Research Article

Urban Traffic Signal System Control Structural Optimization Based on Network Analysis

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Received 14 August 2013; Revised 24 October 2013; Accepted 3 November 2013

Academic Editor: Wuhong Wang

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Advanced urban traffic signal control systems such as SCOOT and SCATS normally coordinate traffic network using multilevel hierarchical control mechanism. In this mechanism, several key intersections will be selected from traffic signal network and the network will be divided into different control subareas. Traditionally, key intersection selection and control subareas division are executed according to dynamic traffic counts and link length between intersections, which largely rely on traffic engineers' experience. However, it omits important inherent characteristics of traffic network topology. In this paper, we will apply network analysis approach into these two aspects for traffic system control structure optimization. Firstly, the modified C-means clustering algorithm will be proposed to assess the importance of intersections in traffic network and furthermore determine the key intersections based on three indexes instead of merely on traffic counts in traditional methods. Secondly, the improved network community discovery method will be used to give more reasonable evidence in traffic control subarea division. Finally, to test the effectiveness of network analysis approach, a hardware-in-loop simulation environment composed of regional traffic control system, microsimulation software and signal controller hardware, will be built. Both traditional method and proposed approach will be implemented on simulation test bed to evaluate traffic operation performance indexes, for example, travel time, stop times, delay and average vehicle speed. Simulation results show that the proposed network analysis approach can improve the traffic control system operation performance effectively.

1. Introduction

Advanced urban traffic signal control systems normally use multilevel hierarchical control mechanism to simplify the network control process. In this mechanism, several key intersections of traffic network will be selected and the network will be divided into several control subareas in which the signal of intersections will be optimized according to the traffic states variation of key intersections. In 1971, Walinchus [1] firstly built the concept of "traffic control subarea." Stockfish [2], Pinell et al. [3] and Kell and Fullerton [4] proposed the guideline for computer signal system selection based on intersection traffic state analysis, road segment length, vehicle arrival rate, and so forth. Yagoda et al. [5] and Chang [6] defined the traffic control index and threshold value of algorithm for traffic control subarea division. However, they have not considered the characteristics of dynamic traffic network topology, and typical advanced traffic signal

control systems like SCOOT [7] and SCATS [8] normally executed the "control subarea division" and "key intersection selection" based on traffic counts and link length between intersections. In practice, this configuration process relies on the experience of traffic engineers [9, 10]. It is difficult to assure the reasonability and effectiveness of the system control structure configuration because of lack of reliable theoretical support.

Generally traffic network can be represented as a weighted network graph, where an intersection corresponds to a node, a road segments to a link, and traffic flow parameters of the segments (like traffic flow, link length, travel time, etc.) to link weight. This type of weighted network has typical topology characteristics like nonhomogeneous and scale-free. However traditional traffic signal system structure configuration does not consider these characteristics. It is necessary to apply traffic network analysis method to reduce the uncertainty of traffic network control configuration and

ensure the process of key intersection selection and subarea division.

Recently, there are several papers and research results in this area. In aspect of key node assessment, several approaches can be referred, for example, the betweenness method, node deletion method, node contraction method, network nodes nearness and neighborhood key degrees assessment, and so forth [11, 12]. In aspect of network subarea division, it is found be similar with the network community discovery. Although there are several community discovery algorithms have been developed, to the best knowledge of authors, there is still lack of direct findings on how to realize the control structure optimization for traffic signal networks. For example, K-L algorithm [13] needs to know the size of the two communities; spectrum bisection method [14] can only divide the network into odd communities; G-N algorithm [15] cannot confirm the suitable iteration process easily while amount of the community structure is unknown; and W-H algorithm [16] is mainly used to dig the community structure that contains designated nodes.

In this paper, we will improve the network analysis approaches and apply them into traffic signal control field, especially using modified C-means clustering method for node assessment and improved community discovery algorithm for control subarea division. In Section 2, traffic network will be abstracted as network graph and typical indicators of network graph are introduced. In Section 3, traffic signal intersection importance assessment will be implemented by the C-means clustering approach. And then community discovery algorithm will be applied to the implementation of traffic signal network subarea division in Section 4. Finally, experiment conducted by SCOOT system and VISSIM simulation platform will be constructed to compare and verify the effectiveness of network analysis approach based on real traffic data of Beijing city.

2. Traffic Network Modeling

As mentioned above, urban traffic network can be abstracted as a weighted graph in which the intersection corresponds to a node, the road section to a link, and the link length to the link weight. Based on this type of weighted network graph, the following indicators will be used in this paper.

- (1) Node connectivity (i.e., node degree) $\langle k \rangle$: the number of links connecting to node k .
- (2) Node betweenness $C(i)$: the ratio of the number of the shortest path crossing the node i to all the shortest paths between the nodes in the network:

$$C(i) = \sum_{s \neq t \neq i} \left[\frac{g_{st,i}}{n_{st}} \right], \quad (1)$$

where $g_{st,i}$ indicates the number of the shortest paths through node i between node s and node t and n_{st} is the number of all the shortest paths between node s and node t .

- (3) Network module degree Q :

$$Q = \text{Tr}(E) - \|E^2\|, \quad (2)$$

where E is a symmetrical matrix with elements E_{ij} representing the ratio of the number of links connecting community i and j to the number of whole network links, and $\|E^2\| = \sum_i \sum_{j,k} E_{ij} E_{ik}$; $\text{Tr}(E)$ is the trace of matrix E .

3. Traffic Network Node Importance Assessment Based on Clustering

It is known that weighted network normally has typical non-homogeneous and scale-free characteristics, which means that the importance of each node in traffic network is different. Existing network nodes importance assessment methods are basically derived from graph theory and need to be improved for traffic control application. In traffic engineering fields, we normally describe the signal intersection as “key,” “important,” “general,” “unimportant,” and other types. Therefore, we select C-means clustering method [17] to classify the traffic intersections of network.

C-Means clustering method can be used to classify the nodes of network into different categories and describe the degree of node in each category. The basic ideas of the clustering process can be described as follows: assume the cluster centers and calculate distance from each node to the centers; adjust the cluster centers according to the sum of distance until the clustering process meets minimize conditions.

Specifically, suppose that there are n samples $X = \{x_1, x_2, \dots, x_n\}$, where $x_k = (x_{k1}, x_{k2}, \dots, x_{km})^T \in R^m$, $k = 1, \dots, n$ is the eigenvector of sample x_k ; c , $2 \leq c \leq n$ is the number of categories that all samples will be divided into; $P = (p_1, p_2, \dots, p_c) \in R^{m \times c}$ constitutes a cluster prototype matrix, where $p_i = (p_{i1}, p_{i2}, \dots, p_{im})^T \in R^m$ is the i th clustering prototype; $U = (\mu_{ik})_{c \times n} \in R^{c \times n}$ is a matrix with elements $\mu_{ik} \in [0, 1]$ meaning the degree of sample x_k to p_i ; then the objective function of clustering can be expressed as

$$\min J_b(U, P) = \sum_{k=1}^n \sum_{i=1}^c (\mu_{ik})^b (d_{ik})^2, \quad (3)$$

$$\text{s.t.} \quad \sum_{i=1}^c \mu_{ik} = 1, \quad k = 1, 2, \dots, n,$$

where b is a flexible parameter in $[1.5, 2.5]$ and d_{ik} represents Euclidean distance between x_k and p_i .

It is obvious that the type of data samples is important for clustering. In traffic network, the data samples for assessments of intersection not only need to reflect the static topology characteristics, but also need to contain the information of dynamic traffic flow. In this paper we select three typical indicators to form the data samples of each network node.

- (1) Node connectivity $\langle k \rangle$ reflects the characteristics of the topology of the node.
- (2) Node betweenness $C(i)$ reflects the control ability of nodes among the network traffic flow dissemination.
- (3) Node traffic flow in rush hour reflects the dynamic traffic counts variation and capacity of the intersections.

FIGURE 1: Traffic control network of wangjing area in Beijing. (a) Map of control network. (b) Topology graph of traffic signal network.

TABLE 1: Intersection importance evaluation index (18:00-19:00, October 17, 2011).

No. of node	Intersection name	Node degree	Node traffic flow	Node betweenness
1	Nanhuxiyuan South	2	1933	0.0023
2	Futongxidajie South	2	3123	0.0116
3	Wangjingxilu-Jinyuguoji	2	2971	0.0105
4	Nanhu-Zhongyuan Ertiao West	2	3234	0.0128
5	Wangjingxilu-Nanhuzhongyuan	3	2557	0.0302
6	Huguang Beijie West	3	3410	0.0372
7	Heyin West	3	1918	0.0418
8	Wangjing Xilu North	3	2249	0.0221
9	Lizexierlu	3	1311	0.0035
10	Lizexi Street	3	1676	0.0279
11	Nanhu Beilu North	3	3573	0.0232
12	Huguangbei Street	3	7067	0.0232
13	Huguangzhongjie East	3	5012	0.0256
14	Hongtaixijie West	4	6828	0.0383
15	Heyinzhonglu West	4	6642	0.0476
16	Lizezhongjie West	4	6325	0.101
17	Wangjing Beilu-Guangshunbeidajie	3	5034	0.0604
18	Lizezhongyilu	3	3197	0.0139
19	Lizezhongyilu South	3	2154	0.0116
20	Lizezhongerlu	3	3812	0.0186
21	Lizezhongjie	4	2632	0.0453
22	Xiyangzhonglu Mid	4	1173	0.0778
23	Heyinzhong	3	2213	0.1626
24	Hongtaixi Street	2	3384	0.0383
25	Hongchang Road	3	1588	0.0581
26	Hongchang Peds	2	1634	0.0767
27	Wangjingxiyuansanqu Peds	2	1856	0.072
28	Furongjie-Fuanlu	1	1188	0.0023
29	Wangjingjie-Fuan	3	3249	0.1463
30	Fuanlu-Futongxidajie	2	2855	0.0778
31	Fuanlu-Guofengbeijing	1	813	0.0023
32	Lizedongerlu	3	1587	0.0232
33	Lizedong Street	4	1070	0.1498
34	Lizedongerlu South	3	1645	0.0581
35	Xiyang East	2	1177	0.0035
36	Wangjing Beilu East	3	842	0.0302

Then, the node assessment algorithm can be described by the following steps.

Step 1 (parameter settings). The data sample x_k includes three items: node degree $\langle k \rangle$, node betweenness $C(i)$, and rush hour traffic counts. Let category factor be $c = 3, 4$ corresponding to different number of node categories. To realize the advantages of clustering, let index $b = 2$, iteration termination threshold $\varepsilon = 0.001$, initial iteration counter $t = 1$ and then produce a prototype model of clustering $P^{(t)}$.

Step 2. Calculate the partition matrix $U^{(t)} = \{\mu_{jk}^{(t)}\}$. For for all i, k , if $\exists d_{ik}^{(t)} > 0$, there are $\mu_{ik}^{(t)} = \{\sum_{j=1}^c [(d_{ik}^{(t)} / d_{jk}^{(t)})^{2/(b-1)}]\}^{-1}$; if $\exists i, r$ such that $d_{ir}^{(t)} = 0$, there is $\mu_{ir}^{(t)} = 1$; and when $j \neq r$, there is $\mu_{ij}^{(t)} = 0$.

Step 3. Update cluster prototype matrix $P^{(t+1)} = \{p_i^{(t+1)}\}$, $p_i^{(t+1)} = (\sum_{k=1}^n (\mu_{ik}^{(t)})^b \cdot x_k) / (\sum_{k=1}^n (\mu_{ik}^{(t)})^b)$.

Step 4. If $\|P^{(t)} - P^{(t+1)}\| < \varepsilon$, the algorithm stops and outputs partition matrix U and cluster prototype P ; otherwise let $t = t + 1$ and turn to (2). Normally $\|\cdot\|$ can use F -norm; that is,

$$\|P^{(t)} - P^{(t+1)}\|_F = \sqrt{\sum_{i=1}^m \sum_{j=1}^c (p_{ij}^{(t)} - p_{ij}^{(t+1)})^2}.$$

4. Traffic Control Subarea Division Based on Community Discovery

In this paper, using the network module degree in (2) as assessment indicator, we modify Newman cohesion community discovery [18] approach for traffic control subarea division. The division algorithm can be described as follows.

FIGURE 2: C-means result with $c = 3$. (a) Node cluster distribution, (b) Plane projection of betweenness and traffic flow indicators.

FIGURE 3: C-means result with $c = 4$.

Step 1. Divide the traffic network diagram into N communities which means that each node represents one community. The initial E_{ij} and the sum a_i of its rows of matrix E satisfy

$$a_i = \frac{k_i}{2m},$$

$$E_{ij} = \begin{cases} \frac{1}{2m}, & \text{if there exists link between } i \text{ and } j \\ 0, & \text{otherwise,} \end{cases} \quad (4)$$

where k_i is the degree of node i and m is the total number of links in the network.

Step 2. Merge the communities that contain links and record the increment of the network module degree $\Delta Q = 2(E_{ij} - a_i a_j)$. Merging should be executed along the direction that can make ΔQ toward maximum values. Then, renew E_{ij} and add the ranks and rows related to the community i and j .

Step 3. Repeat Step 2 until the whole network merges into one community.

Step 4. Consider the dendrogram of community structure and select the max module degree. Then, determine the optimal division of network community.

5. Experiment

5.1. Traffic Network Modeling. Choose Wangjing area in Beijing illustrated in Figure 1(a) as test bed to evaluate the effectiveness of above proposed traffic control network structure optimization methods. The abstracted weighted network graph can be referred to in Figure 1(b).

5.2. Experiment Traffic Data Collection. On the basis of traffic raw data in October 17, 2011 from Beijing Traffic Management Bureau, we calculate the indexes of node degree, nodes betweenness, and node rush hour (18:00-19:00) traffic flow as shown in Table 1. The calculation process follows steps as follows.

- (1) Calculate the node degree of each node according to the weighted network topology.
- (2) Calculate the weight of sides of each segment according to the link length, the distance matrix D between the nodes, and the shortest distance R . Then acquire the number of each node in the shortest distance matrix to calculate the betweenness of each node.
- (3) Count the vehicle flow data in rush hours and calculate the flow rate for each intersection.

5.3. Intersection Importance Assessment. Apply C-means clustering algorithm described in Section 3 to get network nodes importance clustering. Figures 2 and 3 show the cluster distribution as $c = 3$ and $c = 4$, respectively, in which x -axis

FIGURE 7: Control subarea division of Wangjing network based on community discovery.

FIGURE 8: Control subarea division of Wangjing network based on distance and traffic flow.

node 16, node 24, and node 32 as the key nodes as big points shown in Figure 4 and bold in Table 1.

5.4. Traffic Control Subarea Division. Complete the community merging process mentioned in Section 4 and record the value of module degree Q at each step. The variation curve is shown in Figure 5 in which the horizontal axis represents the combination times and the vertical axis represents the module degree.

From the module degree change curve in Figure 5, we can see that the 17th calculation corresponds to the maximum value of network module degree $Q = 0.5843$, which means that when $n = 17$, we can get the best community discovery division of network. The result of proposed community discovery is shown as Figure 6 and the corresponding division of traffic control subarea of Wangjing network is shown as in Figure 7. It is necessary to mention that there are two key traffic intersections selected in Section 5.3 locating in the same control subarea. For this situation, we need to decide the right one according to the requirement of practice.

5.5. Traffic Simulation. To test the effectiveness of network analysis approach, a hardware-in-loop simulation environment has been built as the following steps: (1) construct the traffic network simulation of Wangjing area based on VISSIM simulation platform and (2) implement online real-time control on road network with PC-SCOOT system. To avoid the influence of signal control algorithm to different control structure configuration, the same traffic signal control algorithm has been applied in simulation with traditional configuration based on distance between intersections and node traffic flow shown as Figure 8 and proposed configuration by this paper as Figure 7.

Configure the simulated road network using PC-SCOOT system as the following steps: (1) set the SCOOT system structure by traditional method and proposed method separately; (2) assign the control subareas and the intersections Modern and IP address utilizing the DBAS commands; (3) make configuration to each intersection in detail; (4) set the simulated intersection model with IP address, phase information, and detector information of signal controller utilizing VB software based on VISSIM COM interface; (5) set traffic detectors at Wangjingxi Road and Guangshunbei Street (as shown in Figure 8) in VISSIM model and input traffic data. Then, three different traffic demand inputs: 300 veh/hour/lane, 600 veh/hour/lane, and 1000 veh/hour/lane, have been loaded separately into the network to simulate the traffic state in low hour, flat hour and rush hour of one day.

Tables 2 and 3 show the traffic operation performance comparison of SCOOT system based on traditional approach and proposed network approach. In Table 2, the SCOOT system based on proposed method achieves better operation performance during low hour, flat hour, and rush hour. Specially, the travel time from North to South of Wangjingxi Road average decreased by 3.1% and from South to North of Wangjingxi Road average decreased by 7.3%; the travel time

TABLE 2: Average travel time of Wangjingxi Road and Guangshunbei Street (s).

	Wangjingxi Road		Guangshunbei Street	
	N to S	S to N	S to N	N to S
Low hour				
Traditional method	293	213	254	204
Proposed method	292	191	189	210
Decrease	-0.34%	-10.32%	-25.59%	2.94%
Flat hour				
Traditional method	254.76	227.64	322.92	191.50
Proposed method	254.72	212.16	221.04	198.29
Decrease	-0.0157%	-6.8%	-31.54%	3.55%
Rush hour				
Traditional method	292.46	216.57	339.24	210.51
Proposed method	267.43	205.96	218.31	205.96
Decrease	-8.56%	-4.9%	-35.65%	-2.16%
Average decrease	-3.1%	-7.3%	-31.41%	-1.35%

from South to North of Guangshunbei Street decreased by 31.41% and from North to South decreased 1.35%.

In Table 3, traffic network performance has been improved based on proposed configuration method, in which the network average stop delay decreased by 12.5%, the network average stops decreased by 19.61% and the network average speed increased by 11.74%. It is obviously verifying the availability and feasibility of the proposed approach in this paper.

6. Conclusion and Future Research

Traditional key intersection selection and control subarea division method for advanced traffic signal control system do not consider the inherent characteristic of topology structure of the traffic network. In this paper, we use three different indexes based on network analysis to integrate the network topology structure indicators with traffic flow conditions which reflect the characteristic of the network from both static and dynamic aspects. It is more reasonable in theoretical analysis and traffic engineering in practice. Moreover, the advanced community discovery methods are applied to establish or adjust the traffic network control structure before the traffic signal control system come into operation where the proposed approach does not change their original system control strategy and signal optimization algorithm. In our traffic simulation research, compared to traditional method, the proposed control structure optimization approach will obviously decrease the travel time and stops of the test area. It really provides strong support for the application of this network control structural optimization in traffic signal network control.

However, the following issues still need to be aware of in future research: how to achieve more reasonable concordance between key node assessment and control subarea division in practice; whether the dynamic division of subcontrol area

TABLE 3: Wangjing traffic network simulation performances.

	Average stop delay (s)	Average stops	Average delay (s)	Average speed (km/h)
Low hour				
Traditional method	78.115	2.192	113.105	34.221
Proposed method	74.518	2.203	109.349	34.663
Decrease	-4.6%	-0.50%	-3.32%	1.29%
Flat hour				
Traditional method	99.04	4.574	185.926	27.222
Proposed method	89.91	4.056	144.688	30.878
Decrease	-24.76%	-51.84%	-41.19%	27.33%
Rush hour				
Traditional method	117.599	7.454	278.869	21.689
Proposed method	108.882	7.025	246.971	23.565
Decrease	-7.41%	-5.76%	-11.44%	8.65%
Average decrease	-12.5%	-19.61%	-19.42%	11.74%

is feasible and how to actualize this process; whether the stability of the network traffic control system will be affected after network analysis approach is applied.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This paper was supported by China National Natural Science Foundation (51308005), Scientific Research Project of Beijing Education Committee (PXM2013_014212_000029, 000031, 000028, KM20111009011), the Importation and Development of High-Caliber Talents Project of Beijing Municipal Institution (CIT&TCD201304002), and China National 863 High Technology Plan (2012AA112401).

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