A control sub-areas division method based on improved FN algorithm

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Abstract. In order to implement signal control more effectively and improve the operating efficiency of urban traffic systems, this paper proposes a control sub-area division method based on an improved FN division algorithm. Comprehensively consider the intersection spacing, link flow, traffic dispersion, signal cycle, link traffic state and other factors, respectively calculate the correlation degrees of link flow, the intersection signal cycle, the link traffic state of adjacent intersections. Then introduce the intersection correlation degree to improve the FN algorithm to divide the regional road network traffic district. Finally, the paper select the regional traffic data of Beijing’s road network to verify the model. The result shows that the sub-area division based on improved FN algorithm is more reasonable and effective.

1. Introduction
In the management and control of urban road network, due to the complexity and huge scale of the road network, effective management and control cannot be directly carried out. It is necessary to divide the intersections in the road network into different control sub-areas. Implementing targeted and refined coordinated control strategies for intersections in each sub-area can improve the traffic efficiency of the road network and reduce traffic delays.

The concept of traffic control sub-areas [1] was first proposed in 1971, and current research mostly uses correlation as the basis for dividing control sub-areas. Shen Guojiang et al. [2] classified the congestion levels of oversaturated intersections, based on the vehicle capacity ratio, the impact of the traffic demand and the length of the road on the correlation of the intersection, and proposed the dynamics sub-areas division strategy; Tian Xiujuan [3] improved the Newman algorithm and introduced the degree of intersection correlation to divide the road network of the traffic area. Lu Kai et al. [4] quantified the correlation degree of intersections, and established a calculation model for the correlation degree of adjacent intersections and the combination correlation degree of multiple intersections. Then based on this, they divided traffic sub-areas; Chen Shanshan [5] proposed a sub-areas division method based on self-organizing map neural network algorithm, combined with the selection of relevance-related dynamic indicators in the division process and the real-time identification of key intersections, realized the dynamic division of control areas. Tian et al. [6] comprehensively considered the influence factors such as travel speed, number of stops, link flows and intersection spacing, constructed a calculation model for the correlation between intersections in the road network area, and realized the
coordinated control of the intersection through heuristic algorithms. Lin Dan [7] selected the distance between two intersections in the traffic road network and the traffic flow per unit time to construct the edge weights, and divided the communities based on the weighted network.

In the above studies, indexes of the correlation are not comprehensive and the sub-areas division is rough; some model parameters lack the support of actual traffic data; the influence of road network topology on the division of control sub-areas is ignored. In this paper, a comprehensive correlation degree model is established and the traffic control area is divided by the improved FN algorithm.

2.Construction of comprehensive correlation degree model
Correlation degree quantitatively describes the relationship between two adjacent nodes and reflects the necessity of coordinated control between nodes. It is determined by static factors (intersection spacing) and dynamic factors (flow, cycle, queue length, dispersion, etc.). Considering the above factors, this paper proposes a comprehensive correlation degree calculation model.

2.1 The correlation degree of link flows
Whitson model [8] is the most widely used model in the calculation of correlation degree, as shown in equation 1. The model considers that when the correlation degree value is greater than 0.4, the two intersections should be classified into the same sub area; when the correlation degree value is less than 0.3, it is not necessary; when the correlation degree value is between 0.3 and 0.4, it depends on the actual traffic operation.

\[
I_{AB} = \frac{1}{2(1+T)} \left( \frac{nq_{\text{max}}}{\sum_{i=1}^{n} q_i} - 1 \right) \tag{1}
\]

Where \( I_{AB} \) is the correlation degree of link flows between adjacent intersections; \( T \) is the average travel time of vehicles(s); \( n \) is the number of traffic flows from upstream intersections to downstream intersections; \( q_{\text{max}} \) is maximum traffic flow from upstream intersections(pcu/h); \( \sum_{i=1}^{n} q_i \) is the total traffic flow of vehicles from the upstream intersection A to the downstream intersection B(pcu/h).

Whitson model only considers the influence of intersection spacing, road flow and average travel time of vehicles on the correlation value while ignoring the influence of the dispersion of traffic flow and different types of intersections. In view of this, this paper introduces the discrete coefficient and the number of vehicle flow directions \( n \) in the Robertson model [9] to improve the model.

\[
\theta = \frac{1}{2(1+\theta T_{AB})} \left[ \frac{nq_{\text{max}}}{\sum_{i=1}^{n} q_i} - (n - 2) \right] \tag{2}
\]

Where \( \theta \) is a constant whose value is between 0.1-0.15, and the value in this paper is 0.125 [10]; \( T_{AB} \) is the average travel time of the vehicle from intersection A to intersection B is 0.8 times [11] (s).

The traffic flow between the upstream and downstream of the intersection is bidirectional, and the difference in the degree of bidirectional correlation between each other should be fully considered. Therefore, the final flow correlation value should be the larger of the two directions:

\[
I_{AB} = \max(I_{AB}, I_{BA}) \tag{3}
\]

2.2 The correlation degree of intersection signal cycle
In addition, the signal cycle is also an important factor affecting regional coordinated control. Considering the coupling relationship between signal cycle duration and intersection correlation value [3,12], the correlation degree with intersection signal cycle is shown in formula (4).
\[ CI_{AB} = \frac{2}{\varphi - 1} \times \min \left\{ \left[ \varphi + 1 - \frac{\max (C_A, C_B)}{2 \min (C_A, C_B)} \right], 0.5 \right\} \quad (4) \]

Where \( CI_{AB} \) is the value of correlation degree of signal cycle, whose range is 0-1; \( \varphi \) is the maximum ratio of cycle length, generally 2; \( C_A, C_B \) is the cycle length of intersection.

### 2.3 The correlation degree of Link traffic state

In addition to the influence of intersection spacing, section flow, traffic flow dispersion and signal period on the correlation value, the difference of road traffic state mode is also an important indicator to reflect the change of correlation degree value. As an important parameter of traffic flow characteristics, link density describes the density of traffic flow on the road section, which can be used to quantitatively reflect the traffic state mode of the road section. Based on the existing research [3], the calculation formula of correlation degree value considering the mode of road traffic state is given:

\[ \omega_{AB} = \frac{\sum_{i=1}^{k} q_i}{kl} \quad (5) \]

\[ ZI_{AB} = \min \left[ \max \left( \frac{\omega_{AB}}{\omega_{AB}^A}, \frac{\omega_{AB}}{\omega_{AB}^S} \right), 1 \right] \quad (6) \]

Where \( ZI_{AB} \) is the correlation degree of Link traffic state and the value range is 0-1; \( \omega_{AB} \) and \( \omega_{AB}^A \) are the average number of vehicles between intersection A and B at the analysis stage and saturation stage respectively; \( k \) is the number of lanes; \( q_i \) is the number of vehicles in lane i; \( l \) is the length of the section.

### 2.4 Comprehensive correlation model

The three correlation degrees mentioned above are different in dimension. Therefore, a comprehensive correlation degree model for dynamic sub region division is constructed by using the dimensionless extreme value processing method [13], as shown in equations (7) and (8).

\[
\begin{align*}
I' &= (I_{max} - I) / (I_{max} - I_{min}) \\
CI' &= (CI_{max} - CI) / (CI_{max} - CI_{min}) \\
ZI' &= (ZI_{max} - ZI) / (ZI_{max} - ZI_{min})
\end{align*} \quad (7)
\]

\[ I^A = I' + CI' + ZI' \quad (8) \]

Where: \( I_{max}, CI_{max} \) and \( ZI_{max} \) are the maximum values of the correlation degrees of link flow, the intersection signal cycle, the link traffic state; \( I_{min}, CI_{min} \) and \( ZI_{min} \) are the minimum values of the three correlation degrees.

### 3. The sub-areas division method

Newman et al.[14] proposed fast Newman algorithm (FN algorithm for short) on the basis of GN algorithm, which is mainly aimed at community division of unweighted networks. Considering the correlation of intersections in the road network, this chapter introduces \( a \) as the weight of the connecting edge, and proposes a new sub-area division method.
3.1 FN algorithm

FN algorithm is based on the idea of greedy algorithm, whose core principle is to regard any node in the complex network as an independent community, and merge the nodes according to the direction of maximum modular increment. When all nodes in the network are merged, the algorithm ends and the tree view of node connection relationship corresponding to the maximum modularity is selected for segmentation, which is the optimal community division result [15]. Modularity is an expected value which is the value of $Tre$ minus $a_i$ after community division and can be obtained as follows:

$$Q = \sum_i (e_{ij} - a_i^2) = Tre - \| e^2 \|$$

(9)

$$\| e^2 \| = \sum_i a_i^2 = \sum_i \sum_j e_{ij}e_{ij}$$

(10)

Where $Q$ is the modularity, and the larger the value, the better the result of community division; $e_{ij}$ represents the ratio of the number of connected edges to the number of all edges in the community; $Tre$ represents the ratio of the number of connected edges of nodes within the same community to the number of all edges in the network, namely $Tre = \sum_i e_{ij}$; $a_i$ represents the ratio of the number of edges connected between a node in community $i$ and other community nodes to the number of all edges, namely $a_i = \sum_j e_{ij}$.

3.2 The sub-areas division method based on FN algorithm

In order to make FN algorithm suitable for weighted network partition [7], this section improves it on the basis of comprehensive consideration of the correlation degree between intersections, focusing on the modularity and auxiliary matrix element $E = (e_{ij})$ in the previous section of FN algorithm, and combining the correlation degree value between adjacent intersections, the edge weight between intersections in subarea division is constructed. The modularity after redefinition and the auxiliary matrix element in the improved FN algorithm are given by formula (11) and (12) respectively.

$$Q^{\text{weight}} = \sum_i (c_{ij} - v_i^2) = Tre - \| C^2 \|$$

(11)

Where $Q^{\text{weight}}$ is the improved modularity, $c_{ij}$ is the sum of edge weights of communities $i$ and $j$ and $\| C^2 \|$ is sum of all elements of matrix $C^2$.

$$e_{ij} = \begin{cases} 0 & \text{Others} \\ I_{ij} / \sum_{i,j} I_{ij} & \text{When nodes a and B are connected by edges} \end{cases}$$

(12)

Where $I_{ij}$ is weight of the connected edges of nodes $i$ and $j$.

Based on the above research, the detailed steps of the sub-areas division method based on FN algorithm are as follows:

1. Step1: calculate $I_{ij}$, the comprehensive correlation degree of adjacent intersections.
2. Step2: initialize road network area and construct auxiliary matrix $E = (e_{ij})$ and one-dimensional array $A = (a_i)$.
3. Step3: merge nodes connected by edges in the network and calculate the corresponding $\Delta Q$.
4. Step4: merge nodes along the direction where $\Delta Q$ is the largest and calculate the corresponding modularity.
5. Step5: add the rows and columns related to the merged community node to update element $e_{ij}$.
6. Step6: repeat steps 4 and 5 until all nodes in the network are merged into one community, then the
algorithm ends.

Step 7: output control sub-region division tree diagram, and select the division result when $Q^{\text{weight}}$ is the largest as the optimal division result.

4. Model validation
This paper selects the actual road network in a certain area of Beijing, China for simulation verification, which includes 16 intersections and 23 links. The road network structure topology is shown in Figure 1. This paper proposes three schemes to compare and verify the sub-areas division method based on FN algorithm. Scheme 1: Use the Whitson model to calculate the correlation degree according to formula (1), and divide the sub-areas according to the model threshold. Scheme 2: Use the traditional FN algorithm to divide the sub-area under the unweighted network. Scheme 3: Introduce the comprehensive correlation degree into the improved FN algorithm for sub-area division.

4.1 The traditional sub-region division result
The classic Whitson model is used to calculate the correlation degree value and the sub-areas are divided according to the correlation degree threshold. The road network is divided into four control sub-areas. The total correlation and the specific sub-areas division result are shown in Figure 2.

4.2 The sub-area division result based on FN algorithm
Without considering the weight, MATLAB software is used to divide the control sub area according to FN algorithm. The tree diagram of the node merging process is shown in Figure 3. The road network is divided into three control sub regions, and the specific sub area division result is shown in Figure 4.
4.3 The result of sub-area division based on improved FN algorithm

The comprehensive correlation degree of each node is calculated and introduced into the improved FN algorithm, and the tree diagram is shown in Figure 5. The road network is divided into 3 control sub-areas, and comprehensive correlation and sub-areas division result are shown in Figure 6.

4.4 Model validation

In this paper, average delay, average number of stops and road travel time are used as evaluation indicators to measure the effectiveness of the three control sub-areas division methods. First, the paper uses Vissim software to simulate the built road network area, outputs the simulation evaluation results before division. Then it uses the phase difference optimization method to coordinate the signal control of the divided road network according to the three sub-area division methods mentioned in the article, obtains the corresponding signal timing plan for each sub-area intersection and outputs the road network benefit evaluation results corresponding to sub-area division methods as shown in Table 1.

| Methods                  | Total travel time (h) | Total average delay at intersections (s) | Total parking times per vehicle |
|--------------------------|-----------------------|-----------------------------------------|-------------------------------|
| Before                   | 1310.5                | 394.9                                   | 8.05                          |
| Traditional division     | 1286.9                | 381.2                                   | 7.64                          |
| FN algorithm             | 1222.5                | 354                                     | 7.45                          |
| Improved FN algorithm    | 1214.7                | 301.7                                   | 7.16                          |

It can be seen from Table 1 that the total travel time, the total average delay at intersections and the average number of stops per vehicle in the road network after the division are reduced to a certain extent. The total travel time of the sections of traditional sub-area division, FN sub-area division and improved FN sub-area division has been reduced by 1.80%, 6.71%, and 7.31% respectively; the total average delay at intersections has been reduced by 3.47%, 10.36%, and 23.60% respectively; The average total number of stops decreased by 5.09%, 7.45%, and 11.06% respectively. The result shows that the three sub-area division methods are helpful to reduce the average delay of vehicles in the road network, reduce the travel time and average parking times of vehicles, and improve the overall traffic efficiency of the road network in different degrees. Moreover, the result of sub-area division based on improved FN algorithm is better.

5. Conclusion

In this paper, a comprehensive model of correlation degree is constructed to quantify the correlation between nodes. Then Based on the improved FN algorithm, a new method of traffic control cell division is proposed. Finally, the traditional sub district division, FN community division method and improved FN community division method are evaluated by three indicators of average delay, average parking
times and road travel time. The result shows that the improved FN sub area division method has a better effect and is more reasonable and effective.

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