to establish the coordination control model of the tram line in Huaian city, in order to validate the proposed method.

1. Introduction
With the rapid growth of the economy, the number of motor vehicles grows rapidly, and the transportation problems are getting worse. We need to develop public transportation to solve the congestion problem. Compared to the subway system, the construction cost of trams is lower, and the construction period is shorter. Besides, trams have a higher service level than conventional buses. Therefore, Trams have been widely used all around the world. In order to improve the operation efficiency of trams, the traffic signals along the arterial require coordination, and the signal priority is needed to provide to trams when specified conditions are met.

McGinley and Stolz [1] studied Melbourne’s tram priority control system. McBrayer [2] compared Light Rail Transit (LRT) and Bus Rapid Transit (BRT) in many ways, and concluded that LRT is more effective and more economical than BRT in alleviating urban traffic congestion. For the shortcomings of the existing tram priority strategy, Kaczmarek and Rychlewski [3] proposed to divide the trams and other vehicles into multiple priorities, and implement different strategies based on different priorities. Hahn, Min and Ha [4] studied the conditional priority of public transportation. The public transportation will get the priority only when specified conditions are met. Sermpis, Fousekis and Papadakos [5] introduced the priority control method of trams and the signal induction control method of trams under the coordination of arterial, and demonstrated by example of Athens trams. Skabardonis [6] studied the priority control method of tram signals under the coordination of arterial, and made
comparisons between various priority strategies. Jeong, Kim [7] proposed the TRANBAND model based on the MAXBAND model. The model focuses on passive priority and provides priority for trams on the arterial.

Cui [8] gave priority to trams based on the time trams reached the stop line and the change of delay at the intersection. Zhong [9] considered the coordination of trams, taking the total loss of the intersection as the objective function, and used genetic algorithm to calculate the difference of phase between the intersections. Zhang [10] chose different priority control strategies according to the time at which trams reached the stop line. Li, Mao and Zhang [11] determined different tram signal priority strategies according to different types of intersections, and proposed a tram signal calculation formula. Liu and Zhao [12] proposed different signal priority methods for trams under different right of way. Lu [13] proposed an adaptive induction control method based on the signal priority of single-point intersections of trams, and validated the effectiveness of this method using VISSIM. Ma and Yang [14] analyzed the effectiveness of the green leading, green lagging, and phase insertion strategies based on the delays of vehicles at the intersection.

Priority control at intersections requires trams to obtain traffic phases when trams reach intersections. When the frequency of trams is high, there may be two or more trams arriving at the same time in the same period. But the capacity of a tram station cannot accommodate multiple trams at the same time, and the length of the signal at the intersection is difficult to satisfy the continuous passing of multiple trams. Therefore, it is necessary to coordinate the design of the tram signal control and the dispatch schedule, ensuring that no more than one tram arrives at the intersection within a signal period.

For the problem of the departure interval and frequency of trams, Novales, Orro and Bugarin [15] introduced the method of the trams and the railways operations on the same arterial, in Karlsruhe, Germany. Currie and Shalaby [16] compared the signal priority control methods of modern trams in Toronto and Melbourne, and established an effective tram schedule model. Zhao [17] proposed an active priority strategy based on tram frequency, under the assumption that there is only one tram phase per signal cycle and the tram frequency is not high.

In this paper, we use green wave model to design the coordinated control scheme of the tram, and combine different signal priority strategies to establish a set of signal priority control method. Finally, we propose a method to adjust the departure interval to maintain the coordination between the dispatching and signal control of the tram.

2. The Revise of Intersection Distance

The main idea of the programming model of the arterial green wave coordinated control is on the basis of the enumeration method, which adjusts the expected speed and signal period of the arterial green wave to approach the ideal synchronous control mode or interactive control mode.

The traditional green wave programming model only considers the traffic demand of general traffic. The physical distance between intersections can be expressed as follows:

\[ X_k = L_k \]  \hspace{1cm} (1)

Where \( L_k \) represents the actual distance between intersection \( k \) and intersection \( k+1 \). \( X_k \) represents the distance calculated by programming model between intersection \( k \) and intersection \( k+1 \).

As the study analyzes the coordinated control method for the intersections along the arterial, the traditional programming model needs to be revised. Unlike general traffic, the tram needs to slow down, stop and then accelerate while encountering the tram stop during traveling. Therefore, the components of travel time are complicated compared to the general traffic. The basic assumption of the programming model is that the green wave travels at a constant speed. Therefore, the extra time caused by the tram stop needs to be converted into the extra distance, so that the traditional green wave programming model can be applied.

The acceleration time of the tram between intersection \( k \) and intersection \( k+1 \) can be expressed as follows:

\[ t_{k, acc} = \frac{N_k \cdot v}{2a} \]  \hspace{1cm} (2)
Where $N_k$ represents the number of tram stops between intersection $k$ and intersection $k+1$, $a$ represents the average acceleration of the tram.

The deceleration time of the tram between intersection $k$ and intersection $k+1$ can be expressed as follows:

$$t_{k,\text{dece}} = \frac{N_k \cdot v}{2b}$$  \hspace{1cm} (3)

Where $b$ represents the average deceleration of the tram.

The dwelling time of the tram between intersection $k$ and intersection $k+1$ can be expressed as follows:

$$t_{k,\text{stop}} = \sum_{h=1}^{N_k} \tau_{kh}$$  \hspace{1cm} (4)

Where $h$ represents the number of tram stops between intersection $k$ and intersection $k+1$. $\tau_{kh}$ represents the average dwelling time of the $h$-th stop between intersection $k$ and intersection $k+1$. The revised intersection distance can be expressed as follows:

$$X_k = L_k + v \times (t_{k,\text{dece}} + t_{k,\text{dece}} + t_{k,\text{stop}})$$  \hspace{1cm} (5)

Where $v$ represents the speed of the tram.

After the distances between intersections are revised, the classical programming model can be used to optimize the signal offsets of all the intersections.

3. Active Priority Strategy of the Tram

3.1. The Position of Tram Detectors

The tram signal priority control system requires tram’s position and operation information. The system uses traffic detectors to obtain the data of the tram when it approaches the intersection. It needs to predict the arrival time and departure time of the tram, so as to implement tram priority strategies more effectively. The priority method proposed in this study will set three detectors for the approach of an intersection, as shown in Fig.2.

Detector 1 is used to detect when the tram leaves the stop, and decide which control strategy to use based on the estimated travel time. The detector’s position should ensure that during the maximum green extension time, the tram can pass the intersection safely. Hence, the position of the detector 1 can be expressed as follows:

$$L_{d1} = \Delta t_{\text{max}} v - L_w - L_i$$  \hspace{1cm} (6)

Where $L_{d1}$ represents the distance between detector 1 and intersection stop line. $\Delta t_{\text{max}}$ represents maximum green extension time. $L_w$ represents the length of the tram. $L_i$ denotes the width of the intersection.

Detector 2 is used to detect the arrival of the tram and switch the signal phase to the tram phase. The detector’s position should consider the yellow time. For absolute priority, the signal cannot switch to tram phase immediately, when the arrival of the tram is detected by detector 2.
Figure 2. The location of the intersection detector

It should be ensured that the vehicle in the conflict direction has sufficient buffer time to stop, that is, the yellow time. Therefore, the position of the detector 2 can be expressed as follows:

\[ L_{d2} = A \cdot v \]  

(7)

Where \( L_{d2} \) represents the distance between detector 2 and the stop line. \( A \) represents yellow time.

Detector 3 is used to detect the departure of the tram, and restore the tram phase to the normal signal phase. Therefore, the position of the detector 2 can be expressed as follows:

\[ L_{d3} = L_w \]  

(8)

Where \( L_{d3} \) represents the distance between detector 3 and the stop line.

When the tailstock passes the intersection, the headstock just reaches the position of the detector 3. At this point, the tram exits the intersection safely, and the tram phase ends.

3.2. Tram Priority Strategies

To ensure that the tram does not stop when it reaches the intersection, we use a combination of relative priority and absolute priority. The relative priority will be used if conditions permit. Otherwise, we will use absolute priority to guarantee the tram’s efficiency of passing the intersection. We assume that there are four phases in the traffic signal timing scheme, and that the tram’s phase is phase 1.

3.2.1. Green extension

When tram reaches detector 1 in phase 1, we need to compare \( t_1 \) with \( t_{\alpha} \), where \( t_1 \) represents current remaining green time. \( t_{\alpha} \) represents the time, in which the tram pass the intersection safely from now on. If \( t_1 < t_{\alpha} \), extend the green time by \( t_{\alpha} - t_1 \). Under the green extension strategy, the cycle of traffic signal is unchanged. The next phase of the tram phase is shortened, as shown in Fig.3.

If \( t_1 \geq t_{\alpha} \), keep the current signal control scheme. The green time of the tram phase cannot be extended without limit, otherwise it will have a serious impact on the efficiency of the next phase. Therefore, we need to set an upper limit on the extended time. The next phase will be shortened because of the extension of the tram phase. And the remaining time should be longer than the minimum green time of this phase.

Figure 3. Green lagging strategy
3.2.2. Absolute priority
When the tram reaches detector 1 in phase 2 or phase 3, the system does not adjust the signal control scheme temporarily, until the tram reaches detector 2. If the tram is still in phase 2 or phase 3 when it reaches detector 2, the absolute priority strategy is activated. The traffic light turns yellow, and then switches to the tram phase. All general traffic phases are red to ensure that trams can pass the intersection directly. Until the detector 3 detects the arrival of the tram, the tram phase ends.

In the absolute priority strategy, we should determine whether to switch to the original phase or to the next phase according to the remaining time of the original phase, after the tram passes the intersection. The specific decision conditions are: When the remaining time of the original phase is less than the minimum green time of the phase, switch to the next phase. When the remaining time of the original phase is longer than the minimum green light time, the original phase is restored.

3.2.3. Green leading
When the tram reaches detector 1 in phase 4, we should compare the remaining time of the current red time \( t_2 \) and \( t_a \) to determine which priority control strategy should be adopted. Here \( t_a \) represents the time that the tram run from detector 1 to the stop line.

If \( t_2 > t_a \), it indicates that the red light cannot end, and the current phase meets the minimum green time, then switch to the next phase \( t_2 - t_a \) in advance, to ensure the tram goes through the intersection. As shown in Fig.4, under the green leading strategy, the cycle of traffic signal is unchanged, and the tram phase is extended, so the previous phase is shortened.

If the minimum green time is not met, the tram will keep waiting before the stop line. The current phase will end and the next phase will start, when the minimum green time is met. If \( t_2 \leq t_a \), keep the current signal control scheme.

3.3. Departure Interval of Trams
Departure interval of trams affects the service level of the tram system. If the departure interval is too short, more than one tram may arrive at the intersection within a cycle, and it is difficult to guarantee the priority control. If the departure interval is too long, the passengers’ waiting time at the tram stop will increase, which reduces the capacity and service level. Therefore, the minimum departure interval is related to the traffic signal cycle of the intersection.
The minimum train departure interval at the intersection guarantees that no more than one tram arrives at the intersection in one cycle. The formulas are as follows:

\[ T_{\text{min}} = \max(t_{\text{1min}}, t_{\text{2min}}) \] (9)

\[ t_{\text{1min}} = C_{\text{max}} \] (10)

\[ t_{\text{2min}} = \begin{cases} \frac{v_{\text{max}}}{a'} + t_s + \frac{2L_w}{a} & L_w \leq \frac{v_{\text{max}}^2}{2a} \\ \frac{v_{\text{max}}}{a'} + t_s + \frac{v_{\text{max}}}{2a} + \frac{L_w}{v_t} & L_w > \frac{v_{\text{max}}^2}{2a} \end{cases} \] (11)

Where \( T_{\text{min}} \) represents the minimum departure interval of trams. \( t_{\text{1min}} \) represents the minimum train departure interval at the intersection. \( t_{\text{2min}} \) represents the minimum train departure interval at the tram stop. \( C_{\text{max}} \) represents the maximum signal cycle. \( t_r \) represents reaction time. \( t_s \) represents the time which the tram spend at the stop. \( a \) represents the acceleration of the tram. \( a' \) represents the deceleration of the tram. \( v_{\text{max}} \) represents the maximum speed of the tram. \( v_t \) represents the speed of the tram arriving at entrance of the intersection. \( L_w \) represents the length of the tram.

Therefore, the minimum departure interval of the tram can be expressed as follows:

\[ T_{\text{min}} = \max(C_{\text{max}}, t_{\text{2min}}) \] (12)

4. Case Study

4.1. Case Study

This study selects the modern tram line, and four adjacent intersections along the line in Huai’an city as the example. There are four lanes in the major approaches of the intersections, including two straight lanes, one right-turn lane and one left-turn lane. Minor approaches have three lanes, including one straight lane, one right-turn lane and one left-turn lane. The tramway is in the middle of the road.

![Figure 6. Layout of the tram line and intersections in the case](image)

| Intersections         | Spacing(m) | Number of Stops | Revised Spacing(m) |
|-----------------------|------------|-----------------|--------------------|
| Chuzhou Road—Huaxi    | /          | /               | /                  |
| Road                  |            |                 |                    |
| Chuzhou Road—Yonghuai Road | 505        | 0               | 505                |
The actual distance and the revised distance between intersections are shown in Table I. The average speed of the tram is 40km/h, and the average acceleration and deceleration is 3m/s².

According to the field investigation, each intersection is a 4-phase intersection. The phase diagram is shown in Fig.7. The signal timing scheme of each intersection is shown in TABLE II. The flow of each lane at the intersections is shown in TABLE III.

We select the cycle of the key intersection as the common period of the arterial, and then adjust the time of each phase according to the common cycle. The revised phase time is shown in TABLE IV.

According to the distance between each intersection and the green ratio, use the programming model to calculate the phase offsets. The results are shown in TABLE V. TABLE VI gives the evaluation indicators of the green wave scheme.

### TABLE II. THE SIGNAL TIMING SCHEME OF EACH INTERSECTION

| Intersections               | Phase 1 (s) | Phase 2 (s) | Phase 3 (s) | Phase 4 (s) | Yellow (s) | Cycle (s) |
|-----------------------------|-------------|-------------|-------------|-------------|------------|-----------|
| Chuzhou Road—Huaxi East     | 39          | 21          | 21          | 17          | 3          | 110       |
| Chuzhou Road—Yonghuai Road  | 35          | 22          | 25          | 14          | 3          | 108       |
| Chuzhou Road—Guantianpei    | 45          | 22          | 23          | 18          | 3          | 120       |
| Road—Nanxun Road            | 35          | 20          | 25          | 20          | 3          | 112       |

### TABLE III. TRAFFIC FLOW AT THE ENTRANCE OF EACH INTERSECTION

| Intersections               | Approach      | Traffic Flow (pcu/h) |
|-----------------------------|---------------|----------------------|
| Chuzhou Road—Huaxi East     | East Straight | 1386                 |
| Road | Right Turn | Left Turn | Straight |
|------|------------|-----------|----------|
| West | 400        | 236       | 1350     |
| North | 300        | 151       | 500      |
| South | 300        | 186       | 500      |
| Chuzhou Road—Yonghuai Road | 1281 | 222 | 610 |
| East | 369        |           |          |
| West | 1281       | 350       | 610      |
| North | 350        | 220       |          |
| South | 300        | 200       |          |
| Chuzhou Road—Guan Tianpei Road | 1440 | 200 | 1425 |
| East | 191        |           |          |
| West | 210        | 201       |          |
| North | 226        | 186       |          |
| South | 232        | 186       |          |
| Chuzhou Road—Nanxun Road | 1236 | 221 | 1260 |
| East | 395        |           |          |
| West | 400        | 221       |          |
| North | 300        | 276       |          |
| South | 590        |           |          |
| Intersections                  | Phase 1 (s) | Phase 2 (s) | Phase 3 (s) | Phase 4 (s) | Yellow Light (s) | Cycle (s) |
|-------------------------------|-------------|-------------|-------------|-------------|-----------------|----------|
| Chuzhou Road—Huaxi Road       | 43          | 23          | 23          | 19          | 3               | 120      |
| Chuzhou Road—Yonghuai Road    | 39          | 21          | 27          | 21          | 3               | 120      |
| Chuzhou Road—Guantianpei Road | 45          | 22          | 23          | 18          | 3               | 120      |
| Chuzhou Road—Nanxun Road      | 36          | 20          | 26          | 26          | 3               | 120      |

**TABLE V. THE PHASE DIFFERENCE OF EACH INTERSECTION**

| Intersections                  | Phase Offset Between Chuzhou Road—Huaxi Road (s) |
|-------------------------------|-----------------------------------------------|
| Chuzhou Road—Yonghuai Road    | 40                                            |
| Chuzhou Road—Guantianpei Road | 105                                           |
| Chuzhou Road—Nanxun Road      | 38                                            |

**TABLE VI. THE EVALUATION INDICATORS OF THE GREEN WAVE SCHEME**

| Intersections                  | Chuzhou Road—Huaxi Road | Chuzhou Road—Yonghuai Road | Chuzhou Road—Guantianpei Road | Chuzhou Road—Nanxun Road |
|-------------------------------|-------------------------|-----------------------------|-------------------------------|--------------------------|
| Green Ratio (%)               | 35.8                    | 32.5                        | 37.5                          | 30.0                     |
| Green Time Loss (%)           | 9.5                     | 9.5                         | 3.1                           | 8.0                      |
| Effective Green Ratio (%)     | 26.3                    | 23.0                        | 34.4                          | 22.0                     |

To ensure that no more than one tram arrives at the intersection in one cycle, set the tram departure interval as 300s. According to the ideal situation, set the tram speed to 40km/h, the social vehicle 60km/h.

4.2. *Simulation Results Analysis*

We established intersection model using VISSIM simulation software as shown in Fig.8, and used the VAP module to set the signal control type as the inductive control mode. Firstly, we made the
simulation without any optimization for the system. And then we simulated the system using tram priority strategies and arterial signal coordination. The software output the delay of the general traffic of main road and side-streets, and the average delay of trams. The results are shown in TABLE VII and Fig.9.

![Figure 8. Vissim simulation scenario](image)

As is shown in Fig.9, using priority strategies and arterial coordination can decrease the average delay of main road and the tram by 16.0% and 60.1% respectively. The average delay of side streets is increased by 14.8%.

| Measures          | Delay of Main Road | Average Delay of Trams | Delay of Side Streets |
|-------------------|--------------------|------------------------|-----------------------|
| No optimization   | 128.4              | 185.3                  | 46.1                  |
| With optimization | 107.9              | 73.9                   | 52.9                  |

![Figure 9. Comparison of delays before and after implementing priority strategies](image)

The implementation of the tram priority strategy increases the delay of the general traffic in side streets, but the reduction in the delay of general traffic on the main road is greater than the increase in
the delay of general traffic in the side streets. This method can reduce the delay of trams and the overall delay of general traffic.

5. Conclusion
According to trams’ characteristics, this study revised the formula for calculating the distance between intersections in the green wave programming model. The tram priority control strategy is proposed by combining the relative priority and the absolute priority together. The method for determining the position of detectors and the departure interval of trams are also proposed. The case study shows that the delay of general traffic on the main road and the trams will be reduced using tram priority strategies under the arterial coordination. The delay of traffic on the side streets will be slightly increased. But the overall delay of the system will be reduced. We should mention that the method of arterial signal coordination proposed in this paper is suitable for symmetrical signal-controlled intersections, and the tramway is in the middle of the road. Further studies can analyze tram priority control method in asymmetrical signal-controlled intersections and other complex layouts of the tramway.

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