A Recognition Method of Ring Pattern in Road Networks Based on Graph Theory

Xiaojie Cui¹, Xianyong Gong¹,*, and Qi Zhang¹
¹Information Engineering University, Zhengzhou 450001, China
* Corresponding author: gongxygis@whu.edu.cn

Abstract. As a kind of typical structural knowledge, the spatial pattern is important to cartographic generalization, multi-scale representation, and spatial data matching. In an urban road network, the global ring is a common pattern, which represents a closed, circular ring that surrounds the city center. To overcome the deficiency in multi rings recognition, a two-step method for global ring patterns is developed in this paper. Preliminary rings are extracted based on the angle and deflection side of the connected road segments. Moreover, global rings are selected from the preliminary rings based on the index of compactness. Simulated and actual road network data are used to validate the proposed algorithm. The results show that the proposed algorithm is capable of recognizing global rings with multi-layer conditions in urban road networks.

1. Introduction
Spatial pattern recognition involves mining structural knowledge that conforms to human spatial cognition from basic geographic data, which can effectively improve the availability of spatial data (i.e., data enrichment). It has drawn more and more attention to the researchers in the fields such as cartographic generalization, multi-scale representation, location query and navigation, and urban structure analysis [1-6].

The urban road networks are the skeleton of the city, which contain rich and multilevel spatial patterns such as Grid, Ring, Star, and Stroke [3, 4, 7]. The large rings that surround a city centre, referred to as global rings in this study, can be frequently observed in cities [8]. However, few studies have focused on this topic. Heinzle et al (2006) described how to extract circular roads with three steps: determination of the central meshes, aggregation of the meshes, and selection of the meshes to compose the ring [8]. This algorithm enables the detection of rings with arbitrary shapes and different sizes. Xie and Levison (2010) defined ring patterns from the perspective of graph theory and extracted the largest circuit block from the arterials as the motor rings [9]. However, when several nested rings (multi-layer rings) exist, these approaches do not work.

Although current research has shown that the global ring is a closed structure formed by connected roads on a macro scale [8-9], vagueness exists in the definition of the global ring. Based on Gestalt theory, when the shape of a closed structure is a circle or approximate circle, it can be referred to as a global ring (e.g., Chengdu and Moscow). However, if the shape is a rectangle, this closed structure should be referred to as a global grid (e.g., Beijing and Manhattan). Due to the differences in the formation cause and the distribution characteristics, the recognition algorithms of the global grid and global ring are different from each other.
This study focuses on the global ring pattern and develops an automatic recognition method based on graph theory. This method involves two key steps. First, the angle and deflection side of road segments are calculated, and the preliminary rings are extracted. Second, the global rings are selected by index of compactness ($C_t$).

2. Extracting preliminary rings

Preliminary ring extraction refers to recognizing all possible rings composed of road segments. According to the continuity, common direction and closure of the Gestalt visual perception, two characteristics are summarized for the ring pattern: the first is that adjacent road segments are smoothly connected, and the second is that the closed structure formed by the road segments should have high convexity. Furthermore, the preliminary rings are identified based on the angle priority strategy and the deflection priority strategy.

2.1 Extraction parameters

Two parameters are employed in preliminary ring extraction, including the angle and the deflection side of connected road segments.

2.1.1 Angle $\theta$ of road segments

$\theta$ refers to the angle formed by the intersection point of two connected road segments and their endpoints ($\theta=[0^\circ, 180^\circ]$), as shown in Fig. 2(a). Fig. 2(b) shows the relationship between angle $\theta$ and the shape of the closed structure. The larger the angle is, the higher the direction consistency is, and the higher probability that a closed structure form a circle is.

![Fig. 1: (a) Geometrical significance of the angle $\theta$; (b) Relationship between angle $\theta$ and the shape of the closed structure.](image1)

2.1.2 Deflection of road segments.

For two sequentially connected road segments, the deflection refers to the deflection side of the succeeding road segment relative to the preceding road segment. Three types of the deflection side exist, including left, right, and collinear, as shown in Fig. 2(a).

![Fig. 2. Illustration of the deflection side: (a) Three types of deflection sides; (b) Calculation example of consistency of deflection side.](image2)
In a convex shape, the connected road segments should have the same deflection side—either all left sides or all right sides. Thus, determining the consistency of the deflection side is a key step in preliminary ring extraction. The specific method is described as follows.

In Fig. 2(b), \(AB, BC, \) and \(CD\) are three sequentially connected road segments. If the following equation is satisfied,

\[
(\overrightarrow{AB} \times \overrightarrow{BC}) \cdot (\overrightarrow{BC} \times \overrightarrow{CD}) < 0
\]

then the deflection side from road segment \(AB\) to road segment \(BC\) is opposite of that from road segment \(BC\) to road segment \(CD\), i.e., the deflection sides are inconsistent; otherwise, the deflection sides of the three road segments are consistent.

2.2 Extraction algorithm

The extraction algorithm describes the connecting rules and strategies of the road segments based on the two previously mentioned parameters. As shown in Fig. 1(b), the shape looks more like a circle with a smaller angle \(\theta\). Thus, the threshold \(\delta_{01}\) must be the minimum angle that forms a ring. In the ideal situation, road segments with an angle \(\theta\) higher than \(\delta_{01}\) and consistent deflection sides can form a circular ring, as shown in Fig. 3(a). However, there might be some road segments with opposite deflection sides in an actual ring, as shown in Fig. 3(b). The reason for permitting an inconsistent deflection side in a ring is that the angles of these road segments are large enough to be considered collinear. To improve the practicality of the extraction algorithm, another threshold \(\delta_{02}\) (\(\delta_{02} > \delta_{01}\)) is employed in the extraction rules. When \(\theta > \delta_{02}\), the deflection of the adjacent road segments are consistent when forming a ring.

![Fig. 3. Situations of the road segments to form a ring: (a) Ideal situation; (b) Actual situation.](image)

According to the previously mentioned connected rules, three types of road segments exist when composing a ring:

- **Type I**: road segment that has a \(\theta\) that is greater than \(\delta_{02}\) with the preceding road segment;
- **Type II**: road segment that has a \(\theta\) that is greater than \(\delta_{01}\) but smaller than \(\delta_{02}\) with the preceding road segment and an unchanged deflection side.
- **Type III**: road segment that has a \(\theta\) that is greater than \(\delta_{01}\) with the preceding road segment and an unchanged deflection side.

Based on the priority of the road segment type, we designed two strategies for extracting the preliminary rings, namely, the angle priority strategy and the deflection priority strategy. In the angle priority strategy, type I road segments are searched first; if no type I road segments exist, type II road segments will be searched. In the deflection priority strategy, type III road segments are searched first; if no type III road segments exist, type I road segments will be searched.

A step-by-step method is employed to extract preliminary rings. The following steps are performed:

- Establish the adjacency matrix of road segments;
- Calculate the deflection side of the road segment, which is in the adjacency list of the starting segment and has the largest angle with the starting segment, and note the result as SideTag0;
- Search for adjacent road segments based on the angle priority, add the identification number (ID) of each road segment that satisfies the conditions to the list SegIDList, and sequentially repeat until no road segments satisfy the conditions or all road segments are closed;
- Search for adjacent road segments based on the deflection priority, add the ID of each road segment that satisfies the conditions to the list SegIDList1, and sequentially repeat until no road segments satisfy the previous conditions or all road segments are closed;
If the endpoint of the ending road segment in the list SegIDList (or SegIDList1) is the same as the starting point of the starting road segment, record the list SegIDList (or SegIDList1).

### 2.3 Thresholds of the extraction parameters

In the preliminary ring extraction, the values of $\delta_{\theta_1}$ and $\delta_{\theta_2}$ are determined as follows. We divide the angle interval $[0^\circ, 180^\circ]$ into six sections on average, namely, five key values of 30°, 60°, 90°, 120°, and 150° exist within the angle range. Referring to [10], the threshold $\delta_{\theta_1}$ is set to 120° to ensure good continuity (angle consistency) of the road segments. The threshold $\delta_{\theta_2}$ should be greater than $\delta_{\theta_1}$, and it is set to 150° in this study. As shown in Fig. 2(b), when the angle of two segments is larger than 150°, the angle consistency is sufficient for neglecting the deflection side when forming a ring.

### 3. Shape filtering of rings

Due to the complexity of the spatial distribution of actual road networks, the preliminary rings extracted using the previously mentioned algorithm may have shape variations (e.g., stretching and local sharp corners). Thus, the degree of compactness ($C_t$) is used to describe the degree of similarity between a preliminary ring and a standard circle. $C_t$ is calculated as

$$C_t = \frac{A}{\pi P^2}$$

where $A$ and $P$ are the area and the perimeter of the preliminary ring. $C_t$ falls in the interval $[0, 1]$. The higher $C_t$ is, the more distinct the circular characteristics of the preliminary ring will be.

Referring to the $C_t$ of regular polygons ($C_t$ (square)=0.785 and $C_t$ (regular pentagon) = 0.864, respectively) and considering the diversity in the road networks, the threshold of $C_t$ ($\delta_{\text{ct}}$) is set to 0.8. When $C_t < \delta_{\text{ct}}$, the preliminary ring has a relatively high level of shape variation, and thus, cannot be a global ring.

### 4. Experiments

To fully illustrate the effectiveness and applicability of the proposed algorithm, simulated and actual road network data (Chengdu, China) are employed. The experiments were conducted in the Visual Studio programming environment.

#### 4.1 Simulation demonstration

The simulated data consists of 508 road segments and presents a complex ring pattern. Fig. 4(a) and (b) presents the simulated data and the ring pattern in human eyes. By using the extraction method, six preliminary rings are searched, as shown in Fig. 4(c). Furthermore, the compactness of preliminary rings was calculated. The results are summarized in Tab. 1. We can see that, ring I has a $C_t$ of 0.662, which suggests a relatively high degree of shape abnormality. Thus, there are 5 global rings recognized by this method. A comparison of Fig. 4(b) and 4(d) shows that our algorithm recognized the same global rings as those recognized by human eyes.

![Fig. 4: (a) Simulated data; (b) The human interpretation results; (c) Results of the preliminary ring; (d) Results of the global ring pattern.](image)
Table 1. The $C_t$ results of the preliminary rings in simulated data.

| ID | $C_t$ | ID | $C_t$ |
|----|-------|----|-------|
| I  | 0.662 | IV | 0.949 |
| II | 0.955 | V  | 0.952 |
| III| 0.926 | VI | 0.939 |

4.2 Case study

Fig. 5(a) presents the road network in Chengdu, which exhibits a typical ring-layered distribution pattern. According to the traffic planning map (in Fig. 5(b)), there are 5 concentric rings totally. From the 2,641 road segments, we extracted 7 preliminary rings, as shown in Fig. 5(c). And then, the $C_t$ index was calculated and we summarized the results in Tab. 2. The VII ring has a lower $C_t$ of 0.711 and can’t be selected as a global ring, so there are 6 rings in the final recognized results, as shown in Fig. 5(d).

Table 2. The $C_t$ results of the preliminary rings in Chengdu.

| ID | $C_t$ | ID | $C_t$ |
|----|-------|----|-------|
| I  | 0.889 | V  | 0.963 |
| II | 0.943 | VI | 0.948 |
| III| 0.822 | VII| 0.711 |
| IV | 0.935 |

Comparison of Fig. 5(b) and Fig 5(d) shows that the global rings by our method might contain the local rings like III. This is because we only consider one factor—the shape, for the global rings. According to [8], the global ring always surrounds the city centre. Therefore, besides the compactness, the centrality of the ring location and the activity degree within the ring should be considered for the global characters of the ring pattern in the next.

Fig. 5: (a) Road networks of Chengdu; (b) Constructed rings in Chengdu; (c) Results of the preliminary rings extraction; (d) Results of the global rings.

4.3 Discussions

Two angle thresholds $\delta_{\theta 1}$ and $\delta_{\theta 2}$ are employed in this preliminary ring extraction algorithm, which substantially affect the results: the smaller $\delta_{\theta 1}$ and $\delta_{\theta 2}$, the higher the probability that the connected road segments will form a ring. Fig. 6 shows the results of the comparative experiments conducted with different parameter values based on the simulated data.
Fig. 6. Preliminary rings by different parameter thresholds: (a) $\delta_{\theta1}=110$, $\delta_{\theta2}=150$; (b) $\delta_{\theta1}=120$, $\delta_{\theta2}=150$; (c) $\delta_{\theta1}=130$, $\delta_{\theta2}=150$; (d) $\delta_{\theta1}=120$, $\delta_{\theta2}=140$; (e) $\delta_{\theta1}=120$, $\delta_{\theta2}=150$; (f) $\delta_{\theta1}=120$, $\delta_{\theta2}=160$.

The results in Fig. 6 (a)-(c) demonstrate that when $\delta_{\theta1}$ is low, extra preliminary rings without practical significance are recognized; as the threshold increases, the number of extracted preliminary rings decreases. The extraction results remain unchanged whether the value of $\delta_{\theta2}$ is greater or smaller than 150°, as shown in Fig. 6 (d)-(f). This finding implies that $\delta_{\theta1}$ is more sensitive than $\delta_{\theta2}$ for the preliminary ring extraction. We recommend that the extraction parameters be set as follows: $\delta_{\theta1}=120^\circ$ and $\delta_{\theta2}=150^\circ$. In a practical application, a tolerance of 5–10° can be set for $\delta_{\theta1}$ to moderately increase the accuracy.

5. Conclusions

The recognition of global ring patterns in road networks is of great importance to multi-scale representation and urban structure analysis. A two-step recognition algorithm based on graph theory is proposed in this study. We apply this algorithm to simulated road networks and Chengdu road networks to test its performance. The experimental results reveal that the proposed algorithm is capable of extracting rings with multi-layer. Further research will focus on the centre pattern recognition, thus to comprehensively measure of the global characters of the ring pattern by estimating centrality of the ring location and the activity degree within the ring.

References

[1] W. Mackaness, G. Edwords, Proceedings of the Joint ISPRS/ICA Workshop on Multi-scale Representations of Spatial Data. (Ottawa, 2002)
[2] S. Steiner, Enabling Pattern Aware Automated Map Generalization. (University of Zurich, Zurich, 2007)
[3] F. Heinzle, K. H. ANDERS, Generalization of Geographic Information: Cartographic Modeling and Applications. 233-253 (Elsevier Ltd, 2007).
[4] Q. Zhang, Proceedings of ICA Workshop on Generalization and Multiple Representation. (Leicester, 2004)
[5] B. Yang, X. Luan, Q. Li, Computers, Environment and Urban Systems, 34(1), 40-48 (2010)
[6] X. Gong, F. Wu, Geocarto International, 33(2), 1-45 (2016)
[7] S. Marshall, Streets & patterns. (SponPress, London, 2005)
[8] F. Heinzle, K. H. Anders, M. Sester, Proceedings of the 4th Geographic Information Science. 153-167 (Münster, 2006)
[9] F. Xie, D. Levinson, Geographical Analysis, 39(3), 336-356 (2010)
[10] M. Yang, T. Ai, Q. Zhou, Acta Geodaetica et Cartographica Sinica, 42(4), 581-587 (2013)