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Dynamic partition of urban network considering congestion evolution based on random walk

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The successful application of perimeter control of urban traffic system strongly depends on the macroscopic fundamental diagram of the targeted region. Despite intensive studies on the partitioning of urban road networks, the dynamic partitioning of urban regions reflecting the propagation of congestion remains an open question. This paper proposes to partition the network into homogeneous sub-regions based on random walk algorithm. Starting from selected random walkers, the road network is partitioned from the early morning when congestion emerges. A modified Akaike information criterion is defined to find the optimal number of partitions. Region boundary adjustment algorithms are adopted to optimize the partitioning results to further ensure the correlation of partitions. The traffic data of Melbourne city are used to verify the effectiveness of the proposed partitioning method.

Keywords: urban road networks, dynamic partitioning, random walk, Akaike information criterion, perimeter control

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1. Introduction

Congestion control is crucial for the efficient functioning of urban traffic system.[1] Geroliminis and Daganzo verified that, although the flowoccupancy data of single detector is highly discrete, when all data of detectors in a reasonably large network are aggregated, the traffic flow and occupancy relationship can be fitted into a curve with a small degree of dispersion, called as macroscopic fundamental diagram (MFD).[2] For large road networks, the heterogeneity of traffic flows in the road network will lead to excessive dispersion in the shape of MFD, which can hinder the successful implementation of traffic control. Therefore, Ji and Geroliminis proposed to partition highly heterogeneous road networks into sub-regions with homogeneous traffic flow properties.[3] They first divided the road network using the N-cut algorithm initiated from image segmentation. Then the sub-regions are optimized using the merging and boundary adjustment algorithms. Following their work, other image segmentation algorithms such as community detection[4] and seed region growth[5] were also applied to road network partitioning. Guo evaluated six hierarchical partitioning techniques based on three agglomerative clustering methods, namely single linkage clustering (SLK), average linkage clustering (ALK), and complete linkage clustering (CLK).[6]

Present researches were mainly focused on static partitioning. To alleviate congestion, the perimeter control of congested regions in urban road networks was intensively discussed. Most work of perimeter control were carried out based on a static partitioning of urban regions.[7,8] Due to the fact that traffic congestion will evolve and propagate in the network,[9] the partitioning result at a certain time may no longer be applicable at the next moment.[10] It is necessary to dynamically partition the road network into regions. But traditional partitioning methods like N-cut cannot ensure the correlation between continuous partition results. Saeedmanesh and Geroliminis proposed an "SNAKE" algorithm to link congested road together.[11] Saeedmanesh *et al.* used a mixed integer linear optimization model combined with heuristic partitioning algorithms to find traffic sub-regions with uniform flow levels.[12] Yan *et al.* developed a dynamic partitioning method based on Moran's I index with the evolution/ spatiotemporal correlation of traffic flow.[13]

A dynamic partitioning method should ensure the correlation of congestion partition to provide a stable background for perimeter control. Hamedmoghadam *et al.* proposed a perimeter control with dynamic boundaries based on percolation theory.[14] Ding *et al.* proposed to expand the boundaries of targeted region based on density similarity.[15] However, with most of existing partitioning methods, the continuity of successive results cannot be well guaranteed. Moreover, when the problem comes to multi-regional control, the number of subregions should be optimized. Meanwhile, if congested sub-

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regions were not defined, so that all subregions need boundary adjustment, making subsequent perimeter control difficult to implement.[16] Therefore, dynamic partition of urban network remains an open question and needs further consideration.

This paper proposes a novel dynamic partitioning method considering congestion evolution based on random walk algorithm. A modified random walk algorithm (MRWA) is developed to achieve reliable dynamic partitioning result while ensuring the correlation of partitioning results over time. The position of random walker for congested region is fixed at the location of congestion from early morning. By this means, the partitioning method provides a reliable and correlated result of dynamic partitioning throughout the investigated period.

Compared to the works in literature, the main contributions of this paper include the following: (i) A modified random walk algorithm is introduced to consider the congestion evolution over time, while keeping a small variance in link densities of the congested region. (ii) Congested sub-regions are defined, so as to reduce the number of sub-regions that needs boundary adjustment. (iii) A modified Akaike information criterion (MAIC) is also defined to find the optimal number of partitions.

The remaining of this paper is organized as follows. Section 2 presents the methods for static and dynamic partitioning. Section 3 presents the partitioning results of Melbourne city center network. Finally, Section 4 presents the conclusion remarks.

2. Dynamic partition considering congestion evolution

Traffic congestion evolves in urban system by the dynamics of traffic flow. It is affected by multiple factors, such as traffic demand, road network topology, drivers' route choice behavior, etc. In general, congestion will first appear in a CBD road section in early morning, and gradually propagates to surrounding neighborhood. In order to mitigate congestion, the congested region should be precisely detected. In the literature, various algorithms have been applied in the preliminary partitioning of road networks.[3,17,18] The random walk algorithm has been applied to various fields, including image segmentation.[19] One advantage of random walk algorithm lies in that it can maintain correlation of partition results over time, because the result will strongly depend on the initial location of random walkers. When the locations of random walkers are properly chosen, the shape of congested partitions will be similar and correlated.

The goal of partitioning is to divide the road network into multiple homogeneous sub-networks. Specifically, the following requirements for partitioning are proposed: (i) minimize the variance of vehicle speed or density in each subregion; (ii) maximize the difference in vehicle speed or density between sub-regions; (iii) internal connections within subregions and boundaries have a smooth shape.[3] In order to meet these requirements, we improve the algorithm to make the sub-regions smoother and correlated over time:

(I) For the positions of random walkers, the congested nodes with high eigenvector centrality are selected. Meanwhile, a non-congested node is selected to ensure that non-congested sub-regions can be identified.

(II) A modified Akaike information criterion (MAIC) is proposed to find the optimal number of subregions.

The method is described as follows. Construct a graph $G = (V,E)$, where V is the set of nodes and E is the set of edges, where each node represents a road-segment, while edges represent the neighboring relationships. The density of road-segment in the network is represented by node weight d_i. The shortest distance between two nodes i and j is denoted as $r(i,j)$. The weight $w(i,j)$ of link (i,j) reflects the similarity or difference between node i and node j:

$$w(i,j) = \begin{cases} \exp(-(d_i - d_j)^2), & r(i,j) = 1, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where it decreases exponentially with density difference $(d_i - d_j)$.

In the morning, the congestion begins at some road segments and evolves. Importantly, certain road segments are always congested at certain times (e.g., during on or off duty). Inspired by this, the nodes with high centrality of eigenvectors are selected as the beginning of congest partitions, while other nodes are also selected to ensure the dispersion of random walkers. For instance, the partitioning can start with selecting a congested node, and a non-congested node.

In the process of partitioning, it is important to determine the number of sub-regions. If the subregion number is too large, although the density variance within each subregion is minimized, the perimeter control will be difficult to implement. On the other hand, if the subregion number is too small, the congested area will be large and inhomogeneous. In order to find the optimal number of subregions, a modified Akaike information criterion is proposed here. Akaike raised the criterion in the research of information theory.[20] Here we modify the criterion as

$$\text{MAIC} = 2m + 2\ln(V) + P(m), \tag{2}$$

where m is the number of partitions, V is the cumulative sum of the node density variances in congested areas, and $P(m) = \lambda m$ is the penalty function. The minimum value of MAIC corresponds to the optimal number of partitions. When there is a significant variance in the densities, the second term on the right hand of Eq. (2) will be the largest. When there is no significant variance of densities, the first term and the penalty function will be larger. Therefore, MAIC can maintain a balance between density variance and the number of partitions.

Then the network is divided based on the probability of reaching the random walker. The task can be modeled as a discrete Dirichlet problem.[19] The preliminary partitioning can be described as follows. First mark the random walkers X_{M}, then compute the probability that all the unmarked points X_{U} in the undirected graph first randomly wander to a differently marked point, and then take the label s as corresponding to the largest probability of the classification to which the point belongs.

In the above step of preliminary partitioning, the number of subregions can exceed the number of random walkers. Therefore, it is necessary to merge sub-regions. In practice, the sub-region with the closest average node density is selected to join its neighboring sub-regions. Merging ends until the number of sub-regions is equal to the number of random walkers.

Traffic control should be implemented on the sub-regions that contain congested road sections. Therefore, congested sub-regions should be defined. Here the congested sub-regions are defined as the sub-regions with the normalized node density greater than or equal to 0.7. After the preliminary partitioning, the sub-regions should be adjusted to further smooth the boundaries.[3] To decrease the complexity, only the boundary of congested subregions is adjusted.

Finally, the quality of partitioning is measured by normalized total variance (TV_{n}).[11] Here normalized total variance (TV_{n}) is defined as the ratio between the total variance of the partitioned and unpartitioned networks. Smaller TV_{n} values imply a larger improvement gained by partitioning.

$$TV_{\mathrm{n}} = \frac{\sum_{i=1}^{N_{\mathrm{s}}} N_{A_i} \times \mathrm{var}(A_i)}{N \times \mathrm{var}(A)}, \tag{3}$$

where $A = \bigcup_{i=1}^{N_{\mathrm{s}}} A_i$ denotes the whole set of clusters, N_{A_i} denotes the number of links in cluster A_i, N is the total number of links in the network, and $\mathrm{var}(A_i)$ denotes the variance of the speed (or density) of all links belonging to cluster i.

3. Results and discussion

The CBD area of Melbourne is selected as our research subject (later called the city center). The government of Melbourne collects and shares the traffic data on the locations of traffic lights of the city center. As density of road segment cannot be directly measured by detectors, this value can be approximated by the space-effective mean length l_{m} of a car. Here this value is assumed to be $l_{\mathrm{m}} = 6.3$ m. The results of MRWA-merging-boundary adjustment are compared with the Ncut-merging method of Ji and Geroliminis.[3]

We use traffic data for a certain working day in February 2023. The data were collected since 6:30 AM when congestion occurred, and the data are updated every 30 minutes. Figure 1 shows the density profiles of the road network at $t = 6:30$ AM, 7:00 AM, 7:3 AM, and 8:00 AM (denoted as $t = 0$, $t = 30$, $t = 60$, and $t = 90$, respectively). One can see that, the network is less congested at $t = 0$ (6:30 AM). At $t = 30$ (7:00 AM) and $t = 60$ (7:30 AM), congestion gradually developed and propagates. At $t = 90$ (8:00 AM), the congestion spread widely.

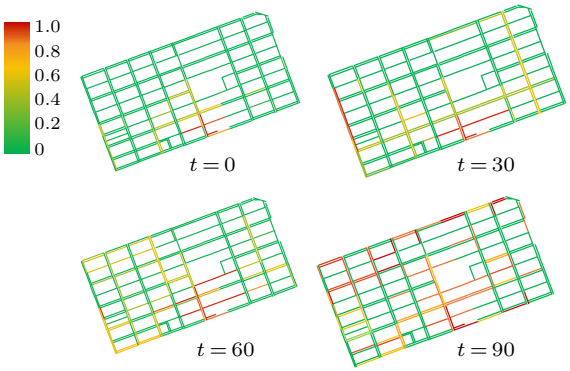


Fig. 1. Road network density for four consecutive moments.

We first show the partitioning result of $t = 0$ (6:30 AM). In Fig. 2, we show results of optimal number of partitions based on the minimum MAIC, and the minimum average NS value.[3] One can see that, the optimal number of partitions obtained by both algorithms is 2 for $t = 0$ (Fig. 2(a)).

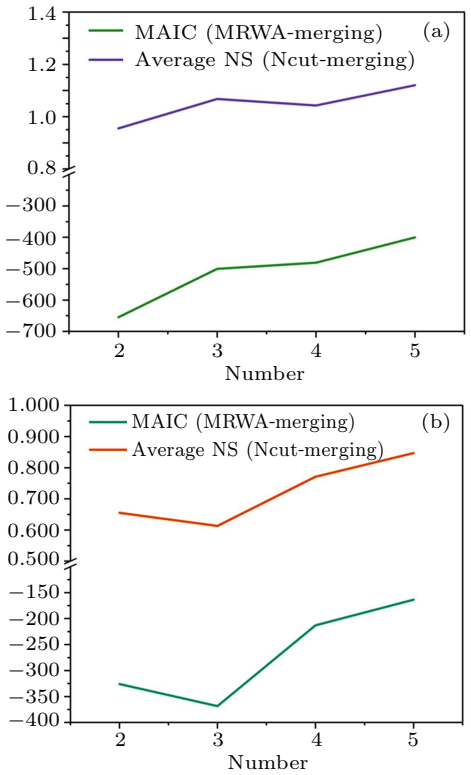


Fig. 2. Quality comparison of different algorithms at $t = 0$ (a) and $t = 90$ (b).

Figure 3 shows the partitioning results of MRWA-merging, Ncut-merging, and MRWA-merging-adjustment. In the result of MRWA merging, subregion 1 (A_1, marked as red) is a congested region, while A_2 is non-congested. Next, the boundary of congested subregions is adjusted. The results are

shown in Fig. 3(d). One can see that the results of MRWA-merging are better than those of Ncut-merging in terms of smoothness of the boundary and lower value of normalized total variance TV_n (as shown in Table 1). The last row of Table 1 shows the variances after the boundary adjustment. The variance of A_1 is further reduced by 0.00282, while the variance of A_2 (the non-congested) increased slightly by 0.00087. Since the traffic control focused on the congested subregion, the increase of variance in the non-congested region will not affect the efficacy.

Table 1. Density variance of sub-regions at $t = 0$.

	var(A_1) (red)	var(A_2) (blue)	Total variance	TV_n
Ncut-merge	0.13231	0.01452	0.14683	0.83
MRWA-merge	0.8583	0.1534	0.10117	0.76
MRWA-merge-adjust	0.8301	0.01621	0.9922	0.74

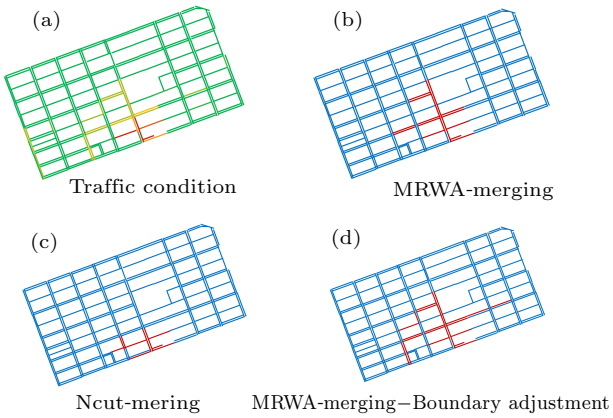


Fig. 3. Partition result of sub-regions at $t = 0$.

At $t = 90$ (8:00 AM), congestion in the road network is more complex than the first three moments (Fig. 4(a)). The optimal number of partitions for both MRWA-merging, and Ncut-merging methods is 3 (Fig. 2(b)). Figures 4(b) and 4(c) show the partitioning results respectively. Table 2 shows the variances of MRWA-merging and Ncut-merging results. The variance of node density of all three subregions partitioned by MRWA-merging is lower than that of Ncut-merging. Meanwhile, the value of TV_n is also lower. Figure 4(d) shows the result of MRWA-merging-adjustment. Also shown in Table 2, the total variance after the boundary adjustment is further reduced by 0.01618.

Figure 5 shows dynamic partitioning results of MRWA-merging from $t = 0$ (6:30 AM) to $t = 90$ (8:00 AM). The sizes of the congested subregion (A_1, marked as red) at $t = 0$ (6:30 AM), $t = 30$ (7:00 AM), and $t = 30$ (7:30 AM) change with the propagation of the congestion and the position of the random walker, but still maintain a high degree of overlap. The results demonstrate good continuity, with minimal variation within sub-regions. This confirms the efficacy of the partitioning process.

At $t = 90$ (8:00 AM), as congestion develops and density heterogeneity increases, the optimal number of partitions becomes 3. Even through there is a change of partition number, the congested region (A_1, marked as red) remains similar for $t = 60$ (7:30 AM) and $t = 90$ (8:00 AM).

Table 2. Density variance of sub-regions at $t = 90$.

	var(A_1) (red)	var(A_2) (blue)	var(A_3) (green)	Total variance	TV_n
Ncut-merge	0.14356	0.08622	0.06591	0.29569	0.84
MRWA-merge	0.13471	0.0934	0.6346	0.28851	0.8
MRWA-merge-adjust	0.13047	0.08017	0.6169	0.27233	0.78

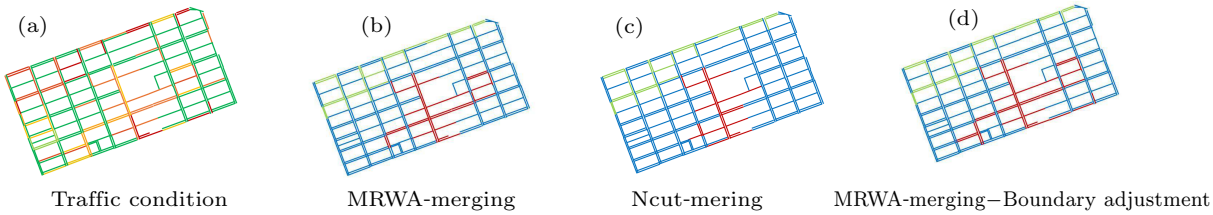


Fig. 4. Partition results of the sub-regions at $t = 90$.

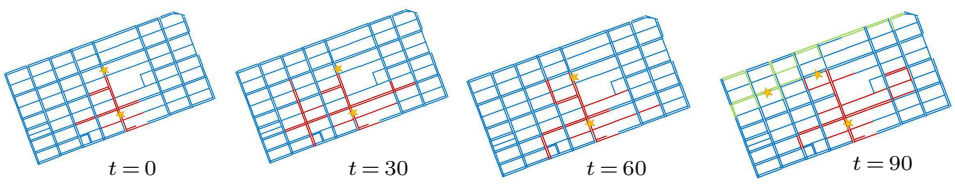


Fig. 5. Dynamic MRWA-merging partition results, with stars showing random walkers' initial positions.

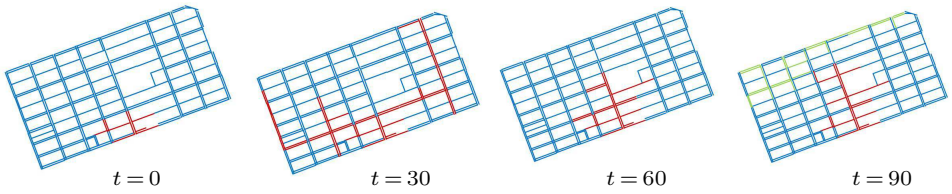


Fig. 6. Nut-merging partition results of four continuous moments.

Figure 6 shows the results of Ncut-merging partitioning. The results show a relatively small overlap between successive times. The congested subregion will not have continuously varying MFDs. This will greatly increase the difficulty of dynamic perimeter control.

4. Conclusion

In summary, a dynamic partitioning method of road networks with good continuity is proposed based on the modified random walk algorithm (MRWA). A modified Akaike information criterion (MAIC) is also defined to determine the number of sub-regions. Compared with traditional methods like the Ncut algorithm, the proposed method shows better partitioning results, displaying smaller variance of density within the congested region. Although this paper did not investigate the propagation of congestion, it is expected that the method can benefit the successful implementation of dynamic perimeter control over urban networks.

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