Research on coordinated control optimization of adjacent intersections based on numerical solution

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Abstract. In order to improve the efficiency of traffic flow and reduce the delay of arterial intersections, a coordinated signal control method based on numerical solution is proposed. Firstly, considering the factors such as the shortest green time and saturation of a single intersection, the intersection delay model is established. Secondly, the traffic capacity of the trunk line is improved by optimizing the public cycle and the green ratio of each intersection. Finally, an optimization model with minimum delay as the optimization objective is constructed, and the signal coordination of arterial intersections is realized by taking Yancheng City as an example. The results show that the coordinated control model of adjacent intersections based on the numerical method can reduce the average vehicle delay of two-way vehicles, achieve the purpose of green wave coordinated control of road sections, and improve the road traffic capacity.

1. Introduction

The rapid development of China’s economy has brought a surge in traffic volume, so the coordinated control ability of urban road network is particularly important, and the intersection as the traffic fortress of the road network plays a very important role. Domestic and foreign scholars have done a lot of research on signal control at intersections.

The TRRL method is used to optimize the signal timing of the intersection, and the VISSIM simulation is carried out again. The traffic efficiency of the signal intersection is significantly improved[1]. Ye[2] optimized the signal of the intersection with comprehensive indicators such as total delay, number of stops, service level and fuel consumption, and effectively improved the overall service level of the intersection. Chen[3] used the green light extension method to reduce vehicle travel delays and passenger travel delays in the road network; Zhou[4] included the number of car stops into the optimization index for research; Zhang et al[5] established a microscopic road traffic flow model for the intersection and carried out simulation optimization to reduce the average waiting time; Shen et al[6] quantitatively evaluated the signal timing optimization effect of different timing optimization methods under different saturation states. Guo et al[7] used the webster method to optimize the signal timing of urban intersections, which reduced the longest queue length and delay time; Chen and Vieira et al[8-10] began to take the stop station into account to study the signal control delay at the intersection, and the optimized signal timing scheme reduced the total travel delay at the intersection.

The above studies all optimize the design from the perspective of intersection signal timing. However, less consideration is given to the study of road network coordination signal control. Therefore, this paper takes multiple adjacent intersections as control units to study the optimization of arterial coordination control. According to the basic principles of signal intersection control method and green wave control method, the arterial traffic volume and signal phase timing scheme are analyzed to determine the linkage control scheme of intersections, and finally achieve the purpose of reducing delays.

2. Optimization design of arterial coordinated control at adjacent intersections

In order to optimize the coordinated control ability of the road network, the total average vehicle delay of adjacent intersections is selected as the optimization control target. Based on the optimization design of signal timing at a single intersection, the signal timing is re-optimized by adjusting the common cycle of multiple adjacent intersections.

\[
\min \sum_{i=1}^{f} d_i
\]

In the formula, \( d_i \) represents the average vehicle delay at the \( i \)th intersection, \( s \).

The constraint condition is:

\[
\begin{aligned}
&\text{s.t.} & g & \geq g_e \\
& & 0.7 \leq x^i & \leq 0.9
\end{aligned}
\]

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In formula 2, \( g \) represents the green light time for each phase of the intersection, \( s \); \( g_e \) represents the effective green light time for each phase of the intersection, \( s \).

2.1. Car delay at a single intersection

The average delay formula is calculated by the following formula:

\[
\overline{d_i} = \frac{c(1 - \lambda^j)^2}{2(1 - \lambda^j x^j)} \frac{x^j}{2q_i^j (1 - x^j)}
\]  

(3)

In the formula, \( \overline{d_i} \) denotes the average vehicle delay of the \( i \)th phase \( j \) at the intersection, \( s/pcu \); \( J \) represents the total number of signal phases at the \( i_{th} \) intersection; \( x^j \) represents the saturation of the \( j_{th} \) phase of the \( i_{th} \) intersection; \( q_i^j \) represents the car flow at the \( j_{th} \) phase of the \( i_{th} \) intersection, \( pcu/h \); \( \lambda^j \) denotes the green ratio of the \( j_{th} \) phase of the \( i_{th} \) intersection.

The average delay of vehicles at intersections is represented as:

\[
d_i = \sum \overline{d_i} q_i / \sum q_i
\]  

(4)

2.2. Coordinated control optimization design of adjacent intersections

2.2.1. System period length

According to the inherent flow ratio relationship and signal loss time of each intersection, the cycle of each intersection is calculated, and then the largest cycle is selected as the cycle of the trunk system. The intersection is called the key intersection. If the cycle length of an intersection in other intersections is close to the alternative cycle, this cycle is re-selected as the premise of the trial calculation, and it is necessary to test whether the cycle can ensure the effective and safe operation of each intersection. The expression is as follows.

\[
C_i = \max C_j \quad (i = 1, 2, \ldots, I)
\]  

(5)

In the formula, \( C_j \) is the signal period of the key intersection, \( s \); \( C_i \) is the signal cycle length of the \( i_{th} \) intersection, \( s \); \( I \) is the total number of intersections.

For a single intersection, the current cycle can be actually measured. For the signal timing design, the Shanghai method is used for calculation. The technical methods used are as follows:

\[
C_i = \frac{1.5L + 5}{1 - Y}
\]  

(6)

In the formula, \( L \) represents the total loss time of the signal cycle of the \( i_{th} \) intersection, \( s \); \( Y \) represents the sum of the maximum flow ratios of all phases in the composition period:

\[
Y = \sum \max (y_j, y_{j'})
\]  

(7)

In the formula, \( y_j \) represents the ratio of the actual arrival flow to the saturated flow of the \( j_{th} \) phase, which is the maximum flow ratio of the \( j_{th} \) phase.

2.2.2. Time difference

Time difference, also known as phase difference, is indicated by the letter \( O_f \). The green time difference in the linkage control scheme mostly takes the green light as the starting point. In order to enable the vehicle to travel with less travel time when passing through the linkage control system, the timing scheme must be adjusted according to the green time difference, so the time difference is another important parameter to realize the linkage control of the road section.

3. Case study

3.1. Basic situation of the case

In order to further obtain the results to verify the feasibility of the model, the case selected Jiefang Road (Jianjun Road-Daqing Road section) as the research path, selected appropriate methods for traffic survey, including traffic volume survey, cycle survey, headway survey, etc., and basically processed the survey data. Due to the limited space of the paper, this section introduces the main information and the new results obtained after the adoption of the model.

3.1.1. Traffic census

The Jiefang Road in Yancheng City is selected as the research path of the trunk line, and the intersections of Jianjun Road-Jiefang Road (Int # 1 ), Xinximen Road-Jiefang Road (Int # 2 ), Yanche Road-Jiefang Road (Int # 3 ), Shuangyuan Road-Jiefang Road (Int # 4 ), Daqing Road-Jiefang Road (Int # 5 ) are used as control units to optimize the coordinated control of the trunk line.

The schematic diagram and flow of each intersection shown in figure 1 and in figure 2.

Figure 1. Schematic diagram of each intersection in Jiefang Road section.
3.1.2. Optimization situation

The basic method and process of signal timing at each intersection are simulated by VISSIM simulation. The delay of each intersection is obtained, and the performance index is compared and analyzed. The delay of the intersection before the optimized signal timing and the intersection of the optimized signal timing is calculated and recorded in figure 3.

Through the delay comparison of the line chart, it can be seen that the delay of each intersection of Jiefang Road (Jianjun Road-Daqing Road Section) is reduced after the optimal timing design. Under the premise of ensuring the smooth driving of the road section during the peak period, this scheme is the most reasonable, but it still needs the coordinated control scheme to further optimize the design.

3.2. Research on arterial coordinated control

By using the numerical solution method, the Jiefang Road is implemented with a linkage control scheme, and finally the delay data is compared and analyzed by VISSIM simulation.

3.2.1. Arterial intersection optimization scheme

Because the road is a two-way road, the numerical method is used to optimize the intersection of the main road, and the traffic signals of each intersection are connected to carry out linkage control. The 5th cycle of the intersection is the largest. As a key cycle, other intersections make corresponding adjustments (in table 1).

Table 1. The cycle length of each intersection of the trunk line after timing.

<table>
<thead>
<tr>
<th>Spacing (m)</th>
<th>Int # 1</th>
<th>Int # 2</th>
<th>Int # 3</th>
<th>Int # 4</th>
<th>Int # 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>90</td>
<td>90</td>
<td>80</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

The cycle time of Jianjun Road, Xinximen Road, Yanhe Road and Shuangyuan Road intersections are adjusted accordingly, and the timing is recalculated.

The key cycle is used to adjust the actual green time of each intersection, and the ideal signal time difference is determined by the numerical method, as shown in table 2.

Table 2. The numerical solution determines the ideal signal time difference (m).

<table>
<thead>
<tr>
<th>Spacing a</th>
<th>Int # 1</th>
<th>Int # 2</th>
<th>Int # 3</th>
<th>Int # 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>16</td>
<td>33</td>
<td>49</td>
<td></td>
</tr>
</tbody>
</table>

Thus, the ideal signal time difference is determined. According to the numerical solution table, the most suitable ideal signal spacing is 33. That is, when the ideal signal spacing takes the maximum value, the difference between the corresponding actual signal and the ideal signal is the minimum amount of movement from each signal intersection to the ideal signal. Finally, the green time difference is calculated, as shown in table 3.

Table 3. Green time difference calculation.

<table>
<thead>
<tr>
<th>Int # 1</th>
<th>Int # 2</th>
<th>Int # 3</th>
<th>Int # 4</th>
<th>Int # 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal signal</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Position of each signal</td>
<td>R</td>
<td>L</td>
<td>R</td>
<td>L</td>
</tr>
<tr>
<td>Green ratio(%)</td>
<td>31</td>
<td>30</td>
<td>30</td>
<td>38</td>
</tr>
</tbody>
</table>
According to the green time difference of the intersection, the timing scheme of the trunk intersection is continued to meet the requirements.

### 3.2.2 Performance evaluation of arterial intersection

Through VISSIM traffic simulation, the delay of the intersection linkage control scheme before and after optimization is obtained (in table 4), and the comparative analysis is carried out.

**Table 4.** Two-way delay table of arterial roads obtained by three different schemes.

<table>
<thead>
<tr>
<th>Timing plan</th>
<th>Delay(s)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N-S</td>
<td>S-N</td>
</tr>
<tr>
<td>Scheme 1</td>
<td>146.4</td>
<td>116.8</td>
</tr>
<tr>
<td>Scheme 2</td>
<td>144.5</td>
<td>113.7</td>
</tr>
<tr>
<td>Scheme 3</td>
<td>127.2</td>
<td>90.4</td>
</tr>
</tbody>
</table>

In the above table, 'Scheme 1' represents the delay of the road section caused by the original intersection timing scheme, 'Scheme 2' represents the delay of the two directions of the road section after the improvement of the single intersection timing scheme, and 'Scheme 3' represents the delay of the two directions of the road section after the improvement of the intersection timing scheme using the system cycle length re-adjustment in the arterial coordination control scheme.

Through the comparative analysis of the simulation data, it can be found that before the system cycle is not adopted, under the new signal timing scheme, the delays in both directions of Jiefang Road ( Jianjun Road-Daqing Road Section ) are reduced, and the delays at each intersection and road delays are reduced to a large or small extent. Although the service level of each intersection remains unchanged, the traffic capacity of each intersection is improved. After the system cycle is rescheduled, that is, the delay of the main road is reduced after the green wave coordinated control, which makes the delay of the whole road section greatly reduced, reflecting the necessity of the coordinated control of the main road section.

### 4. Conclusion

In this paper, the method of minimizing the average delay of the intersection and the two-way delay of the trunk line is proposed to optimize the green wave coordinated control. Compared with the intersection before the timing, the delay of each intersection is reduced. On this basis, according to the calculated green time difference, the timing scheme of each intersection of the trunk line is adjusted again. Through VISSIM simulation analysis, it is concluded that the two-way delay of the road section after coordinated control is much lower than that before linkage control. However, the impact of pedestrian crossing on motor vehicles has not been taken into account. In the future, intersection signal timing optimization design will be carried out to consider the impact of pedestrian crossing.

### Acknowledgments

This paper is one of the phased achievements of the university-level project “Introduction to Civil Engineering ‘Curriculum Construction Research’ (2022XK(J)05) of Nantong University of Technology”, “The research topic of education informatization in colleges and universities in Jiangsu Province ‘Innovative Research on Teaching and Learning Paradigm under the Background of Education Digitalization-Taking the Introduction to Civil Engineering Course as an Example’ (2023JSETKT123), and “The second batch of young and middle-aged backbone teachers training project of Nantong University of Technology (ZQNGGJS202209)”; “First-class undergraduate course of Nantong Institute of Technology(JWYK2020019)”; “The provincial Science and Technology Service Platform cultivation project of Nantong Institute of Technology(XQPT202102)” ; “Research on the path of improving students’ learning quality based on PBL concept(2023JG020)”.

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